19th IMEKO TC10 Conference
"MACRO meets NANO in Measurement for Diagnostics, Optimization and Control"
Delft, The Netherlands, September 21–22, 2023

Flexible Manufacturing Concept at Bosch: A low-cost implementation of an Industry 4.0 concept

László Fükő[1], Ádám Szaller[2,4*], Eduardo Colangelo[3] Gábor Nick[4], Botond Kádár[4]
[1]*Bosch Power Tool Ltd., 3526 Miskolc, Hungary*
[2]*Institute for Computer Science and Control, 1111 Budapest, Hungary (adamszaller@sztaki.hu)*
[3]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany*
[4]*EPIC InnoLabs Nonprofit Ltd., 1111 Budapest, Hungary*

Abstract – Nowadays production companies are in a difficult situation since batch sizes are decreasing, the number of product variants is growing, and the demand is difficult to forecast. New technologies enable to design more complex production systems capable of handling these challenges, but these "Industry 4.0 solutions" are often very expensive and hard to implement. In Bosch Power Tool Ltd. (Hungary), a flexible manufacturing concept was implemented, which enables to produce efficiently even with batch size one, requires much less space from the shop floor, prevents disruptions in production, and last but not least realized in from a relatively small budget. The concept introduced in this paper can be used as a best practice for manufacturing companies facing similar challenges.

Keywords: flexible manufacturing, smart manufacturing, Industry 4.0

I. INTRODUCTION

Dynamic customer requirements, accompanied by decreasing batch sizes and increasing product variance, as well as rising rationalization pressure due to increasing competition, are challenging companies. In addition, on the basis of the last years' happenings, customer demand is increasingly difficult to predict [1]. These pose significant challenges to traditional production systems, which are basically optimized for mass production. It is becoming clear that the accuracy of the forecasts can only be improved to a small extent, or not at all, despite the efforts. Major changes and major trends are downright unpredictable, because they are mostly induced by external factors that cannot be predicted either. Based on these, a quick response to rapidly changing needs is a viable path. Nowadays, exclusive differentiation based on product price and quality is no longer sufficient, a holistic approach is needed to ensure success. In particular, versatile production systems have been gaining in importance for several years as a success factor for competitive production in volatile markets (see [28] p. 103). The adaptability of production describes the ability to redesign (as a reaction to changing framework conditions) as required with minimal effort. The aim is to switch between different operational modes with little financial effort and thus ensure economic success in volatile markets. A recent survey also points out that according to the opinion of companies and research institutes, flexibility and reconfigurability of production systems are ways to cope with the above-mentioned challenges [7]. Examples of changeability enablers of production systems are universality, scalability, modularity, compatibility and relocatability [24]. Under these aspects, a number of versatile production systems - mostly conceptual - have been established in the literature.

Flexible Manufacturing Systems (FMS) enable the adjustment of production capacity and functionality within a fixed flexibility corridor (e.g. a family of parts) [2]. This requires the use of predefined functionalities, which leads to additional costs and higher complexity. The retooling of an FMS beyond the held flexibility corridor takes several weeks or months, compare [10][4][19][15][14][8][25]. FMSs are thus configurable within a corridor but not reconfigurable beyond it. *Reconfigurable Manufacturing System (RMS)* resolve this limitation. In contrast to FMS, RMS allow the adaptation of the production system across fixed flexibility boundaries. RMS thus combine the advantages of dedicated manufacturing lines and FMS, compare [9][10][11][21][22]. According to [17], the productivity of an RMS is higher than that of a line, for example in large, complex systems. However, efficient algorithms are necessary for real-time control of an RMS. These are also correspondingly complex [18][21]. The *Matrix Manufacturing Systems (MMS)* consists of flexibly linked, usually dedicated process modules. Each process module provides predefined sets of technological functionalities necessary for production. MMS enable new production control functions, as each product is able to determine an individual production path by selecting its process modules, depending on the available process module functionalities, the assembly precedence graph and the current state of production resources. The cycle times of the process modules are no longer uniform

[13][12]. Based on the mathematical considerations of [20] about fractals, [26] and [27] develops the so-called *Fractal Factory (FF).* The concept of FF takes advantage of the properties of fractals (self-organization self-similarity and self-optimization) and proposes, that a production enterprise is composed of small components or fractal entities. The goals of the individual systems must be free of contradictions and must correspond to the goal of the overall system. To this end, the fractals are interconnected via efficient information and communication systems [26]. Building on the work of [26], [23] propose the so-called *Cyber-Physical Production System (CPPS).* [6] and [5] also sees the core requirement of increasing complexity in the autonomy and decentralization of systems.

