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TECHNICAL AND ORGANIZATIONAL CONDITIONS OF DESIGNING WAREHOUSES WITH DIFFERENT FUNCTIONAL STRUCTURES

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Abstract

The article presents a discussion on designing warehouse facilities and processes as a part of logistics systems. The main technical and organizational conditions of designing and modelling warehouses as well as internal and external factors influencing warehouse operation are presented. The stochastic nature of these factors is indicated. In the next part, a six-piece model of the warehouse facility is presented and discussed. The model embraces spatial conditions of the object and hierarchical division of space for functional reasons, internal transport subsystem with its resources, warehousing process and a set of organizational assumptions for modelling and designing.
Typical elements of warehousing process, classification of warehouses due to their functions and tasks, functional classification of warehouse facilities, technological and organizational conditions of designing warehouse facilities, warehouse designing loop, the determinants of warehouse designing, the elements of the model of a warehouse, functional structure of a warehouse, warehousing process, internal transport system, logistics task, work organization rules and informatics system are presented in the paper.

Keywords: *warehouse designing, warehousing, logistics system design, modelling*

1. Introduction

Principles of designing warehouses (storage facilities) are analysed by theorists (like: [1-3, 7 or 19, 23]) and practitioners of business applications of engineering ([4 or 5]). The diversity of issues related to implementation of warehousing processes is determined by business, types of handled materials, customer requirements, etc. Currently, due to technological and process advantages and increasing market requirements, customers expect above-standard services and minimize operating costs, increased safety and reliability of processes. The fulfilment of these requirements depends on several technological and organizational factors.

PN-84/N-01800 standard defines warehouse as “a functional and organizational” unit intended for the storage of material goods (inventory) within a separated area of the warehouse building under specified technology. It is equipped with appropriate equipment and technical means, managed and operated by skilled people. Storage of material goods is a part of warehousing process. The quoted Standard defines warehousing process as a set of ordered, monitored and archived steps consisting of receiving, buffering, storage, order picking, handling, maintenance and shipping materials” (Fig. 1).

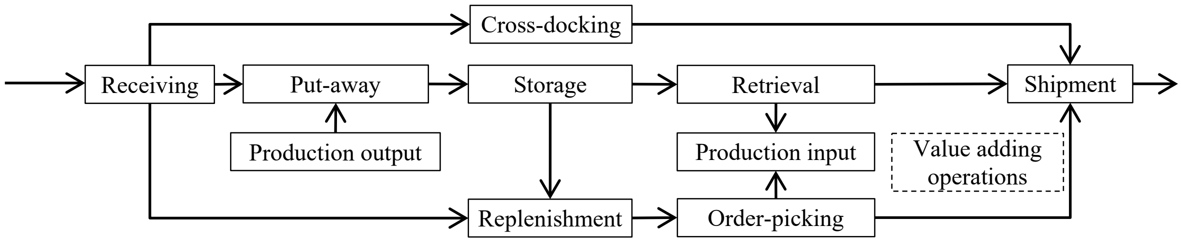

Fig. 1. Typical elements of warehousing process

Warehousing process contains also other operations adding value to the products. The final form of a process is dependent on warehouse functions and tasks realized for a supply chain.

The definition of warehouse and warehousing process identifies designing areas, and hence applications of modelling tools. Modelling tools supporting the designing may be helpful in achieving higher productivity and lower labour costs of the proposed facility. Different classes of models developed for designing purposes are used to optimize work organization, increase storage and handling capacities, plan space and select appropriate technologies and lower costs. The models relate to the following issues (cf. [5, 12]):

- data analysis (formulating logistics task, warehouse activity profiling, audit, data mining),
- selection of storage technologies in accordance with structure of material flows,
- spatial configuration of functional areas,
- warehouse inventory planning and ordering strategies,
- organization and scheduling of warehousing process,
- allocation of resources (equipment and manpower) to warehousing tasks,
- modelling areas and processes of receiving and put-away,
- modelling work processes in functional areas (like reserve area),
- modelling areas and processes of picking and shipping,
- slotting,
- space configuration (different perspectives),
- additional processes (cross-docking, value adding processes, etc.),
- safety of work and materials,
- functional reliability (different perspectives).

