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FIBER-OPTIC SENSORS AS A COMPONENT OF LEAN TECHNOLOGIES

The problems of forming an ecosystem of production systems of the future, primarily affecting the specific experience of implementing Lean technologies and environmental solutions in the real sector of the economy of the Republic of Belarus, actualizes the need to study a number of theoretical and applied issues. On the one hand, it is necessary to characterize modern theoretical approaches to the paradigm of lean production, which in domestic conditions is inextricably linked with issues of environmental protection and rational use of natural resources. On the other hand, it is necessary to show the potential of specific technical developments and technological solutions, considered from the point of view of the effective use of Lean technologies in the sectors of the real sector of the Belarusian economy in order to minimize losses, increase efficiency and labor productivity.

The specifics of the current economic situation lie in the fact that economic efficiency today is determined by the synthesis of technologies, resources and cultural factors. For any manufacturer, the necessary conditions for its activities are: organization of effective teamwork, transparency of corporate communications, intensive information exchange, elimination of losses and ensuring continuous improvement of all business processes. That is why, in modern conditions, lean manufacturing is considered as a complex of "mutually complementary and mutually supportive ways to achieve optimally efficient manufacturing of goods, works, and services" [1, p. 80].

The term "Lean production" first appeared in American management thanks to John F. Krafcik in 1988, who used it to describe a new type of management and the specific corporate culture of Japanese automakers (Toyota), interpreted as factors of their competitive success in the American automotive market [2]. For Japanese corporations, the driving force behind the introduction of this new type of management was the need to ensure a greater variety of products at lower cost and shorter development cycles. Krafcik claimed that enterprises operating according to the principles of lean production have a higher level of quality and productivity of workers than enterprises not operating according to these principles [2, p. 51]. He also claimed that the risks associated with the introduction of lean manufacturing principles and methods into practice can be reduced through the development of a well-trained, flexible workforce, detailed design of high-quality products and a highly efficient supplier network [2, p. 51].

However, in the developed world, it quickly became clear that the values and principles of lean manufacturing, a management methodology aimed at minimizing losses and optimizing production processes, are universal. Therefore, they work well not only in industry, but also in the service sector, utilities, healthcare, logistics and public administration. Accordingly, this led to the complication of this concept and to the expansion of its methodological guidelines into the political and social spheres.

In a broad sense, the concept of lean production focuses on a certain style of thinking and an appropriate corporate culture with a small planning horizon. Thus, T.V. Tselyutina, considering the issues of lean personnel development management, states: "The Lean philosophy of continuous improvement offers an alternative to large, long-term, top–down reorganizations - less global, but continuous improvements that not only change the situation for the better, but also provide the employees an opportunity to positively influence conditions and results of their work, turning them from passive performers into active participants (generators of ideas and rational proposals) in educational and production processes" [3, p. 86].

A hypothetical ideal lean manufacturing system consists of all participants exchanging information and resources in a multifunctional environment. In this system, the competencies of employees, their skills and abilities to exchange information and work in multifunctional teams are the key foundations for its normal functioning. Such economic actors must be able to quickly change focus, diversify, modernize, and rebuild their businesses to achieve a specific goal, because the windows of opportunity do not remain open for long. However, in this context, lean manufacturing cannot be formalized in the form of a standard model with a set of well-defined indicators.

In a narrow sense, in modern economic theory, the concept of lean manufacturing is mainly used to characterize certain technological processes and a specific method of flexible production, consistent with the demand for certain goods in the maximum number of parameters. First of all, lean manufacturing combines product design, procurement, distribution, manufacturing, accounting, marketing and management under a common name. In the context of the digital transformation of the economy, this method allows companies to proactively, promptly and flexibly respond to any market changes, dynamically adapt to external and internal environmental factors, fashion trends and changing consumer requirements [4]. In this interpretation, the lean manufacturing model, while maintaining quality and cost control, involves reducing production cycles, product flows, and related time costs by eliminating components that are not valuable to the consumer. This approach allows the company to significantly reduce the cost of storage facilities, stocks of materials and components, minimize their losses from improper storage, etc. [5].

However, in practice, the lean manufacturing model requires manufacturers to forecast demand accurately, to produce regularly, to manage their business processes, and to secure reliable suppliers. At the same time, it creates serious stressful conditions for all the employees, both directly employed in production and working outside the production process (accounting, marketing and advertising, service departments, etc.), due to inflexible working conditions and the risks of unstable employment and high requirements for their qualifications.

From an optimization perspective, the structure of Lean technologies, which are a phenomenon of socioengineering nature, can be supplemented with a component that was not originally there – various technical devices (sensors, sensors, etc.).

Functionally, this component should provide monitoring of certain processes and automatic fixation of the necessary parameters of the activity of economic actors (for example, for constructing a value stream map (VSM) or determining the defect-free process).

