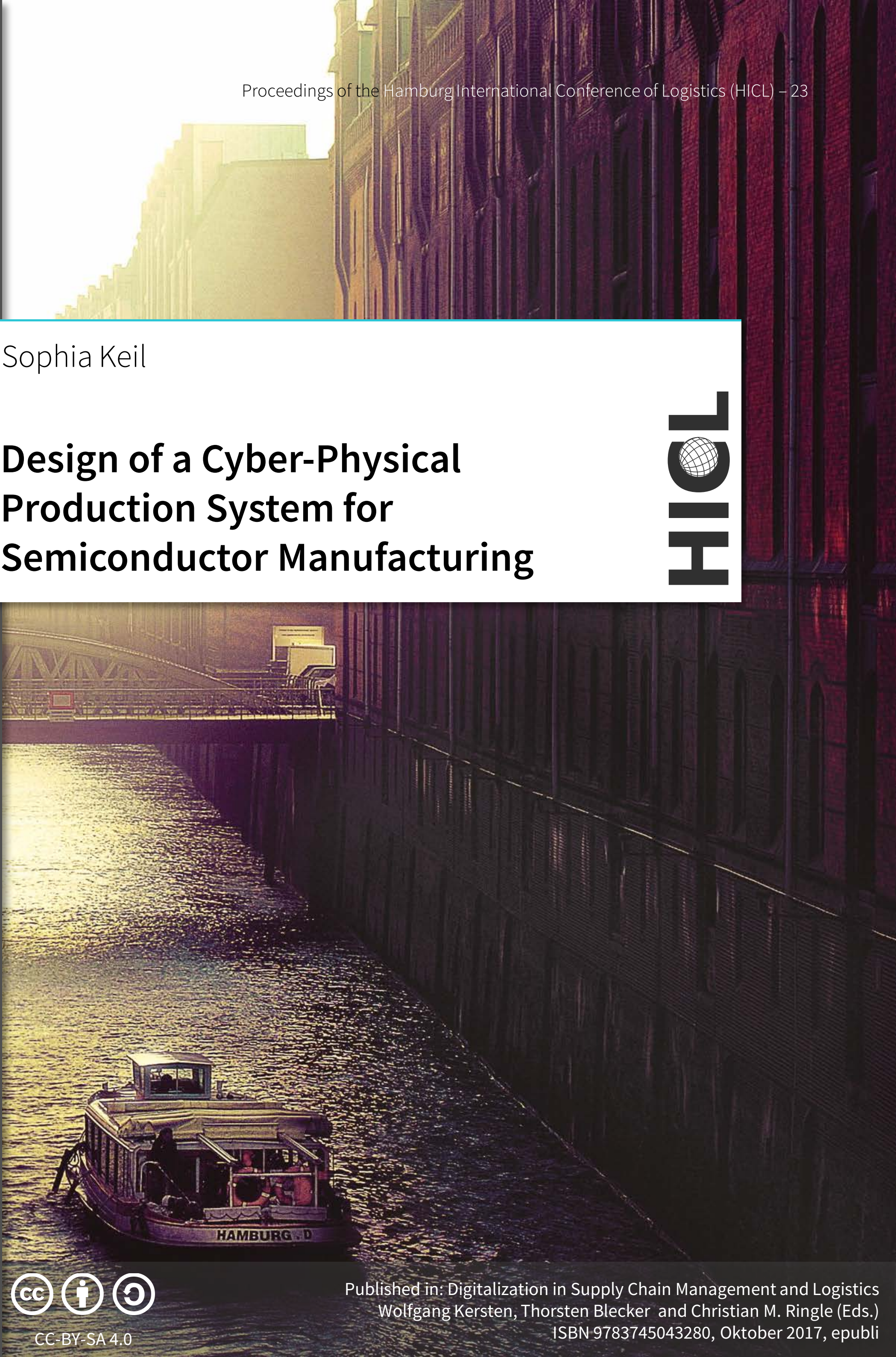
Proceedings of the Hamburg International Conference of Logistics (HICL) – 23



Sophia Keil

Design of a Cyber-Physical Production System for Semiconductor Manufacturing

HICL

Published in: Digitalization in Supply Chain Management and Logistics
Wolfgang Kersten, Thorsten Blecker and Christian M. Ringle (Eds.)
ISBN 9783745043280, Oktober 2017, epubli

Design of a Cyber-Physical Production System for Semiconductor Manufacturing

Sophia Keil[1]

1 – Technische Universität Dresden

Due to the highly dynamic markets, an increasing complexity, and individualization of products, efficient and robust logistical processes are difficult to achieve through the use of central planning and control approaches. The aim of the contribution is the design of a decentralized, autonomous control system for high tech production systems. An interdisciplinary perspective was adopted as methods of artificial intelligence and mechanical as well as electrical engineering were used. The results are a hardware concept for an intelligent, cyber-physical production lot and a software concept based on a hierarchical multi-agent architecture. The basic idea of autonomy and self-control is not new. It can be traced back, for example, to the ideas of "Evolutionary Management", or cybernetics.

However, for the first time this contribution shows a practical application for a complex semiconductor manufacturing system. Until now, the hard and software concepts have been implemented prototypically. A long-term integration into the existing IT landscape of a semiconductor factory is planned. A well established and functioning centralized system should be supplemented by the new decentralized system, especially in areas in which there is not yet such a high level of automated processes, e. g. in wafer test facilities.

