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LEARNING SIMULATION-BASED DIGITAL TWINS FOR DISCRETE MATERIAL FLOW SYSTEMS: A REVIEW

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ABSTRACT

Digital Twins play a crucial role in the fourth industrial revolution. In the context of discrete material flow systems, companies under constant competitive pressure seek for solutions to minimize cost and maximize performance. Simulation-based digital twins can help taking optimal decisions in the design, planning and control of these systems. Such twins are until now developed and updated by domain experts producing costs and are often not considering the advances made in machine learning to improve prediction quality. Learning digital twins out of data could be the solution for a broader application. A lot of works has already been done that contributes to this endeavor, yet relevant building blocks originate from different Dscientific areas resulting in use of different terminology. Thus we present a holistic review of relevant work and analyze the state of the art based on a new classification scheme deriving relevant building blocks and gaps for future research.

1 INTRODUCTION

Digital Twins (DT) are one of the key drivers of the fourth industrial revolution (Shen et al. 2022). All these twins have in common that they are able to process a constant data flow from the corresponding physical system to a virtual copy of this system, use the virtual system to analyze and evaluate possible changes of the system and respond with the best change suitable for a given scenario (Michael W. Grieves and J. Vickers 2017). Following this definition, a DT consists of three parts: A physical system in real space, a virtual system in virtual space and the connection which ensures steady bi-directional data flow between these two systems. DT are often distinguished from digital models (DM) and digital shadows (DS) with respect to the degree of automation of this data flow (Kuehner et al. 2021). While DM have a bidirectional manual data flow, DS rely on an automated data flow into the virtual system and DT have an automated flow in both directions.

DT are used in a lot of industries, ranging from classical manufacturing to defense, automotive, and recycling. The paper at hand focusses on the manufacturing industry, more generally discrete material flow systems (DMFS). They can be characterized as systems processing discrete objects (parts) that move at regular or irregular intervals along transportation routes or conveyor lines, comprising of production and logistic systems (Arnold and Furmans 2006). DM have been used to design, plan and control these DMFS for decades, e.g. in the context of material flow simulations, logistic assistance systems and the digital factory (Thiede et al. 2013). With DS and DT the focus from models for single use cases shifted to a holistic approach to have a virtual copy during the whole life-cycle of the DMFS (Farah Abdoune et al. 2023). The aspect of an automated data flow from the model to the physical system is not all that relevant for the management of DMFS, since human decision makers are in the loop and decisions are not time-critical within seconds. Therefore, we will from here on refer to DS and DT as digital twins. Aside from the aspect of representing the current state as well as managing the historical data of the physical system, a core task of DT is predicting behavior and evaluating changes. Especially in the area of DMFS the use of (discrete-event) simulation DES within DT is widespread, which is why we will focus our work on Simulation-based digital twins (SBDT) (Lugaresi and Matta 2021).

Based on the rise of attention in Artificial Intelligence (AI) and Machine Learning (ML) and supported by the aspect that DT basically are a huge storage of Big Data, the topic of auto-generating or learning DT from data has recently become an interesting topic in research and application for three main reasons: The broad application for SBDT has been hindered by the difficulty to create them. On the one hand, creating (simulation) models of DMFS is still a labor intensive task for expert (Charpentier and Véjar 2014). On the other hand, a DT once created has to be kept up-to-date when the underlying system changes (Friederich et al. 2022), which again can only be done manually by experts (Denno et al. 2018). Thus, *reducing the manual expert labor to create DT models* (1) and *automatically updating the DT models* (2) are two of the reasons for learning DT from data. Updating must be differentiated from synchronizing. While synchronization based on transaction data is the standard behavior of every DT, updating refers to structural changes of the model based on changes in master data of the system (e.g. new processes, resources or changed behavior). Since accuracy of the prediction is an important aspect of decision making (Grieves 2022), *improving prediction accuracy of the DT model* (3) e.g. by using ML is the third reason.

To get an overview of the state-of-the-art in this area is not trivial since contributions are made from a wide range of different scientific areas. From the DT community *data-driven DT* are investigated aiming at using data to create and update DT for production environments (e.g. Friederich et al. 2022). Besides that, coming from the area of software automation, low code approaches are carried out to create process-aware digital twin cockpits (Bano et al. 2022). From the simulation community, work has been done in *automated model generation* (Goodall et al. 2019) and *data-driven simulation* (Biesinger et al. 2019). From the business process engineering field, *process mining* deals with generating predictive models from event log data (van der Aalst 2012) mainly focusing on business process in general rather than manufacturing. Production system identification aims at bridging this gap focusing on information about infrequent events (Denno et al. 2018). Lastly, from the data science community details models are learned from big data, that could be relevant for an overall SBDT for DMFS: *Process time prediction* (e.g. Müller and Grumbach 2023), *product quality prediction* (Czimmermann et al. 2020), *predictive maintenance* (Nunes et al. 2023).

The aim of this paper is to provide an overview of the different contributions, identifying useful approaches, building blocks as well as existing gaps. Aside from looking at the scientific field, the application area, the methods used, and the data required, we will have a look at the reasons for learning the DT in the specific case. Furthermore, we propose a novel classification scheme based on the single model elements needed to create a SBDT for DMFS. Relevant literature contributions are examined based the proposed framework. The rest of the paper is organized as follows: In Section 2 we provide a brief overview of related work of the different area mentioned above. Section 3 describes the research methodology used for literature gathering and the novel classification scheme is presented. Section 4 summarizes the main findings of the literature review, followed by Section 5 which discusses the findings and gaps. We conclude the paper with Section 6 where we give an outlook on future research possibilities.

