AEM JOURNAL.ORG

Overview of the Development of Material Handling Machinery

Huili Zhu[1,2], Cheng Li[1], Zhenyu Jiang[3], Mengmeng Wang[2], Jinhu Su[2], Xiaojie Ma[2]
[1]College of Mechanical and Power Engineering, Zhengzhou University, Zhengzhou 450008, Henan, China
[2]College of Mechanical Engineering, Henan Institute of Technology, Xinxiang 453003, Henan, China
[3]Changyuan Branch of Henan Special Equipment Inspection and Technology Research Institute, Changyuan 453400, Henan, China

Corresponding author: Cheng Li (e-mail: Chengli@zzu.edu.cn)

ABSTRACT This review introduces the characteristics, historical evolution, current development status, and future trends of material handling machinery. Material handling machinery, including lifting machinery, continuous conveying machinery, industrial vehicles, and logistics warehousing equipment, is essential for spatial movement of materials in industrial production. The paper reviews the historical development of material handling technologies, from early lifting and conveying tools to modern large-tonnage cranes, belt conveyors, automated guided vehicles, and intelligent logistics systems. It further discusses the development of modern technologies in response to carbon peaking, carbon neutrality, and green low-carbon transformation. Key topics include ultra-large-tonnage equipment, safety standards, lightweight structural design, cyber-physical systems, energy-efficiency evaluation, and emerging intelligent equipment forms. Based on extensive data review and accumulated industry experience, the paper evaluates the future development direction of material handling machinery, emphasizing lightweight design, automation, intelligent sensing and control, electromechanical integration, and energy-efficient operation.

INDEX TERMS material handling machinery, special equipment, lightweight design, cyberphysical systems, electromechanical systems

I. INTRODUCTION

MATERIAL handling machinery is an important mechanical equipment in modern life and industrial production that requires the spatial movement of industrial products or items. It mainly includes lifting machinery, continuous handling machinery, industrial vehicles, and logistics warehousing machinery used for internal material transportation within enterprises. Material handling machinery has two basic functional characteristics: load-bearing and transport, that is, using specific steel structures to meet the requirements of material load-bearing, and using lifting, running, dragging, and other methods to achieve spatial transport of materials (as shown in Figure 1). In recent years, with the development of Technological convergence of material handling machinery and computer, sensor, information fusion, communication, artificial intelligence and

automatic control, not only the overall automation and intelligence level of material handling equipment has been improved qualitatively, but also new forms of handling equipment such as automatic guided vehicle (AGV) have been derived.

II. CHARACTERISTICS AND HISTORICAL EVOLUTION OF MATERIAL HANDLING MACHINERY

Since humanity entered the history of civilization, material handling has always been an important component of human labor and life, and the improvement of human material handling ability reflects the degree of industrial progress and prosperity.

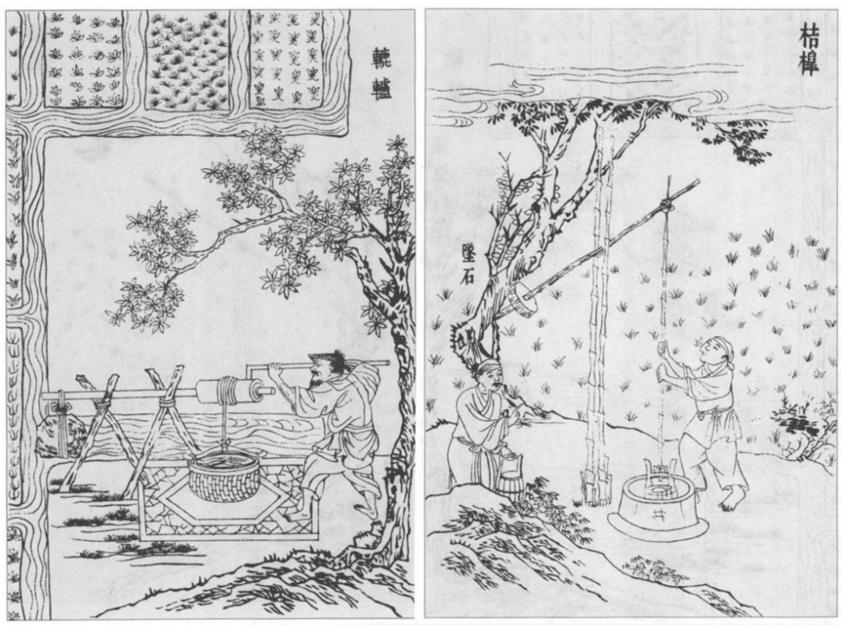
In the 17th century, "Tiangong Kaiwu" [1] written by Song Yingxing, a scientist in the Ming Dynasty, was praised as "the Encyclopedia of Crafts in China in the 17th century". It recorded in detail the transportation and lifting tools used in agriculture at that time, such as Lulu and Jugao. As shown in Figure 1.3, these tools skillfully realized the transportation and transfer of goods by inventing specific devices.

