Abstract

Within the framework of the German Government’s High-Tech strategy, the Industry 4.0 initiative was created, aiming to develop the “Smart Factory”. The approach assumes increased automation and a transparent, user-centred Production Planning and Scheduling. The “intelligent components” communicate with people and systems independently and find the optimal route through production.

Keywords: Cyber-Physical Systems (CPS), Smart Factory Lemgo, Self-Organizing Production Units (SOPU)

Introduction

A new Industrial Revolution is beginning in the manufacturing industry. The first and second Industrial Revolutions were characterized by mass production, based on the division of labour. From the mid 1970s the third Industrial Revolution began, this was characterized by the use of electronics and Information Technology (IT), as well as by the automation of production processes.

The fourth Industrial Revolution is characterized by the intelligent networking of machines, products and personnel using Cyber Physical Systems (CPS) in “Smart Factories”. This, fourth Industrial Revolution was enabled by the “Internet of Things”. Production in Smart Factories is highly flexible, highly productive and conserves resources; the Value Chain process is optimized based on real time requirements and employees benefit from intelligent control systems.

Design of Smart Factories must, however, take into account the German economic environment, primarily:

- Increasing global competition
- Demographic change and ageing workforce

With almost 1 million employees, in over 6000 companies, the mechanical engineering sector is one of Germany’s key industries. Export accounts for a 60% share of the economy, at more than 200 billion Euros (Federal Statistical Office 2012). International trade in machinery increased by 14.8 per cent in 2011, to approximately 863 billion Euros. With more than 16.5% of the global market, German mechanical engineering is one of the leading machine providers, ahead of Japan (11.8 percent) and the USA (11.3 %). China, with 10.2 %, is currently in fourth
place, but has been able to continually expand market share over the past few years (VDMA 2013).

The population of Germany will continue to decrease in the coming years. Current forecasts predict approximately 70 million inhabitants by 2060, compared to 81 million at present. Furthermore, due to the low birth rate, the percentage of older workers will also continue to rise (Federal Statistical Office 2012). The challenge that will face mechanical engineering in Germany is that the demand for skilled manpower will outstretch the supply of young employees, resulting in a generally older workforce.

Smart Factories must, therefore, adopt measures that enable production to stay competitive and also facilitate working to a higher age.

Smart Factories

The technological foundations of Smart Factories are Cyber-Physical Systems (CPS) and the Internet (Jasperneite 2012). CPS are distinguished by the integration of information technology into component parts and are characterized by the possession of embedded sensors or actuators for relevant data acquisition (Kagermann et al. 2012).

Component parts are able to communicate wirelessly with each other, as well as with operational resources and personnel using, for example, “Augmented Reality” Systems. CPS functions are also integrated into resources (equipment and raw materials), which change configuration independently, according to the task at hand and dictated by the next item to be processed (Geisberger and Broy 2012). Furthermore, machinery is able to learn from completed tasks and to optimize settings. This information is then shared with other machines, which, in this scenario are called “Social Machines” (Kagermann et al. 2012).

Humans assume the task of decision maker (Kagermann et al. 2012). This work is supported by the creation of multi-modal, learning, human-machine interfaces (Geisberger and Broy 2012) and “Augmented Reality” systems are used. The use of such systems can, for instance, support the training of new employees, or improve the execution and efficiency of a production process.

In the Smart Factory, the combination of resources, equipment and the necessary personnel creates “production units”. If a fault occurs to equipment, for instance, new routes through production must be found in order to fulfil orders on time. In order to do this, alternative work schedules and the resulting production costs and times must be analysed. New production units arise through the new combination of resources, equipment and personnel per order. This is de-centralised and autonomous, they are, therefore, Self-Organizing Production Units” (SOPU), that seek the equipment and personnel necessary for the order, as well as planning the equipment time required. This requires close interaction between equipment, resources and personnel with a master computer, which manages the alternative routes as well as production capacity (Fig. 1).
The Smart Factory requires flexible, networked production. Flexibility means that the operating resources (resources and personnel) must be able to carry out a variety of different production processes. Employees are required to have a very broad range of qualifications. Furthermore, flexibility requires a very high availability of operating resources. Networked means that all of the relevant information for the manufacture of a product is shared, in real time, between all of the systems and people involved in the process. This, in particular, is information about machine breakdown, delays to an order, missing parts, personnel or resources. Integration of data from diverse systems is, therefore, essential. Further research is needed here, particularly in the development of reference architecture and the subsequent application thereof. This is accompanied by the challenges of integrating mobile solutions for Supply Chain Management, as well as the demands of Big Data.

The transformation process to SOPU assumes increased automation, the integration of people into decision making and a transparent, user-centred Production Planning and Control (PPC) in order to control the production networks in real-time. “Intelligent SOPU” communicate independently with people and systems, for example Manufacturing Execution Systems (MES), and control physical entities (Wahlster 2012). That is to say de-centralized, autonomous control (Kempf 2013). This allows improvements to be achieved in order fulfilment, production, material management, supply chain management and life cycle management (Kagermann et al. 2013).