Keywords: cyber-physical production system; multi-agent system; intelligent production lot; semiconductor manufacturing

1 Introduction

Competitive semiconductor companies need to deliver high quality products in a fast, timely, and cost-efficient manner in the context of highly dynamic markets, which are characterized by rapidly declining prices, short product life cycles, and a high frequency of technology changes (Sonar et al., 2013). Short product life cycles, an increasing complexity, and individualization of products, which are usually provided in a high number of variants, lead to sophisticated requirements with respect to logistics processes and systems. Hereby, centrally controlled systems reach their limits concerning their capabilities to deal with the arising complexity to plan, control, and monitor changeable systems (Schuhmacher and Hummel, 2016). Ten Hompel (2010) proposes the adoption of individualization as a design principle for logistics processes and systems. A key approach in this context is the concept of self-control. Self-controlled systems promise the advantages of increased (Brettel et al., 2014)

- flexibility, in terms of changeability of the system;
- robustness, as the decision-making competence is shifted to individual logistical objects; and
- data availability as well as transparency of complex material flow structures.

Self-control includes two main concepts: decentralization and autonomy. The degree of decentralization indicates on which system level control decisions are made. Self-control is attained when the degree of decentralization reaches the level of the physical material flow. That means the individual logistical objects such as the goods to be transported and the load carriers, but also the transport systems, make autonomous control decisions. The degree of autonomy indicates how many decision making opportunities the individual logistic object has. A prerequisite for the realization of self-controlled systems is a certain level of intelligence, which is realized by ICT technologies and, more importantly, cyber physical systems (Scholz-Reiter et al., 2005).

Following these thoughts, the main research question of the contribution is as follows: How should a cyber-physical production system for the semiconductor industry be designed to enable manufacturing excellence? To answer the question, the paper is organized in the following manner: after this introduction, Section 2 includes a short overview about the theoretical background of Cyber-Physical

Systems and Cyber-Physical Production Systems as well as existing research and industrial approaches. Section 3 comprises a characterization of the case study of semiconductor production. Section 4 includes the design of a semiconductor manufacturing specific CPPS, including with the software and hardware concept as well as a validation of the concept. Lastly, a summary and outlook for future tasks are put forth.

2 Theoretical Background

2.1 Cyber-Physical Production Systems

Figure 1 shows the structure of a Cyber-Physical System (CPS) schematically. Within a manufacturing system, an embedded system in the sense of a CPS is integrated within physical systems, e. g. the machines or production lots. The embedded system includes sensors to gather physical data and electronic hardware as well as software to save, and analyze data. The results of the data processing are the foundation for an interplay with other physical or digital systems by means of actuators (Lee et al., 2015). Furthermore, a CPS comprises a human machine interface, e. g. for exchange of information and supervision (Geisberger and Broy, 2015). A cyber-physical production system (CPPS) can be formed when numerous cyber-physical systems are linked and cooperate through digital networks (Seitz and Nyhuis, 2015).

CPSs are intelligent objects of class 4 as they are characterized by the features: identification, memory capacity, data processing and interaction/ communication (Zbib et al., 2008). Thereby, CPSs enable the design of intelligent logistics systems, where autonomous self-control is one characteristic of intelligent systems (Reinhart et al., 2013; Ostgathe, 2012). Further characteristics of intelligent systems are described in the following Section 2.2.

2.2 Characteristics of Intelligent Systems

In order to understand artificial intelligence within systems, it is useful to first characterize human intelligence, which cannot be described by a single feature. During a symposium held in 1986, experts provided answers to the question what

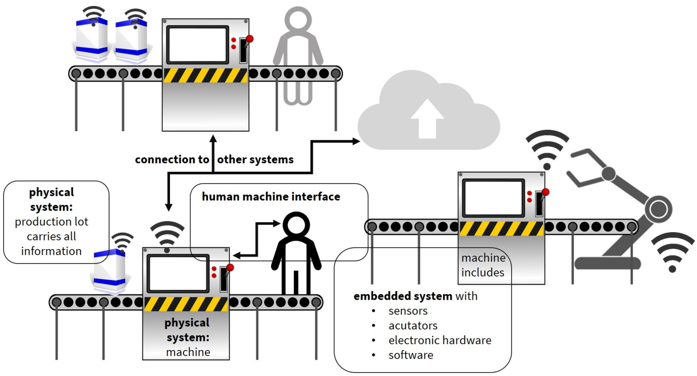


Figure 1: Structure of a CPS

human intelligence is (Sternberg and Detterman, 1986). These experts most frequently used the following characteristics to define the concept of intelligence:

First, intelligence involves elementary processing processes (perception, sensitivity, attention). Individuals must be able to perceive their environment, have knowledge, and then reach a higher level of processing, such as logical conclusions, imagination, problem solving, and judgments. In addition, the adaptability to a changing environment belongs to the concept of intelligence. Kail et al. (1988) analyzed numerous definitions of human intelligence. They found that most definitions include the ability of humans to think abstractly and to reason and derive purposeful actions from it.

The dimensions of thinking and action are also considered in the research field of artificial intelligence (AI). There are two approaches: First, researchers can try to understand how human beings think and act, and then model or simulate it on a computer. Second, the researcher tries to find an optimal approach independent of how humans would solve the problem, which would be represented by the rational view. A system is rational when it does the right thing according to its own knowledge (Russel and Norvig, 1995). Thereby, strong and weak AI are distinguished. The aim of strong AI is to develop AI to the point where the machine's intellectual capability is functionally equal to a human's or even surpasses it, e.g. Blue Brain Project. Weak or narrow AI is machine intelligence that is limited to specific application domains, e.g. expert systems (Russel and Norvig, 1995; Ertel, 2009)

In general, intelligent systems should be autonomous, proactive, adaptive, self-explanatory, fault-tolerant, self-optimizing, adaptive, goal-oriented, flexible, and cooperative. There is no system worldwide that maintains all of these features; but if none of these features are present, the system is also not considered intelligent (Wahlster, 2013).

