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EVOLUTIONS OF GROUP MANAGEMENT DEVELOPMENT OF MOBILE ROBOTIC PLATFORMS IN WAREHOUSING 4.0.

The **subject** of this research is the technology of management of mobile robot groups in the concept of Industry 4.0 and its composition. The **purpose** of this article is to find ways to implement an effective strategy for building and managing mobile robotic platforms in Warehousing, as a key tool of Lean Production. To achieve this goal, it is necessary to solve the following **tasks:** to analyze the management of supply chains in Smart Manufacturing, within Industry 4.0 and its impact on achieving the goals of Lean Production; to study the evolution of technologies used in Warehousing in the dynamics of the Industrial Revolution; to analyze the evolution of Warehouse Management Systems (WMS) as one of the most important components on the basis of which the requirements for automation of Warehousing automation in Smart Manufacturing with group management of mobile robotic platforms are implemented and achieved; to compare the impact of the technologies used by Warehousing 4.0 and Warehouse Management Systems on the key indicators of Lean Production. **Results:** One of the promising ways to achieve the effectiveness of the implementation of Lean Production tools in WMS systems is the use of Collaborative Robot System technology, which makes it possible to ensure a high density of product storage in Warehousing. However, modern mobile robotic platforms have their limitations both in the methods of loading and unloading products, and in the design. Therefore, the authors see the task in improving the design of mobile robotic platforms, which will develop a new intelligent group method of loading and unloading products, increasing the storage density for a variety of goods. **Conclusions:** The paper compares the impact of Warehousing 4.0 and Warehouse Management Systems on key Lean Production tools, which shows how the introduction of new group management technologies for robotic platforms in Warehousing 4.0 and Warehouse Management Systems (WMS) affects the effectiveness of Lean Production tools such as Heijunka, Just-in-time, 5S. This suggests that the introduction of new models and methods of managing complex warehouses with high density and chaotic storage of products, through the use of mobile robotic autonomous systems, will significantly optimize the process of supply chain management in Smart Manufacturing.

Keywords: Industry 4.0; Smart Manufacturing; Logistics 4.0; Warehousing 4.0; Lean Production.

Introduction

The introduction of Industry 4.0 has brought about a number of dramatic changes in industrial process management systems, in operations and supply chain management (SCM) processes. Rapid changes in manufacturing and service systems have resulted in phenomenal productivity gains that are reflected in the Smart Manufacturing (SM) concept. A rapidly changing environment creates new challenges and opportunities for manufacturing that are associated with adapting to new technologies such as the Industrial Internet of Things (IIoT) and cyber-physical production systems (CPPS), artificial intelligence (AI), robotics, cybersecurity, data analytics, block chain and cloud technologies, which directly affect the achievement of economic results, by creating the prerequisites for the implementation of Lean Production. Therefore, the implementation of the modern concept of Industry 4.0 in SM is impossible without creating more efficient distribution strategies (Logistics), storage (Warehousing) and supply chain management (SCM). Warehousing 4.0 is an automated intelligent warehouse concept for tasks such as automatic replenishment of stocks, autonomous identification of stocks, order picking and routing of delivery systems for loading and unloading using group control of robotic autonomous vehicles. Autonomous transport robotic vehicles that can “scan” their surroundings with laser scanners, infrared sensors, and RFID chips for autonomous navigation in warehouses. Each of them has the ability to make autonomous decisions about their movements, route selection and transit priorities, exchanging data about their location and status with other transport robotic vehicles. The implementation of Warehousing 4.0 in enterprises can reduce operating costs through more efficient inventory management, optimize supply chain management and access to resources, and research into this area of Industry 4.0 is an urgent task.

Analysis of recent research and publications

In [1], a study of the Logistics 4.0 maturity model is carried out in the general concept of Industry 4.0, the authors focus on the influence of the development of supply chain management on the improvement of the entire production process. At the same time, the authors of [1] do not define the positive dynamics of Lean Production parameters as an important factor in determining the level of implementation of Industry 4.0 in an enterprise.

The author [2], in his work, focuses on the fact that Warehousing 4.0 is a new area of storage and retrieval of goods using shuttle storage systems and autonomous transport robotic means to retrieve and store objects. But, in turn, this is impossible without improvements in the technology and management system of Warehousing 4.0, which will reduce and optimize the storage, accounting and preparation for transportation of items necessary for production in Smart Manufacturing.

