INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.218

Self-optimizing digital factory twin: an industrial use case

Christian Nigischer [1,✉], Florian Reiterer [2], Sébastien Bougain [1] and Manfred Grafinger [3]

[1] Austrian Center for Digital Production, Austria, [2] Nemak Linz GmbH, Austria, [3] TU Wien, Austria

✉ christian.nigischer@acdp.at

Abstract

Digital Twins (DTs) are intended to be utilized for a wide range of applications, promising benefits like visualization, monitoring, simulation and control of a physical system. Not only the development of a DT for a production facility is a time-consuming task, but also to keep the virtual counterpart up to date in the use phase. In this work, the implementation of an industrial-scale DT of an automotive supplier production site based on a Discrete-Event Simulation (DES) model with self-optimization capabilities for easier maintainability and increased simulation accuracy is presented.

Keywords: digital twin, discrete-event simulation, self-optimising systems, industrial use case

1. Introduction

While "Digital Twin" is a well-known term in many industry sectors and fields of research, and a lot of companies, authors and institutions have highlighted their point of view with their own definitions, a generally accepted definition is still missing (Liu et al., 2021). The 3 core components that are present in almost every definition are the physical entity, a virtual representation of that real-world object, system or process, and a kind of data exchange between those 2 that allows synchronization. Focusing on DTs in the area of manufacturing systems, additional characteristics that appear in various definitions are real-time data exchange (e.g., Singh et al. (2021)), simulation capabilities of the virtual counterpart (e.g., Shao and Kibira (2018)) and the presence of the DT over the entire lifecycle of the physical entity (e.g., Grieves and Vickers (2017)). Another widely recognized sub-classification of DTs concerning the level of data integration between physical entity and virtual representation is given by Kritzinger et al. (2018): A Digital Model (DM) incorporates only manual data flow between physical and digital object, while an unidirectional automated data flow from the physical to the digital object characterizes a Digital Shadow (DS) and a bidirectional automated data flow between the virtual and real-world counterparts constitutes a Digital Twin (DT).

Whatever definition or classification is used to describe a DT, the most important point is – as highlighted in the definition given in the ISO 23247 (ISO, 2021) – the predefined purpose of the DT that determines which digital models and levels of fidelity for the virtual representation are needed, and if simulation capabilities or real-time updates are necessary to achieve a certain goal. With respect to these requirements the most suitable technologies can be selected during the conception phase of the DT development process.

Although the installation of a DT potentially entails a variety of benefits, establishing a DT is undeniably linked with a lot of effort: The creation of new models or adaptation of existing ones, implementation of data exchange interfaces, development of algorithms for a variety of tasks within a DT are time-consuming tasks and often not trivial. Therefore, it is important for a practical DT realization in an industrial context to find an architecture that is able to fulfil the given requirements but keeps the implementation and maintenance effort manageable.

The contribution of this paper is the presentation of the results for a DT implementation for an industrial use case from the automotive supplier industry. The foundation of the research is a relatively simple DT architecture based on a Discrete-Event Simulation (DES) model as digital representation of the production site and a SQL database as data integration platform, which is able to provide monitoring for the real-world system as well as optimized changeover instructions to the shop floor operators and the option for simulating alternative scenarios. Furthermore, the concept includes self-optimization functions that keep the maintenance effort for parametrical changes for the DES model as low as possible.

The remainder of this paper is structured as follows: Section 2 gives a brief overview of related work concerning manufacturing DTs. In section 3 the applied research methodology is stated, while section 4 describes the industrial use case. Section 5 explains the utilized DT architecture. The obtained results during the implementation of the concept are discussed in section 6. The paper closes with final conclusions, giving hints for further research demand and a short outlook on current and future work in the ongoing research project.

2. Related work

With the increasing interest in DTs, especially since 2015 (Liu et al., 2021), a variety of frameworks for the development of manufacturing DTs has been introduced, like the reference model for Digital Twin-driven smart manufacturing stated by Lu et al. (2020), the DT enhanced Industrial Internet reference framework towards smart manufacturing developed by Cheng et al. (2020), and others. Lately, the ISO 23247 introduced the Internet of Things (IoT) framework for DTs in manufacturing (ISO, 2021) with the intent to standardize the setting for DT development in manufacturing. The DT architecture presented in this work is based on the 4-space architecture described by Pöchgraber et al. (2023), divided into physical, virtual, data and service space. This approach is discussed in detail in section 5.