Autonomy is a main feature of self-controlled systems. Methodological approaches with respect to self-control have already existed for many years. They can be regarded from different scientific perspectives. According to the system's perspective, a system can be divided into the levels decision system, information system, and execution system (Ropohl, 1979). The research with respect to logistics systems includes the self-controlled physical flow of materials and goods and their accompanying information flow and technology realization as well as the management of self-organizing logistics processes (Freitag et al., 2004).

The decision system is reflected by the management and organization literature (Windt, 2006), with a major research area focusing on the Evolutionary Management approach. Hereby, researchers transfer approaches of the evolution of natural organic systems to the evolution of enterprises (Malik and Probst, 1984). The information and execution system are reflected by research in the areas of science, technology, engineering, and mathematics. Hereby, two major approaches are to apply swarm intelligence and multi-agent systems (MAS) (Windt 2006; Scholz-Reiter and Höhns, 2006, Monostori, 2014; Wang et al., 2015). Examples for the application of swarm intelligence and MAS in the context of CPPS are the research projects CoCos, InnoCyFer, and SMART FACE (Bundesministerium für Wirtschaft und Energie, 2016). The research projects show that agent technology is a promising approach to implementing a decentralized and autonomous production controlling system. Therefore, it will be used to achieve the research goal of designing a self-controlled production system for semiconductor manufacturing (Section 4.1). A characterization of semiconductor manufacturing is described in the following Section 3.

3 Characterization of the Case Study of Semiconductor Production

3.1 Manufacturing Organization within the examined Factory

Generally, semiconductor fabrication facilities are organized in a job shop (Chien et al. 2016, Chen et al., 2008; Puffer, 2007). Here, the manufacturing tools are clustered according to their function. This enables high capacity utilization, but causes rather long lead times in contrast to the organization according to flow production where the installation of machines follows the product workflow (Miltenburg, 2005).

In the investigated factory, the job shop manufacturing organization is reflected in the bay-chase fab layout. The production floor is structured into different bays, the “job shops”. Each of these shops comprises similar types of machines, which accomplish one function (Meyersdorf and Taghizadeh 1998; Chang and Chang 1998). These production bays, which are also called intrabays, are linked to a connecting corridor, the interbay (see Figure 2). Between the bays are maintenance chases (grey room) (Chien et al. 2016). Besides, Figure 2 shows also elements of the Automated Material Handling System: stocker and lifts, which are described in the Section 3.2.

3.2 Material Handling System within the examined Factory

The following explanations describe the Automated Material Handling System (AMHS) of the investigated semiconductor company. This is necessary since the individual system elements are part of the decentralized control system to be designed. Within the company it is called the wafer transport system. Wafers represent the raw material for the production of Integrated Circuits (ICs). They are formed of highly pure (99.9999999% purity), single crystalline material (Winzker, 2008).

The task of the wafer transport system is to connect the various production areas with a material handling technique. For this purpose, a defined transport unit is transported in carriers from work station to work station. Main components of the wafer transport system are (Deutschländer et al., 2005; Heinrich and Pyke, 1999):

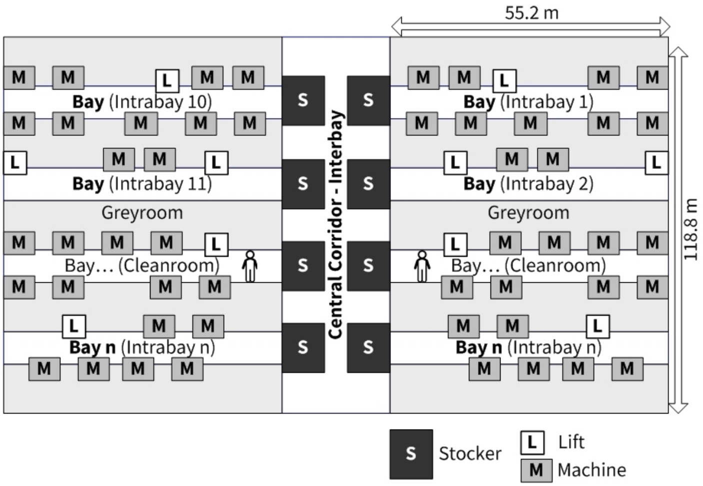


Figure 2: Bay-Chase Facility Layout

Figure 3: Part of the conveyor AHMS – depicting open carrier transportation on top left (Courtesy of Infineon Technologies Dresden GmbH)

conveyor, carrier, lift, lower and upper buffer, stocker, and the Material Controlling System (MCS).

Linking the production machines is carried out by a conveyor. On the conveyor tracks, open carriers move at a speed of 0.23 m/sec. The total length of the conveyor is 4.2 km, which is installed on the ceiling of the clean room. The transport and the machine processing are divided into two different levels. This results in a high machine density in the clean room area. The height difference is 2.70 m from the floor (machine processing level) to the transport level at the ceiling (see Figure 3) (Niekisch, 2001). Carriers are used as conveying aids (see top left of Figure 3). They can hold 25 wafers each. This transport unit corresponds to a production lot.

Each carrier can be tracked (conveyor path, current location) by means of carrier identification. The lot number and carrier identification are stored in the memory chip of the carrier. Lifting and lowering stations connect the transport with the shop floor level. These technical devices, hereinafter referred to as lifts, are typically arranged near the production machines to minimize handling efforts (Niekisch, 2001).