The work [3] shows that warehouse services are an important component of logistics and play a decisive role in achieving the success of the company and achieving the goals of Lean Production. The author [3] points out that these systems are constantly being revised to ensure a continuous flow of products in logistics. At the same time, the author [3] does not disclose the issue of the development of warehouse management systems of their evolution and does not consider the solution of this issue in combination with the study of the development and evolution of Warehouse Management Systems (WMS),

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which in total does not provide complete information about the requirements for modern Warehousing 4.0 systems.

In [4], theoretical studies are carried out that show the positive effectiveness of the impact of Logistics 4.0 on the operation of SM, in the framework of assessing the performance of warehouse facilities. At the same time, the work [4] does not pay attention and unreasonably misses the thesis that the efficiency of Logistics 4.0 is based on minimizing the loss of time by improving Warehousing 4.0 by introducing autonomous transport robotic means.

The authors of [5] consider the work as a stimulating factor for SM, the introduction of modern technologies in logistics supply chains and their use in Industry 4.0. To substantiate this assumption, the authors cited Unity Industry 4.0. Roadmap: Logistics, where they made the assumption that Warehousing, in the framework of Industry 4.0, is not needed. This assumption is incorrect from the point of view of organizing supply chain management in cyber-physical production systems, since the need to provide the technological process with consumables, transport blanks or move finished products to another production area, is one of the key parameters in SM [6].

Based on the analysis of the publications, it can be seen that many authors do not pay enough attention to the study of Warehousing and Warehouse Management Systems, which are some of the important elements of SM organizations.

The **aim** of this article is to implement an effective strategy for building and managing mobile robotic platforms in Warehousing 4.0, as a key tool for achieving Lean Production.

1. The Role of Supply Chain Management in Smart Manufacturing

Modern digital production is a seamless connection of all the main and auxiliary elements of the production process, which includes all the necessary stages from the stage of product design, planning the use of production and material resources. One of the key elements of the SM organization is the implementation of high-quality Supply Chain Management (SCM), within the framework of the Logistics 4.0 concept, using modern technologies for storing and processing data in Cloud Computing (CC), obtaining information about the location of an object in SCM using identification systems and tracking at all stages of production, storage and delivery in real time. An example of building an SCM in SM is shown in fig. 1.