In addition, many of the agricultural tools depicted in "Tiangong Kaiwu" have similarities and differences with modern material handling machinery. For example, the Lulu uses a drum winding rope to achieve vertical lifting of heavy objects, similar to the principle of an electric hoist, as shown in Figure 2 (a); Jugao uses the lever principle to lift and transfer heavy objects, which is similar to the tower crane principle, as shown in Figure 2 (b). The ancients used diligence and wisdom to promote the development of industrial technology, enabling generations of engineering and technical personnel to stand on the shoulders of giants and drive the wave of world industrial development.

Material handling machinery has been used for thousands of years worldwide.

In the field of lifting machinery, Ancient Egypt and the Roman Empire built huge city walls with original fixed wooden supports. According to the description of the Roman

FIGURE 1. Application of Material Handling Machinery



2(a) 2(b)

FIGURE 2. Agricultural Tools and Modern Material Handling Equipment in "Tiangong Kaiwu"

engineer Vitruvius, this pulley block crane was drawn (Figure 3 [2]). Some ancient books also claimed that this crane was invented by Archimedes in the third century BC. In the 14th century, Europe saw the emergence of rotating boom cranes driven by human and animal power. By the early 19th century, important wear parts such as shafts, gears, and lifting appliances began to be made of metal materials, and hydraulic drives became popular. The longest used crane in the world is the UK's Hubble Point Crane, also known as the "Harbor Crane", built in 1951. It has been in use for over 70 years and is one of the most well preserved and still in use steam powered cranes in the world, mainly used for unloading ships and loading heavy goods.

In the field of continuous conveyor, the early conveyor is mainly the belt conveyor, has more than 200 years of history, Oliver Evans published in 1795 in Philadelphia, USA, "Miller's Guide" described the belt conveyor conveyor as "thin and soft wide ring belt or canvas belt rotating on two rollers in a frame or trough". In the middle of the 17th century, the aerial ropeway began to be used to transport bulk materials, in the middle of the 19th century, a variety of modern structure of the transport machine has appeared, in 1868 in the United Kingdom appeared large Angle belt conveyor, 1887 in the United States began to appear screw conveyor, 1905 steel belt conveyor appeared in Switzerland, in 1906 inertia conveyor appeared in the United Kingdom and Germany. In 1913, the American Henry Ford created the world's first automobile assembly line (Figure 4), this work system is known as the "Ford system", characterized by the use of mechanization and automation in factory operations, high labor productivity, and gradually widely promoted around the world.

The history of lifting machinery in China mainly originated in the early days of the founding of the People's Republic of China. In 1954, Beijing Jianhua Iron Plant, the predecessor of Beijing Lifting Machinery Plant, successfully trial produced the "Shaoxianshi" crane, which uses an electric winch to lift goods. Its steering and walking are driven by human power. In September of the same year, Fushun Heavy Machinery Plant successfully trial produced a 2 ∼6 t Tower crane. At the end of 1957, Beijing Lifting Machinery Plant made K32 truck crane by copying the mechanical truck crane of the former Soviet Union, Becoming the first domestic enterprise to produce wheeled cranes, in September of the same year, Fushun Heavy Machinery Factory successfully trial produced China's first grab bucket crane, which can load and unload 90 tons of coal per hour.

III. DEVELOPMENT STATUS OF MATERIAL HANDLING EQUIPMENT

A. RESEARCH AND DEVELOPMENT OF ULTRA LARGE TONNAGE PRODUCTS

With the rapid development of the electrical industry, various modern handling machinery and equipment powered by electric motors or internal combustion engines have gradually developed since the 1920s. Especially in the past three decades, the rapid development of the global industrial economy has led to the continuous emergence of super engineering projects in fields such as energy, metallurgy, shipbuilding, and petrochemicals, which has given rise to the demand for ultra large tonnage material handling equipment. In order to handle ultra large (overweight) heavy objects, various well-known enterprises have unique core technologies and fully utilize new technologies to enhance product competitiveness [3].

