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Simulation Platform for Energetic Considerations in Matrix Production Systems

Plattform zur Simulation von energetischen Einflussfaktoren in Matrix-Produktionssystemen

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Abstract: Matrix production systems are designed to be flexible and productive at the same time. This is to be achieved by a modular design and high degree of automation in terms of process control, material transport and work distribution. This also affects the flow of energy which results in a highly variable energetic behaviour of the overall system. This contribution presents a synthetic simulation platform approach to investigate the energetic behaviour of matrix production systems. The setup and modules of the approach are pointed out based on the typical characteristics of matrix production systems. An experiment study is showcased to demonstrate the approach and give an insight into the results of the simulation.

1 Introduction

Matrix production systems (MPS) are perceived as a system variant that can cope with various internal and external change drivers and stay competitive within a turbulent market environment. These systems are designed to be scalable and flexible and still allow it to produce high output volumes (Greschke et al., 2014).

Especially assembly systems for customized serial production can benefit from this kind of systems in terms of scalability, flexibility and modularity. Currently, rigidly connected systems are the dominant design variant that allow high efficiency as long as the product spectrum remains stable in volume and variants (Foith-Förster and Bauernhansl, 2016). Here, product variability complicates the dispatching of jobs in pearl chain systems, and thus also the vulnerability of the overall supply chain. These challenges are to be tackled with MPS by dissolving the rigid flow and design a flexible and demand-oriented system with process modules that are designed to be variable in skills and location (Bauernhansl et al., 2020).

MPS show a strong penetration of cyber-physical system elements that enable entities on all system levels to connect to each other, to communicate and engage elevated control approaches. A drawdown of these concepts is of course the higher effort in domination of complexity or development of suitable operational concepts (Müller et al., 2020). Especially for the assessment of system solutions simulation is a suitable tool. Various authors conducted studies based on simulation so far, e.g.:

- for the comparison of conventional assembly systems with matrix-structured ones (Greschke, 2015)
- for the validation of designs for matrix-structured assembly systems (Foith-Förster, 2022)
- for planning and control of modular assembly systems (Kern, 2021)
- for assessing the operational and routing flexibility (Perwitz et al., 2022).

Despite the current focus on assembly systems, the concept of MPS itself is meant to be adaptable by other production or manufacturing paradigms as well (Greschke et al., 2014). Distinct simulation-based approaches that investigate the general system behaviour have been, among others, showcased by:

- Filz et al. to analyse different material supply strategies (Filz et al., 2019)
- Schönemann et al. to investigate different system configurations (Schönemann et al., 2015).

So far, only Schönemann et al. (2015) gave an outlook on possible energetic considerations in MPS. Kurle et al. conducted a study on energy- and time-efficient production planning and control strategies in manufacturing systems with "[…] a dynamic system behaviour and decentralized decision making logic of individual elements such as jobs and its products" (Kurle et al., 2016, p. 442) with a pictorial presentation of a matrix-structured manufacturing system but did not mention MPS in particular. Hence, similar system might have been investigated so far, but MPS have not been mentioned explicitly. However, Thiede (2022) emphasizes the role of cyber-physical production systems (CPPS) for further decarbonization in manufacturing industry. Especially energy efficiency and energy flexibility are potential levers for environmental improvements by Industry 4.0 technologies, e.g., energy aware process design or dimensioning of energetic infrastructure (Thiede, 2021). MPS can provide support here as well, but the potential remains unclear.

One main aspect to successfully operate CPPS such as MPS is to integrate analytical and simulation-based approaches (Monostori et al., 2016). Simulation of energetic considerations has been investigated extensively. Exemplarily, Kouki et al. (2017) provide a review of different approaches for input data management in DES that includes the considered energy, input data acquisition, modelling boundaries and fields of application. Roemer and Strassburger (2016) conducted another review and identify various approaches that deal with the integration of energy data in simulation as well as the simulation-based optimization of energy efficiency. This underpins the relevance of simulation in this context, even though further sources might be mentioned here. Hence, this paper aims to start filling this gap with the explicit consideration of energetic aspects in simulation of MPS. Especially the flow electrical energy is of uncertainty due to reactive behaviour of material flow and production processes. Technologies such as automated guided vehicles (AGV), load strategies and the flexible allocation of material to production processes with dynamic change of operational states are examples of these influences. The approach for the simulation study in Figure 1 incorporates the procedure model of VDI 3633 (VDI 3633 - 1).