For the purpose of synchronization of consecutive process steps within the manufacturing processes, storage devices, so called buffer, are installed in the semiconductor factory. They are arranged in the immediate vicinity of a lift. If the buffer nearby the machine is being used to capacity, the lots are stored in stockers which are directly located in front of a production bay (Niekisch, 2001). The existing central production control system is a Manufacturing Execution System (MES) based on legacy Workstream, which is a trademark of the firm Applied Materials (Heinrich and Pyke, 1999).

4 Design of a CPPS for Semiconductor Industry

4.1 Multi-agent oriented Software Concept

As described in Section 2.2, the agent technology is a promising approach to implementing a decentralized and autonomous production control system. In agent technology, a multi-agent system (MAS) is seen as a society of independent actors which solve different tasks under competition or in cooperation (Bussmann et al., 2004). A software agent can be described as *"a self-contained program capable of controlling its own decision making and acting, based on its perception of its environment, in pursuit of one or more objectives"* (Jennings and Wooldridge, 1996, p. 1). A set of interacting agents is referred to as an MAS (Bussmann et al., 2004). In the case of software agents, the interaction is based in particular on the exchange of messages, while in robotics the common physical work is also considered (Scholz-Reiter and Höhns, 2006). A generally accepted definition for MAS and their applications in complex production systems has not been established to this day. Rather, the agent is characterized by its role, tasks, and the skills required for it. Wooldridge and Jennings (1995) name four properties which are a basic prerequisite for agents:

— Autonomy: agents run sans involvement of people and have control with respect to their activities and condition (Castelfranchi, 1994);

— Social ability: agents work together with other agents (also people) through an agent communication language (Genesereth and Ketchpel, 1994);

— Reactivity: agents notice their surrounding conditions and respond to variations; and

— Pro-activeness: agents are able to show purposeful behavior, grasping the nettle.

For the design of the MAS, the Process for Agent Societies Specification and Implementation (PASSI) approach was applied which includes five models: systems requirements model, agent society model, agent implementation model, code model, deployment model (Cossentino and Seidita, 2014). Exemplarily, the system requirements model is described in the following, as this model is the major input parameter for all the other models. A hierarchical agent society was chosen,

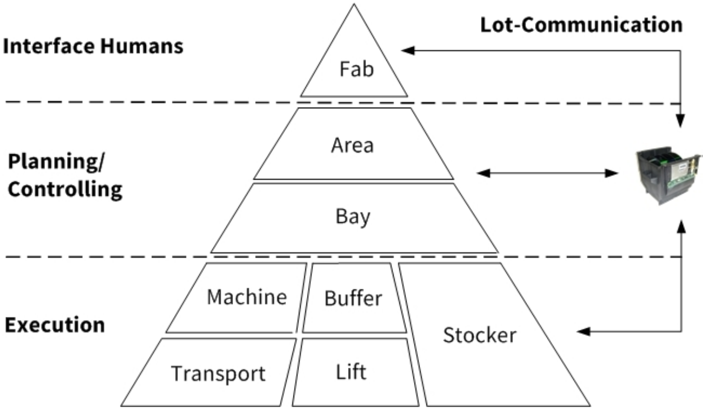


Figure 4: Hierarchical Agent Society

as this is the standard approach for production control of complex production systems, such as semiconductor manufacturing (Mönch and Stehli, 2006).

Figure 4 shows the three main levels of the system pyramid consisting of

- Interface Humans
- Planning/Controlling
- Execution

The top level of the pyramid, "Interface Human", is used to monitor and control the entire system by humans. This allows them to access the system directly, supported by the fab agent. For this purpose, a graphical interface is provided which visualizes the status of the fabrication facility and offers the possibility of interacting with the system. The planning and controlling level follows the thoughts described in Keil et al. (2011). Hereby, the lot agent plays a central role and is provided with a clock based production schedule and cumulative quantities (Löding, 2008) by the area agent. Based on the schedule, the lot agent negotiates with the identified agents, e. g. with the bay agent regarding the processing capability.

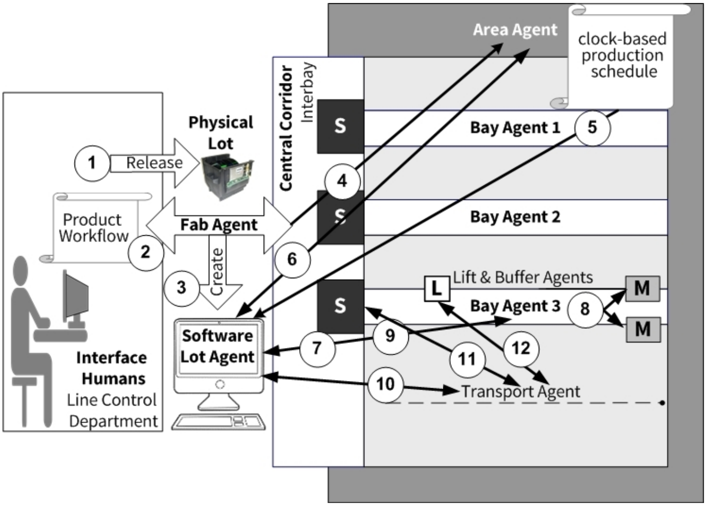


Figure 5: Hierarchical Agent Society and roles according to PASSI

The lot agent is able to communicate over all levels of the pyramid. He can act directly in the event of disruptions or deviations from the plan. In addition, the lot agent is able to perceive its environment by means of corresponding hardware at the carrier, which is described in Section 4.2. This enables the lot agent to react quickly to external influences.

