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# Agent-Based Simulation for Multi-Criterial Planning and Control of Automated Electroplating Lines

***Agentenbasierte Simulation für multikriterielle Planung und Steuerung von automatisierten Galvanik-Linien***

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**Abstract:** The paradigm of sustainable production including recent regulations from *REACH* ask for an increasing process and energy transparency in the plating industry. Manufacturing systems simulations is a promising approach here. To date simulation models rarely focus on the characteristics of highly automated electroplating lines in metalworking industry. This paper shows an integrated simulation framework to model industrial automated electroplating lines as part of a cyber-physical production system. Line integrated pre- and post-treatment processes as cleaning and degreasing are considered as well as their dynamic interactions. Three cases show the applicability of the developed framework and benefits using a simulation approach for industrial plating lines.

## 1 Introduction

Industrial electroplating processes are characterised by a high variety of process parameters. Due to dynamic interdependencies between and within process steps, the relationship between process parameters, surface structure and surface properties including energy and resource demand are not fully understood. Especially highly automated barrel plating lines are complex dynamic systems of subsystems which influence each other. Improvement measures in subsystems often influence other subsystems, for example, the drag out from plating baths influences the following post-treatment baths. These interdependencies are often not considered in the planning phase nor during operations.

In Germany 149 companies from the surface finishing and heat treatment sector are eligible to reduce their tax burden as they are classified as electricity cost intensive companies (Bundesamt für Wirtschaft und Ausfuhrkontrolle 2019b). Many companies from this group operate electroplating lines. To benefit from this regulation, these companies must fulfil transparency requirements from the environmental management systems according to DIN EN ISO 50001 or EMAS (Bundesamt für Wirtschaft und Ausfuhrkontrolle 2019a). This transparency shall enable companies to increase the energy and resource efficiency of their plating processes and track the success of efficiency measures. Recently, in the EU stringent requirements under the REACH regulation require increased process transparency and measures to increase the occupational safety and health (OSH) situation of the workers in electroplating facilities (European Chemicals Agency 2019).

To address the resulting requirements an integrated multiscale and multilevel simulation approach has been developed. The simulation is used as part of the cyber system and embedded in the cyber-physical production system (CPPS) which is the basis for a comprehensive decision support system. This approach increases the process transparency significant allowing to estimate the energy and resource demand (including an allocation to single products) as well as to evaluate the OSH situation a priori. These aspects benefit significant from a simulation approach as experiments and manual or automated measurements are very costly and often not realizable in a productive manufacturing environment. Further, specific electricity or exposure measurements only consider static situations and neglect the dynamic character of plating process line.

Electroplating combines discrete and continuous processes. The workpieces are typically stored in barrels or racks and go through the cleaning, rinsing and plating processes in batch mode, and have a discrete character. Fluids for cleaning, rinsing, plating and post-treatment flow continuously through the system. (Kuntay et al. 2006) Therefore, a combined discrete and continuous simulation approach within an agent-based simulation environment has been selected as simulation paradigm.

## 2 Background

This chapter describes the relevant research background regarding automated barrel electroplating systems and the simulation of manufacturing systems.

### 2.1 Automated Barrel Electroplating Systems

Automated barrel plating lines allow plating high volumes of small to medium sized parts at high quality and reproducibility. Figure 1 provides a schematic overview of an automated industrial electroplating line. In the plating facility, a set of tanks, filled with pre-treatment, plating and post-treatment fluids, is aligned in one or multiple lines. A rail mounted hoist (RMH) system transports the barrels, or more generally the carriers, between the single tanks starting from pre-treatment processes as cleaning and degreasing, to the electroplating process and finally to post-treatment processes as rinsing or passivation (Schmid and Jeswiet 2018). Peripheral systems as exhaust air systems support the process baths and ensure that workplace concentrations are not exceeded. (Ritzdorf 2010; Hofmann and Spindler 2010)

Typically, the carriers follow the direction of the plating line but due to space restrictions and to enhance the flexibility backwards and lateral movements to parallel tank lines are required. Further, storage spaces can be included to store carriers between processing steps to enhance the productivity of the plating system.