The above list of issues is not exhaustive, but demonstrates the complexity of storage facilities. Practically all of these issues are considered separately or in slight conjunctions, but they are rarely worked out all in a complex project. Therefore, the paper proposes a comprehensive approach engaging all designing issues. A holistic approach to the problem allows for a comprehensive assessment warehouse operation under supply chain requirements while operation costs are claimed as a primary factor in the development of logistics infrastructure.

2. Classification of warehouses due to their functions and tasks

Warehouse designing requirements result from their place and role in logistics network. Warehouses are buffering (regulating) elements of supply chains, directing and transforming material flows. Apart from that, warehouses fulfil tasks adding value to the products and increase their availability. All warehouses, despite of the type and purpose, dispose functional areas for buffering (long- and short-term storage), and internal transport and transhipment systems. The use of other functional areas responsible for advanced material transformations and division depends on warehouse functional classification (Fig. 2).

Warehouses are engineering structures designed for storage of material stocks. The design maximally takes into account vulnerability of stocks. Storage facilities are characterized by high diversity resulting from following grounds ([13, 14, 18 or 22]):

- types of materials and their vulnerability for handling and storage,
- storage period (inventory turnover),
- readiness for mechanized handling,
- mechanization and automation of warehouse processes.

Thus, each warehouse facility is characterized by specific:

- design parameters – including dimensions, permissible loads, shape or functional layout,
- operational parameters – disposed surface and volume of space (total, for storage or handling) capacity, productivity, specified internal transport technologies.

Fig. 2. Functional classification of warehouse facilities

Apart from features presented in Fig. 2 warehouse facilities can be divided also according to the following ([4, 6, 14]):

1) technical and construction solutions and the vulnerability of warehouse inventories:
   - open storages (storage yards),
   - semi-open storages (shelters, sheds, etc.),
   - closed storages:
     - on-ground (storey or multi-storey buildings, low, medium and high storage, with or without loading ramps),
     - underground (basements, bunkers), special warehouses for flammable and explosives materials, cold stores, silos, etc.
2) the level of warehousing processes mechanization: non-mechanized (manual), mechanized and automatic,
3) functions and economic destination.

Technical equipment of warehouses has a significant impact on the implementation of logistics processes in supply chains (compare [4, 12, 13, 16, 18, 20-22). The high quality material flows, inventories security, performance of handling processes, machinery and transportation equipment, and other depend on:

- size and role that the warehouse,
- type of material and their transportability and storage vulnerability,
- packaging forms – logistics units,
- storage methods,

- material handling methods,
- methods and types of maintenance and packaging operations,
- type of protection against damage, fire, explosion, natural conditions, etc.

Technical equipment of a warehouse includes machinery and transport equipment, storage equipment and constructions and ancillary equipment. In addition, storage facilities are equipped with loading ramps or docks adapted for transhipments with trucks, trailers or rail carts.

3. Technological and organizational conditions of designing warehouse facilities

3.1. Designing procedure

Designing warehouse facility of any functional structure is a looped process consisting of several basic steps (Fig. 3). The procedure also includes operation and logistics controlling stages that are the basis for the identification of development needs and determining the scope of future projects.