The SGC-250 crane launched by the Belgian company Sarens has a maximum lifting capacity of 5000 tons, 6 power units, 12 engines, and a main boom length of 118 meters that can extend to 160 meters. After being connected to a 100 meter auxiliary boom, the boom length exceeds 250 meters. In 2018, it was certified by the World Record Certification Authority (WRCA) as the "world's largest crane". Mainly completed the construction of the Hinkley Point C nuclear power plant in the UK, which has all the functions of a fully mobile circular crane and 360° rotation capability.

In August 2020, Baihetan Dam with a total capacity of 16 million kilowatts successfully hoisted the giant rotor of No. 1 generator unit. The outer diameter of the hoisted rotor is about 16.2 meters, the maximum height is about 4.1 meters, and the hoisting volume is 2100 tons. It was slowly lifted by two 1300 ton Overhead crane under the parallel lifting traction. After about 300 meters of horizontal movement, the rotor was lifted into the machine pit. In November 2022, the XCA2600 all terrain crane developed by XCMG will be the first wind turbine generator set installed in Changyi, Shandong Province. The lifting capacity can reach 2600 tons, and the ultimate lifting capacity can reach 173 tons at a lifting height of 160 meters, marking that China continues to maintain the world's largest tonnage and strongest all terrain crane research and development record.

The mobile gantry crane manufactured by China Honghua Group in 2014 has a span of 124 meters, a total weight of 14800 tons of steel structure and lifting tools, and a maximum lifting height of 71 meters. There are 48 lifting points designed on two arched crossbeams, each with a lifting capacity of 300 tons. The working power of the crane is 1800 kW, which can lift objects up to 22000 tons to a height of 65 meters. It is mainly used for building the hull of platform supply ships.

Western Sahara belt conveyor is mainly used to transport Apatite ore from open pit mine in plateau area to the seaport. The line is 100km long and consists of 11 conveyors with a length of 6.9–11.8km. It was put into use in 1972, with an average annual transportation volume of 10 million tons of Apatite ore (200t/h). Large scale lifting equipment is a key equipment in engineering construction, which puts forward higher requirements for the work site, environmental conditions, technical operations, and safety risk control during the construction process. In the future, it is necessary to accelerate the upgrading of supporting technologies to better adapt to the increasingly changing construction needs.

B. SAFETY REQUIREMENTS AND STANDARDS

Hoisting machinery, elevators and electric flat cars in the field of material handling machinery are all special equipment related to life safety. In order to ensure the safe operation of special equipment, the State Council of the State Council of the People's Republic of China has promulgated the Regulations on Safety Supervision of Special Equipment, which supervises the production, use, inspection and testing of special equipment throughout the process [4-6].

FIGURE 3. Reconstruction drawings of ancient Roma cranes from liber X of Vitruviusby

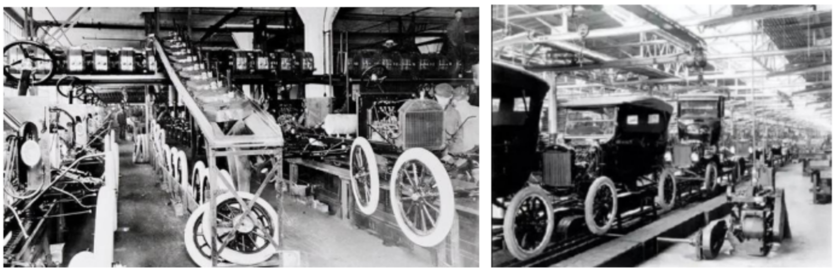


FIGURE 4. The world's first automobile assembly line

With the rapid development of the economy and society, China has established one national level safety supervision institution and 33 provincial-level special equipment safety supervision institutions. We have comprehensively implemented and strengthened safety access measures in accordance with the law, strictly implemented regular inspections, and standardized on-site safety supervision. Special equipment inspection and testing personnel can only engage in inspection and testing work after passing the classification and grading assessment conducted by national and provincial special equipment safety supervision departments and obtaining the qualification of inspection and testing personnel. The State Administration for Market Regulation has successively issued 9 regulations, 88 safety technical specifications, and more than 1100 technical standards, gradually forming a regulatory and standard system for special equipment in China. In the field of lifting machinery, a National Technical Committee for Standardization of Lifting Machinery has been established to be responsible for standardization work in the field of lifting machinery. As of September 1, 2022, there are 207 national standards under its jurisdiction. In addition, specific information such as industry standards, mandatory standards, and recommended standards is shown in Table 1.