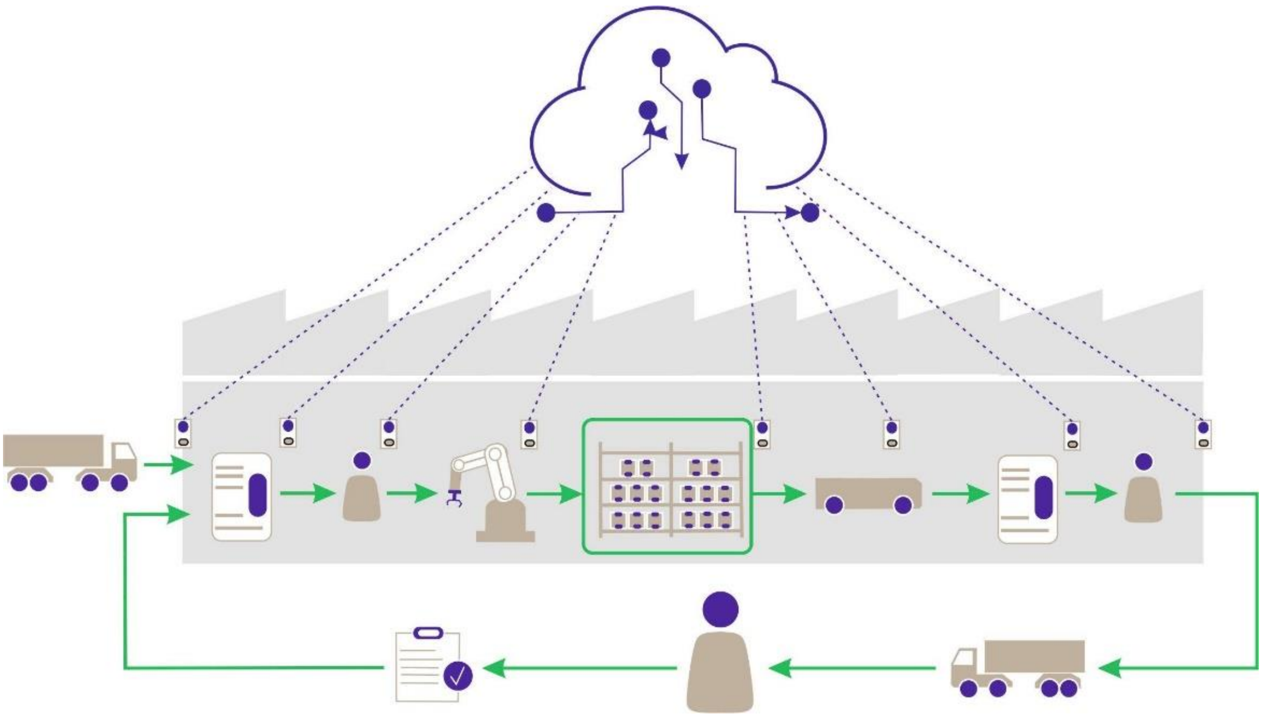

Fig. 1. Supply Chain Management in Smart Manufacturing

Correctly implemented SCM allows: to provide uninterrupted production, storage, reception and shipment of products to customers [7-10]. By analyzing SCM, within the framework of the Logistics 4.0 concept for SM, you can see that warehousing is a complex organizational and technical structure. Therefore, in order to achieve the goals in SM, it is necessary to develop and implement modern technologies in Warehousing management systems [11-14].

2. A study of the evolution of Warehousing in the dynamics of the industrial revolutions Industry 4.0

The evolution of Warehousing cannot be viewed in isolation from the stages of the Industrial 4.0 revolution. In the classical view, the industrial revolution went through four stages of development, such as: Industry 1.0 – Mechanization, Steam Power, Weaving Long (circa 1784); Industry 2.0. – Mass Production, Assembly Line, Electrica Energy (circa 1870); Industry 3.0. – Automation,

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computers and Electronics (circa 1960); Industry 4.0 – Cyber physical system, Industrial Internet of Things (IIoT), Network (since 2011) [15-18]. Based on the analysis, the authors propose to trace the stages of the Warehousing revolution, depending on the achievements of the technology for each revolution. As a result, the following technologies were considered as the key ones that were used in Warehousing at different stages of Industry development. The results of the comparative analysis are presented in table 1.

Table 1. *Stages of the Industrial Revolution Industry and the Evolution of Warehousing Development*

Stages of the industrial revolution development	Technologies	Evolution stages	Technologies
Industry		**Warehousing**	
Industry 1.0 (1784-1860)	Mechanization of production; steam power [19-20]	Warehousing 1.0	Manual System; Mechanical System; Bulk/Case Handling; Bulk & Horizontal Storage; Wide Aisle Configuration; Oral-Based Communication; Individual Decision
Industry 2.0 (1861-1947)	Electricity and production assembly lines; mass production [21-22]	Warehousing 2.0	Electrical System; Electrical-mechano System; Pallet Handling; Block-Stracking & Verticla Storage; Narrow Aisle Configuration; Paper-Based Communication; Group Decision.
Industry 3.0 (1947-2010)	Partial automation of production processes; computer systems; mobile robots [23-24]	Warehousing 3.0	Information System; Automated System; Automatic Handling; Dense& High-Level Storage; Very Narrow Aisle Configuration; Computer-Based Communication; Centralized Decision.
Industry 4.0 (2011- uptill now)	Industrial Internet of Things; Smart Manufacturing; Cyber-physical system [25-27]	Warehousing 4.0	Collaborative System; Autonomous System; Smart Handling; Chaotic and Compact Storage; Dynamic Aisle Configuration; Interconnection-Based Communication; Decentralized Decision

As you can see from the table 1 technologies that are used in Warehousing are directly dependent on the level of development of the basic technologies of the current industrial revolution. Considering the modern technological advances that have found application in Industry 4.0, you can see that modern Warehousing 4.0 systems are aimed at solving the problems of Smart Manufacturing and should implement the following functions:

- Collaborative System is a synthesis of systems, on the one hand - an operator who monitors the warehouse through the Human-machine interface (HMI), on the other hand - automatic robotic platforms (Shuttle) based on artificial intelligence (AI) that can work together with a human for solving problems of optimal storage of different types of products;