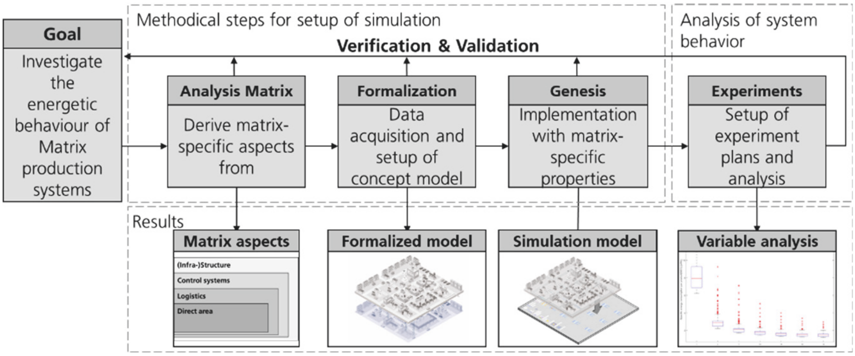

Figure 1: Approach to investigate energetic considerations in MPS with simulation

This includes the analysis of current MPS-related literature to derive matrix-specific design fields and aspects. Based on an industrial context, relevant data for the simulation is acquired and together with the matrix-specific aspects implemented in a simulation model. The goal is to ensure a wide variability of parameters and variables in the model to conduct a wide range of experiments.

2 Characteristics and simulation of MPS

MPS are meant to unite three aspects: flexibility, changeability and reconfigurability. From a system perspective, they are highly flexible and able to balance temporary alterations of workload and product mix very well. This is due to the modular design that enables a flexible material flow (Greschke et al., 2014).

A characteristic feature from a system perspective, especially in existing pictorial presentations of MPS, are the process modules being structured in rows and lines. The work contents are not segmented and usually clustered in multipurpose machines. The material flow is not interlinked to decouple cycle times and reduce productivity losses (Echsler Minguillon, 2020) and is not directed so that every product can have its individual path through the processing stations. Fries et al. (2020) illustrate this principle along with other characteristics of material flow.

So far, many approaches investigated MPS in the context of assembly systems. The main goal here is to keep the efficiency of a rigidly linked system but to increase the product variability in the overall system. The core idea of MPS in assembly is to divide the overall system in smaller sub-systems and decouple cycle times from subsequent stations. This avoids the sub-systems to all have the same cycle time. Instead, the average cycle time of all sub-systems has to meet the average process time from all processes (Greschke et al., 2014). This requires it to assign at least two work contents to every work stations and to realize redundancy, hence, flexibility in the overall system (Greschke, 2015). Job shops on the other side usually incorporate the principle of decoupled processes with a higher degree of flexibility in work content assignment to process modules but lack an automated and flexible material flow to optimize the utilization of stations and reduce blocking and starving of processes. In both cases, intelligent system structures enable the transition to MPS. Cyber-physical elements, real-time location systems, information and communication technologies (ICT), autonomous production and transport resources enable for decentralized decision making, surveillance and system control. The allocation of these aspects towards control systems, production and building infrastructure, logistics, personnel and production processes enable MPS to reach a high utilization by varying product portfolio and to quickly adapt to changes of market demands. Reconfiguration processes give the opportunity to redistribute work contents and react to altered production programmes (Greschke et al., 2014).

But these principles do also lead to more unforeseeable effects in process control and logistics. Dynamic and stochastic effects are increasing and need to be investigated properly when designing these kind of systems, e.g., presented by Filz et al. (2020) for the logistics system in early planning phases. Due to the less foreseeable critical factors in system design, the reconfiguration management needs to be considered during operation of the system (Müller et al., 2020). Overall, a wide range of design aspects as well as their interconnections must be examined when investigating the general behaviour MPS. A classification taking up the extended system model approach from Eversheim (Bauernhansl, 2020) shows the main design aspects of production design in general, that can also be applied in MPS. These are clustered to similar groups of design fields in Figure 2.