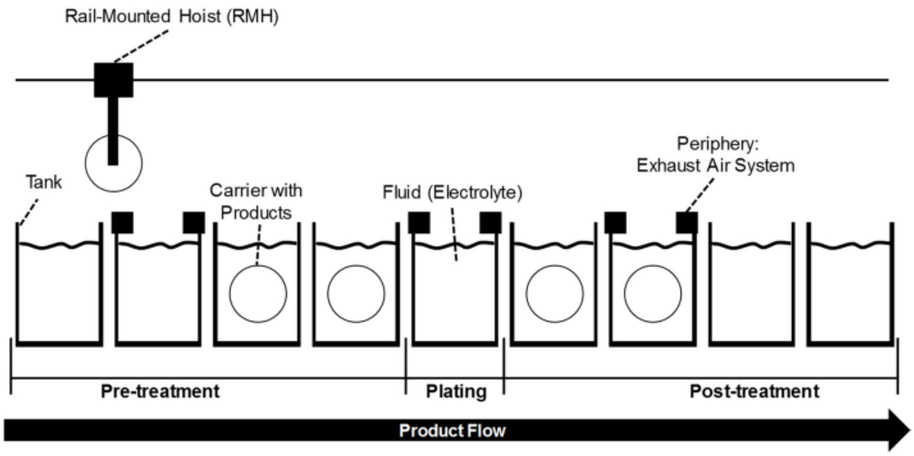


***Figure 1:*** *Schematic overview of an industrial automated electroplating line*

## 2.2 Simulation of Manufacturing Systems

Today most available simulation tools for manufacturing systems are capable to model discrete manufacturing systems focussing on material and product flows. Within the last decade the simulation of energy flows has been included (Duflou et al. 2012). In the following the most relevant simulation approaches from other authors with focus on manufacturing systems are presented: Hesselbach et al. (2008) introduce a model coupling approach to consider the production and technical building system within one environment. The approach by Thiede (2012) is generic and supports simulating many different production systems but mainly focuses on the energy demand. Bleicher et al. (2014) developed a simulation with a focus on the energy demand simulation for machining processes and also included the TBS into their simulation. The approach by Eisele (2014) focuses on the energy demand of machine tools. Schönemann (2017) developed an approach which allows live linking of simulation tools and focusses on battery production systems. Kurle (2018) partially included electroplating processes into his approach but mainly focusses on the heat flows in the production system. Xu et al. (2005) model the resource flows in electroplating and rinsing systems in detail but neglect the energy demand and further systems of the plating line. This detailed approach also allows simulating only one specific product.

In difference to existing approaches, the developed simulation focusses on automated barrel plating lines and considers these special characteristics. In particular, the continuous and discrete behaviour is integrated by an agent-based simulation approach. Specific models for electroplating lines are developed and new innovative visualisations to map the OSH situation are integrated.

## 3 Development of a Framework for Manufacturing Systems Simulation of Electroplating Lines

CPPS contain a physical and a cyber system which are interlinked with a data acquisition and a feedback/control systems (Thiede et al. 2016). For this study, an automated barrel electroplating line is used as physical system and the simulation as cyber system (see Fig. 2). Relevant data is acquired from the electroplating line and used as input for the simulation. The simulation is the basis for a comprehensive decision support system and allows predicting the future behaviour of the plating line. Compared to a stand-alone simulation, the integration of the simulation in the CPPS allows a comprehensive decision support for multi-criterial planning and control of the electroplating line, while using live data from the electroplating line.