Due to the advancing digitization in the course of Industry 4.0, these changeable production systems are outgrowing the concept stage and are increasingly being implemented in practice [28].CPPS can record their environment directly with their corresponding sensors, evaluate it with the help of available data and services, store it, and they can affect the physical world with the help of actuators. A production system that is designed based on this concept is characterized by the following features [28]:

- **Intelligence** – the elements are able to absorb information from their environment and act autonomously.
- **Connectivity** - the elements have the ability to make and use connections to the other elements of the system (including humans) for collaboration and cooperation, and to knowledge and services available on the Internet.
- **Responsiveness** – the system is able to react to internal and external changes

When it comes to practical implementation, the degree of changeability is limited on the one hand by product, process-specific and organizational requirements. On the other hand, a healthy measure must be chosen in the sense of an economically sensible solution.

In recent years, companies have increasingly relied on the implementation of various (partial) concepts of the versatile production systems mentioned above. With the "CubeTruck" concept, *Daimler Trucks Beijing* is implementing a modularly designed body shop for utility vehicles. This allows efficient production of the multi-variant product range. Thanks to the standardized structure of the process modules, the production system can be scaled and adapted to changing requirements. Thus, it is possible to reconfigure the individual process modules by changing tools and reprogramming the robots with little effort and with little investment (see [28] p. 27.)

Sew-Eurodrive enables high productivity internally and high customer satisfaction externally by using an integrated matrix production system. The system consists of flexibly interlinked process modules. In the assembly area, a process module corresponds to a classic U-line specialized in a product group. Process modules for mechanical production and assembly are partly interlinked units, partly individual systems. Employees are flexibly assigned to the individual process modules as required. The concept is accompanied by digital support tools from Industry 4.0 (see [28] p. 28).

Audi Ingolstadt implemented a prototype matrix production consisting of standardized manual process modules at which the materials are provided for assembly. In addition, an automated testing station is integrated. The subassembly to be assembled is moved to the individual modules by automated guided vehicles and thus completed step by step. The assembly remains assigned to a vehicle during the assembly process and is mounted on it via a fixture. (see [28] p. 33).

Within this paper, the practical implementation of a flexible production system named *High Flexible Unit (HFU)* at *Robert Bosch Power Tool Ltd*. (Bosch) in the city of Miskolc in Hungary is introduced. The products assembled in this plant are mainly power tools (e.g., hand drill) and gardening products (e.g., hedge trimmer, lawn mower) which are typical examples for seasonal and occasionally unpredictable demand, for example due to COVID-19. In the following sections, first, motivation and comparison of the flexible and traditional manufacturing concepts will be presented. Then, the concept will be described in detail, and technical implementation will also be introduced. The novelty of the concept is that Bosch realized a very effective and practical Industry 4.0 solution with a relatively low price, which can be a useful best practice for manufacturing companies from other industries, as well.

II. FLEXIBLE MANUFACTURING CONCEPT AT BOSCH

It is important to highlight that the goal for the basic concept was not to consciously design an Industry 4.0 system, but to create a production concept that would make it possible to cost-effectively implement the serial production of products, even with one-piece series size. In addition to flexibility, the other basic goal was to reduce costs, which can be achieved, among other things, by (1) minimizing production losses and also by (2) reducing fixed costs of investment. We aimed to completely eliminate two basic losses that arise from errors in the continuity of production and the direction of the material flow. The dream was a production system that (1) practically never stops completely due to disruptions, (2) there is always a product that can be manufactured, (3) where the direction of the material flow is strictly only forward along the value creation chain, i.e., there is no backward material flow, (4) the equipment in the production area operates at the highest possible utilization rate and (5) customer orders can be fulfilled with a very short lead time. As a True North goal, the vision was that the customer's order comes directly into the system via online channels and the finished products are delivered to the customer from the end of the production line.

A. Comparison to traditional concepts

In traditional production areas, basically, two types of production line concepts are used for the production of hand tools. In both cases, the typical form is the U-shaped production line, where operations are sequential, and workers perform limited, relatively simple operations with short cycle times. The raw materials required for the products are loaded into the production line's containers from outside the U cell. In the case of a product type change, the unused materials are removed from the production line, returned to their storage locations and the new material is loaded to the line. This concept can be operated economically in case of a specific series size, where the appropriate ratio of utilization and type changeover times are ensured.