Figure 5 shows exemplarily the negotiation relationships between the agents. At the interface between the human and the fab agent, the employee physically releases a production order (lot) (1) and renders the product workflow (2) of the product to the fab agent. The fab agent creates a software lot agent (3). Afterwards, the fab agent communicates with the area agent and asks him to create a clock-based production schedule for the new lot (4). The software lot agent gets the production schedule from the area agent (5). Based on this schedule, the lot agent asks the area agent which bay agent is responsible for the needed first production step (6). After receiving the answer, the lot agent asks the responsible bay agent to offer him production capacity in a certain time frame with respect to

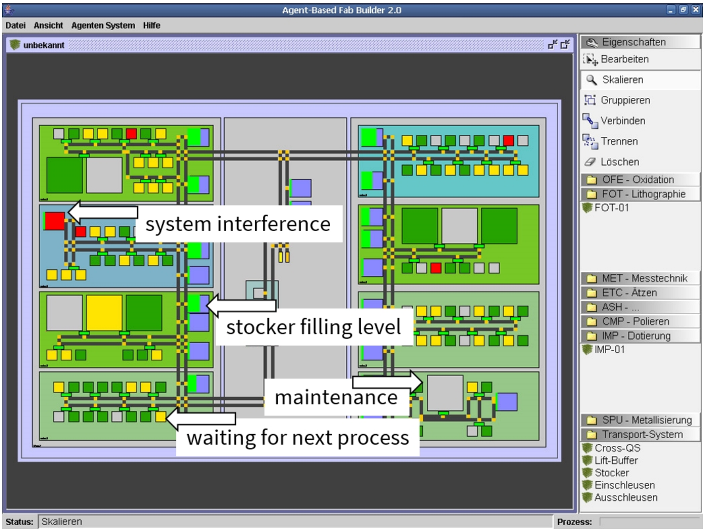


Figure 6: FAB-Monitor for visualization of the status characteristics of the semiconductor factory

a certain production recipe (7). For example, the bay agent asks for two machines in his bay which are able to carry out the needed production step (8). Maybe machine 1 responds: “I am down due to a failure” and machine 2 says: “currently, I am carrying out production step x, but in 50 minutes I will be available”. Then the bay agent offers the capacity to the lot agent, who accepts the offer (9). Now, the lot agent asks the transport agent: “could you transport me to bay x, and lift y?”. Maybe the transport agent says “yes, in 30 minutes, I can take you to the destination and in the meantime I will transport you to stocker y for an intermediate storage” (10).

In the background, the transport agent has asked the responsible stocker agent with respect to his capacity for temporary storage (11). Furthermore, the transport agent organizes the transport of the lot from the stocker to a buffer nearby a lift and the transport to the operation level by the respective lift (12).

The JADE (Java Agent Development Framework) was selected as an appropriate framework for implementing the presented MAS as it is in compliance with the Foundation for Intelligent Physical Agents (FIPA) which offers generic agent technologies. Thus, the communication with other agent platforms is safeguarded and the integration effort is decreased (Bellifemine et al., 1999; Bellifemine et al., 2008). The realization of the MAS occurred in two steps. Hereby, the production system was implemented in the first step. This enabled the modeling of a semiconductor factory and to feed in production orders. For the visualization of these tasks, the visualization tool ”FAB-Monitor” was designed (see Figure 6), which directly represents the activities of the MAS. Hereby, at the “interface humans” the employees can see, for example, which machines are in maintenance or where system interferences actually occurred. Unlike traditional visualization tools which are based on a central data structure, the newly deployed decentralized solution does not rely on a higher-level node. The advantages lie in the relief of the entire system as well as in a maximum topicality of the visualized data.

In the second step, the module for the planning of production orders was developed. For this purpose, current manufacturing data, such as machine failures, capacity bottlenecks, and processing times, are used. These data are provided by the lot agent, the hardware concept of which is described in Section 4.2.

4.2 Hardware Concept for a Cyber-Physical Production Lot

The goal is to develop a cyber-physical production lot. Therefore, a microcomputer with communication technology, a sensor system, and a power supply is integrated into the wafer carrier. For the receiving, evaluation, and further processing of the sensor data, access points are used. These access points are supplied with energy by means of Power over Ethernet. The hardware concept, which is schematically illustrated in Figure 7, is discussed in detail below.

To determine the processing times of the single production steps, it is necessary to measure the time span from the removal of the first wafer to the completion of the last wafer. For this purpose, forked light barriers are located in each slot of the carrier, which can detect the presence of a wafer. The data of the sensors are collected by an ATMega32 microcontroller from the firm Atmel. This controller communicates via the SPI interface with another microcontroller, an NA1TR8 of the firm Nanotron Technologies. This controller is responsible for the evaluation, conversion, and transmission of the collected sensor data.

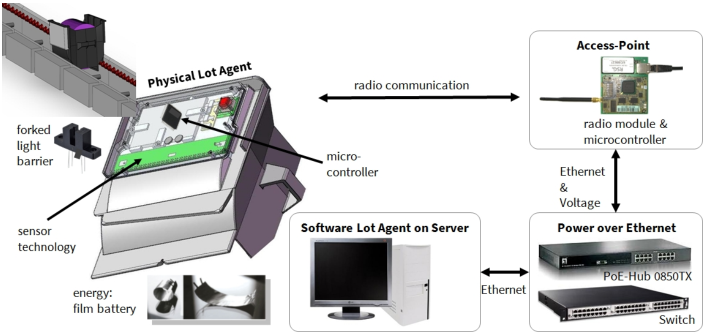


Figure 7: Hardware Concept of the Cyber-Physical Production Lot (CPPL)

The data are transmitted using the approach Chirp Spread Spectrum (CSS), which is part of the Multi Dimensional Multiple Access (MDMA) approach. This method provides high data transfer rates and extremely low power consumption and was included in the NA1TR8 controller by the company Nanotron Technologies (Nanotron, 2017).For the purpose of easy handling, all electronics (ATMega32, NA1TR8, SMD antenna, and other components) are located on one circuit board with dimensions of 95 x 20 x 4 mm (width x height x depth). An additional circuit board is required for the sensors and their control electronics.