TABLE 1. Composition of Safety Standard System for Lifting Machinery

Category Name	Standard Level		Standard properties		Total
	National	industry	Mandatory	recommended	
Basic (General) Standards	132	88	5	215	220
Basic (General) Standards	132	88	5	215	220
Safety management standards	43	5	0	48	48
Safety protection standards	32	12	0	44	44
Total	207	105	5	307	312

The regulatory models of European and American countries (regions) mainly include the model of government regulation extending to inspection (commonly known as the US model), the combined model of regulation and inspection (commonly known as the Canadian model), and the relatively independent social management of regulation (commonly known as the German model). Although different countries have different regulatory models for special equipment, they have issued regulations for specialized inspection and testing personnel and established specialized agencies and industry organizations to implement strict management. The United States adopts a model of industry organizations conducting assessment and training for inspectors, such as elevator inspectors who should obtain ASME QEI (Elevator Inspector Qualification Standards) qualifications. The European Union often uses inspection institutions to train and assess inspectors, and industry organizations to issue inspector qualifications.

The World Materials Handling Alliance (WMHA) is jointly initiated and established by the Chinese Society of Mechanical Engineering, Beijing Institute of Crane Transport Machinery Design and Research, European Material Handling Federation, Japan Logistics System Machinery Association, and the American Material Handling Association. The association is committed to promoting international cooperation in the field of material handling in terms of market, technology, standards, and other aspects. Actively promoting China's

participation in the formulation and promotion of international standards. Material handling machinery, especially in the fields of lifting machinery and continuous conveying machinery, currently dominates the market with technology in China.

C. PROGRESS IN LIGHTWEIGHT DESIGN

The load-bearing part of material handling machinery is mostly steel structures composed of trusses or plates. The dead weight of steel structures is an important indicator to measure the cost of material handling machinery. For example, the dead load of general Overhead crane is 1 ∼2 times its rated weight, the dead load of portal crane is 8 times or more of its rated weight, and the dead weight of steel structures is also large due to the long conveying distance of continuous conveyor.

Under the dual carbon background of "carbon peak" and "carbon neutrality", optimizing the design goal of structural lightweight to achieve energy conservation and emission reduction is currently a hot research and application topic in the field of material handling machinery. After long-term research on theory, design method, design criteria and experimental verification, we have accumulated rich research results including topology optimization, shape optimization, size optimization, Surrogate model optimization and other optimization technologies. The lightweight design technology using finite element simulation analysis has been widely promoted and applied, as shown in Figure 5. At the same time, under the real working condition of Multiphysics simulation coupling and multi-function constraints, there is still room for improvement in the research of structural lightweight simulation design [7,8].

D. NEW FORMS OF EQUIPMENT IN DEVELOPMENT

With the development of emerging industries and industries, there have gradually been new forms of material handling equipment with novel functions and diverse forms, which are new forms of traditional material handling equipment.

1) AGV(Automatic Guided Vehicle)

AGV is a kind of transportation equipment with navigation device and moving automatically according to the determined path. It has attracted attention since the beginning of the 21st century. In recent years, it has developed at a high speed and is flexibly applied to logistics, chemical industry, manufacturing and other working environments. During the implementation of the "Made in China 2025" strategy, the demand for AGV in various industries has increased dramatically [9]. Jiangxi Danbach Heavy Duty AGV can reach a full load speed of 5km/h, carry a load of 10t, climb equipment above 10%, and stop with an accuracy of ± 50mm. It is equipped with a laser radar to achieve obstacle avoidance function, accurately detect obstacles, seamlessly connect with upper level systems such as enterprise MES, and achieve automation and intelligence of information management, as shown in Figure 1. At present, path planning, visual navigation, trajectory tracking, fuzzy control, magnetic navigation, laser navigation, etc. are all research focuses of AGV navigation.