For products with a higher annual number of units, *dedicated production lines* are built, which are prepared for the production of different versions of a product family. Here, the utilization, even for one product family, reaches the minimum expected level. The advantage is that the line is relatively simple, there are not too many and complicated type-changing activities, and the assembly workers can be trained relatively quickly. The investment cost is medium to high, but the complexity is low. Another disadvantage is that due to the sequential operation line, the entire line stops if a malfunction occurs at one of the workstations. Many similar production lines, designed for different products, occupy a significant part of the valuable production area. In the case of lower annual quantities, usually combined, *multi-purpose production lines* are created that are suitable for the production of several (usually 2..3), but morphologically similar products. Here the advantage is that they can be operated with higher utilization than dedicated production lines, and they can reduce the area required for the production of one product type. Investment costs can be reduced by using a significant part of the line for all products assigned to it, and only for product-specific operations should individual machines, equipment and tools be dedicatedly integrated. On the other hand, the disadvantage is that the type change losses increase, the complexity is higher and it takes more time to train the workers. The risk of line stoppage due to sequential production is similarly high as in the case of a dedicated production line.

Traditional U-shaped production lines can be used economically mostly in the case of large or medium annual quantities and low volume (complexity) of product types. However, the following common disadvantages can be identified for both production line concepts: there is a significant risk of line stoppage in the event of disturbances, economical production requires a certain series size, type change losses occur, and there is a reverse material flow. Based on the above-mentioned settings, a product portfolio with a high complexity but a low number of pieces per year, is difficult to handle using such production lines. This way, when developing the flexible production concept, the aim was to eliminate these common disadvantages and to design a concept for the production of the high-complexity but low-volume portfolio (see Figure 1).

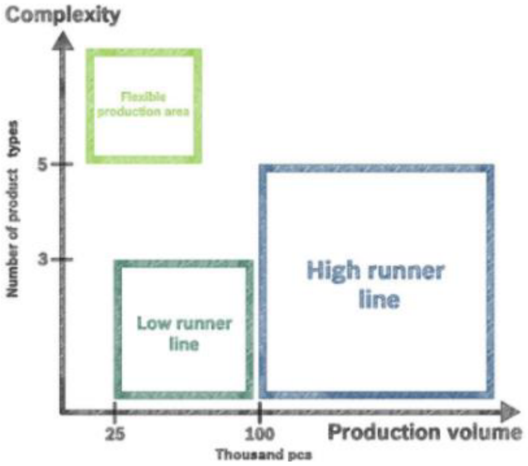

Figure 1. Positioning the new concept

B. Simplifying the supply chain

In case of power and gardening tools, logistics costs represent a significant part of the sales price of the products. These consist mainly of transport, handling and storage costs. By simplifying the supply chain, logistics costs can also be reduced, and delivery times can be shortened. The introduced production concept also offers a solution for this through the implementation of one-piece serial sizes.

At the end of traditional production lines, typically homogenous pallets of finished products are made, and the goals are to (1) create the most compact stack possible, (2) to increase the number of products placed on the pallet and (3) to minimize the delivery volume. In this way, economical transport can be ensured. These homogeneous product pallets are delivered to the warehouses in the distribution centers. From these homogeneous pallets, a product mix that matches the customer's orders are prepared and delivered to the customer's warehouses. From here, the unique product that the customer finally buys is transported on the store shelves. It is a complex process that requires a large inventory and many transportation and handling operations, on top of which the capital cost of the inventory is added.

The introduced flexible production concept offers a solution to simplify this logistics chain through the one-piece series size. As a first step, a product-mix had to be created in the shop floor, that can be delivered directly to the customer's warehouses according to the composition of the order. Here, costs related to the distribution center can be saved and the delivery time can be also reduced. This way, the most significant part of the logistics chain and its related costs can be eliminated, nevertheless, this solution requires a complete transformation of the business model.

Based on what was outlined above, there is a fundamental difference between production with a defined series size and one-piece series production in terms of stocks. In the case of lot size manufacturing (used when operating traditional lines), production is aimed at replenishing a defined finished product stock in a significant number of cases (make to stock). Here, fluctuations in customer demand are handled by *the finished product stock*, and replenishment is carried out based on a smoothed production plan (2 weekly leveling) **Error! Reference source not found.**. The size of the finished product and raw material stock are determined based on the sales forecasts, which is therefore of particular importance.