However, production planning and control is, regarding methods and techniques used, as well as the commercially available IT Solutions, predominantly designed for mass-production with central planning and control concepts. Material requirements and production planning are systematically based on successive planning of quantities, deadlines and capacities. A computer aided optimization procedure is lacking and an improvement of logistics performance, which is a very important unique selling point for medium sized enterprises, is not possible with these systems. In fact, networking of production resources and a transparent, user-centred PPC is required.

Manufacturing execution systems (MES) contribute to improvements in transparency and user-centred design, which enable real-time, central monitoring and control of the production process (Kletti 2012). These systems are offered as add-ons to ERP systems and connected to
process automation modules, for instance to machines, personnel and support services, as well as to all the other processes which have an immediate effect on manufacture and assembly processes. They facilitate fast reaction to malfunction as well as monitoring or control of manufacturing in real time. At present, data collection is generally achieved through terminals or interfaces situated in production. However, production planning and control is, explicitly, not possible with these systems. Present systems responses are simply too inflexible (Schuh 2012), lack transparency and are not user-centred. The MES should, in fact, be able to provide autonomous SOPU with relevant information in order to make communication more effective (Kletti 2012). Communications should also be kept transparent enough that users are not overwhelmed with information whilst still being able to see the current planning and control status at any time (Kagermann et al. 2013).

The result is a paradigm shift away from centrally planned PPC towards an autonomous, decentralized control, with self-organizing production units, to so-called Ad-Hoc value added chain (Gausemeier 2013), where ERP and MES form the backbone of the manufacturing and information flow within the company.

Integration with Manufacturing Execution Systems

The application of SOPU without an MES is hardly conceivable (Wahlster 2012). MES schedules and plans the resources necessary for production orders. On the one hand this produces the manufacturing date of the production order and on the other hand, it is possible to calculate the manufacturing costs using this data. These costs and deadlines determined by MES provide the default value (desired value) for the SOPU.

If no manufacturing breakdown occurs, then the processing proceeds exactly according to the MES parameters, should one of the processes temporarily fail, due to resource or personnel shortage, then communication with the SOPU becomes necessary. The SOPU then attempt to find an alternative route through production autonomously, one that meets the cost and deadline requirements: creating temporary production networks, which utilize alternative resources and personnel (Fig. 2).

Manufacturing breakdown can occur suddenly, so the SOPU must be permanently informed of important disturbances; this occurs through an interface with the Production Data Capturing (PDC). Continuous control is necessary for this reason, which is carried out by a control circuit model. Control circuits may be deployed to describe processes as well as mathematical output calculation, in this example costs and deadlines shall be calculated.

If the alternative production network meet the MES parameters, then the SOPU are able to begin the alternative route through production autonomously, the MES merely requires a completion note, so that the data it requires is always up to date. Only if one of the desired values (cost or deadline) would not be met by the new route is an alert note sent to the MES, in order for the planner to intervene manually.
Costs and deadlines will be determined by MES (desired parameters), when disruption occurs the SOPU will calculate the costs and deadlines of alternative routes and check whether they are within the desired parameters. The control parameter is the output value of the straight line; this is compared with the MES desired parameters and the deviation between the control parameter and the desired parameter is the controller’s input value.

The controller can change adjustable parameters, which should minimize the deviation between the control parameter and the desired parameters over the straight line. Because the straight line can be influenced by external factors, confounding variables must also be taken into account (Fig. 3).

Control Parameter, Desired Parameters and Deviations: SOPU have to find routes through production that fulfil the MES desired values, this requires comparison of the alternative routes, which means that the straight line (cost and deadline) must be calculated. SOPU make use of
operational resources, raw materials and personnel; the loading rate of these must also be
determined and compared with the MES desired values.

Straight Line: Temporary production networks are straight lines. If a SOPU takes an
alternative route through production, the MES determined process time changes. This comprises
lead-time, handling, transport and idle time. The relevant costs are personnel and raw materials,
which are calculable through cost per time unit (k), time per unit \( (t^E) \) and number of units (n)
(Corsten 2000):

\[
\text{Cost per Resource} = t^E \cdot k \cdot n \quad (1)
\]

The handling costs \( (K^B) \) can be calculated by process time per unit \( (t^B) \), processing costs
per time unit \( (k^B) \) as well as the lot size \( (n) \) per material for all resources \( (s) \) across all periods \( (P) \):

\[
\text{Handling costs (K}^B) = \sum_{i=1}^{P} \sum_{j=1}^{n} \sum_{m=1}^{i} t^B_{i,j,m} \cdot k^B_{i,j,m} \cdot x^P_{i,j,m} \quad (2)
\]

Learning effects can be achieved in production networks if similar products are produced,
this results in a reduced cost per time unit, as these are calculated by distributing the total cost of
all the resources \( (K_F^m) \) over the operating time (Wildemann 1998):

\[
\frac{K_F^m}{T_m} \cdot x^P_{i,m} \quad (3)
\]

