DESIGN OF A SMART PRODUCTION CELL

M. Fertsch, A. Stachowiak
Faculty of Engineering Management, Poznan University of Technology, Poznan, Poland

Abstract
The article presents an original method of designing a smart production cell - a production unit operating under the conditions of the Industry 4.0. The starting point of the discussion is the identification of technical and economic factors shaping the operating conditions of production cells. Each of the identified factors will be briefly characterized. On this basis, a forecast of the production and organizational conditions under which the smart production cell is expected to operate will be developed. Next, a method of designing a smart production cell, which will adjust its performance to the identified conditions will be presented.

Keywords:
smart production cell, Industry 4.0, cell design

1 INTRODUCTION
As the world changes, operating conditions of manufacturing cells are changing as well. Contemporary management paradigms refer to turbulence of business environment and flexibility and agility of enterprises which have to cope with it. To be flexible and agile companies change not only their strategy, but also structure at all the levels of hierarchy.

The goal of the paper is to present an original method of designing smart production cells, as authors believe that managers are lacking simple and straightforward procedures concerning implementation of elements of contemporary strategies and approaches, such as Industry 4.0. Companies are aware of potential benefits, however often do not have expertise allowing them to win them.

The article is focused on operational aspects and presents an original method of designing a smart production cell - a production unit operating under the conditions of the Industry 4.0. The starting point of the discussion is presentation of the Industry 4.0 idea and some general assumptions concerning smart factory and smart production cells. Next, of technical and economic factors shaping the operating conditions of production cells are listed. Each of the identified factors is briefly characterized. On this basis, the forecast of production and organizational conditions under which the smart production cell will operate will be developed. The discussion is followed by the original method of designing a smart production cell, which will adjust its performance to the identified conditions. Last section of the paper is brief summary and conclusion on the work done.

2 INDUSTRY 4.0 CONTEXT
2.1 Industry 4.0
The world changes in every dimension, and the industry changes with it, benefiting from new solutions (technical and organizational), opportunities, and dealing with new threats and constraints.

The changes in industry are usually presented as a continuum of the so called revolutions, starting with the breakthrough in 19th century and introduction of mechanization of processes and application of steam power (1st industrial revolution), evolving in mass production with all its consequences (2nd industrial revolution), changing profile and focusing on information and its processing (3rd industrial revolution) and finally developing the tools and methods enabling production systems work almost on their own, communicating and to some extent making decision concerning processes they are expected to perform (4th industrial revolution). The common graphical interpretation of the changes is presented in the figure 1.

![Diagram of industrial revolutions](image)

**Figure 1. Industrial revolutions**

Source: [13].

The beginning of the Industry 4.0 is dated on 2011, when the term "Industrie 4.0" (Industry 4.0) was revived at the Hannover Fair [1]. Works o develop the concept were dynamic, and in October 2012 the Working Group on Industry 4.0 (with its members representing German academic and industrial environments, and recognized as the founding fathers and driving force behind Industry 4.0) presented a set of Industry 4.0 implementation recommendations to the German federal government. On 8 April 2013 at the Hannover Fair, the final report of the Working Group a consortium of universities, research institutes and industrial plants in Germany developing the Industry 4.0 idea was presented [2]. It included discussion on investment, development awareness, ideas and further research on the implementation of Industry 4.0.

The Industry 4.0 concept offers a complex and comprehensive solutions helping to deal with challenges of contemporary business environment thanks to a broad spectrum of innovations in the areas of IT, manufacturing technology and materials science. Thanks to application of the solutions developed and recommended within Industry 4.0 concept business is supposed to [3, 4]:
- successfully deal with complexity of data, products, processes (including management process) and market environment,
- be able to identify the level of resources and capacity required to implement innovation to products and processes,
- be able to provide security of data transferred from and to market environment, as well as between stakeholders within value chains,
• obtain desired level of flexibility, of products (their configuration), processes and customer service. The solutions developed or identified as suitable for Industry 4.0 differ on account of character, reference area and place in management/corporate strategy. Hence, they can be classified to cover the following dimensions [5]:
  I. Industrial policy dimension: development of new business models based on traditional value chains
  II. Employment policy dimension: development of high-skilled jobs
  III. Data security dimension: active protecting confidential data from unauthorized access
  IV. Middle class company’s policy dimension: innovative action of the middle class companies
  V. Regulatory dimension: reference architectures and application in order to achieve competitive advantages

and deal with both internal and external aspects of an organization.