2) Offshore lifting crane

In 2011, the VB10000 offshore lifting crane was developed by Versabar Company in the United States. It is approximately 25 floors high and has a lifting capacity of 7500 tons. The main structure is a "horseshoe" gantry crane supported by two large barges, which performs offshore operations such as salvaging sunken ships or dismantling old oil drilling platforms.

3) Light and small material handling equipment

Light and small material handling equipment has the characteristics of light weight and flexible operation. The UK's UNIC URW-094 is a lightweight mini crawler crane with a boom length of 5.49 meters, a maximum hook height of 5.6 meters, and a self weight of 1000 kilograms. It can lift nearly one ton of heavy objects, especially when folded, it is only 0.6 meters wide and can be transported by small trailers. When deployed, the chassis structure is very spider like, and it has a wide sales and rental market in Europe and other places.

4) Sheet Handling Workstation

The plate handling workstation is a conveying device that assists the work of a robotic arm and cooperates with it to achieve automatic feeding. It recognizes, grabs, and trans-

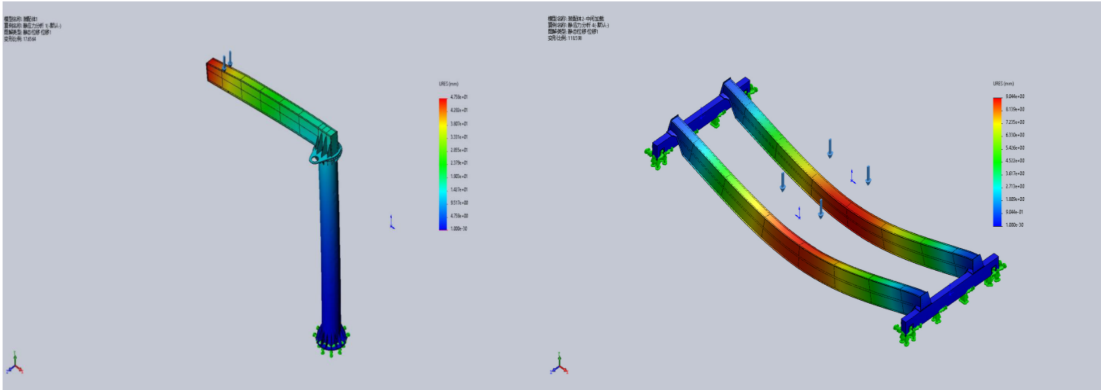


FIGURE 5. Strain nephogram of Overhead crane main beam simulation analysis

ports the plates through the auxiliary flipping of the intermediate workstation, achieving automatic feeding, posture adjustment, and automatic transportation of the plates. The board handling workstation developed by Weihua Group adopts vacuum flexible suction cups for automatic adsorption and release, with intelligent control and unmanned operation throughout the entire process. As shown in Figure 6.

5) Yacht handling crane

Yacht handling crane is the main handling equipment for yachts or small vessels entering and exiting the water, entering and exiting the warehouse. Its lifting capacity ranges from 15 to 1000 tons, and it has the characteristics of simple operation, flexible movement, and high safety and reliability. As shown in Figure 7.

IV. DEVELOPMENT TRENDS OF MATERIAL HANDLING MACHINERY

With the rise of the fourth industrial revolution in the 21st century, major technological countries such as China, Japan, Germany, and the United States have made qualitative leaps in fields such as artificial intelligence, robotics, clean energy, virtual reality, and biotechnology. In October 2021, China formulated the Action Plan for Carbon Peak by 2030, announcing the official start of the clock of national independent contribution goal to tackle climate change by 2030. Governments and enterprises at all levels actively respond to the major strategic decisions of carbon peak and carbon neutrality, accelerating the pace of green and low-carbon transformation. At the same time, the transformation and upgrading of digital intelligence in the industrial field is also urgent, and the success of digital intelligence transformation directly affects the future and destiny of enterprises.

At present, green and low-carbon development and digital intelligent transformation and upgrading are important driving forces for the development of the material handling machinery industry. Based on existing research, material handling machinery will actively explore and develop from the following aspects.