- Autonomous System is an autonomous self-healing system for storing data on the arrival, transportation, movement of products inside the warehouse and their issuance for the implementation of the Lean Production concept (Just in Time and 5C), which allows you to reduce the loss of time waiting for materials, parts, semi-finished products or the necessary information for production process;

- Smart Handling – identification of products by a robotic platform (Shuttle) using modern Near Field Communication (NFC), Radio Frequency Identification (RFID) technologies, as well as the use of computer vision to recognize 2D barcodes, ISBN and QR codes;

- Chaotic and Compact Storage – storage of different types of products on the same level of the shuttle system of storage racks (Pallet Shuttle system), to achieve the highest possible storage density;

- Dynamic Aisle Configuration – implementation of methods for constructing a route of movement of a robotic platform (Shuttle) in both horizontal and vertical projections for loading and unloading products, using intelligent decision-making systems;

- Interconnection-Based Communication – the use of multiple computer networks (wired, wireless), since any pair of hosts on connected networks can exchange messages, regardless of their hardware-level networking technologies, within the overall Industrial Internet of Things for Smart Manufacturing;

- Decentralized Decision – making decisions on the placement, movement and path of unloading products from storage racks is delegated to a robotic platform (Shuttle), and general information on the number and type of products stored in the warehouse (s) is in the general control system implemented on Cloud Computing.

The stages of the evolution of Warehousing with the technologies used for the development of industrial technologies are shown in fig. 2.

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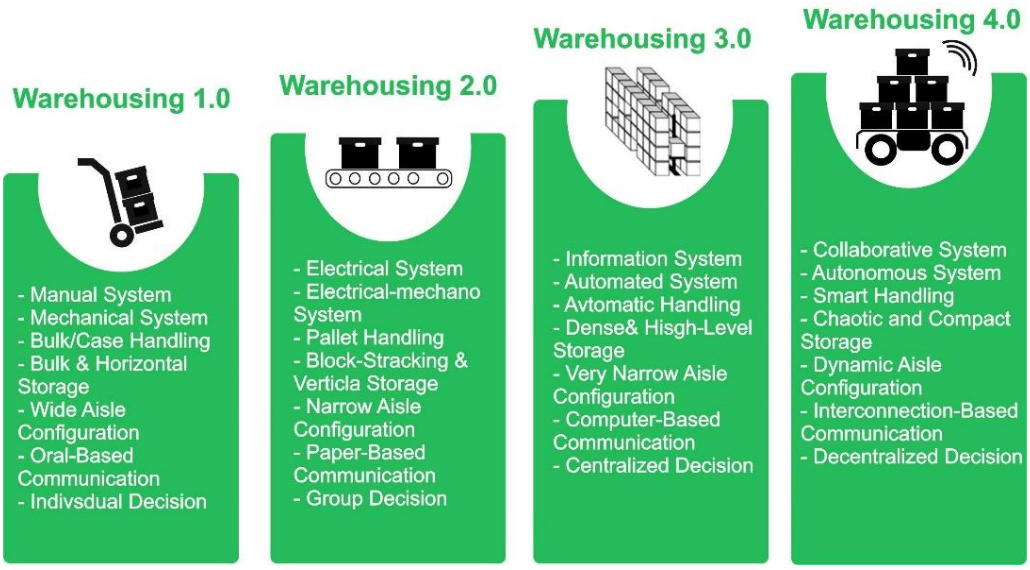

Fig. 2. Evolution of Warehousing

Analyzing the technologies that led to the development of Warehousing, it is worth paying attention to the evolution of Warehouse Management Systems (WMS), as one of the most important components on the basis of which the requirements for warehouse automation in Smart Manufacturing are implemented and achieved [28-32]. Based on the analysis, the following technologies were selected as the basis for each stage of WMS development, which are presented in table 2 for ease of comparison.

Table 2. *The use of basic WMS technologies in the evolution stages of Warehousing*

Evolution stages	Warehouse Management Systems	Technologies
Warehousing 1.0	Mechanical Handling System	Manual or Hydraulic Pallet Jack; Manual or Hydraulic Pulley; Manual or Hydraulic Crane; Manual or Cravity Conveyor
Warehousing 2.0	Electro-Mechanical Handling System	Electro-mechano Pallet Jack; Forklift; Order-Picker Truck; Electro-mechano Crane; Electro-Mechano Conveyor
Warehousing 3.0	Automated Handling System	Automated Guided Vehicle; Automated Storage and Retrieval System; Horizontal Carousel; Vertical Life Module
Warehousing 4.0	Autonomous Handling System	Mobile Autonomous Rack System; Autonomous Vehicle Storage and Retrieval System; Compact Storage and Retrieval System; Collaborative Robot System.