Thereof both effects are consequences of temporary production networks that must also
be taken into consideration. Taking learning effects \( (1-\beta) \) into consideration results in handling
costs as follows (Wildemann 1998):

\[
\text{Handling costs (K}^\text{Learn}) = \sum_{i=1}^{P} \sum_{j=1}^{n} \sum_{m=1}^{i} t^B_{i,j,m} \cdot (1 - \beta_{i,j,m}) \cdot \frac{K_F^m}{T_{i,m}} \cdot x^P_{i,j,m} \quad (4)
\]

Preparing materials for processing an order causes Setup costs \( (K^R) \). These are calculated
by the sum of all materials \( (s) \) and all production orders \( (FA) \):

\[
\text{Setup costs (K}^R) = \sum_{i=1}^{P} \sum_{j=1}^{FA} \sum_{m=1}^{i} t^R_{i,j,m} \cdot k^R_{i,j,m} \cdot x^R_{i,j,m} \quad (5)
\]

Taking specialization effects into consideration results in \( (1-p) \) (Wildemann 1998):

\[
\text{Setup costs (K}^\text{Spez}) = \sum_{i=1}^{P} \sum_{j=1}^{FA} \sum_{m=1}^{i} t^R_{i,j,m} \cdot k^R_{i,j,m} \cdot (1 - \rho_{i,j,m}) \cdot x^R_{i,j,m} \quad (6)
\]

Costs of transportation depend on time \( (t^T) \) and the means of transportation \( (k^T) \):
Cost of transportation ($K^T$) =

$$K^T = \sum_{i=1}^{P} \sum_{j=1}^{n} \sum_{m=1}^{s} T_{i,j,m}^T K_{i,j,m}^T X_{i,j,m}^T$$  

(7)

Because the routing plan is set by the MES, idle time is not a relevant factor. The maximum capacities of operating equipment, means of transport, personnel and warehouse are all constraints, which must also be considered. The following must be applied to all \(i = (1...P)\):

Maximum equipment capacity:

$$\sum_{j=1}^{n} \sum_{m=1}^{s} X_{i,j,m}^P T_{i,j,m}^B + T_{i,j,m}^R \leq C_{BM}^{max}.$$

(8)

Maximum personnel capacity:

$$\sum_{j=1}^{n} \sum_{m=1}^{s} X_{i,j,m}^P T_{i,j,m}^B + T_{i,j,m}^R \leq C_{MA}^{max}.$$

(9)

Maximum warehouse capacity:

$$\sum_{j=1}^{n} \sum_{m=1}^{s} X_{i,j,m}^P - X_{i,j,m}^L \leq C_{Li}^{max} \ AND \geq 0$$

(10)

Maximum means of transport capacity:

$$\sum_{j=1}^{n} \sum_{m=1}^{s} X_{i,j,m}^P \leq C_{Li}^{max}.$$

(11)

The total costs can be fully calculated by means of handling, setup and transport costs, taking the constraints mentioned above into consideration. The controller calculates the difference between the control variables and the desired parameters, if the MES input value will not be met then the SOPU seeks an alternative route through production. SOPU must be able to find the personnel and machines able to fulfil the order, these must also have capacity to do so. Modelling of this extremely extensive problem is not yet complete; this is a central aim of the research activities in “Smart Factory Lemgo”.

Disturbance values are, particularly, manufacturing breakdown; in case of this, SOPU must spring into action. If the SOPU can calculate an alternative route through production, taking the MES parameters into account, they can autonomously take it. In the case that cost and deadline parameters will not be met, an alert note is sent to the MES and an operator must manually intervene.

**Model Incorporation**

The calculation of the cost of alternative routes through production is done through straight line. The controller proposes possible courses of action, which lead to temporary networks of combined orders and materials, from which the adjustable parameters result. Disturbance values are identified as manufacturing breakdown of resources that lead to continuous re-planning, the instruments of which are shown below. The following costs are identified as control parameters:

$$K^{Ges} = \Sigma (K^B + K^R + K^T)$$

(12)

These have been extended to include efficiency and capacity coefficients, which are required when rough planning, into account. The factors determined in the survey, are therefore the basis of this model:
Summary

The complexity of production planning and controlling has increased in many companies over the past few years. Manufacturing breakdown of resources reinforce this complexity and require manual intervention by a planner, for instance with MES. However, Cyber Physical Systems could autonomously solve many of these breakdowns, so that the planner is relieved of the work and a solution found much faster. The use of Self-Organizing Production Units leads to increased automation and user centred Production Planning and Control allowing real time control of production networks. The control of this network is presented in this paper. In order to facilitate continuous regulation, this is based on the control circuit model control system of cybernetics. Control is carried out taking the MES values, in this case costs and deadlines, into consideration. SOPU are able to find alternative paths through production, thus planning time is reduced, costs are reduced and improvement of logistical performance is possible.

Bibliography


Kletti, J. 2012. MES 4.0 unterstützt die Industrie 4.0. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb (3): 159-161.