While a lot of research focuses on theoretical frameworks and small-scale proof-of-concept implementations, publications with industrial-scale DT implementations are scarce. However, there are some similar works using DES models as virtual counterpart of an industrial production system already. Jiang et al. (2021) present a generic framework for creating and connecting DES models to heterogenous manufacturing systems, establishing a DT using real-time capable connection technologies like the Open Platform Communications Unified Architecture (OPC UA) standard. The framework is still in concept stage, and although it is applied to a practical use case, a detailed examination of the connectivity aspect is missing. Lin and Low (2019) propose a DT architecture similar to the one presented in this paper. The DES model – representing a Surface-Mounted-Technology (SMT) production line – is hosted in the DES platform FlexSim as well, and the communication between FlexSim and the physical production system is handled via a SQL database. The DT is used for visualization and simulation aspects but does not give automated feedback to the shop floor. Morabito et al. (2021) present an approach using DES models to replicate the behaviour of physical production systems to provide monitoring and simulation capabilities. Like the work of Lin and Low (2019), an automated feedback loop from the DES environment to the production system is missing but is declared as future work. Santos et al. (2020) also use a DES model as digital counterpart in their DT approach, which is practically demonstrated in a use case of the aeronautical industry. Like in this work, optimization instructions for human operator behaviour are fed back into the production system. The connection between the DES platform – also FlexSim in this case – and the data source (ERP operations reports) was established via an Excel dashboard with customized interface code – instead of the direct SQL connection functionality of FlexSim used in this work.

3. Methodology

The method used for the Digital Twin development process, consisting of 3 phases, is depicted in Figure 1. In the DT design phase, the use case and the requirements are defined to formulate the purpose of the DT. Based on the requirements, the conceptual design of the DT is generated. For the conception the above-mentioned DT architecture presented by Pöchgraber et al. (2023), comprising a physical, virtual, data and service space has been utilized. The 4 spaces are further explained in section 5. The DT implementation phase starts with the activities to generate the virtual model. In this case, a single DES model is built to represent the real-world manufacturing system with the necessary level of fidelity. A detailed description for the iterative DES model development process is stated in Nigischer et al. (2023). The additional DT functionalities that have been added to the DES model are as well described in detail in the DT architecture section. As a next step, the data space – in this case the existing SQL production database – was extended to function as central repository for all kind of data within the DT environment. After setting up all the necessary data structures, the data connections between the virtual model and the data space have been implemented. The last step in the implementation phase is an extensive testing phase to fix all major bugs before the virtual counterpart got deployed to the IT infrastructure of the production environment.

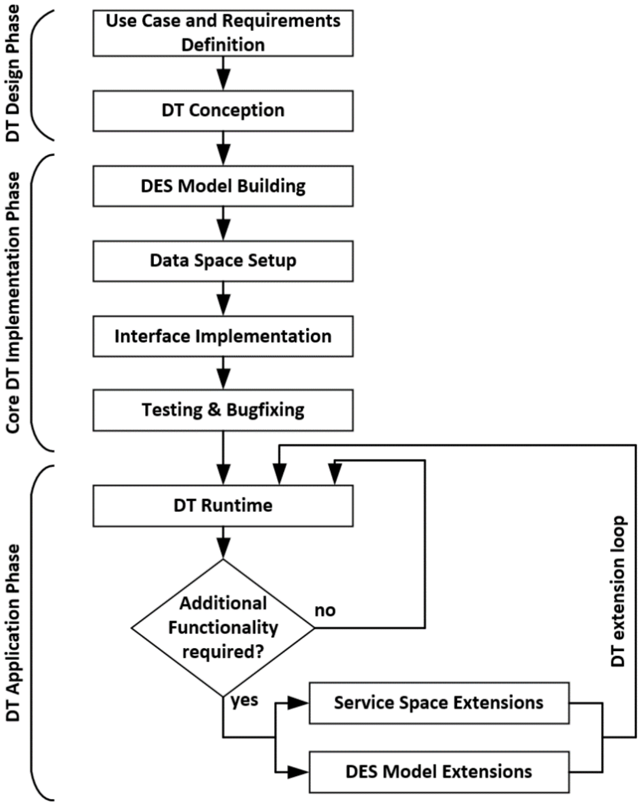


Figure 1. Digital Twin development process

Within the DT application phase, the DT continuously runs in parallel to the physical system, providing monitoring for the whole production system and functionalities that create optimization suggestions for the real-world system. Additionally, the DES model can perform simulation runs to investigate alternative scenarios. For an extension of the existing functionality of the DT an extension loop allows the addition of applications in the service space or the implementation of further DES model functions directly in the virtual representation. The extension activities include all necessary development steps (conception, implementation, testing, deployment) for each new functionality, but these sub-steps are not depicted in Figure 1.