To implement the requirements for modern WMS, within the framework of Industry 4.0 concepts for SM, it is necessary to implement basic technologies that allow providing the following functions:

- Mobile Autonomous Rack System – Shelving systems that fit into a rail system so that the shelves can move back and forth along the rails. The advantage of mobile shelving systems is that it is possible to transform small sections of a building into storage rooms that can accommodate a large number of items. Modern WMS uses mobile robotic platforms (Shuttle) or automated forklifts that move along or inside the racking system;

- Autonomous Vehicle Storage and Retrieval System (AS / RS) – the use of automated controlled lifting and transport devices that deliver products to the warehouse and retrieve them from there as needed. Automated warehouse systems allow you to save storage space, which speeds up warehouse operations and improves control over SM inventory, based on the use of technologies for identifying products and their location in the warehouse. AS / RS, as a rule, is used in warehouses where large cargo is moved with high intensity, with high storage density due to space constraints;

- Compact Storage and Retrieval System – automated systems that efficiently and safely store products in a compact size. They also allow operators to retrieve items quickly and easily, provided with an extensive list of alternative names as needed, such as: dynamic storage systems, high-density storage and retrieval systems, and custom picking technology;

- Collaborative Robot System – a system of automatic group control of mobile robotic platforms, which interacts with the operator, in order to share the workspace, to solve the problems of storage, loading, unloading of products.

The levels of development of basic WMS technologies, at the stages of the evolution of Warehousing, are shown in fig. 3.

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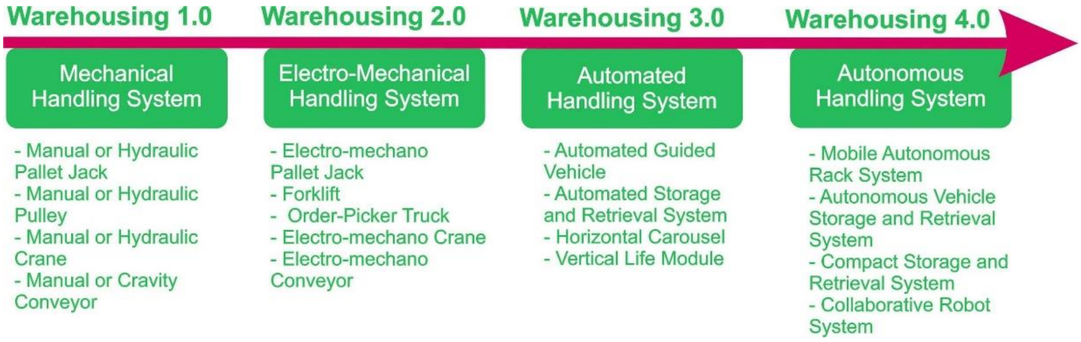

Fig. 3. Levels of development of basic WMS technologies in the stages of evolution of Warehousing

3. Analysis of the implementation of modern technologies Warehousing 4.0 for Lean Production indicators, within the framework of the industrial revolutions Industry 4.0

One of the complex indicators of the effectiveness of the implementation of modern technologies in Warehouse Management Systems (WMS), in the form of Warehousing 4.0, is its impact on the performance of Lean Production [33-35]. Table 3 shows the results of a comparative analysis of the impact of Warehousing 4.0 and Warehouse Management Systems technologies on key LP indicators: Heijunka, Just-in-time, Kanban, Total Productive Maintenance (TPM), Optimize the ergonomics of the place of work (5S), Single Minute Exchange of Die (SMED), and Mistake proofing (Poka yoke).