For the power supply, film batteries are used which have a depth of about 3 mm. In order to guarantee sufficient energy supply over a period of 50 days (approximate cycle time of a lot), two batteries with 430 milliampere hours (mAh) capacity each are required. Since the weight of the batteries together is about 27 grams, and the cassette must be balanced, the batteries are attached to the opposite carrier wall.

Access points are available to receive data sent from the sensor nodes. Due to the absence of high transmission power, it is necessary to install several access points in the semiconductor factory. The hardware of the access points consists of a radio module from Nanotron Technologies and a microcomputer (PXA270), which was provided by the company Phytec. This microcomputer has the full functionality of a personal computer. On the Linux operating system, a program for receiving and evaluating data is installed. This data can be forwarded to the requesting agent via Ethernet. The concept of Power over Ethernet is used for power supply. Hereby, the data is provided and at the same time the voltage is supplied via a single Ethernet cable. Thus, no further power supply cable with adaptor is necessary, which significantly increases the flexibility with respect to the positioning of the access points.

The described hardware concept can be easily expanded if new functions are required. Further steps include, for example, the function perceiving the surroundings of the carrier by means of further sensor technology. Thus, for example, "lost" wafers can be detected at an early stage after cleaning operations. This contributes to a stability of production processes, since disturbances can be detected at an early stage. A task of the microcomputer is the collection of all essential processing data of the lot. This ensures, on the one hand, the actuality of the data and, on the other hand, the achievement of a high maturity level of technological processes. Development, process, maintenance, and product engineers have the opportunity for easy data evaluation since all collected data (e.g. process temperatures, end point times, processing and material flow times) are available for one lot at one location. This allows quick decisions and reactions of the engineers. In addition, the "intelligent" lot, which is equipped with the microcomputer, is able to carry out the tasks of production scheduling independently on the basis of predetermined targets.

4.3 Validation of the Concept

The validation of the concept includes three important aspects:

- Design and test of the radio network in the semiconductor factory,
- Integration of the carrier with the new electronic components in the existing factory, and
- Integration of the MAS in the exiting IT landscape

To point 1: Since the software lot agent runs on a server and not on the physical production lot carrier like the sensor technology, the communication between the carrier and the server must take place via a radio network. Therefore, the construction of a stable radio network is an important prerequisite for the implementation of the concept. As described in Section 4.2, the data is transmitted via the MDMA approach, which enables low energy consumption in contrast to other technologies like WLAN, Bluetooth, or ZigBee (Masini, 2015). This is of critical importance since the physical production lot agent stays in the factory for about 50 days.

In a first step, the transmission quality had to be determined. A measurement was carried out in the laboratory of the University of Applied Sciences Stralsund under the following conditions:

— line of sight between transmitter and receiver: distance 80 meters,
— without direct line of sight between transmitter and receiver: distance 40 meters, and
— without a visual connection through a wall: distance 8 meters.

The results of the measurements did show that an acceptable transmission quality exists at a transmission power of 8 dBm and a distance of 40 m without a visual connection. Due to tolerances and possible interferences, the distance between an access point and a sensor node should not exceed 30 meters. Based on these results, a statement about the positioning of the access points in the semiconductor factory can be made. As an intrabay has a length of 55.3 meters (see Figure 2), one access point is integrated in the middle of each intrabay. Additional access points in the interbay enable communication between several intrabays. 38 access points are required for the entire production system.

In a second step an access point was positioned in an intrabay of the regarded semiconductor manufacturer. The field test in the company did show that some of the machines emit interfering electromagnetic fields. Therefore, in the following field tests it is necessary to separately determine the transmission quality in each intrabay. If there is a reduced transmission quality, additional access points must be stationed in the respective intrabay. In addition, a possible negative impact of the radio waves on the machines has to be investigated.

An alternative to the described radio network based on the MDMA approach would be to use the existing WLAN network of the company or to use the radio network of a network operator. Then a new energy concept for the cyber physical production lot would have to be designed, as the data transmission within these networks would consume more energy. One alternative approach to solving the energy issue would be to load the carrier during the waiting times in the stocker.

To point 2: Due to clean room requirements, the carrier has to be cleaned approximately every 100 days. Therefore, in a second step, a watertight box, which includes the electronic components, was designed. In general, several thousand carriers are used in the production system. When the system is introduced into the factory, the company would have to ask the carrier supplier to integrate the electronics into the carrier during the manufacturing of the carrier. Furthermore, the retrofitting of the system requires rather high investment costs. In general, there is more than one solution for the technical realization of the cyber physical production lot. The realization depends on the material flow technique used in the respective company.

To point 3: The MAS system currently works in a simulation environment. So far, the focus has been set on the visualization of factory status (see Figure 6). Until now, about 100 production lots have been introduced into the system. The next steps are to examine the system behavior with respect to lead times and capacity utilization at a more realistic number of several thousand production lots. A huge challenge is the connection of the MAS to the existing material execution system. As the existing dispatch rules cannot be overridden due to the risk of loss of production for the firm, a step-by-step approach is required. It is proposed to use the new cyber physical production system in less automated production areas. For the semiconductor industry this would be factories that test wafers. In those factories the functionality of the manufactured products is tested, e.g. with respect to electrical parameters or through stress tests.