A. INTELLIGENT MANUFACTURING TECHNOLOGY FOR MATERIAL HANDLING EQUIPMENT

The manufacturing process of material handling machinery will shift towards intelligent manufacturing. In CPS based intelligent manufacturing systems, the equipment, facilities, and raw materials used in manufacturing constitute the physical environment of the system. The CPS system utilizes embedded modules in the physical environment, such as sensor recognition modules, robot modules, and security maintenance modules, to design, manufacture, assemble, and store material handling equipment through network communication systems Massive data generated in the process of operation and maintenance services are collected in real time, and decisions are made after the Big data in the physical world is mined and processed in the information layer, so as to control the system in the physical layer. The system realizes the deep integration of the physical layer, network layer and information layer in the manufacturing process (Figure 8) [10,11].

B. APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGY IN MATERIAL HANDLING EQUIPMENT

Intelligent equipment is a necessary hardware condition for realizing intelligent production lines, and also the core carrier of intelligent manufacturing concepts. It is a highly integrated and innovative modern manufacturing process, information technology, and intelligent technology in material handling equipment products. Artificial intelligence technology, including image recognition, intelligent perception, intelligent algorithms, etc., will completely change the working mode of traditional material handling equipment, promoting the significant development of equipment intelligence and refinement [12].

1) Image recognition technology

Image recognition technology has broad application prospects in material handling machinery, and the functions based on visual recognition in the working process of material handling equipment are target recognition and system positioning. Target recognition is the "eye" of equipment, which uses a CD camera to collect image information from

FIGURE 6. Plate Handling Workstation

FIGURE 7. Yacht Handling Crane

a specific moving object. It is transmitted to an industrial computer through optical fiber, and after rapid processing and feature extraction, the shape, position, and state of the target moving object are analyzed. Industrial control computers accurately execute various handling actions based on visual targets and the equipment's own status, achieving intelligent control and optimization.

2) Digital twin technology [13]

The digital twin technology of material handling machinery includes basic model data, real-time sensing data, and expert knowledge. It constructs a real-time "follow-up" twin model with multi-disciplinary and multi-scale coupling characteristics, emphasizing the precise simulation and mapping of real physical body morphology and properties in virtual space. Digital twin can be seen as a specific engineering practice under the CPS basic theoretical framework.

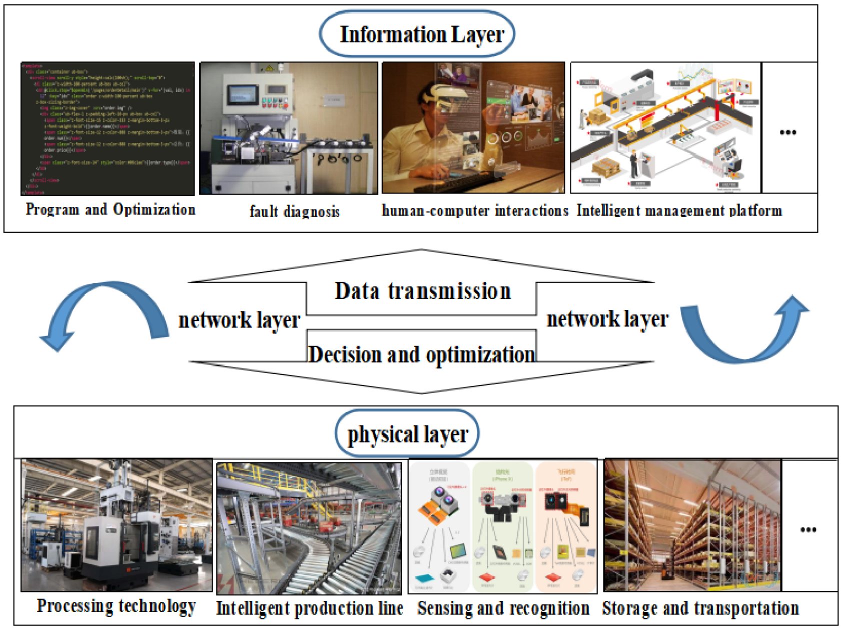


FIGURE 8. Flow Chart of CPS Based Intelligent Manufacturing Collaborative System for Material Handling Machinery

3) Intelligent Control of Handling Operation Process [14,15]
The research on the handling operation process involves calculating, analyzing, and planning data and information to predict various safety, efficiency, and other issues that cranes may encounter when executing the above operation plans. At the same time, according to changes in environmental conditions, the above operation plans and decisions are continuously improved, self-adapted, and updated in real-time. That is to say, intelligent cranes truly possess self-prediction, self-learning, self-evaluation, self-simulation, self-decision-making, and adaptation self-compensation and other intelligent abilities that humans only possess.