Table 3. *Comparison of the impact of Warehousing 4.0 and Warehouse Management Systems technologies on LP key indicators*

Industry 4.0	Instruments of Lean Production						
	Heijunka	**Just-in-time**	**Kanban**	**TPM**	**5S**	**SMED**	**Poka yoke**
Warehousing 4.0							
Collaborative System	+++	+++	++	+	+++	+	+++
Autonomous System	++	+++	+	+	+++	+++	+
Smart Handling	+++	+++	+	+	+++	+++	+++
Chaotic and Compact Storage	++	++	-	+	++	+	++
Dynamic Aisle Configuration	+++	+++	-	+	++	++	++
Interconnection-Based Communication	+++	+++	+	-	+++	+++	+
Decentralized Decision	+++	+++	+	-	++	+++	+++
Warehouse Management Systems (WMS)							
Mobile Autonomous Rack System	+++	++	+	+	+++	+++	+
Autonomous Vehicle Storage and Retrieval System	+++	+++	-	+	+++	+	+++
Compact Storage and Retrieval System	++	++	+	+	+++	-	+
Collaborative Robot System	+++	+++	++	-	+++	+++	+++

"+++" – strong impact; "++" – medium impact; "+" – weak impact; "–" – no impact

Results

Analyzing the results obtained, it can be concluded that the introduction of advanced technologies in WMS, in the framework of Warehousing 4.0, will improve the process of supply chain management of the necessary materials for the smooth functioning of cyber-physical production systems in the SM concept. One of the promising directions for achieving the effectiveness of the implementation of Lean Production tools in WMS systems is the use of Collaborative Robot System technology, which makes it possible to ensure high density of storage of goods in Warehousing. It is worth noting that modern control systems for mobile robotic platforms, such as Toyota RadioShuttle, Raymond RadioShuttle, Rochiev RadioShuttle, have their own limitations in the methods of warehousing, loading and unloading goods (First-In-First-Out (FIFO), Last-In -First-Out (LIFO)) and in design. These limitations do not allow such systems to be used in the implementation of Warehousing systems with high density chaotic storage. Consequently, the authors see the task in improving the designs of mobile robotic platforms, which will allow developing a new intelligent group method for the implementation of loading and unloading goods, increasing the storage density for unlike goods (chaotic storage).

Conclusions

Research in this area has shown that Industry 4.0 has become an impetus in the development of modern production, due to the introduction of new technologies: Industrial Internet of Things; Smart Manufacturing; Cyber-physical system, which requires a change in management mechanisms, construction and support of production processes. The authors, during the literary

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analysis of publications, drew attention to the fact that the existence of Smart Manufacturing is impossible without the implementation of a more effective strategy for building and managing supply chains (SCM), which is based on the synthesis of distribution strategy (Logistics), storage (Warehousing) and Lean tools. Production. Based on this, the stages of development of technologies used in the framework of the industrial revolution Industry were investigated, and their impact on the evolution of Warehousing, in terms of functionality, and therefore made it possible to conduct research on the development of Warehouse Management Systems (WMS) technology. To prove the need for research and search for new solutions for the implementation of storage tasks with high randomness and density, in the framework of Warehousing 4.0 for Smart Manufacturing, a table was developed comparing the impact of Warehousing 4.0 and Warehouse Management Systems technologies on key Lean Production tools. This table shows how the implementation of new technologies in Warehousing 4.0 and Warehouse Management Systems (WMS) affects the efficiency of Lean Production tools such as: Heijunka, Just-in-time, 5S. This makes it possible to assert that the introduction of new models and methods for managing complex warehouses with chaotic storage of high-density products is impossible without the use of mobile robotic autonomous systems, which will optimize the supply chain management process in Smart Manufacturing.

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ЕВОЛЮЦІЇ РОЗВИТКУ ГРУПОВОГО УПРАВЛІННЯ МОБІЛЬНИМИ РОБОТИЗОВАНИМИ ПЛАТФОРМАМИ В WAREHOUSING 4.0.