In the case of the flexible production concept, a defined stock of raw materials is kept, for the production series size of one piece, which ensures the raw material supply for a given period. The size of the raw material stock depends on the planned annual quantities, possible seasonality and the speed of replenishment. The raw material stock is replenished with min/max stock control. Since there is no stock of finished products with this concept, the *safety stock is on the raw material side*, and it is essential that the suppliers are located near the manufacturer's site in order to ensure fast replenishment.

C. Description of the production line

In order to achieve the goals described earlier, in HFU the individual production equipment and workstations are not placed sequentially in a row, but separately in the production area according to a specific arrangement. The layout within the HFU strongly affects production metrics, thus, it is optimized for the given number of pieces in a given product portfolio using a discrete-event simulation model. Optimization parameters were production time of high runner products, output, route length made by the workers, and cost. If the product mix changes over time, it may be necessary to run the optimization again and modify the layout. Therefore, the machines located in the HFU are built as mobile stations, this way changing the position of one machine takes only some minutes. The cell can also be modularly expanded with additional machines to increase production capacity.

On traditional production lines, the product always moves a specific path inside the cell and one operation follows another in the same order. The sequence of production operations is determined when the production line is built, after which it remains constant. In HFU, the products can be assembled on different routes. The production process and the associated route are determined by the system according to the given parameters. In the optimization function, the route length, production time and cycle time of the stations (the route should pass through stations where the cycle times are nearly the same) are considered. During preparation for running a specific product on HFU, a default routing is determined. Depending on the number and availability of the production equipment, an alternative route for a specific production order can be also assigned; if other production operations within the area, the availability of workstations and equipment, or other parameters make this necessary and possible. For example, if a machine with a screwdriver tool, which is part of the default routing is temporarily unavailable, the system will assign the screwing step to another station that has the same tool (but may other functions, too). Deviation from the default routing is also possible on e.g., packaging, pressing and function testing stations.

Before implementing HFU, dedicated production lines were in operation on the shop floor. In these cases, many workstations and equipment types were found multiple times in one production line. Nevertheless, the utilization of these lines was low due to the nature of the product portfolio. During the design process of the HFU, it was examined that how much and what kind of equipment is in the production lines in total, and this was compared with the number of the specific equipment that is needed to produce the annual number of a certain product. In this way, it became possible to remove and radically reduce the number of necessary devices and the production area became significantly smaller, also.

Among the redundant equipment, some machines were kept, classified as critical and placed in an area named the Reserve Technical Capacity (RTC) close to the HFU. The importance of the RTC is manifested in the management of possible technical failures. If a station within the HFU fails, it can be replaced with the equipment in the RTC. There are two solutions for this: first, if the equipment can be easily moved, it can be replaced in some minutes from the RTC. If not (e.g., in the case of a heavy machining equipment), product routing is automatically changed to send the product to the equipment in the RTC area instead of the station in the HFU. In this way, although the production process differs from the optimal one, the interruption can be avoided.

There may be a case when a significant number of orders for a specific product are received at short notice. In this case, HFU in its original form is less efficient than traditional production lines. Nevertheless, there is a possibility to temporarily create a medium or high-capacity production line from the HFU stations for higher efficiency. After the order has been fulfilled, the equipment can be rearranged according to the HFU concept. The function of the RTC area and the way of scaling up are visualized in Figure 2.