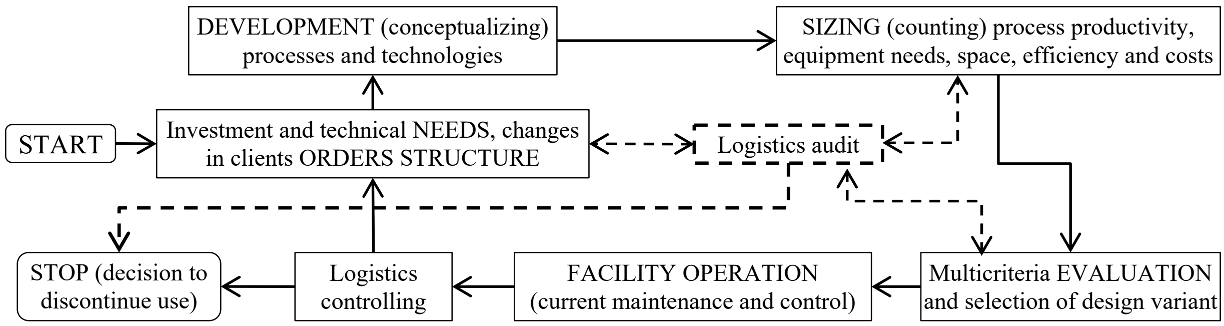

Fig. 3. Warehouse designing loop

All presented design stages need specific tools supporting design work, such as models, algorithms, comparative databases and computer applications with simulation tools to support the rationalization of design solutions. The details of presented procedure are discussed in [4] or [10].

3.2. The determinants of warehouse designing

Factors determining warehouse design can be of two types:

- external – resulting from surroundings and working under specified supply chains, and
- internal – resulting from technologies and organization of warehousing process.

External factors are associated with randomness of the intensity and structure of material flows on the warehouse input and output, as well as the variability of offered assortment. The structure of material flow processed in a warehouse reflects the structure of client orders. Client orders and offered assortment of products are dependent on market conditions. Timely and correct execution of customer orders is therefore essential constraint of warehouse operation. This in turn makes warehouse dependent on external time windows of deliveries and shipments and efficiency of transport services and production capacities of subordinated and superior elements of supply chain.

Quality and quantitative characteristics of deliveries and shipments are changeable and cannot be exactly predicted in long term. This necessitates using medium flow volumes, which result in an under-performance of the logistics facility or near maximum values causing overestimation of installed potential. The ability to response non-standard enforces is an essential criterion for assessing the quality of warehousing facility (see [8, 18 and 20]).

Internal factors result from implemented storage technologies and construction of warehouse process. Internal factors affect warehouse tasks realization time, the availability of handling resources and space, as well as the size and kind of the tasks. Internal factors can be expressed by functional dependencies and described by language adequate to the class of built model. Selected internal factors influencing designing procedure are related to:

1. Required handling technologies (equipment, staff and spaces) suited for logistics task.
2. Reliability and technical performance of disposed/planned technical equipment.
3. The physical structure of the warehouse system, terrain conditions.
4. The structure and volume of material flows entering and leaving warehouse.
5. Changeability of material flow structure.
6. Information systems and information processing schemes.
7. Work organization and schedule of warehousing process tasks.
8. Skills and theoretical efficiency of required employees.
9. Safety and law regulations.
10. Investment expenditures.

Any kind of unforeseen internal or external interference potentially causes a postponement, protraction or even interruption of warehousing tasks realization, the choice of alternative routes or temporary reorganization of the whole process. Interferences disturb the use of inter-operational buffer spaces and storage areas and eventually affect the performance of a warehouse. External and internal factors affecting the implementation of warehouse processes must be identified and − parameterized using theoretical, available in the literature, methods and tools.