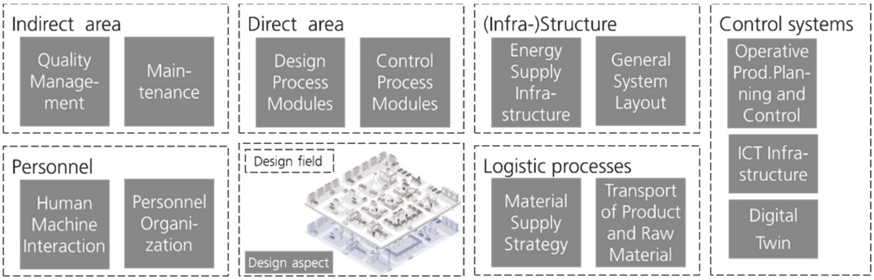

Figure 2: Main aspects of MPS design

The main point to consider when simulating MPS were subsumed by Schönemann et al. (2015). They elaborated the general principles of flexible routing of material and products, redundancy in work contents within the system, process modules with various skills for processing and individual cycle times for products per process module. To transfer these properties into a simulation model, the elements products, workstations, material flow and buffers need to be considered accordingly. Their analysis results of the simulation study consider utilization of work packages, the blockage of system elements as well as a dynamic visualization of the process stations (Schönemann et al., 2015). Filz et al. (2019) investigated the material supply of matrix systems by means of simulation and conducted experiments with different material supply, routing strategies and configuration of the respective AGV. So far, the material flow and system design have been analyzed by various other authors as well (Greschke, 2015; Kern, 2021; Schukat et al., 2022), but there are shortcomings in the energetic perspective of MPS, whereas only specific parameters such as embodied energy per product have been mentioned as future topics of interest (Schönemann et al., 2015).

3 Setup of simulation platform

The gap in energetic considerations of MPS is addressed by the introduction of a simulation platform. The goal is to design a platform that employs the main characteristics of a MPS and allows to vary a wide range of parameters for experimental exploration of energetic and logistical metrics. The modelling approach follows the recommendation of Perwitz et al. (2022) to create easily adaptable and configurable structures to efficiently generate a wide range of experimental setups. This condition is addressed by focusing on the adaption of many parameters that define the basic system behaviour. Hence, complex control algorithms for material transport or other special interests are not considered. The typical features of MPS reflect the main characteristics of the simulation platform. This includes a flexible work distribution, multiple and redundant work contents, automated and flexible product transport or variable processing times. The energetic infrastructure is integrated by modelling the energy consumption of processing and transport system. Based on Krückhans and Meier (2013), who compare different strategies to integrate energy consumption profiles into simulation environments, a state-based approach of mean values per operating state has been chosen to maintain simulation performance. Figure 3 gives an overview of the derived main characteristics to model MPS in a simulation environment and an insight into the manipulable parameters for the platform.

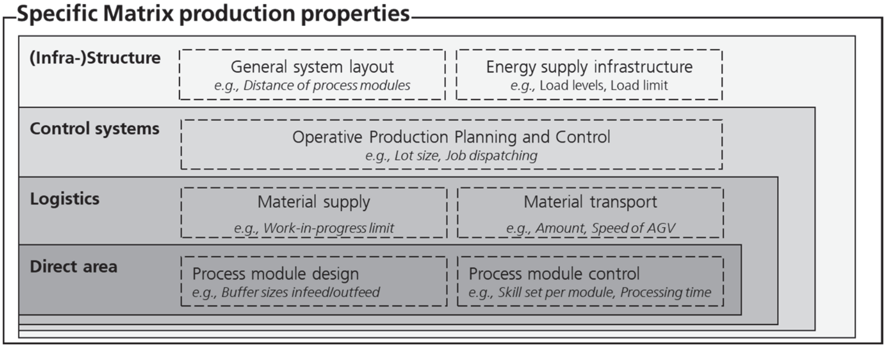

Figure 3: Properties for energetic simulation of MPS with examples (in italics)

The simulation platform is set up with the discrete-event simulation software Siemens Tecnomatix Plant Simulation (STPS). It employs the outlined characteristics and is based on a modular framework to configure various system variants and parameters and conduct experiments within a job-shop-oriented manufacturing system. The underlying use case from industrial context that was shown by (Stoldt et al., 2018) and has been adapted to a MPS design. According to the paradigms of energy flow simulation, discrete-event simulation with integrated evaluation of energy flows is applied (Thiede, 2012). Precisely, the state-based approach of STPS is has been adopted to evaluate the energy consumption. The general principles of material flow and behaviour were verified during the setup of the model itself. This was conducted by continuous testing of methods and analysis of material flow behaviour in distinct experiments and analysis of key performance indicators, correlation matrices or visual verification during runtime. The framework and pipeline of the simulation platform for MPS is depicted in Figure 4.