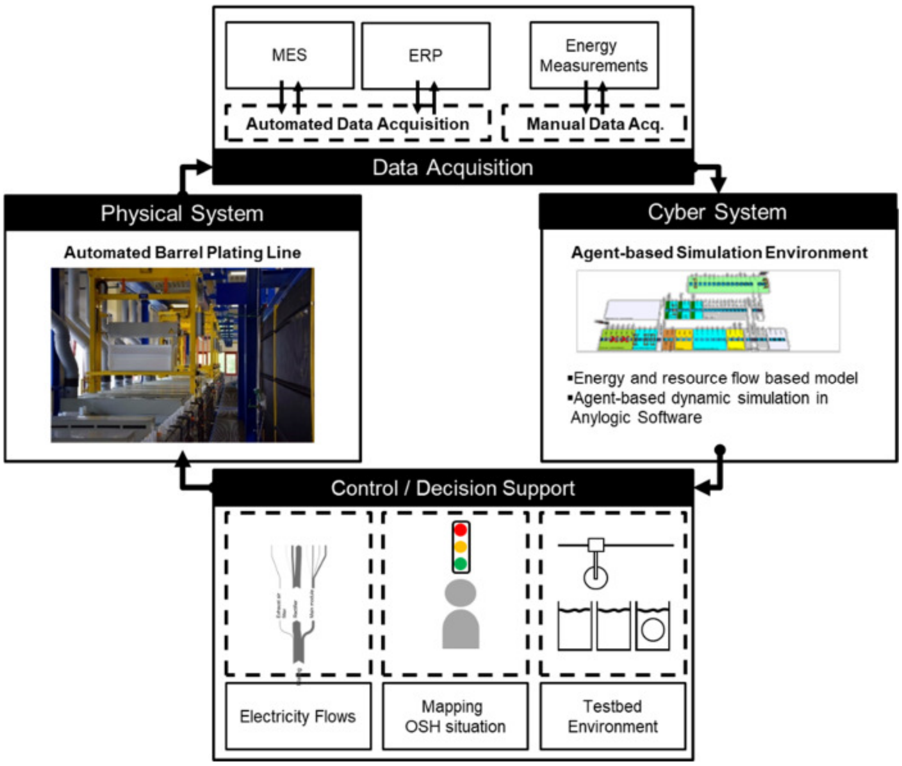


***Figure 2:*** *Integration of simulation as cyber system into a CPPS*

Decisive for an efficient CPPS realisation is an efficient data acquisition from the physical system. Already available sensors and data are used and enhanced by additional manual measurements. From the Manufacturing Execution System (MES), the pending production batches with their characteristics and the process chain are transmitted. At the same time, product-specific data is retrieved from the Enterprise Resource Planning System (ERP). MES and ERP were connected with file-based interfaces to the simulation to allow an automated data transfer. Additionally, electrical power and chemicals concentration measurements were conducted to build an electricity and resource flow model for the behaviour of the plating line. Compared to the installation of various sensors for electricity and power measurements this approach is more efficient and no extensive additional sensor network is required.

The acquired data is the basis for the parametrisation of the agent-based simulation. Figure 3 provides an overview of the simulation model. Seven state-based multi-parameter models were developed to build up a framework for the simulation model. Each model represents an agent type and can be multiplied to build the whole plating line.

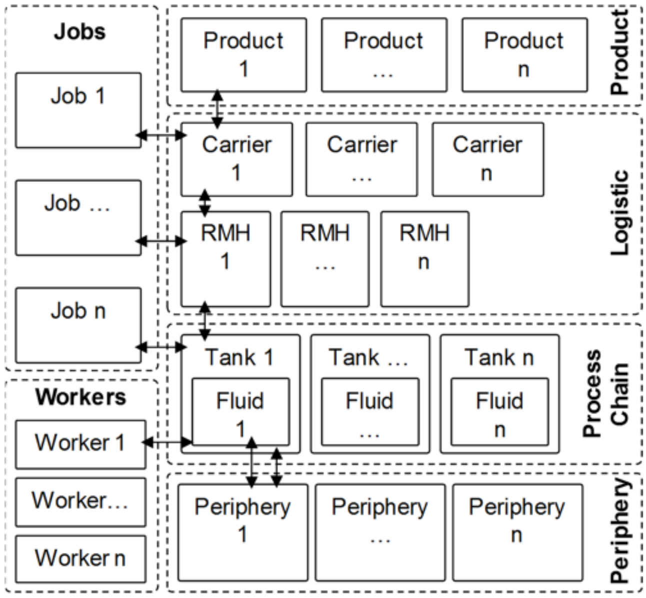


***Figure 3:** Structure of the simulation model*

The agent type *product* represents the product to be plated and contains the products properties as surface, volume, weight, material or drag-out behaviour. These properties are required to calculate the energy demand and the drag-out behaviour of specific products. *Carriers* are filled with a defined number of products and are used to transport the products to different tanks. *RMHs* transport the carriers between the tanks. The operation area of RMHs is restricted and contains a state based model, which also allows modelling the energy demand. The RMHs can be controlled by commands from the MES system or by algorithms within the simulation environment.

The agent type *tank* represents the fluid tanks to build of the plating process chain. Again, a state based model represents the current situation (empty, occupied, in process and waiting for RMH) and is the basis for the energy model of the tank. The energy demand of local energy consumers, for example the drives for rotating the carriers during plating or rectifiers for the electroplating process, are modelled within this agent. Tanks can be filled with a *fluid* or remain empty in case a tank is used as storage space. It is possible to use one fluid for multiple tanks in case the tanks are connected with a piping system. Additional *periphery* can be connected to the fluid (e.g., in case of circulation pumps for multiple baths), to multiple tanks (e.g., in case of tank state-controlled exhaust air systems) or depended from factors outside of the process chain (e.g., in case of cooling units for control systems).