4. The elements of the model of a warehouse

4.1. General assumptions

Technical and organizational conditions of designing warehouse facilities can be described overall in a mathematical model useful for design purposes. Adapting the approach proposed in [11] and [21], a model of any warehouse facility of any functional structure is given as ordered six:

$$\mathbf{MM} = < \boldsymbol{S}, \boldsymbol{T}, \boldsymbol{\Lambda}, \boldsymbol{P}, \boldsymbol{O}, \boldsymbol{I} >, \tag{1}$$

where:

- $\boldsymbol{S}$ – functional structure – describes the spatial conditions of the facility. It is based on a hierarchical division of a warehouse area into functional areas grouping warehouse locations and placing them in space to estimate distances and define spatial relations.
- $\boldsymbol{T}$ – internal transport – describes handling technologies, technical resources like equipment and manpower and their technical parameters, functionalities, access limitations and other. It links warehousing process with a physical structure of a warehouse.
- $\boldsymbol{\Lambda}$ – logistics task – defines volumes and range of transformations of material flows resulting from clients orders and requested supplies.
- $\boldsymbol{P}$ – warehousing process – reflects a sequence of operations carried out with units of materials by internal transport system within a functional areas of a warehouse to complete clients orders.
- $\boldsymbol{O}$ – work organization rules – determine other, necessary for modelling and designing warehouses, assumptions like: warehousing process schedule, rules of assortment slotting, assigning labour resources to the tasks, routing rules ([9, 15]), principles of processing client orders, construction of picking lists and so on.
- $\boldsymbol{I}$ – information system – defines the scope of transformation information associated with warehousing process realization.

4.2. Functional structure of a warehouse

Warehouse space is divided into functional areas processing subsequent parts of warehousing process (as presented in Fig. 1) and using different technologies. Universal hierarchical functional structure of the warehouse consists of the following elements:

- *Logistics units (containing particular sku[1])*: indivisible portion of a specific material described by physical, business and logistics characteristics,
- *Location* (*address*): basic unit of space division in a warehouse, a place where certain amount of logistic units is directly stored. Location is uniquely described by a unique address (coordinates in space), has known dimensions, loading and storage capacity,
- *Rack cell* (*rack shelf*): space limited by structural elements of racking system (of any type) or otherwise (like a temporary storage places outlined on the floor by painted lines). Rack cells group locations and determine their physical parameters. Position of rack cells is unambiguously defined in the space,
- *Rack*: storage construction allowing vertical placement of logistics units usually formed as a wall, largely determining the course of transport corridors. Racks group rack cells. Their position is clearly defined in space,
- *Subarea*: any grouping of racks or their fragments resulting from the requirements of warehousing process. Subareas can be dedicated to handling specific types of logistics units (products), specific types of skus, selected customers and so on,
- *Functional areas*: reflect the stages of warehousing process (Fig. 1), thus typical warehouse disposes reserve area, order-picking area, receiving/shipping areas etc. The functional area uses specific storage and handling technologies fitting actual stage of a warehousing process. Functional areas group subareas but also they can group only individual racks or rack cells. The connection between inputs and outputs of functional areas reflects warehouse process,
- *Warehouse areas*: group functional areas depending on needs.

Each location is described by length, width, height, loading capacity and coordinates in space. The physical structure of the warehouse may be given as a structural graph. Examples of such a graph used to describe picking areas are presented in [15]. This kind of space division and classification is universal and can be applied to any facility and any process. The mail applications of this division are:

- estimation of distances between the locations for constructing paths (routing),
- determining potential fitness of logistics units to locations,
- localizing logistics units, as well as equipment and staff at the facility,
- determining location, subarea or functional area space utilization.

4.3. Warehousing process

Warehousing process is a sequence of transformations performed on logistics units (units of material). Each <u>step</u> (Fig. 1) of warehousing process contains <u>tasks</u> composed of transport/transformation <u>cycles</u> ([16]). These transformations are threefold:

1. *buffering* material flows (including storage, but costs related to reserve storage are different in nature than the costs of moving, so storage itself is considered separately),
2. *conveying* materials in space,
3. *changing* physical form of materials.

Therefore, assuming that warehouse handles materials of various types and properties described by consecutive sku numbers, and technological structure of logistic units used in the warehouse is given, transformations performed on material units are:

- *packing* (repacking, consolidation, deconsolidation, labelling): not changing the physical matter of sku, but only logistics form,
- *processing* (merging skus), through which some sets of skus are changed into other skus of different physical/business properties,

[1] Stock keeping unit

- *repacking with processing*, through which sets of skus of precisely defined logistics form are changed into other sets of skus of other logistics forms.
- *moving*: transporting logistics units between locations.
- *delay* of material flow related to information processing, control and addressing.