C. ENERGY EFFICIENCY EVALUATION MECHANISM AND STANDARDS

Material handling machinery belongs to heavy equipment with high energy consumption. With the increasingly severe energy and environmental issues and the need for green and low-carbon industrial transformation, strengthening energy conservation supervision, exploring energy-saving measures and testing and evaluation technologies, improving energy utilization efficiency, and promoting energy conservation and consumption reduction have become important research topics in the future [16,17].

Energy efficiency evaluation refers to the evaluation of the energy utilization efficiency of the effective work done during the energy utilization process. Energy efficiency testing is conducted on equipment through technical means to test the work done and electrical energy consumed by the equipment during a working testing cycle. Energy efficiency evaluation analysis is used to develop energy-saving measures [18]. According to the form of energy transmission and loss, it can be divided into two forms: electrical energy loss and mechanical energy loss. For example, frequency converters have significant energy loss, which is mainly consumed by highspeed switches of power devices, and electrical energy consumed by running electric motors during speed change and stop processes. These electrical energy are converted into thermal energy and transmitted to the surrounding environment; The energy loss of the transmission system mainly includes non load or load energy loss, including bearing loss, oil stirring loss, and meshing loss, as shown in Figure 1. The relevant standards now include GB/T 31050 “Energy Efficiency Testing Methods for Metallurgical Cranes”, GB/T 30028 “Energy Efficiency Testing Methods for Electric Hoists”, and GB/T 36410 “Energy Consumption Evaluation Methods for Port Equipment”.

In addition to the structural optimization analysis techniques mentioned earlier in this article, energy-saving measures can also use emerging composite materials with characteristics such as corrosion resistance, high strength, and high toughness, which can reduce the overall weight to a certain extent, thereby achieving the goal of energy conservation and consumption reduction. At the same time, the energy recovery technology of variable frequency speed regulation braking has the advantages of smooth lifting and landing, low energy consumption, and researching new energy recovery technologies is still an important energy-saving measure.

D. SYSTEMATIC CUSTOMIZED MATERIAL SOLUTIONS

With the continuous upgrading of automation level in manufacturing enterprises, relying solely on several universal equipment in the manufacturing workshop for material transportation cannot meet the overall efficient operation needs of the enterprise.

Material handling design companies change their design strategies by customizing scenarios to suit customers' needs, in order to better achieve efficient production based on high standards and high safety systems.. Rudemag Crane provides Propapier Group with solutions for the operation and maintenance of the wet and dry parts of paper machines, as well as automatic warehousing [19]. The lifting capacity of the crane above the wet part is 130t/65t/65t, and it can also be used for the lifting and maintenance of paper machine components on a regular basis. The crane for cadres has a weight of 130t and 90t, which is used for efficient and safe transportation of paper rolls during the production process. In addition to the cranes in the production workshop, Demag has designed two cranes for handling equipment required in the production process in the user storage reserve area, as well as three special cranes equipped with Demag Storage System (WMS), responsible for transporting them to the paper roll storage warehouse. The warehouse management system is used for communication between the transportation system and various mechanical equipment, while processing detailed data of all paper rolls. The crane combined with a vacuum lifting device can automatically stack paper rolls weighing up to 5300 kg to a height of 17.5 meters in a two span storage area.

V. CONCLUSION

The material handling machinery has moved from the original handling to the automated production line, from the steam age to the intelligent age. With the digital intelligent chemical plant gradually entering the promotion and application stage, the material handling machinery has always been the core equipment of human industrial production. Looking ahead to the next 10 years, the material handling machinery will provide Intelligent design and manufacturing, accurate identification and response, operation precision control, green energy conservation, systematic customization and other technical information, It is fully integrated into the Industrial internet of things with dynamic scheduling decisions, bringing the most shining light to the epoch-making transformation of human industry.

AUTHOR CONTRIBUTIONS

Zhu Huili: Writing the initial draft of the paper;

Li Cheng: Propose research ideas and framework;

Jiang Zhenyu: Collecting and Analyzing Data;

Wang Mengmeng: Apply for and manage research funding;

Su Jinhu: Revise and improve the content of the paper;

Ma Xiaojie: Revise and improve the content of the paper.

CONFLICTS OF INTEREST

The authors declare no competing interests.