5 Summary and Outlook

The megatrends toward individualization of products and shorter delivery times together with rising cost and efficiency pressures, lead to an increasing complexity with respect to the organization, planning and control of production processes. Through the development and introduction of CPPS, this trend can be countered. By using the example of semiconductor manufacturing, a decentralized and autonomous production controlling system based on multi agent technology supported by a cyber-physical production lot was presented.

The sensor technology within the cyber-physical production lot enables data collection, which enhances the transparency of the production system. For example, in case of disturbances, employees can react fast and negative effects on other products can be avoided. This is achieved by the presented fab monitor, which visualizes the data collected by the lots. In general, the presented lot agent can enhance the data quality for production planning and control. Nevertheless, new production control strategies and accompanying technologies do not replace the need for designing lean processes. Furthermore, the next step is to design a control system for production networks.

Although the technology for CPPS is available, production systems of firms cannot be changed from day to day as it is challenging to integrate advanced production control strategies into legacy software systems of firms. Here firm specific transition concepts are needed.

For the future, it is of major importance to answer the question how the role of the human is defined in a CPPS as job profiles and the work division between CPPS and the humans will alter in the face of the technical progress. In addition, organizational forms have to be changed to facilitate decisions of employees, e.g. by swarm organizations and flat hierarchies, which reflect the decentralization, and autonomy in CPPS.

Acknowledgements

The development work was pursued under the leadership of Arthur Deutschländer, Sophia Keil and Mathias Kuttig at the University of Applied Sciences Stralsund with the support of Robert Kohn, Andreas Nack, Christoph Nagel, Ricardo Mussehl, Lars Böcker, Diana Riemer and Bernd Rummler. Thanks a lot to the employees of the company Infineon Technologies Dresden GmbH, especially Germar Schneider and Harald Heinrich who supported the work.

References

Bellifemine, F., G. Caire, A. Poggi, G. Rimassa, and A. Jade (2008). “A white paper”. In: *Telecom Italia EXP magazine* 3.

Bellifemine, F., A. Poggi, and G. Rimassa (1999). “JADE–A FIPA-compliant agent framework”. In: *Proceedings of PAAM (Vol. 99, No. 97-108, p. 33)*.

Brettel, M., N. Friederichsen, M. Keller, and M. Rosenberg (2014). “How virtualization, decentralization and network building change the manufacturing landscape: An industry 4.0 perspective”. In: *International Journal of Mechanical, Industrial Science and Engineering* 8.1, pp. 37–44.

Bussmann, S., N. R. Jennings, and M. J. Wooldridge (2004). *Multiagent systems for manufacturing control: a design methodology*. Science & Business Media: Springer.

Castelfranchi, C. (1994). “Guarantees for autonomy in cognitive agent architecture”. In: *International Workshop on Agent Theories, Architectures, and Languages*. Berlin Heidelberg: Springer, pp. 56–70.

Chang, C. F. and S. K. Chang (1998). “A layer-based layout approach for semiconductor fabrication facilities”. In: *Advanced Semiconductor Manufacturing Conference and Workshop*. IEEE/SEMI, pp. 385–390.

Chen, J. C., R. D. Dai, and C. W. Chen (2008). “A practical fab design procedure for wafer fabrication plants”. In: *International Journal of Production Research* 46.10, pp. 2565–2588.

Chien, C. F., C. H. Hu, and Y. F. Hu (2016). “Overall Space Effectiveness (OSE) for Enhancing Fab Space Productivity”. In: *IEEE Transactions on Semiconductor Manufacturing* 29.3, pp. 239–247.

Cossentino, M. and V. Seidita (2014). “PASSI: Process for agent societies specification and implementation”. In: *Handbook on Agent-Oriented Design Processes*. Ed. by Springer. Berlin Heidelberg, pp. 287–329.

Deutschländer, A., G. Brückner, H. Heinrich, and S. Keil (2005). “Materialflussautomatisierung unter Einsatz von Robotern in der Halbleiterfertigung mit 200 mm-Wafer-Technologie”. In: *Logistik Management, Innovative Logistikkonzepte*, pp. 241–255.

Ertel, W. (2009). *Grundkurs Künstliche Intelligenz*. Wiesbaden.

Freitag, M., O. Herzog, and B. Scholz-Reiter (2004). “Selbststeuerung logistischer Prozesse – Ein Paradigmenwechsel und seine Grenzen”. In: *Industrie Management* 20.1, pp. 23–27.

Geisberger, E. and M. (Broy (2015). *Living in a networked world: Integrated research agenda Cyber-Physical Systems (agenda CPS)*. Herbert Utz Verlag.

Genesereth, M. R. and S. P. Ketchpel (1994). *Software agents*. Tech. rep. Center for Integrated Facility Engineering. Stanford University.

Heinrich, H. and A. Pyke (1999). “The Impact of Conveyor Transports on Factory Performance at Infineon‘s (Siemens) 200 mm Fab”. In: *Semiconductor Fabtech* 10, pp. 15–18.

Hompel, M. ten (2010). *Individualisierung als logistisch-technisches Prinzip. Internet der Dinge in der Intralogistik*. Berlin Heidelberg: Springer.

Jennings, N. and M. Wooldridge (1996). “Software agents”. In: *IEE review* 42.1, pp. 17–20.

Kail, R., J. W. Pellegrino, and A. Hildebrandt-Essig (1988). *Menschliche Intelligenz*. Heidelberg: Verlag Spektrum der Wissenschaft.

Keil, S., D. Eberts, T. Igel, G. Schneider, K. Wilhelm, R. Lasch, and A. Deutschländer (2011). “Innovation and manufacturing excellence in mature multi product semi-conductor fabrication facilities via design for flow by 3”. In: *Semiconductor Conference Dresden (SCD)*, pp. 1–5.