4. Use case

The subject for the DT implementation is a production site for vehicle cast parts of the industrial partner Nemak. In a first step, an iterative modelling approach was applied to generate a DES model of a section of the *CNC Machining* area of the factory. The purpose of that effort was to create a simulation model that fulfils a set of qualitative fidelity requirements and a maximum quantitative throughput discrepancy of max. ±15% between the model and the physical production system. After some examinations for the *CNC Machining* area (bottleneck analyses and alternative future reconfiguration scenarios), the partial model was extended to almost the whole production site to obtain a DM that can be used as foundation for the DT implementation. Figure 2 depicts schematically the structure of the production site and the relevant material flow. The parts to process arrive in the *Incoming Goods* area (top right corner in the figure), where the initial quality control and – if necessary – manual cleaning tasks are performed. The main processing chain starts with a thermal treatment in one of the ovens in the *Solution Annealing* area, followed by some blister removal activities at manual workspaces in the *Blister Clamping* area. The following automated straightening process corrects the thermally induced distortion of the parts (*Straightening* area). If the automated correction for a part does not work, it is rejected by the straightening plant and forwarded to a manual rework station (not depicted in the figure). After straightening, the internal mechanical stress of a part is released within the ovens located in the *Artificial Ageing* area. After this second thermal treatment, the parts are brought to the *Intermediate Storage before Grinding*, awaiting their transport to the grinding plants in the *Grinding* area.

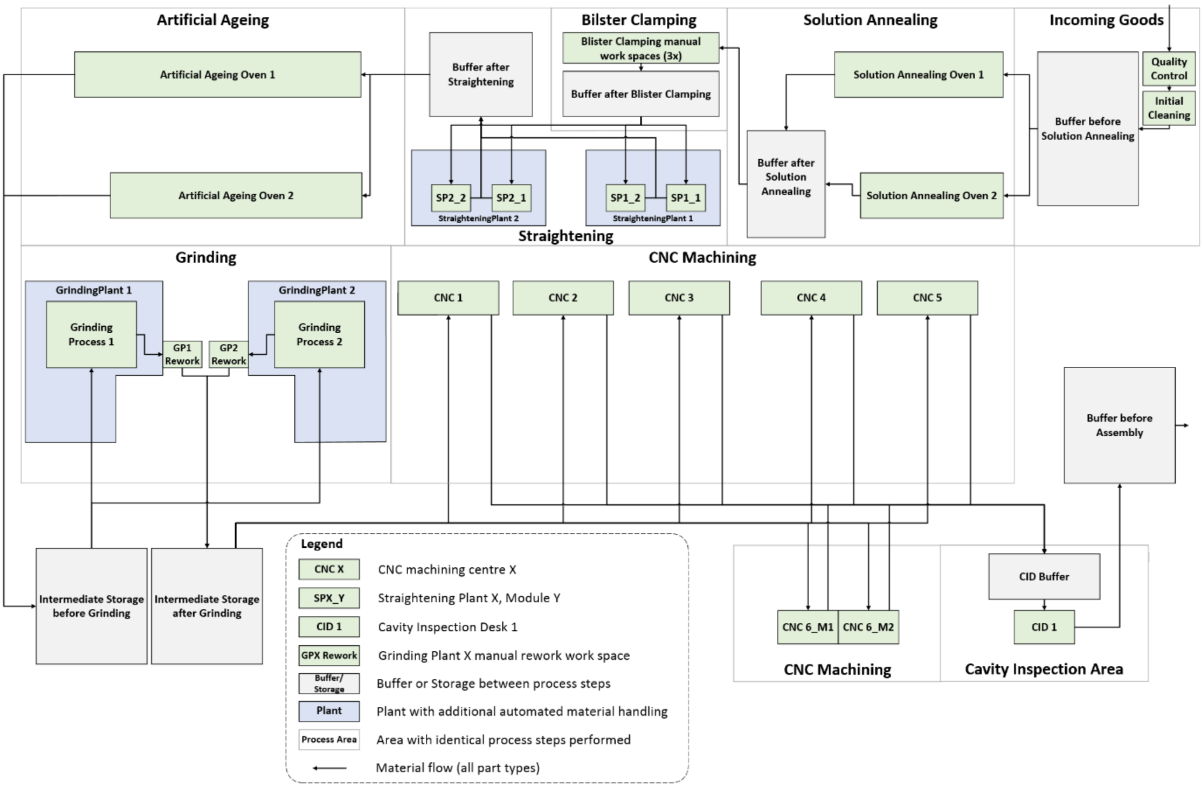
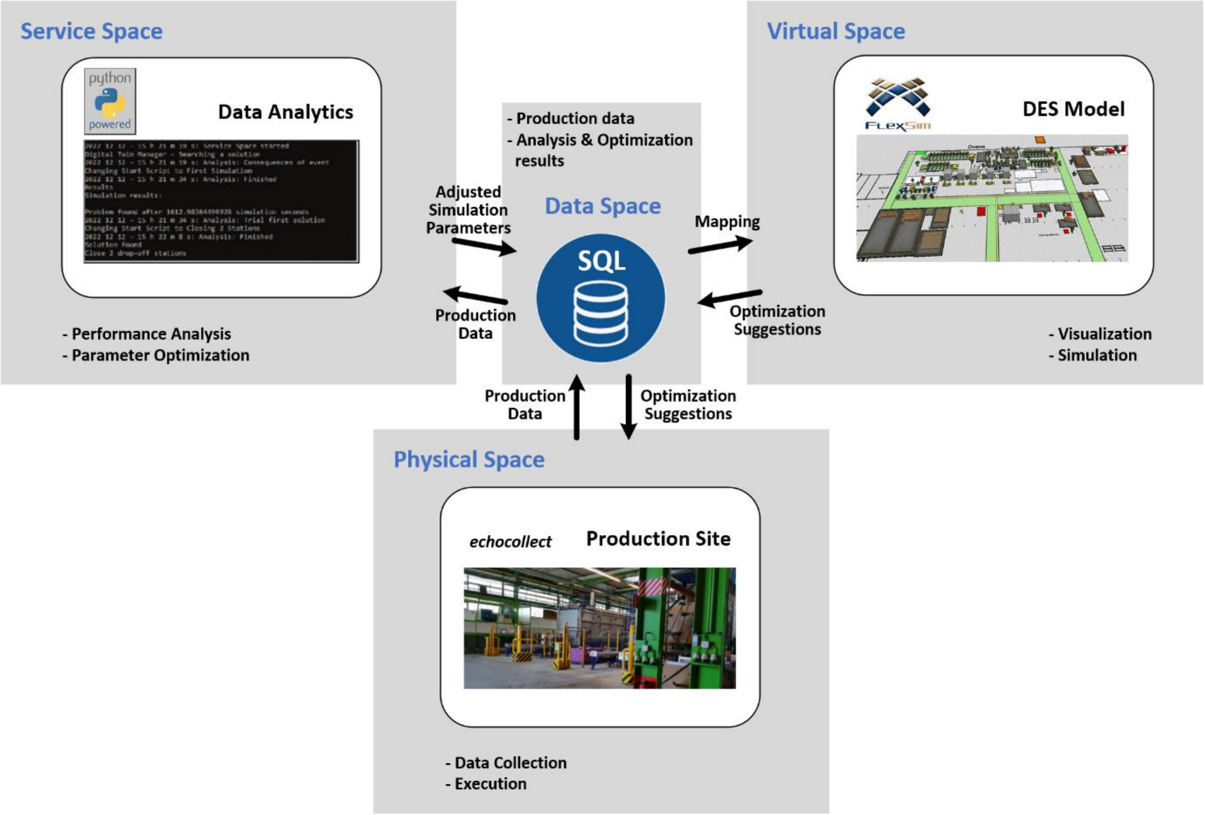