Considering the above, warehousing process comprises:

- *Steps* like receiving, put-away, retrieval, replenishment, picking, consolidation, packing, sorting, shipping and other common components. Steps correspond to functional areas and include the sequences of warehousing tasks.
- *Warehouse task* is composed of a number of transport/transformation cycles. The number of cycle repetitions results from daily material flow volumes related to the execution of client orders and servicing receipts of materials. The tasks have assigned handling resources.
- *Cycle* is most often a simple transport cycle or transformation. Its duration is calculated by summing the duration of simple operations composing it.
- *Operation* is the smallest part of cycle related to physical action like picking or scanning.

Warehousing tasks are sequenced and described with consecutive sku numbers. The daily number of cycles and the cycle duration for each task is known. Different types of logistic units and materials are subjected to different transformations. Both, the number of repetitions and duration can be a constant or variable depending of model requirements.

4.4. Internal transport system

The warehouse area is serviced by internal transport (handling) system performing material flows between indicated locations and transformations. The following arrangement of internal transport system is proposed:

- *Resources* (*equipment and/or manpower*): people or transport means with unlimited field of action and specified loading capacity defined for different types of logistic units like forklift trucks. Labour resources perform warehousing tasks (transport, handling, transformation). The conveyors and other equipment operating continuously with limited field of action can be considered as buffering elements with additional feature of moving units in space,
- *Transport corridors*: inter-racking spaces or spaces outlined in other way used exclusively for transport and handling. The number of and type of labour resources in a single corridor is technologically constrained. The corridors are established by rack walls and group locations in adjacent rack walls or those serviced by particular device,
- *Transport area*: group locations with respect to their access characteristics and handling technology. Transport areas can reflect the specific stages of warehousing process or they can be assigned for specific types of devices. Zones can group transport corridors.

Equipment and manpower categories are described by relevant technological and cost characteristics as well as the ability to be assigned to particular warehousing tasks and functional areas. Cycle duration is dependent on the assigned resource, distances (in three-dimensions) between locations and routing rules ([16]). Realization times may be set as fixed or given by probability distribution. Transport corridors can have specific manpower categories or types of equipment assigned to work in, or even the individual items of equipment. Transport areas group locations. Similarly, the transport area can group transport corridors.

The basic use of described system is:

- determining the ability to handle specific locations by particular resources,
- estimating the duration of cycles of internal transport and transformations,
- localizing assortment, as well as the pieces of equipment and staff within the facility.

4.5. Logistics task

The logistics task is a formal description of the workload realized by logistics system, defined by qualitative and quantitative characteristics. The subsystem of logistics task administers normative and non-normative (random conditions of supply chain) workloads for warehouse.

For the purposes of modelling warehouse facilities, the logistics task is defined by:

- *Structure of material inputs* (supplies) specifying arrival time and amounts of particular skus and logistic units entering warehouse (time domain can be defined as discrete or continuous).
- *Structure of material outputs* (shipping): specifying shipping time and amount of logistic units with appropriate skus exiting a warehouse
- *Organizational and technological parameters* of the facility, labour cost indicators and performance and evaluation criteria.

The structure of inputs and outputs can be described by fixed values, or by theoretical and empirical probability distributions. The subsystem of logistics task is the foundation of constructing input and output generators in the warehouse model. It should reflect the external conditions and requirements of supply chain.