Lee, J., B. Bagheri, and H. A. Kao (2015). “A cyber-physical systems architecture for industry 4.0 based manufacturing systems”. In: *Manufacturing Letters* 3, pp. 18–23.

Lödding, H. (2008). *Verfahren der Fertigungssteuerung: Grundlagen, Beschreibung, Konfiguration*. Berlin: Springer Verlag.

Malik, F. and G. Probst (1984). “Evolutionary management”. In: *Self-organization and management of social systems*. Ed. by S. B. Heidelberg, pp. 105–120.

Masini, M. (2015). *Störungsunempfindliche Informationsübertragung in dynamischer Produktionsumgebung*. BoD–Books on Demand.

Meyersdorf, D. and A. Taghizadeh (1998). “Fab layout design methodology: Case of the 300 mm fabs”. In: *Semiconductor international* 21.8, pp. 187–196.

Miltenburg, J. (2005). *Manufacturing strategy: how to formulate and implement a winning plan*. CRC Press.

Mönch, L. and M. Stehli (2006). “ManufAg: a multi-agent-system framework for production control of complex manufacturing systems”. In: *Information Systems and e-Business Management* 4.2, pp. 159–185.

Monostori, L. (2014). “Cyber-physical production systems: Roots, expectations and R&D challenges”. In: *Procedia CIRP* 17.2014, pp. 9–13.

Nanotron (2017). “Company information”.

Niekisch, T. (2001). “Störungssystematikbestimmte Instandhaltung in einem Wafertransportsystem”. PhD thesis. Technische Universität Dresden.

Ostgathe, M. (2012). *System zur produktbasierten Steuerung von Abläufen in der auftragsbezogenen Fertigung und Montage*. Herbert Utz Verlag.

Puffer, W. (2007). “Technisch-ökonomische Effizienzbetrachtungen für die Halbleiterfertigung”. PhD thesis. Technische Universität München.

Reinhart, G., P. Engelhardt, F. Geiger, T. Philipp, W. Wahlster, D. Zühlke, and P. Stephan (2013). “PCyber-Physische Produktionssysteme. Produktivitäts-und Flexibilitäts-steigerung durch die Vernetzung intelligenter Systeme in der Fabrik”. In: *wt-online* 103.2, pp. 84–89.

Ropohl, G. (1979). “Eine Systemtheorie der Technik”. In: *München*.

Russell, S., P. Norvig, and A. Intelligence (1995). *Artificial Intelligence. A modern approach*. Eglnewood Cliffs: Prentice-Hall.

Scholz-Reiter, B., M. Freitag, H. Rekersbrink, B. L. Wenning, C. Gorldt, and W. Echelmeyer (2005). “Auf dem Weg zur Selbststeuerung in der Logistik-Grundlagenforschung und Praxisprojekte”. In: *Intelligente Logistikprozesse: Konzepte, Lösungen Erfahrungen - Begleitband zur 11. Magdeburger Logistiktagung*. Ed. by Logisch-Verlag. Magdeburg: Wäscher, G., pp. 166–180.

Scholz-Reiter, B. and H. Höhns (2006). “Selbststeuerung logistischer Prozesse mit Agentensystemen”. In: *Produktionsplanung und-steuerung*. Berlin Heidelberg: Springer, pp. 745–780.

Schuhmacher, J. and V. Hummel (2016). “Decentralized control of logistic processes in cyber-physical production systems at the example of ESB Logistics Learning Factory”. In: *Procedia CIRP* 54, pp. 19–24.

Seitz, K. F. and P. Nyhuis (2015). “Cyber-physical production systems combined with logistic models – a learning factory concept for an improved production planning and control”. In: *Procedia CIRP* 32, pp. 92–97.

Sonar, A., S. Shinde, and S. Teh (2013). “Automation: Key to Cycle Time Improvement in Semiconductor Manufacturing”. In: *IEEE/SEMI Advanced Semiconductor Manufacturing Conference 2013*. Saratoga Springs, NY.

Sternberg, R. J. and D. K. (Detterman (1986). *What is intelligence?: Contemporary viewpoints on its nature and definition*. Praeger Pub Text.

Wahlster, W. (2013). *Künstliche Intelligenz: Computer mit Augen, Ohren, Hand und Fuß – aber auch Verstand? Künstliche Intelligenz: Chance oder Risiko?* Tech. rep. Hamburger Akademievorlesungen.

Wang, L., M. Törngren, and M. Onori (2015). “Current status and advancement of cyber-physical systems in manufacturing”. In: *Journal of Manufacturing Systems* 37.2, pp. 517–527.

Windt, K. (2006). “Selbststeuerung intelligenter Objekte in der Logistik”. In: *Selbstorganisation: Ein Denksystem für Natur und Gesellschaft.* Ed. by B. Verlag. Köln Weimar: Vec, M., Hütt, M. T., Freund, A. M.

Winzker, M. (2008). *Elektronik für Entscheider: Grundwissen für Wirtschaft und Technik*. Springer-Verlag.

Wirtschaft und Energie), (für (2016). *Autonomik für Industrie 4.0. Ergebnisse.* Tech. rep.

Wooldridge, M. and N. R. Jennings (1995). “Intelligent agents: Theory and practice”. In: *The knowledge engineering review* 10.2, pp. 115–152.

Zbib, N., S. Raileanu, Y. Sallez, T. Berger, and D. Trentesaux (2008). *From passive products to intelligent products: the augmentation module concept. 5th International Conference on Digital Enterprise Technology*. Nantes, France.