The agent type *job* contains all relevant information to proceed a product through the plating process chain, such as process steps, times and parameters. These information are the basis for a simulation run and this agent type receives job data from the MES. The agent type *worker* represents people working within the plating line. Each worker has a specific order of task, which are related to OSH data. Figure 3 also provides an overview on agent communication and interaction during the models runtime.

For control and decision support, three specific amending decision support modules with visualisations were developed, which are introduced with industrial examples in the following sections:

- Modelling the electricity demand and allocation to specific product carriers;
- Mapping the OSH situation of the workers;
- Testbed environment for new production strategies, energy efficiency and OSH measures;

# 4 Industrial Case Study

The presented framework was tested in cooperation with a small to medium-sized company running an electroplating facility within a combined barrel acid zinc-nickel plating line for small to medium sized automotive parts. Six active plating baths are available as well as all the required pre- and post-treatment baths to fulfil the requirements from the automotive industry. In the following three subsections exemplary use cases from the simulation model as part of a CPPS are introduced.

## 4.1 Electricity Flows

To parameterise the developed model, the system behaviour of all relevant electricity consumers from the plating line was investigated and states defined. For all identified states, electricity power measurement were conducted and interdependencies considered. These electricity measurements were the basis for the parameterisation of the simulation model. In the simulation, the total power P[W] can be calculated as the sum of the power from all plating tanks, all RMHs as well as all periphery agents:

$$P_{total} = \sum_{i=1}^{n} P_{tank;\,i} + \sum_{i=1}^{n} P_{RMH;\,i} + \sum_{i=1}^{n} P_{periphery;\,i} \tag{1}$$

For this specific use case, simulation was the most efficient method to estimate the total electricity demand of the plating line as the electricity is provided from various electricity distribution points. The major electricity consumer in a well utilised electroplating line are the rectifiers (part of the agent tank) for the plating process. Their energy demand depends on the specific process parameters current and voltage in the plating bath. Therefore, the efficiency of the rectifiers has been estimated to calculate the electricity demand of these as product of the efficiency, the current and voltage in the plating bath. Current and voltage are obtained from the MES system via the job-agent.

Figure 4 shows the load profile during unloading and loading carriers with different products in the plating tanks. The start of three different rectifiers has been marked. The ramp up and therefore the power differs due to different product and process parameters.

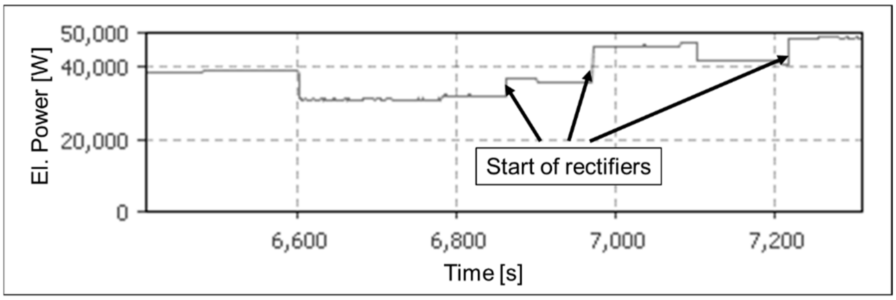


***Figure 4:*** *Load profile of the total plating line*

The agent-based approach allows the allocation of the electricity demand to specific product carriers, which allows determining carrier-specific performance indicators. Electricity demands, which are triggered by a product carrier, are accounted to this carrier. The base-load is divided among all processed product carriers during a simulation run. These results are send to the ERP system and saved to the product data. This allows providing customers the electricity demand per product and calculate the environmental impact resulting from the electricity demand. In nickel plating processes the electricity demand is the main contributor to the impact category global warming potential (Takuma et al. 2018).

## 4.2 Mapping OSH Situation

Recent regulation from the REACH regulation ask for a higher process transparency for the use of critical substances, in particular chromium trioxide in the electroplating industry. The developed simulation approach will be used to calculate the worker's OSH situation based on his job profile. This allows calculating the workplace exposure to a worker and comparing different scenarios a priori without further measurements.