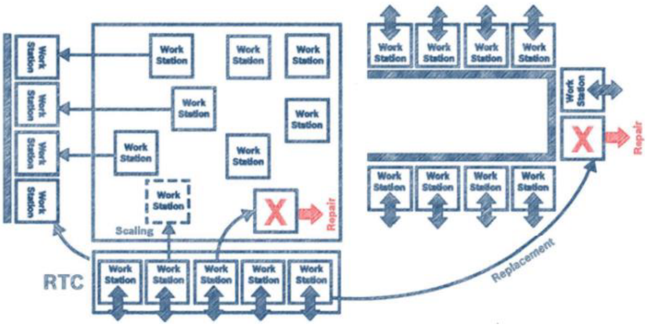

Figure 2. RTC area and scaling up from HFU

Standardized workstations were designed to ensure that the machines can be easily rearranged. They are mounted on rolling frames equipped with wheels, and all of the necessary connections are integrated within one complex connector (electricity, compressed air, IT network). All stations are able to communicate with the MES system and after connecting to it, they log in automatically and are then ready for operation ("Plug and Produce"). The stations are also able to communicate with external wireless devices, which allows certain access for professionals (e.g., during maintenance), automatically sending and receiving data in real time (e.g., process parameters, status parameters). They have the ability to read specific digital identifiers (e.g., RFID or DMC codes), that is used when identifying the product that a worker brings to the station. The machines can also process an automatic changeover, which ensures that the tools and setting parameters required for the given product are set without human intervention by the time the worker arrives to the machine with the product. This is triggered by the signal that is sent when an operation is finished in the previous machine.

D. Internal logistics and material flow

In order to avoid material backflow, the raw material is not placed on the production equipment, but the necessary components are prepared for each product based on production instructions shown to the picking workers on tablets. This set of parts is carried by the assembly worker (on a special tray mounted on a table with wheels) during the assembly process. The worker uses the necessary pieces during the given assembly process. Thus, in the production process, the raw material always moves forward along the value creation chain. Components are stored in a supermarket near the HFU. Picking operators are collecting the components on the above-mentioned special trays (shown in Figure 3), where the parts have to be placed in specific places according to their shape (avoiding mistakes such as missing parts or too many parts prepared for an assembly).

For material storage, a dedicated supermarket is ordered for each type of product. It contains the parts required for all variants of the product type. The supermarket was designed in such a way that it occupies as little space as possible, because it is basically located in the production area (this is much more valuable than warehouse space). The stock level of the parts is be determined based on the refill time, the average daily number of pieces and the size of the parts. The layout of the components in the supermarket is very important because it fundamentally affects the time required for preparation. The accuracy of the inventory in the supermarket has a great impact in reducing the number of material supply interruptions. Thus, a stock register maintained in an ERP system was introduced. Another goal was to eliminate disturbances caused by filling errors (e.g. raw material placed in the wrong place). That's why each storage space is equipped with a sensor that detects whether there is actually a storage box in the given storage space. If there is none, the system indicates a shortage. In other words, an electronic stock register with a physical check was implemented. From the IT perspective, each supermarket has a communication center: the signals from the sensors enter this center, which with the central control system.

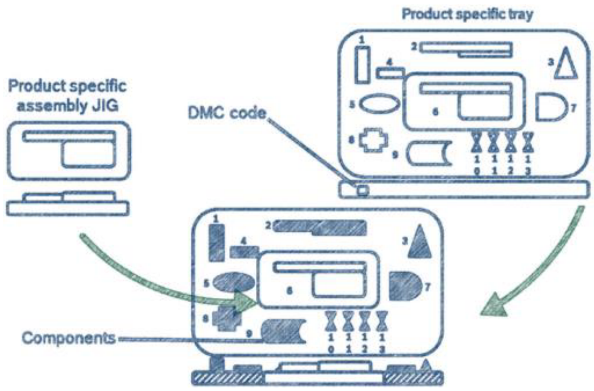

Figure 3. Special tray used to store and move components during assembly processes

The picking workers use electronic devices to perform their tasks, one of which is an industrial tablet. With the tablet, the picking worker can log in and receive the detailed picking instructions. The tablet also helps the operator in which supermarket to start the preparation, as well as where this supermarket is located. It also communicates with the ERP system and shows the operator which parts, how many of them, from which storage location and in which position of the tray they should they place. To achieve this, identification numbers are assigned to the storage spaces and tray positions. Each storage location also has a barcode: when the picking worker takes the part from the given storage location, he scans the bar code with the help of a finger code scanner that communicates with the ERP system, after which the defined quantity is deducted from the storage location's inventory. This may trigger an automatic reordering process from the warehouse. When the picking is finished, the completed set of parts is placed on the input side of the HFU, from where the assembly operators take it with the wheeled tray (after logging with their tablet) and assembly the finished product.

As mentioned, one of the main goals when designing the concept was to prevent disruptions. Thus, before issuing each production order, the system performs a check and makes sure that there are no obstacles in the complete operation sequence of the production order. Thus, before picking begins, it checks whether all parts are available for picking based on the data provided by the supermarket and in the ERP system. It also checks whether all the production equipment required for product assembly is available in the HFU. In addition, it is also checked whether there is an operator working in the HFU who is properly trained to assemble the given product. If all the conditions are met, only then the assembly process can begin. In this way, a significant part of the errors that can be eliminated in advance.