Figure 2. Schematic overview of layout and material flow of the production site

The grinding processes including the single piece movements within the plants are fully automated, followed by manual deburring operations at the rework workspaces. Following another stay in a buffer area (*Intermediate Storage after Grinding*), the cast parts are forwarded to the *CNC Machining* area, where the CNC machining centres perform the machining operations. The machining itself is done automatically, all other handling and cleaning operations are executed by human operators. The last process step that is included in the use case is the semi-automated cavity inspection of the parts in the *Cavity Inspection* area. A detailed description of all handling and setup tasks in the *CNC Machining* and *Cavity Inspection* areas can be found in Nigischer et al. (2023). After cavity inspection, the parts are transported to the *Buffer before Assembly*, where they await their further transport to the *Assembly* area. The different cycle times and capacities of the plants and manual workspaces for various processing steps in dependence of the part type cause discontinuities and therefore the need for buffers and intermediate storages along the material flow in the production site. Not all buffers have been mentioned explicitly in the description above but are depicted in Figure 2. Because of the unsteady material flow, to keep an overview of the whole production line is not an easy task. Therefore, the installation of a DT shall help to keep track of the production system and improve its efficiency.

5. Digital Twin architecture

In the design phase of the DT development process, the DT architecture illustrated in Figure 3, consisting of physical, virtual, data and service space, has been conceptualized. The following subsections describe the content of each space and the interfaces between them.



```
2022 12 12 - 15 h 21 m 19 s: Service Space started
Digital Twin Manager - Searching a solution
2022 12 12 - 15 h 21 m 19 s: Analysis: Consequences of event
Changing Start Script to First Simulation
2022 12 12 - 15 h 21 m 34 s: Analysis: Finished
Results
Simulation results:

Problem found after 1612.98364499928 simulation seconds
2022 12 12 - 15 h 21 m 34 s: Analysis: Trial first solution
Changing Start Script to Closing 2 Stations
2022 12 12 - 15 h 22 m 8 s: Analysis: Finished
Solution found
Close 2 drop-off stations
```

Figure 3. Digital Twin architecture

5.1. Physical space

The physical space of the DT incorporates the real-world shop floor of the production system itself, where production orders are executed and the data acquisition from the physical production processes takes place. The already existing plant data collection at the Nemak production site is covered by “echocollect” industrial gateways, connected directly to the Programmable Logic Controllers (PLCs) of the machines and robots. Each part in the system is uniquely identified by a Data Matrix Code (DMC), which is read by a camera system for automated detection at the machines and plants, while terminals with barcode scanners allow the manual logging of the process and part related information. Both variants of logging generate datapoints in the production database, which is part of the data space described in the next subsection.

5.2. Data space

The data space functions as central hub for all DT relevant data. In this case, the data space consists of 2 separate SQL data schemes. The production database schema has been in place already before the development of the DT and collects data from the shop floor via the mentioned industrial gateways and manual bookings. On the one hand, all bookings for a unique DMC combined deliver the whole process information from the already passed process steps on a single part level, and on the other hand, all resource related datapoints provide information for the status of resources themselves.

The second schema was newly created to store the analysis and optimization results of the external application in the service space and the simulation related data and computation results from the DES model in the virtual space to provide a single data exchange platform within the DT.

5.3. Virtual space

The digital representation of the real-world production system is a DES model created and hosted in the FlexSim simulation environment (Version 22.2.3). As already mentioned, the DES model for the whole production line has been developed from a partial model of the *CNC Machining* and *Cavity Inspection* areas of the production site that has been used for scenario-based material flow and resource utilization optimizations (cf. Nigischer et al. (2023)). The comprehensive model encompasses all production process steps from the incoming goods quality control to the cavity inspection after the CNC machining. Figure 4 shows the FlexSim model during a simulation run. In this figure only the main area names are depicted because of clarity reasons. The machines and plants of the production line are modelled with a combination of FlexSim standard modelling elements like “processors”, “separators”, “combiners” and “queues”, customized elements (e.g., the CNC machining centres have been modelled with customized “basic fixed resource” elements, visualized as grey blocks in the figure) and model logic extensions. Most of the plant specific logic is modelled as “object process flows”, directly attached to the respective objects, while general logic has been implemented using “general process flows”. The underlying logic constructs are not visible in Figure 4. In comparison to the schematic overview in Figure 2, the depicted FlexSim model view includes a lot of additional modelling elements representing part buffers in front of machines and plants (yellow and green “queue” elements), buffer storage locations for empty part carriers (grey “queue” elements with empty palette objects), additional “processor” elements for the representation of transport times, etc. Parts are represented by simple brown “box” elements, packaged on part carriers, symbolized by “palette” objects. Red boxes represent scrap parts – or in the special case of the *Initial Cleaning* area, parts that are not cleaned yet.