4.6. Work organization rules

The structures discussed above require additional assumptions – work organization patterns – to represent real objects and use warehouse model in designing process. Key elements of the organization of work in the warehouse are [5, 7, 17]:

- *Slotting*: distribution of materials within storage locations due to the space utilization and ease of access. Slotting is done firstly as a last stage of design and may be carried out on a regular basis by the warehouse management systems,
- *Routing*: determination of transport paths in respect of spatial and functional configuration, including the path selection and sequencing visited locations in order to minimize distances,
- *Task interleaving*: execution of complex (combined) cycles (merging cycles of various tasks),
- *The rules for processing customer orders*: in particular: batch-picking, multiorder-picking and wave-picking rules for constructing picking lists,
- *Packing and shipping rules* for constructing efficient delivery paths,
- *Internal transport scheduling*: determining the timeframe of the warehousing tasks realization with regard to the allocation of handling resources to tasks (see [16]),
- *The rules of replenishment* picking areas, replenishment thresholds,
- *The principles directing material flows* to and from warehouse locations, including warehouse logics mentioned in [17],
- *Mapping current and periodic changes in the assortment structure*,
- *Mapping current and periodic changes in the material flows* (seasonality).

4.7. Informatics system

Informatics subsystem of a warehouse performs communication between control tools (Warehouse Management Systems, Enterprise Resource Planning – WM modules, Inventory modules, Manufacturing Resources Planning, dispatchers or other), warehouse automation, dimension and weight-scanning devices, automatic data capture devices and employees. It is responsible for communication with the master system (ERPs, Supply Chain Management, Advanced Planning Systems or others) to agree stock levels, manage client orders and supplies, track work and complete master data (data about skus and forms of packaging).

Information processing subsystem realizes the following tasks:

- interpreting information about client orders, supply requests, stocks and master data received

from the master system (like ERP), or directly from,
- confronting them with inventory and available labour and space resources,
- making decisions guiding the material flows to and from warehouse locations (Stock Locator),
- passing operative orders to the resource performing the tasks (equipment, employees),
- register the movement and transformation of materials,
- archiving tasks realization (time stamp),
- encoding and decoding information using available technologies (like GS1 codes, other barcodes, RFiD and others),
- reporting to the master system (or a designated entity) the status of the task,
- updating inventories,
- measuring performance of system components on the base of historical data ([22]),
- controlling access in accordance with delegated powers,
- implementing advanced functions related to planning, analysis and estimation of costs.

The information system implements a sequence of information transformations closely correlated with material handling process, according to the principle that information always precedes, accompanies and completes material flows in the warehouse. Information processing should be described by tools designed to writing processes (like BPMN, UML, IDEF- * notations and others), or possibly realized with common standards like Electronic Data Interchange.

Conclusions

The article presents basic conditions of designing warehouses of various functional structures and, in consequence, the aspects concerning universal model of a warehouse facility, which can be used in designing logistics infrastructure. Presented frame model allows for comprehensive modelling logistics infrastructure elements. The next step should be the choice of practical tools for modelling and visualization of achieved results.

Due to the diversity of issues considered in designing and modelling warehouse facilities, the design must be staged. The first stage of building the model includes key elements leading to the overall picture. In the next stage, as far as experimenting with the model, it should be supplemented with those elements that are important for its aim. This means simplifying certain components and detailing others in accordance with the purpose of modelling.

Formal model of a warehouse facility constructed on a base of provided assumptions will be easy to implement as computer software and then useful tool supporting designing works. It universally reflects all essential technological and organizational components of a warehouse facility and warehousing processes.

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References

[1] Baker, P., Canessa, M., *Warehouse design: A structured approach*, European Journal of Operational Research, 193, 425-436, 2009.

[2] Bassan, Y., Roll, Y., Rosenblatt, M. J., *Internal layout design of a warehouse*, AIIE Transactions, Vol. 12, No. 4, 317-322, 1980.

[3] Berry, J. R., *Elements of warehouse layout*, International Journal of Production Research, Vol. 7, No. 2, 105-121, 1968.