Industry 4.0, being a German idea, is not the only one contemporary solution striving for advancement and improvement of manufacturing companies. The other initiatives that can be mentioned include works of the SMLC (Smart Manufacturing Leadership Coalition) in the USA, actively supporting the development of intelligent manufacturing, and implementation of intelligent tools that operate in real-time increasing efficiency of all production processes [6]. As Internet plays the crucial role in most of the contemporary solutions offered to improve industrial companies performance, the projects aimed to ensure interoperability on the technical level seem to be important as well, hence involvement of Industrial Internet Consortium [7].

2.2 Smart factory

The result of implementation of Industry 4.0 is the structure called smart factory. It integrates data from system-wide physical, operational, and human assets to drive manufacturing, maintenance, inventory tracking, digitization of operations through the digital twin, and other types of activities across the entire manufacturing network, enabling end-to-end, holistic integration through the entire value chain [8], resulting in more efficient and agile system, less production downtime, and a greater ability to predict and adjust to changes in the facility or broader network, possibly leading to better positioning in the competitive marketplace [9]. The structure requires implementation of solutions of various character, including robots, technical instruments but also sensor and monitoring tools that are controlled by dedicated control systems and provide real-time feedback on companies performance. The general idea of a smart factory is presented graphically in the figure 2.

It can be assumed that smart factory is a complex structure composed of elements that can be identified smart manufacturing cells. The structures at the high complexity level (smart factories) are the consequence of implementation of Industry 4.0 principles, but the structures at low complexity levels (smart cells) need specific design procedure, following not only Industry 4.0 principles but also some engineering guidelines.

2.3 Design principles in Industry 4.0

There are four design principles in Industry 4.0. These principles support companies in identifying and implementing Industry 4.0 scenarios and include [10]:

• interoperability: the ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of Things (IoT) or the Internet of People (IoP), resulting in extensive automation of processes [11]
• information transparency: the ability of information systems to create a virtual copy of the physical world by enriching digital plant models with sensor data. This requires the aggregation of raw sensor data to higher-value context information,
• technical assistance: first, the ability of assistance systems to support humans by aggregating and visualizing information comprehensively for making informed decisions and solving urgent problems on short notice. Second, the ability of cyber physical systems to physically support humans by conducting a range of tasks that are unpleasant, too exhausting, or unsafe for their human co-workers,
• decentralized decisions: the ability of cyber physical systems to make decisions on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions, interferences, or conflicting goals, are tasks delegated to a higher level.

Over the Internet of Things, cyber-physical systems communicate and cooperate with each other and with humans in real time, and via the Internet of Services, both internal and cross-organizational services are offered and used by participants of the value chain [10].
3  TECHNICAL AND ECONOMIC FACTORS SHAPING THE PRODUCTION ENVIRONMENT

There are numerous factors shaping the production environment in the Industry 4.0, and they can be classified as technical and economic. The most important technical factors include:

- the development of mechanization of production that leads to the situation where manual work is being replaced by mechanized work and manual work-stands are substituted by machines,
- changes in the construction of machine and tools resulting in the substitution of specialized machines, built to perform one type of processing by machining centers or reconfigurable systems,
- the development of materials engineering providing new construction materials used in production are better suited to the special requirements of the product (example - materials for implants) and for the production of increasingly efficient tools and auxiliary equipment. The use of these materials increases productivity and shortens the processing times,
- the development of automation and robotics,
- the development of computers and popularization in their use in industry and production, especially in the field of production planning and control,
- the appearance of the concept of the Internet of Things and then its dynamic development.

In parallel to the technological factors, the economic factors should be taken into consideration. Their occurrence is linked to the growing wealth of societies, leading to:

- the need to differentiate the offer of producers (broadening the range of manufactured products),
- the intensification of competition, first through the prices and costs of manufactured products, then by reducing the length of the delivery cycle,
- the need to adapt the products to the requirements of individual customers (customization).

The development of mechanization of production leads to the replacement of manual work by mechanized work and substitution of the manual work station by machines. It results in an increase in the efficiency of production processes, decrease in onerous activities and increased safety. Companies are able to produce more varied products in shorter periods of time. The demand for labor force is decreasing, especially in case of simple, uncomplicated activities. At the same time, the demand for certain forms of human work is increasing, especially for the high qualifications or unique skills. Simple physical activities are replaced by intellectual effort, less physical strain and increased workplace safety. There is a growing amount of intellectual effort in the work processes, the ability to adapt to changing environment is required, as well as the ability to make decisions in dynamic changing environmental.