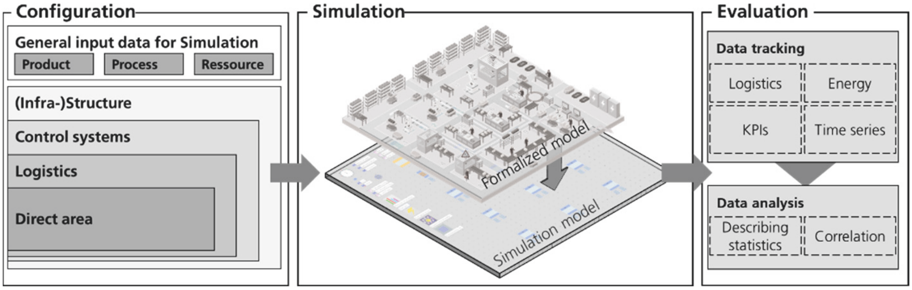

Figure 4: Simulation platform framework and process pipeline for MPS

The simulation is based on a work plan of various mechanical manufactured **products** such as drive shafts and gearing parts. They consist of several production steps ranging from one to seven steps. The **processes** are modelled according to the work plans from the products and include all the necessary manufacturing technologies. The **resources** are modelled generically by adopting a specific setup time for products on every process. Hence, resources for processing are assumed as always available.

The **Simulation** layer employs a generic design of process modules consisting of single production stations with input and output buffers. The material flow is modelled by an AGV fleet. Energetic data is modelled by skill-specific operating states. Setup processes are included, but breakdowns are not considered. Control logics allocate material from source to stations in a reactive manner. The general system layout is arranged in a rectangular order, according to other examples, e.g., by (Filz et al., 2019; Schönemann et al., 2015).

The **Configuration** layer includes a wide range of parameters that can be altered individually for every experiment. Within an experiment building block, these parameters are manipulable for every simulation run what allows to perform a high number of experiments with different configurations. To have better comparison between the simulation run of each experiment design, distribution functions for parameters were neglected. Hence, input parameters such as processing times or transport speed during a simulation run were not distributed.

The **Evaluation** layer of the model consists of data tracking and a data evaluation pipeline to gather detailed information about the energetic and logistic behaviour of the model. This includes time series tracking for load levels of the overall system as well as the analysis of specific key performance indicators such as peak load or specific energy consumption (SEC) per product. The latter is defined by the energy consumption of the overall system divided by the produced goods per simulation run and serves as a measure to compare different system configurations. Functions for data analysis include metric for correlation and describing statistics.

The **(Infra-)Structure** of the model includes the option to alter the general system layout by the amount and distance of the process modules or by choosing an individual layout. The energy supply infrastructure is modelled by a constant supply of energy. Hence, shortages on energy or additional infrastructure such as batteries or decentralized energy supply is not considered. To determine the energy consumption, the load levels for each available energetic state are integrated into the model and are adapted depending on the requested skill for each process module. Also, load limits for the overall system are configurable to determine their effects on logistical parameters. Furthermore, a pausing algorithm for process modules is integrated to shut down machines to energetically lower operating states when waiting for material. Load stations for AGV are configurable in number and loading capacity. Energy-oriented strategies for AGV and process modules are adaptable.

The **Logistics** in the model is realized by automated material transport with a fleet of AGV. Here, the speed and velocity as well as the amount of AGV in the system are configurable. With connection to the energy supply infrastructure, the battery properties of every AGV are individually configurable. Material supply relates to the limitation of work-in-progress in the overall system as flexible parameter. Specific strategies for intralogistics are not modelled in detail, the availability of material by the source is ensured during simulation runs by a dispatcher, that allocates the jobs in a push strategy to the system. The logistics of MPS is a topic of special interest that requires explicit strategies, as elaborated by Fries et al. (2020).

The **Direct area** as location of added value includes the process module control by varying the amount and type of skills or temporal aspects of product processing. Here, skills can be distributed randomly to stations by type and amount. The process module design includes the manipulation of the installed buffer capacities.

The **Control systems** for material flow refer to the operative production planning and control. This is realized by a variable number of parts being dispatched randomly with variable lot sizes. Here, process modules and respective work contents are chosen by rule-based strategies, e.g., least utilization of available process modules.

The combination of these parameters results in a combinatorial window of parameters that reflect various configurations of MPS. This includes systems with a high or low spread between processing and setup times, load levels of operating states, utilization of the transport and processing system or buffer capacities.