The operation of the concept is based on an IT infrastructure composed of several types of systems; the basic subsystems of which are an ERP and an MES system. The ERP system is used for tasks related to the management of raw materials and finished products, while the MES system is used to implement the internal processes of the concept. To ensure automatic data flow between these two connections had to be established. In cases when results of manual processes were sent between these systems and the physical world, appropriate Human-Machine Interfaces (HMIs), for example tablets, finger code scanners, and other devices such as push buttons in the machines were used. The real-time data flow between the physical world and these systems was realized with PLCs which are complemented by the HMIs. All the workstations had to be able to communicate automatically, but in reality, the workstations themselves did not always required a high conversion or financial expenditure.

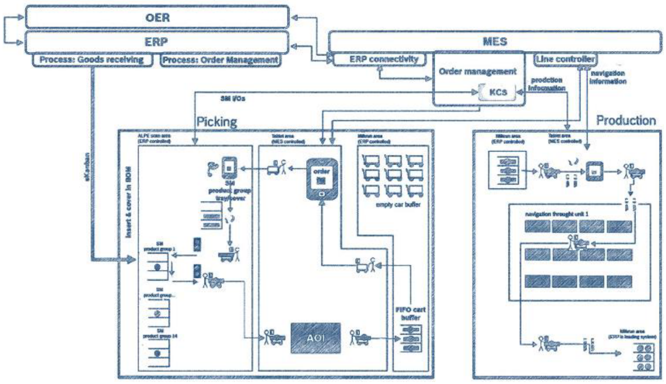

Figure 4. Overview and IT background of the HFU concept

E. Results

With the help of the outlined HFU concept, a product portfolio that was previously located on 1000 m2 on 11 dedicated production lines, could be manufactured in 1 HFU and 2 dedicated production lines located only on 300 m2. The average utilization of technical equipment was increased from 10% to almost 50%. The number of used machines, equipment and workstations were reduced by 70%; and this rate that can also be maintained in the case of new products that may be introduced in the future. With the HFU system, production can respond much better to customer fluctuations and its capacity can be changed on a very wide scale. By using the flexible layout, the area can adapt much better to changes in the product mix and can optimize both output and production times (however, it is difficult to associate concrete metrics with these so-called soft facts).

III. CONCLUSIONS

In the paper, a flexible manufacturing concept named High Flexible Unit is introduced, which was implemented in real life in Miskolc, Hungary, in one of the Bosch Power Tools factories. With realizing this Industry 4.0 solution, the company can react more quickly to non-predictable customer orders, on a lower price, requiring less space from the shop floor. The solution proves that real Industry 4.0 solutions can be implemented at a low price level, using smart, simple and cheap solutions.

IV. ACKNOWLEDGEMENT

This work has been supported by the European Commission through the H2020 project EPIC (https://www.centre-epic.eu/) under grant No. 739592 and by the TKP2021-NKTA-01 NRDIO grant on "Research on cooperative production and logistics systems to support a competitive and sustainable economy".

REFERENCES

[1] **Mohammed, A. R., Hassan, K. S., & Abdel-Aal, M. A.** (2022). Moving Average Smoothing for Gregory-Newton Interpolation: A Novel Approach for Short-Term Demand Forecasting. IFAC-PapersOnLine, 55(10), 749-754.

[2] **Marques, A. F., Alves, A. C., & Sousa, J. P.** (2013). An approach for integrated design of flexible production systems. *Procedia CIRP*, *7*, 586-591.

[3] **Rewers, P., Hamrol, A., Żywicki, K., Bożek, M., & Kulus, W.** (2017). Production leveling as an effective method for production flow control–experience of polish enterprises. *Procedia Engineering*, *182*, 619-626.

[4] **Abele, Eberhard; Wörn, Arno; Martin, Patrick; Klöpper, Robert** (2006): Performance evaluation methods for mechanical interfaces in reconfigurable machine tools. In: International Symposium on Flexible Automation, Osaka, Japan.

[5] **Ansoff, H. Igor** (1979): Model of Environmental Turbulence. In: H. Igor Ansoff (Hg.): Strategic Management. London: Palgrave Macmillan UK, S. 47–71.

[6] **Bauernhansl, T.; Hompel, M.; Vogel-Heuser, B.** (2014): Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung, Technologien, Migration. Wiesbaden: Springer Fachmedien.