FUNDING

This research was supported by two projects:

The Science and Technology Research Project of Henan Provincial Department of Science and Technology "Research on Automatic Flipping and Translation Technology for the Manufacturing of Large Equipment Arch Bar Parts" (Project Number: 232102220092) and Shanxi Provincial Science and Technology Achievement Transformation Guidance Special Project "Research on Dynamic Characteristics and Drive System of Long Distance Belt Conveyors" (Project Number: 202204021301060).

ACKNOWLEDGEMENTS

The authors would like to thank all those who contributed to this work. We are especially grateful to our colleagues for their valuable discussions and technical support.

REFERENCES

[1] Y. Song, "Tiangong Kaiwu," Engraved edition. 1637.
[2] C. Cesariano, "Como," 1521.
[3] Y. Li, "Super Engineering Brings Birth to Super Equipment - Giant Construction Machinery: Equipment Support for Super Engineering," China Economic Weekly, no. 21, pp. 69-71, 2021.
[4] G. Liang, "Overview of Special Equipment Safety Management in the United States," Forestry Labor Safety, no. 01, pp. 18-27, 2005.
[5] Order No, "373 of the State Council of the People's Republic of China," Regulations on Safety Supervision of Special Equipment, 2003.
[6] P. Zhang, F. Lin, X. Wang, et al., "Analysis of the Current Situation and Development Trend of Safety Standards for Lifting Machinery at Home and Abroad," Lifting Transport Machinery, no. 23, pp. 65-70, 2022.
[7] B. Wang, P. Hao, K. Tian, et al., "Research progress in lightweight design and experimental methods for aerospace structures," Journal of Astronautics, vol. 44, no. 04, pp. 596-606, 2023.
[8] Y. Li, D. Xiang, Q. Li, et al., "Research and Application of a Rapid Lightweight Design System for Cranes," Journal of Mechanical Engineering, vol. 54, no. 09, pp. 205-213, 2018, doi: 10.3901/JME.2018.09.205.
[9] Q. Zhang, "Visualization analysis of research hotspots and development trends of AGV navigation technology in China," China Storage and Transportation, no. 06, pp. 171-172, 2023.
[10] H. Zhu, Y. Yang, X. Yin, et al., "Design and key technology research of intelligent manufacturing system for bridge and gantry cranes," Lifting and Transportation Machinery, no. 09, pp. 54-59, 2019.
[11] X. Song, X. Lai, X. He, et al., "Key Technologies for Digital Twin Integration of Major Equipment Form and Performance," Journal of Mechanical Engineering, vol. 58, no. 10, pp. 298-325, 2022, doi: 10.3901/JME.2022.10.298.
[12] Vigorously developing intelligent manufacturing equipment, "Economic Daily," 2023 Jun 9; (012).
[13] C. Zhuang, J. Liu, H. Xiong, et al., "Annotation, architecture and trends of product digital twin," Computer Integrated Manufacturing Systems, vol. 23, no. 4, pp. 753-768, 2017.
[14] A. Kaneshige, S. Nagai, S. Ueki, et al., "Development of the autonomous overhead traveling crane with real time path planning based on observer information," Proceedings of 13th IFAC Symposium on Control in Transportation Systems. Sofia: The International Federation of Automatic Control; 2012. p. 30-36, doi: 10.3182/20120912-3-BG-2031.00007.
[15] X. Song, X. Lai, X. He, et al., "Key Technologies for Digital Twin Integration of Major Equipment Form and Performance," Journal of Mechanical Engineering, vol. 58, no. 10, pp. 298-325, 2022, doi: 10.3901/JME.2022.10.298.
[16] H. Tian, C. Sun, X. Zhang, and G. Liang, "Energy efficiency evaluation and energy-saving research on bridge and gantry cranes," Special Equipment Safety Technology, no. 05, pp. 36-37, 2021.
[17] GB/T 31050-2014, "Energy Efficiency Testing Methods for Metallurgical Cranes," Beijing: China Standards Press; 2015.
[18] Z. Ge, Y. Tong, and X. Li, "Energy consumption analysis and modeling of bridge cranes," Mechanical Design and Manufacturing Engineering, vol. 49, no. 10, pp. 5-10, 2020.
[19] Z. Wang, F. Sun, T. Zou, and W. Zhang, "Material Handling Solutions for the Paper Industry of Demag Crane Machinery (Shanghai) Co., Ltd," Crane Transport Machinery, no. 09, pp. 2-4+6, 2023.