Different measures can be applied to improve OSH situation. Beside personal protective equipment, operations close to the plating baths/dosing tanks should be avoided. In addition, job rotation can be a measure to improve the situation. The simulation approach allows the validation of different measures and to derive recommendations.

To increase the awareness of decision makers in production planning, innovative ways to visualise the worker's OSH situation were developed. For the 3D simulation visualisation, the current situation of a worker is indicated by coloured balls above their head (see Fig. 5). Green indicates no critical exposure, yellow a close to the critical value exposure and red a critical exposure that asks for immediate measures.

As the air emissions exposure highly depends on the location of a worker during a shift, a visualisation to map their location during a shift will help to prioritise measures. Based on the simulation for analysing and visualising of paths in operation rooms from Koshkenar et al. (2017), an heatmap based visualisation has been developed. To visualise the employee's workplaces and paths during a shift, a heatmap is projected on the shopfloor layout. Figure 5 shows the plating line layout with the heatmap, which indicates the number of workers per square meter. The two dark grey points at the upper side indicate a high employee density in an uncritical area, where the controls of the line are located and parts are unloaded. In the critical area (dosing tanks and plating baths at the right side) employees stay for a relatively short duration.

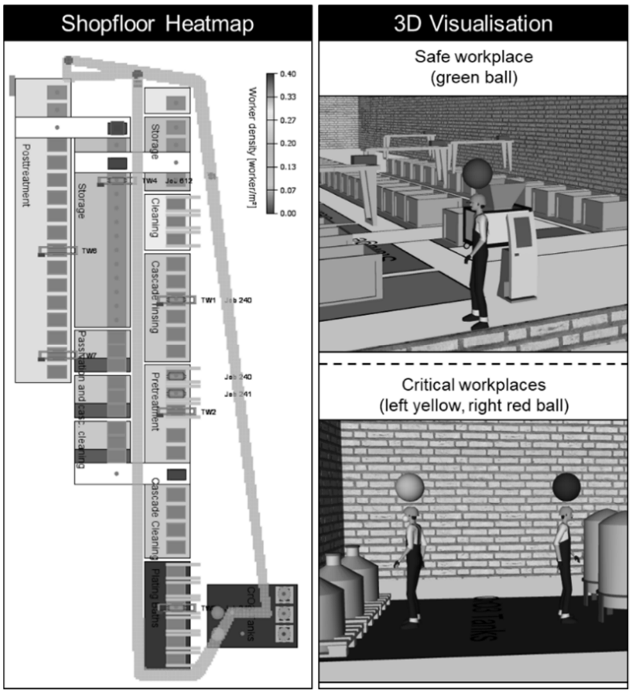


***Figure 5:*** *Visualisation of OSH situation*

## 4.3 Testbed Environment

Through the direct interface to the MES and ERP system, the simulation can be used as testbed platform for various purposes. First, new algorithms from the MES for solving the hoist scheduling problem for the RMHs, can be evaluated within the virtual environment. This allows a risk-free analysis and the energy efficiency of a new algorithm can be rated.

Second, general measures to increase the energy and resource efficiency as well as measures to improve the occupation health situation can be tested before realisation. For example, pumps can be virtually replaced by more efficient models and the impact on the energy efficiency of the whole plating line can be rated.

Third, the impact of different process and plant parameters on the whole plating line can be evaluated from an energy and resource efficiency perspective.

Interdependencies between baths, for example the drag from bath to bath, can be calculated and used as basis for rating current bath state.

## 5 Conclusions, Discussion and Outlook

A framework to use an agent based simulation as part of a CPPS for automated industrial electroplating lines has been introduced. The industrial case study showed the applicability and the benefits from the developed simulation as part of a CPPS. Three specific decision support modules increase the process and energy transparency significants and provide the basis for further developing of the simulation framework.

This approach has a high potential for planning and controlling electroplating lines. Compared to simulations without integration into a CPPS, the simulation operates with real data from a productive system and allows a precise estimation of the future system behaviour. However, it has to be noted that the development of interfaces to other IT systems is complex and only little standardisation is available.

For future steps, it is possible to integrate detailed air emission models to the OSH situation to rate the situation of the workers quantitative without any additional measurement. The CPPS approach can also be used for any other types of industrial plating lines such as rack or single piece plating system. The general properties are the same and no relevant changes in the simulation model are required. Further, the simulation can be the basis for further surface treatment processes as such chemical or electrophoretic coating.

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