At this point, Belarusian State Academy of Communications has certain scientific achievements and technical developments, where, as part of the implementation of the State Research Program "Digital and Space Technologies, Safety of Man, Society and State" for 2021-2025, a team of researchers led by Doctor of Technical Sciences, Professor A.O. Zenevich has developed and patented a range of promising sensors for measuring various physical quantities. This legally secures the intellectual property of the Belarusian State Academy of Communications and paves the way for the implementation of the system in the real sector of the economy.

The new technological product uses a standard telecommunication optical fiber as a sensing element [6]. This opens up new opportunities for industrial, power engineering, and security systems. The key innovation is the use of massive and inexpensive telecommunication fiber to create sensors. Research shows that such fibers can be successfully used to identify liquids and determine the concentration of solutions, responding to changes in the refractive index of the environment.

Turning the data cabel into the sensor itself opens the way to low-cost, distributed, and efficient monitoring systems. In practice, this approach provides a number of significant advantages:

cost-effectiveness: the use of standard components dramatically reduces production costs;

adaptability and ease of integration: sensors can be easily integrated into existing fiber-optic communication lines;

high reliability: the sensors are immune to electromagnetic interference, safe in explosive environments, and resistant to corrosion;

versatility: A single fiber can operate in different wavelength ranges corresponding to transparency windows and transmit a signal over long distances without loss of quality.

In the context of the technical specification, the researchers have created three types of innovative sensors that are capable of operating in a wide range of conditions. The sensors are compact, highly sensitive and respond to the slightest deformation of the optical fiber:

micro-bend sensors are ideal for monitoring vibrations, pressure and deformations in critical structures (industrial structures, pipelines, construction cranes, railway tracks, bridges, conveyor systems, etc.);

macro-bend sensors are reliable and relatively easy-to-manufacture devices for measuring physical parameters in large movements (for example, in an office or workshop), temperature, or structural integrity monitoring.;

reflective sensors are compact sensors that allow precise measurement of certain parameters in hard–to-reach places or aggressive environments (for example, temperature or concentration of substances in solutions).

The developed sensors have a number of critical advantages: immunity to electromagnetic interference, the ability to operate in explosive and fire-hazardous environments, corrosion resistance and high accuracy of parameter measurement.

In practice, the software component of the sensors transforms the sensor into an intelligent decision-making system based on algorithmic parameter analysis. The "output" results in a "smart" device with the ability to connect to IoT networks, which allows you to forget about the factory-hardwired values that rigidly determine the response parameters. The sensor is capable of independent data transmittion to control panels, cloud services, sending notifications, and can be integrated into smart manufacturing and logistics systems.

A multifunctional laboratory of SMART technologies and 3D modeling operates within the walls of the Belarusian State Academy of Communications, on the basis of which small-scale production of such sensors have been developed. From the point of view of the organization of industrial production, a synthesis of two advanced technologies is proposed – fiber-optic sensing and additive manufacturing (3D printing). The production of new-generation sensors using 3D printing makes it possible to create enclosures and mounting elements of any shape, even the most complex, ideally suited to a specific task in the shortest possible time. The synthesis of fiber-optic sensor and 3D printing creates unique opportunities:

creating complex "smart" nodes – the sensor can be printed already embedded in a part or structure, rather than mounting it as a separate extraneous element;

effective protection – 3D printing makes it possible to create an ideal sealed enclosure that protects optical fiber from dust, moisture and mechanical influences, suitable for use in aggressive environments;

speed and personalization – the path from a concept to a working prototype can be reached in hours, quickly testing and refining the design to meet the needs of the customer.

This technical solution opens up opportunities for the use of such sensors in the various sectors of the economy (for example, as a part of Manufacturing Execution Systems (MES)) and other areas of modern Belarusian society:

smart energy: monitoring the condition of high-voltage equipment, cable lines and transformers;

communication systems: monitoring the status of server and telecom equipment;

industrial and environmental safety: control of leaks of hazardous substances, deformations of building structures, dams and bridges, technical condition of railway transport;

chemical and food industry: real-time monitoring of technological parameters of industrial refrigeration units, climate control systems and production lines in aggressive environments;

fundamental research: conducting high-precision laboratory measurements.

Thus, the obtained scientific results and technical developments are a serious step in the development of domestic science and import-substituting technologies. At the same time, they allow, based on the basic provisions of the Lean 4.0 concept [7], to modify the structure of Lean technologies by including a technical component (sensors,

sensors, etc.) that allows monitoring of certain processes and automatic fixation of the necessary parameters of the activities of economic actors. From the perspective of the issue under consideration, such sensors can hypothetically be implanted in such well-known Lean technology tools as Lean Six Sigma (LSS), Business Process Reengineering (BPR), 5S, Poka-Yoke, Event-Driven Process Chain (EPC), etc.

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