Changes in the design of machines and devices increase their versatility, but also increase the complexity of their construction and their operations and exploitation, including maintenance and repair. The productivity of resources - machines and equipment used in production processes is increasing. We need less and less resources (machines and equipment) both regarding their quantity and types to produce a certain amount over a certain period of time. The amount of work that we have to devote to the direct handling of machines and equipment in production processes decreases. The labor-intensive maintenance of machines and production equipment is increasing.

The development of material engineering increases the variability of types of materials used in the production process. This allows to focus on the their proper selection in order to make them more suitable to the conditions of particular production process. The traditional production model, consisting of the multi-stage, long-term and costly processing of a wide range of materials to achieve the desired end-effect, can only be reduced to conditions where obtaining a specific end result requires the use of strictly defined material and process technology. In other cases, the selection of the right material leads to a significant reduction in the duration of the technological process and its costs. This solution places high demands on product design, technology design and logistics.

Introduction in the technical part of the production system of a range of measuring devices and sensors - generally, information delivery devices enable the transmission, storage and processing of this information.

The availability of information creates new opportunities but also places new demands on production planning and control.

Traditionally this process is based on standards - indicators that remain constant through each planning cycle. Availability of information about actual values of individual parameters of the production process creates the possibility of planning and controlling its course based on real time values.

The development of computing power and the advancement in the information-processing technology based on the use of services provided by an external service provider (cloud computing) provides new opportunities for data collection and processing but also generates new security and reliability issues.

The appearance of the concept of the Internet of Things (or the Internet of everything) and its dynamic development creates the need to redefine the two subsystems in the production system - the communication subsystem and the management subsystem. Traditional communication in production systems is characterized by a high degree of formalization and is based on standard documents (kanban cards or so-called "blue prints system"). This ensures the uniqueness of the message and its high communicativeness, and therefore it allows to eliminate the redundancy. Achieving this state in full interoperability - in which we allow the communication between machines, devices, products and services and people using the Internet can be a serious challenge. The management process according to the classical definition is realized "by people and for people". Its functioning is based on the existence of hierarchy. Under conditions of full interoperability there is a problem whether this hierarchy should be included and, if so, at which level, machines, products and services. There is a problem of enforcing compliance with such a "mixed" hierarchy.

In parallel to the technological factors, the economic factors should be taken into consideration. Their occurrence is related to the growing wealth of societies, which leads to the differentiation of customer needs. That implies the following manufacturers' behavior:

- Need to differentiate the offer of producers (broadening the range of manufactured products). It results in a decrease in the repetitiveness of production, a decrease in size of the construction and production series of manufactured products, and decrease in production stabilization.
- Increasing competition, first through product prices, then shortening of the delivery cycle. Manufacturers are under constant competitive pressure, which determines the marketable price of the products. This results in the similarity of the behaviour of the individual manufacturers with respect to the technology
used, the use of similar materials and the use of the same suppliers, the broad use of outsourcing, the same distribution and marketing practices (so-called "best practices").

- Manufacturers limit their activities to the selected product ranges, phases of production or production processes that enable them to gain competitive advantage (the so-called "key competences"). Most of the components are outsourced. It is common practice to cooperate with other manufacturers of similar products on a "give it up" basis. This improves the stability and repetitiveness of production at the components' level while providing a wide assortment of final products.

There is need to tailor the products to the requirements of individual customers. As a result, clients are involved in product design and even in the production process. The standard is to provide the customer with full information on the course of the production process at each stage.

4 FORECAST OF PRODUCTION AND ORGANIZATIONAL CONDITIONS BEING CONSTRAINTS IN DESIGN OF SMART PRODUCTION CELLS

The identification of the technical and economic factors shaping the production environment in the Industry 4.0 on will be included in this section in order to develop a forecast of the production and organizational conditions that will appear as constraints in the design of smart production cells.

The conditions to be met by an smart production cell designer will be defined by the following characteristics:

- The range of products (elements of the final product), produced by the proposed production cell will be very large, theoretically going towards infinity. The only physical limitation of products’ variation will be the structural features, such as: shape, size, properties of the product, the required machining accuracy. Selection of assortment produced in the projected production cell must be based on analysis of structural similarity.

- Production programs manufactured in the projected production cell will be small, striving to 1 and a high demand variability will force the production in „piece by piece” mode.