[7] **Bauernhansl, T.; Szaller, Á.; Nick, G.; Fechter, M.; Fries, C.** (2021): First Results of a Survey on Manufacturing of the Future. Procedia Computer Science 180 pp. 142-149.

[8] **Buzacott, J. A.; Yao, David D.** (1986): Flexible Manufacturing Systems: A Review of Analytical Models. In: Management Science 32 (7), S. 890–905.

[9] **ElMaraghy, H. A.** (2005): Flexible and reconfigurable manufacturing systems paradigms. In: Int J Flex Manuf Syst 17 (4), S. 261–276.

[10] **ElMaraghy, H. A.** (2007): Reconfigurable Process Plans For Responsive Manufacturing Systems. In: Pedro Filipe Cunha und Paul G. Maropoulos (Hg.): Digital Enterprise Technology. Boston, MA: Springer US, S. 35–44.

[11] **ElMaraghy, H. A.** (2009): Changeable and Reconfigurable Manufacturing Systems. London: Springer.

[12] **Foith-Förster, P. Bauernhansl, T.** (2016): Changeable Assembly Systems Through Flexibly Linked Process Modules. In: Procedia CIRP 41, S. 230–235.

[13] **Greschke, P.** (2015): Matrix-Produktion als Konzept einer taktunabhängigen Fließfertigung. Dissertation. Technische Universität Braunschweig.

[14] **Heisel, U.; Meitzner, M.** (2004): Progress in Reconfigurable Manufacturing Systems. In: Journal for Manufacturing Science and Production 6 (1-2), S. 1–8.

[15] **Katz, R.** (2007): Design principles of reconfigurable machines. In: Int J Adv Manuf Technol 34 (5-6), S. 430–439.

[16] Factories, 46/1. Berlin, Heidelberg: Springer, S. 27–45.

[17] **Koren, Y.** (2010): The Global Manufacturing Revolution. Hoboken, NJ, USA: John Wiley & Sons, Inc.

[18] **Koren, Yoram; Gu, Xi; Guo, Weihong** (2018): Reconfigurable manufacturing systems: Principles, design, and future trends. In: Front. Mech. Eng. 13 (2), S. 121–136.

[19] **Landers, R. G.; Ruan, J.; Liou, F**. (2006): Reconfigurable Manufacturing Equipment. In: Anatoli I. Dashchenko (Hg.): Reconfigurable Manufacturing Systems and Transformable Factories, Bd. 40. Berlin, Heidelberg: Springer, S. 79–110.

[20] **Mandelbrot, Benoît B**. (1977): Fractals. Form, chance, and dimension. San Francisco: Freeman.

[21] **Mehrabi, M. G.; Ulsoy, A. G.; Koren, Y.** (2000): Reconfigurable manufacturing systems: Key to future manufacturing. In: Journal of Intelligent Manufacturing 11 (4), S. 403–419.

[22] M**ehrabi, M. G.; Ulsoy, A. G.; Koren, Y.; Heytler, P.** (2002): Trends and perspectives in flexible and reconfigurable manufacturing systems. In: Journal of Intelligent Manufacturing 13 (2), S. 135–146.

[23] **Monostori, L.** (2014): Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. In: Procedia CIRP 17, S. 9–13.

[24] **Nyhuis, P., Hans-Peter W.** (2008): Fundamentals of Production Logistics: Theory, Tools and Applications. Springer

[25] **Sethi, A. K., Sethi, S. P.** (1990): Flexibility in manufacturing: A survey. In: Int J Flex Manuf Syst 2 (4).

[26] **Warnecke, H-J.** (1992): Die Fraktale Fabrik. Berlin, Heidelberg: Springer.

[27] **Warnecke, H-J.** (1993): Revolution der Unternehmenskultur. Berlin, Heidelberg: Springer.

[28] **Hellmich, A.; Zumpe, F.; Zumpe, M.; Münnich, M.; Wiese, T.; Büttner, T.; Ihlenfeldt, S.; Foith-Förster, P.; Trierweiler, M.; Ranke, D.; Berkhan, P.; Rzesnitzek, S.; Bauernhansl, T.** (2022): acatech - Deutsche Akademie der Technikwissenschaften. Umsetzung von cyber-physischen Matrixproduktionssystemen: Expertise des Forschungsbeirats der Plattform Industrie 4.0. München.