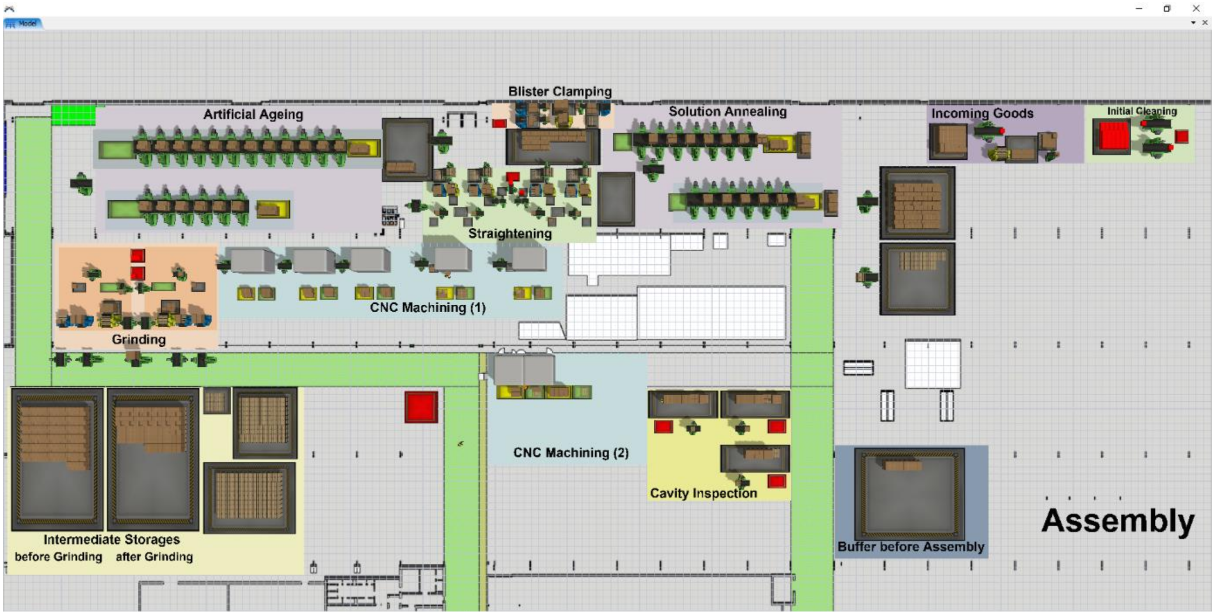


Figure 4. FlexSim DES simulation model of the production site

The developed DES simulation model was extended with additional functionalities, so that it can be used in 2 different operational modes:

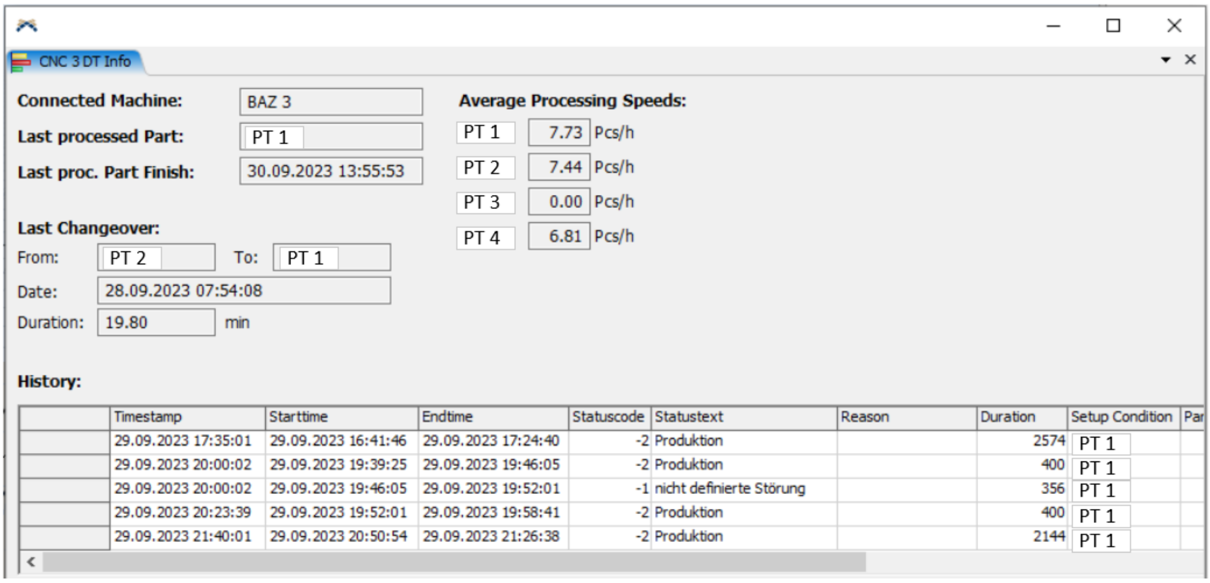
- Simulation mode
- Digital Twin mode

5.3.1. Simulation mode

In simulation mode all the implemented model logic for part and task distribution, production program control, plant setup and changeover control and scrap part rejection, is active. In addition to simulation parameters that are usually considered more or less constant over a defined timeframe, like processing/cycle times, transport times, reject rates, etc., scenario-based input parameters have to be determined manually for specific simulation runs: Initial values for the part inventory at the buffers and storages across the production line and status and setup conditions of machines and plants, as well as planned incoming part arrivals and planned breaks and downtimes. The simulation run is executed in the FlexSim runtime environment with adjustable simulation speed.

5.3.2. Digital Twin mode

In DT mode the aforementioned model logic that controls the behaviour of the production system during simulation is deactivated. Instead, a set of data import functions is triggered recurrently during the model execution to query the current production system information from the production data base utilizing the integrated FlexSim SQL connector. The queried data is divided into 2 kinds of information: Resource-related and part-related. Current resource-related information includes the resource status (production, idle, maintenance, error,…), setup status, last changeover date and duration, average processing speeds for different part types, and so forth. The queried data is assigned to the corresponding virtual model representation via a resource mapping table in FlexSim. A live dashboard of the CNC machining centre “BAZ 3” (“CNC 3” in the FlexSim model) is shown as an example in Figure 5. In the screenshot, the real part numbers have been replaced by generic ones (“PT X” for Part Type X) due to confidentiality reasons.