[4] Fijałkowski, J., *Transport wewnętrzny w systemach logistycznych*, Wybrane zagadnienia, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2003.
[5] Frazelle, E., *World-Class Warehousing and Material Handling*, McGraw-Hill, 2002.
[6] Gołembska, E., *Logistyka jako zarządzanie łańcuchem dostaw*, Wydawnictwo Akademii Ekonomicznej w Poznaniu, Poznan 1994.
[7] Gu, J., Goetschalckx, M., McGinnis, L. F., *Research on warehouse design and performance evaluation: A comprehensive review*, European Journal on Operational Research 203, 539-549, 2010.
[8] House, R. G., Karrenbauer, J. J., *Logistics System Modelling*, International Journal of Physical Distribution and Materials Management (IJPD & MM), Vol. 8, Is. 4, pp. 189-199, 1978.
[9] Jachimowski R., Szczepański E., *Sieci Petriego w analizie problemu wyznaczania tras pojazdów*, Logistyka, 4/2014, pp. 1885-1892.
[10] Jacyna, M., Lewczuk, K., *Wybrane aspekty techniczne organizacji systemów logistycznych*, Wybrane Zagadnienia Logistyki Stosowanej, PAN Komitet Transportu, Oficyna Wydawnicza TEXT, pp. 32-40, Krakow 2007.
[11] Jacyna, M., Wasiak, M., Lewczuk, K. Kłodawski, M., *Simulation model of transport system of Poland as a tool for developing sustainable transport*, Archives of Transport, Polska Akademia Nauk, Komitet Transportu, Vol. 31, Iss. 3, pp. 23-35, 2014.
[12] Jacyna, M., (ed.), *Kształtowanie systemów w wybranych obszarach transportu i logistyki*, Oficyna Wydawnicza Politechniki Warszawskiej, 2014.
[13] Jacyna-Gołda, I., *Some aspects of risk assessment in the logistics chain*, Journal of KONES, Vol. 21, No. 4, pp. 193-202, 2014.
[14] Jakubowski, L., *Technologia prac ładunkowych*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2003.
[15] Kłodawski, M., *Systemy i procesy komisjonowania w obiektach logistycznych*, in: Kształtowanie systemów w wybranych obszarach transportu i logistyki / Jacyna Marianna (ed), Oficyna Wydawnicza Politechniki Warszawskiej, pp. 239-294, 2014.
[16] Lewczuk, K., *Organizacja procesu magazynowego a efektywność wykorzystania zasobów pracy*, Logistyka, Nr 4, pp. 563-570, 2011.
[17] Lewczuk, K., *Zasady organizacji przepływów materiałowych w obszarach funkcjonalnych magazynów*, Logistyka, Nr 2, pp. 865-87, 2012.
[18] Pyza, D., *Multi-Criteria Evaluation of Transportation Systems in Supply Chains*, Archives of Transport, Vol. 23, Iss. 1, pp. 47-65, 2011.
[19] Rouwenhors, B., Reuter, B., Stockrahm, V., J. van Houtum, G., Mantel, R. J., Zijm, W. H. M., *Warehouse design and control: Framework and literature review*, European Journal on Operational Research 122, 515-533, 2000.
[20] Wasiak, M., *Modelowanie przepływu ładunków w zastosowaniu do wyznaczania potencjału systemów logistycznych*, Oficyna Wydawnicza Politechniki Warszawskiej, 2011.
[21] Wasiak, M., *Formal Notation of a Logistic System Model Taking into Consideration Cargo Stream Transformations*, Archives of Transport, Vol. 23, Iss. 1, pp. 91-110, 2011.
[22] Żak, J., Jacyna-Gołda, I., *Using queue theory to analysis and evaluation of the logistics center workload*, Archives of Transport, Vol. 25-26, Iss. 1-2, pp. 117-135, 2013.
[23] Żak, J., *Modelowanie procesów transportowych metodą sieci faz*, Prace Naukowe Politechniki Warszawskiej, Transport, Vol. 99, 2013.