Об'єктом даного дослідження є технологія управління групами мобільних роботів в концепції Industry 4.0 та її складових. **Метою** статті є аналіз шляхів реалізації ефективної стратегії та управління мобільними роботизованими платформами в складських системах, як ключового інструменту Lean Production. Для досягнення поставленої мети необхідно вирішити наступні **завдання:** провести аналіз управління ланцюгами поставок в Smart Manufacturing, в рамках Industry 4.0, і його вплив на досягнення цілей Lean Production; дослідити еволюцію їх застосовуваних у складських технологіях в динаміці розвитку промислової революції Industry 4.0; проаналізувати еволюцію Warehouse Management Systems (WMS), як одного із найважливіших компонентів, які відповідають вимогам до автоматизації складування в Smart Manufacturing за допомогою групового управління мобільними роботизованими платформами; провести порівняння технологій, що застосовуються Warehousing 4.0 і системи управління складом та їх вплив на ключові показники Lean Production. **Результати:** одним із перспективних напрямків досягнення ефективності впровадження інструментів Lean Production у системи WMS є використання технології Collaborative Robot System, яка дає можливість забезпечити високу щільність зберігання товарів у Warehousing. Однак сучасні мобільними робототехнічними платформами мають свої обмеження, як у методах реалізації завантаження та вивантаження товарів, так і у конструкційному виконанні. Отже, автори вбачають завдання в удосконаленні конструкцій мобільних робототехнічних платформ, що дозволить розробити новий інтелектуальний груповий метод реалізації завантаження та вивантаження товарів, збільшивши щільність зберігання різнойменних товарів. **Висновки:** проведено загальний аналіз впливу технологій Warehousing 4.0 і Warehouse Management Systems на ключові інструменти Lean Production, який показує як впровадження нових технологій групового управління роботизованими платформами в Warehousing 4.0 і системи управління складами (WMS) впливає на ефективність таких інструментів Lean Production як: Heijunka, Just-in-time, 5S. Це дозволяє стверджувати, що впровадження нових моделей і методів управління складними складами з високою щільністю та хаотичним зберіганням виробів, шляхом використання мобільних робототехнічних автономних систем, дозволить значно оптимізувати процес управління ланцюгами поставок в Smart Manufacturing.

Ключові слова: Industry 4.0; Smart Manufacturing; Logistics 4.0; Warehousing 4.0; Lean Production.

ЭВОЛЮЦИИ РАЗВИТИЯ ГРУППОВОГО УПРАВЛЕНИЯ МОБИЛЬНЫМИ РОБОТИЗИРОВАНЫМИ ПЛАТФОРМАМИ В WAREHOUSING 4.0.

Предметом данного исследования является технология управления группами мобильных роботов в концепции Industry 4.0 и ее составляющих. **Целью** данной статьи является поиск путей реализации эффективной стратегии построения и управления мобильными роботизированными платформами в Warehousing, как ключевого инструмента Lean Production. Для достижения поставленной цели необходимо решить следующие **задачи:** провести анализ управления цепочками поставок в Smart Manufacturing, в рамках Industry 4.0 и его влияние на достижения целей Lean Production; исследовать эволюцию применяемых в Warehousing технологий в динамике развития промышленной революции Industry 4.0; проанализировать эволюцию Warehouse Management Systems (WMS), как одного из важнейших компонентов, на базе которого реализуются и достигаются требования к автоматизации складирования в Smart Manufacturing при групповом управлении мобильными роботизированными платформами; провести сравнение влияния технологий, применяемых Warehousing 4.0 и Warehouse Management Systems, на ключевые показатели Lean Production. **Результаты:** одним из перспективных направлений достижения эффективности внедрения инструментов Lean Production в системы WMS является использование технологии Collaborative Robot System, которая дает возможность обеспечить высокую плотность хранения изделий в Warehousing. Однако современные мобильные робототехнические платформы имеют свои ограничения как в методах реализации погрузки и выгрузки изделий, так и в конструкционном исполнении. Следовательно, авторы видят задачу в усовершенствовании конструкций мобильных робототехнических платформ, что позволит разработать новый интеллектуальный групповой метод реализации погрузки и выгрузки изделий, увеличив плотность хранения для разноименных товаров. **Выводы:** в работе проведен сравнительный анализ влияния технологий Warehousing 4.0 и Warehouse Management Systems на ключевые инструменты Lean Production, который показывает, как внедрение новых технологий группового управления роботизированными платформами в Warehousing 4.0 и Warehouse Management Systems (WMS) влияет на эффективность инструментов Lean Production, таких как: Heijunka, Just-in-time, 5S. Это позволило утверждать, что внедрение новых моделей и методов управления сложными складами с высокой плотностью и хаотическим хранением изделий, путем использования мобильных робототехнических автономных систем, позволит значительно оптимизировать процесс управления цепочками поставок в Smart Manufacturing.

Ключевые слова: Industry 4.0; Smart Manufacturing; Logistics 4.0; Warehousing 4.0; Lean Production.

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