Connected Machine: BAZ 3
Last processed Part: PT 1
Last proc. Part Finish: 30.09.2023 13:55:53

Average Processing Speeds:

PT 1	7.73	Pcs/h
PT 2	7.44	Pcs/h
PT 3	0.00	Pcs/h
PT 4	6.81	Pcs/h

Last Changeover:
From: PT 2 To: PT 1
Date: 28.09.2023 07:54:08
Duration: 19.80 min

History:

	Timestamp	Starttime	Endtime	Statuscode	Statustext	Reason	Duration	Setup Condition	Par
	29.09.2023 17:35:01	29.09.2023 16:41:46	29.09.2023 17:24:40	-2	Produktion		2574	PT 1	
	29.09.2023 20:00:02	29.09.2023 19:39:25	29.09.2023 19:46:05	-2	Produktion		400	PT 1	
	29.09.2023 20:00:02	29.09.2023 19:46:05	29.09.2023 19:52:01	-1	nicht definierte Störung		356	PT 1	
	29.09.2023 20:23:39	29.09.2023 19:52:01	29.09.2023 19:58:41	-2	Produktion		400	PT 1	
	29.09.2023 21:40:01	29.09.2023 20:50:54	29.09.2023 21:26:38	-2	Produktion		2144	PT 1	

Figure 5. Live monitoring dashboard of a CNC machining centre in FlexSim, model in DT mode

To be able to give a detailed overview of the part flow in the system, the last available process step time stamp for each unique part in the system is queried. The different time stamps are assigned to specific locations in the model – usually buffers – via the already mentioned resource mapping mechanism established in the FlexSim model. A custom function coded in FlexSim creates a new flow object (box) for each unique part, if it is the first time stamp recognized for that specific part, or moves the already existing box to the new location, determined by the mapping. After a query cycle is finished, all unique parts are positioned in the corresponding model location of the last recognized time stamp. Although there is a delay up to max. 5 minutes from the occurrence of a logging event in reality until the time stamp is written to the production database, both information views (part- and resource-related) merged in the DES model in FlexSim form a DS, which is able to draw a quite accurate up-to-date picture of the current situation of the production line and can be used for monitoring purposes.

While the described monitoring functionality has the character of a DS only, the DES model has been extended with an additional function that calculates optimized changeover points in time for the grinding plants based on the current production system state and a set of conditions. Therefore, the developed algorithm uses the current real production speed for the grinding and CNC areas – calculated from the throughput data delivered by the production database – and the available parts for the grinding plants to calculate an effective remaining range per part type with the current setup conditions. The available parts are not only the parts at the intermediate storage before grinding, but also the parts in the upstream processes that will arrive at the grinding plants in time. The main conditions for a changeover are that the part supply for the CNC area production program is guaranteed without interruption, the utilization degree of the grinding plants shall be as high as possible, and the maximum stock levels for the intermediate storages before and after grinding shall not be exceeded. With all these parameters considered, the algorithm delivers a changeover suggestion, consisting of the next changeover point in time for a grinding plant, the new setup condition and the reason for the changeover – e.g. maximum stock level for the currently processed part type at intermediate storage after grinding will be reached. After each update cycle, the changeover suggestions are stored in an intermediate data schema in the SQL database. Thus, the production site information system forwards the information to the shop floor, where it is displayed on dashboard monitors, helping the shift managers to initiate the changeover activities at the optimal point in time.

5.3.3. DT – Simulation changeover

Entering all the already mentioned simulation parameters before performing a simulation run for a whole production system can be time-consuming. To ease especially the simulation of short-term (alternative) scenarios for the production system, another function has been implemented to allow a switchover from the DT model execution mode to the simulation mode, using the current date, part inventories, resource and setup status as initial conditions for the simulation. This switchover is not trivial, especially for the part inventory transfer, because there are some discrepancies between the level of detail of the simulation model and the available data in the production database. E.g., not all process step log entries include data concerning the used part carriers, while the distribution logic in the simulation model needs this information for proper execution. Hence, the transfer function has to generate "dummy" part carriers for the simulation. Another issue are parts that are positioned on auxiliary buffer elements during the DT mode, representing that the part is currently processed in a plant. For the simulation, the parts at these auxiliary model elements have to be relocated to the appropriate processing element for the simulation mode.

5.4. Service space

For the realization of a self-optimizing DT, a python application will be hosted in the service space to analyse the production system data and provide

- optimized parameters to the simulation model and
- additional performance analyses for the production system.