4 Experiment design and results

To test the simulation platform and give an insight into analysis workflow, an experimental study was conducted. The tested MPS design consists of eleven process modules where each has at least two different skills. Each simulation was stopped after 2.000+-10 parts due to the chosen lot sizes and the condition to release only complete batches. Here, a deviation from the configured part amount may appear if the division of part amount and lot size is not an even number. In that case, the simulation run was completed with a full batch of parts but a slight difference to the configured amount. For the configuration, six parameters were manipulated in a full-factorial design. These parameters are the pause control of process modules, the lot size, the number of AGV and respective load stations, the distance of process modules from each other and the speed of AGV. The remaining parameters were constant for the experiments. The design aims to inspect the effects of the transport system on logistical and energetic performance and resulted in 20.384 experiments that were distributed to several workstation.

The analysis started with removing the invalid simulation runs. As a criterion for a successful simulation run without deadlocks, a threshold of at least 1.990 parts was set. This resulted in 12.628 valid runs, which is about 62% of total runs. A ramp-up phase of the system was not considered. The small system size and low buffer capacities led to a quickly obtained steady state. A boxplot was chosen to give an overview on measures of location and dispersion. The box itself visualizes the measures of 50% of overall measurements between the first and third quartile. The distance between bottom and top of the box (interquartile range) shows the distribution of these values. The line in the box, the median, divides the set of measurements in two equal sets that are ordered from low to high. Hence, below the median are the lower 50% and above the top 50% of measurements. The median gives information about if the distribution of values is right-skewed or left-skewed. Outside of the whiskers are outliers located as red points with more than 1,5x the size of the box. Figure 5 visualizes the box plots for the SEC as an energetic measure and overall simulation time as a logistic measure for system performance.

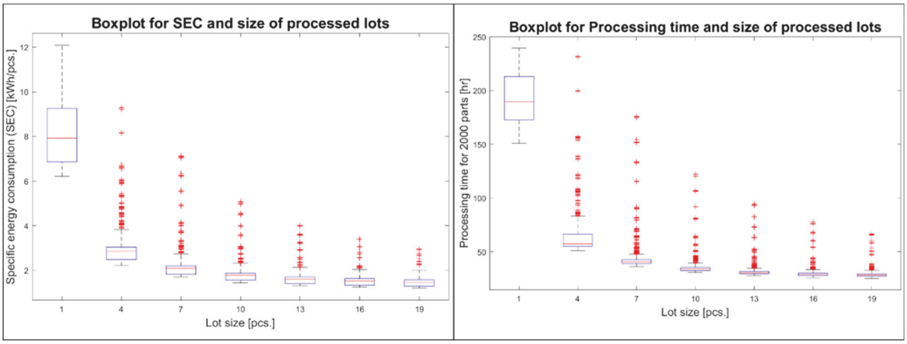

Figure 5: Results of varied lot sizes on SEC and overall simulation time

The results show the varied lot sizes ranging from one to 19 with equidistant steps of three parts, six levels in total. From an energetic perspective, the SEC reduces with increased lot sizes in the model. Furthermore, the size of the box and whiskers decrease, outliers do increase. The logistical perspective shows a reduction of simulation time that is equal to the reduction of the SEC. Both point towards a lower barrier with increasing lot sizes. Also, the box and whiskers decrease in size, the outliers do increase as well. Furthermore, the rate of around 62% of successful experiments point is a result of deadlocks. Here, strategies such as limits for work-in-progress or peak loads seem beneficial to increase valid runs.

5 Conclusion and Outlook

A simulation platform for the analysis of energetic considerations in MPS is introduced. This includes an overview on existing works in the field of simulation of MPS that show shortcomings in the analysis of energetic key behaviour and control strategies of MPS. Hence, matrix-specific configuration parameters were derived from existing approaches and implemented in a simulation platform that allows it to manipulate them in an easily configurable and replicable process. This allows it to conduct a wide range of experiments to collect and analyse a wide range of data. A first experiment design is introduced to investigate the influence of lot sizes on SEC and simulation time. A box plot is chosen to analyse measures of location and dispersion. SEC and simulation time reduce incrementally towards a lower barrier.

Future works from a technical perspective include the further implementation of parameters as well as the management of dead locks. From an analytical view, the results will be analyzed more in depth and further experimental studies are conducted to elaborate the understanding of energetic behaviour of MPS. The methodical view includes future works to derive best-practices when designing and controlling MPS from with energy-oriented production and system design targets.

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