- Repetitiveness of production within the assortment of products in the projected production cell will be low due to low production programs and high demand variability.

The increase in the production programs and production repetitiveness can be achieved if the manufacturer accept the “take to give” approach – by starting collaboration with other manufacturers. This increase will not, however, significantly affect the variability of demand that will force fast delivery of small batches with short delivery cycles.

The increase in production and repetitiveness programs may take place under the terms of the manufacturer's acceptance of the model set out in the preceding chapter as accept “take to give” - cooperation with other manufacturers. This increase will not, however, significantly affect the volatility of demand, which will force fast delivery of small batches with short delivery cycles. 

5 PRODUCTION STRATEGY FOR SMART PRODUCTION CELL

The term "strategy" in the title of this subchapter is used in the sense in which production planning strategy is referred in production planning. It is about choosing a method or mode of action whose application leads to the resolution of existing problems or achievement of goals. 

The goal that the author has set himself is to design a production cell that will best be adapted to operate in an existing environment.

In order to identify the design strategy it is necessary to start with the identification of criteria which should to be taken into account. The overriding factor considered in Chapter 3 is the manufacturer's ability to maintain price competitiveness, thus minimizing production costs. This criterion can be reached by maximizing the use of resources and minimizing their amount. In the design process, however, we are not dealing with a single decision, but a decision problem - a situation requiring a clear set of rules for decision-making.

These rules can be determined by the analysis of the conditions. This analysis will consist of identification of parameters that may influence the design process.

In the design process of smart production cells we rely on minimizing the number of work stations? This does not seem to be a good solution because in the analyzed conditions their number in each type (in individual Homogeneous group of work station JGS) naturally tends to one.

Can we maximize the usage of work stations? This does not seem to be a good solution, because in the analyzed conditions it is random. As a constraint in the design process, we should accept a minimum acceptable level of average occupancy as a prerequisite for maintaining cost competitiveness.

Can we rely in the process of designing smart production cells on minimizing the production space occupied by the work stations? This does not seem to be a good solution, because in the analyzed conditions, it is rather constant.

The only parameter that we can shape in the design process is transport load (transport capacity) in the production system. The problem of minimizing transport load in the production system is the so-called "quadratic assignment problem". (Quadratic Assignment Problem - QAP)

6 SMART PRODUCTION CELL DESIGN PROCEDURE

The procedure for smart production cell design is based on the simple steps and to some extend is an upgrade of design procedure for traditional, product oriented production cell.

The steps of the procedure are listed below:

Step 1. Define the key competencies of the proposed production system (Referring to the "production plant design" stage)

Step 2. Estimate the multiplicity and general features of a set of assortment items produced in the system

Step3. Statistical analysis (selection of types of series):
- Specify the number of groups in which the assortment should be split.
- Specify the number of representatives in each group.

Step 4. Based on the outcome of Step 3. Match the groups of representatives and representatives in each of the groups.

Step 5. Check the structural similarity within groups of products.

Step 6. If the separated groups guarantee reaching the assumed level of workloads go to 9. If not go to 7.

Step7. Check the technological - organizational similarity for a set of elements. If the value of this indicator is less than the value corresponding to the non-rhythmic production line, then use the procedure. If
it gives a positive result go to Step 8. If not, go to Step 9.

Step 8. For a set of assortment items, design a U-shaped line

Step 9. Solve the QAP for a separate set of workstations.

Step 10. Design a communication system and management system for a dedicated production cell.

The procedure is quite general, however lists the most important actions that need to be taken to define the structure of a smart production cell.

7 CONCLUSION

Industry 4.0 is the concept widely discussed among academics and business people, not only in Germany, where it was developed, or in Europe, but all over the world, as its implementation is expected to substantially improve performance of companies and entire economic systems.

Value of the concept is well recognized, however companies, especially those representing SME sector are often reluctant to involve in the idea, as they do not exactly know what they are supposed to do. The important constraint for them seems to be money required for investment in advanced, sophisticated automated solutions.

The paper briefly presents the approach recommended for implementation of simple smart structures – production cells, that can initiate the process of going towards smart factory and following Industry 4.0 idea. The procedure can be applied in production companies disregarding the industry or the size, manufacturing wide range of assortment, working in contemporary market conditions. It can be followed by implementation of Industry 4.0 solutions, but there is no such requirement, and the authors believe that transformation of a manufacturing cell into smart production cell is simply a benefit for the company, as it adjusts it to the market it needs to deal with.

8 REFERENCES