Some parameters (processing times, reject rates,…) are already queried by the DES model itself, but in a rudimentary manner – the values are calculated for a pre-defined amount of lastly produced parts. The python application, which is currently in development, will be able to perform in-depth analysis of the database and will – as a result – provide more accurate parameter values for the simulation model. The optimized parameters will be stored in the SQL schema for simulation and optimization data, and if needed, queried by the DES model from the virtual space.

6. Results and discussion

The described DT implementation for an automotive supplier production line in its current state is designed to provide support for 3 different activities:

- Production system monitoring
- Improved grinding plant changeover control
- Alternative scenario simulation using current production data for initial model state values

The continuously updated DES model executed in the FlexSim runtime environment (= DT mode) in the virtual space provides a comprehensive reflection of the current state of the physical production system. Implemented dashboards on single resource, area and production line level in addition to the visual 3D model and material flow representation ease the mandatory monitoring activities especially for factory and production managers. The calculated optimized grinding plant changeover recommendation based on the current state of the up- and downstream processes supports shift managers and machine operators, giving them the predicted time and necessary action for the next changeover procedure. The simulation capabilities of the DES model (= Simulation mode) allow short-term production planning (e.g., what-if scenarios for incoming production orders, plant maintenance windows or staff shortages, etc.) as well as long-term factory planning (e.g. production line extensions with new plants, material flow redesigns, etc.). The automated transfer of initial parameter values from DT to Simulation mode reduces the need for manual inputs and therefore accelerates simulation tasks.

The currently developed python data analytics application hosted in the DT service space provides more accurate parameters based on the current production data than the basic SQL queries used by the DES model itself. FlexSim is also able to execute python code, so the python scripts could also be integrated in the virtual space directly. But, because of modularity reasons, the python script was conceptualized as separate application in the service space.

The approach using the production database as single source for shop floor data acquisition has some advantages, disadvantages and restrictions. The big advantage is that a production site usually already has some kind of data recording using a SQL database. So, the interface implementation between the 4 defined spaces is, compared to architectures with (close to) real-time capable interface definitions like the OPC UA standard, rather simple – access rights have to be defined properly and the necessary SQL query statements have to be defined. Furthermore, the logging of historical data points is already included. A disadvantage is the time delay in the SQL transaction logging, usually in the range of some minutes. Use cases with the need for fast responses and direct machine control capabilities obviously cannot be covered with the SQL database connection approach. FlexSim also provides OPC UA connectivity for a direct communication with an OPC UA server for the exchange of current shop floor data and control commands almost without delay.

The overall performance of the DT stands and falls with the data quality provided by the production database. If the data quality is not good enough, improvements to the data management and collection mechanisms in the physical and data space have to be carried out. Such additional necessary effort reduces the advantage of a DT implementation intended as an add-on to the existing IT infrastructure.

Self-optimization capabilities in terms of automated parameter adjustments to keep the DES model up to date are important to increase acceptance among users and improve usability and efficiency for the DT related human tasks. Despite a high degree in modularization in the model building process, non-parametrized adaptions to the DES model – e.g. the addition of new resources or layout variants – are still manual tasks to perform.

7. Conclusion and outlook

Aside the defined purpose of monitoring, optimized changeover suggestions and eased alternative scenario simulations with up-to-date parametrization, the main goal of the presented industrial DT implementation was to keep the DT architecture as simple as possible, using the already existing factory infrastructure to generate added value for the target user group of the DT with affordable effort. The monitoring, changeover optimization and alternative scenario simulation is currently in the testing phase, including activities for long-term qualitative and quantitative evaluations of the approach.

While the function for determining optimal changeover decisions for the grinding plants is a big improvement to the pre-DT changeover decisions, that have been solely dependent on the experience of the shift managers, there is still room for improvement. Some criteria like daily production goals are not implemented in the algorithm to date.

Production order management is implemented as far as it is necessary for tracking in DT mode. Part arrivals are manually specified at particular simulation dates in the simulation mode. An automated integration with the existing order management system would further increase the user comfort.

An obvious next step in the presented research is to combine the advantages of both discussed interface integration concepts – using the SQL production database as existing source for historical data as basis for parametrization and in parallel OPC UA for incorporating resource status and individual part tracking in the production line without delay in the DES model.

Details concerning the currently ongoing development of the python data analytics application and a quantitative evaluation of the improvements for the DT accuracy will be published in a separate paper.

Acknowledgement

This work has been supported and funded by the Austrian Research Promotion Agency (FFG) via the "Austrian Competence Center for Digital Production" (CDP) under the contract number 881843.

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