2 RELATED WORK

In this section we review introduce the four different relevant research areas with the corresponding publications: Process mining, data-driven simulation, data-driven DT and ML-based component behavior prediction that consists of process time prediction, product quality prediction and predictive maintenance.

2.1 Process mining

Process Mining consisting of several sub-tasks, aims at automatically exploiting knowledge from event log data that is available in IT systems about business processes. *Process discovery* is used to generate a process model based on petri-nets that can be transformed into a simulation model. *Process conformance checking* compares real and discovered process models. *Process enhancement techniques* aim to extract performance information of the process (Pourbafrani et al. 2020), while *process prediction* tries to predict relevant performance measures from the event logs (Tax et al. 2016). There has been a lot of work on process mining in recent years. Even tough business processes in general are far less complex than material flow systems, we identified a couple of contributions that could be beneficial for the generation of SBDT for DMFS.

Rozinat et al. dive into subfields of process mining, namely decision mining and organizational mining and create a simulation model from the logs deriving different aspect or sub-models from the data. Typical for process mining allows them to learn the part-type based process paths for a 1:1 relationship, not considering supply parts or divergence of the part flow, as well as used resources and process time models. Additionally, they use decision trees to learn part type-based routing and priority rules (Rozinat et al. 2009).

Pourbafrani et al. learn a system dynamics simulation model from the event log which gives insight on parameter influences on business performance indicator. With respect to SBDT they learn the standard information of process path for 1:1 part transformation and used resources (Pourbafrani et al. 2020).

Not only focusing on parts, information about resources is also crucial. Event logs contain valuable insights about resources and their scarcity. The only question is how this information is mined and to which extend (Martin et al. 2015; Martin et al. 2016). The contributions are able to predict resource availability considering information about rare events, digging deeper than just modelling standard availability. They extend their work including process structures and include batch processing knowledge in the model, thus raising accuracy for process execution (Martin et al. 2017).

In the area of process prediction, a focus is set to predicting the next process that will be executed. Thus dealing with learning of situation-specific routing rules (Moon et al. 2021; Evermann et al. 2016) and additional complex process time models (Tax et al. 2016). All three publications use deep learning for the prediction (Large languages models, recurrent neural networks and long short-term memories).

Martin et al. 2015 focus on the prediction of interarrival times of parts at the entry points of a system in the context of business processes. This approach offers the possibility to integrate queuing behavior, making it valuable for practical applications (Martin et al. 2015).

Bano et al. is the only approach dealing with generating digital twins directly. They use a low-code approach to create a “process-aware digital twin cockpit”. Their twin is generated iteratively by log data derived from sensors. The discovered models serve as a foundation for a code generator to create DT as well as for the user-interface to display individual performance indicators and the status of the system. Since the approach generates data classes to capture the data received, it is the closest approach to auto-generate a complete DT. Nevertheless generating simulation models is not part of the approach (Bano et al. 2022).

A different approach aims to predicts the remaining cycle times of products which can be seen as an alternative or supplement to simulation-based cycle time prediction. Also utilizing process mining, Choueiri et al. use multi linear regression and a transition-system to achieve this. Being one of the few approach applied in a manufacturing environment they achieve to learn simple process time models, a process path based on part-types for a job shop problem without considering supply parts or routings.

The last works goes beyond the field of process mining, called *product system identification* (Denno et al. 2018). They focus on manufacturing systems in a flow job setting and use SCADA events including resource failures to generate the model. In addition to process mining, they use genetic programming and probabilistic neural networks to generate a validated information model and create a mechanism to updated the model based on new events. They argue that process mining is not complex enough to model all behaviors of DMFS and achieve auto-generation advances especially for resource models predicting capacities for parallel processing, standard and exceptional availability as well as simple priority rules.

2.2 Automated model generation and Data-driven simulation

Considering material flow simulations, two streams become apparent: automated model generation (Milde and Reinhart 2019) or automatic model generation (Huang et al. 2011) and data-driven simulation (Charpentier and Véjar 2014). Both approaches aim at the use of data to reduce the manual efforts to perform a simulation study. 35% of the effort can be assigned to the model development and 28% to the data analysis (Milde and Reinhart 2019). In both areas there are approaches reaching from automated parametrization of existing models and automated reconfiguration of existing model elements to auto-generation of complete models. Milde and Reinhart auto-generated the simulation model of an job shop manufacturing system based on artificially generated event log and resource error data. They can generate process paths, needed resources, process and setup times as well priority rules and routing rules. The custom-tailored algorithm is generating a core manufacturing simulation data model to be imported for simulation into a standard simulation software (Milde and Reinhart 2019).

Charpentier and Véjar uses the spacial temporal data from a smart manufacturing environment. With individual programming they can generate process paths of part types and part type-based routing rules as well as a process time model and a localization of the resources within the shop floor. They also learn M:N part transformations and design a strategy for a delayed update of the model when the online data changes over time (Charpentier and Véjar 2014). Another approach uses shop floor operational data to update the process time model of the manually modeled simulation of a remanufacturing scenario (Goodall et al. 2019). Lugaresi and Matta entail process mining in their approach to learn a process structure out of event log data. They can generate a model for the main part flow including resources, process times and quota-based routing rules. The also derive part-specific frequencies of part arrival in the source of the system. Furthermore, they stress that model tuning is an important part of simulation, since data from real DMFS can be noisy and the right level of abstraction has to be found (Lugaresi and Matta 2021).

Finally, Smith also learns the model directly from spacial temporal data with an individual programming approach. Generating locations of resources, process time models and the capacity of the resources to process parts in parallel as well as a quota based routing rule (Smith 2015).

2.3 Data Driven Digital-Twin

Whereas the areas so far focused mainly on generating petri-nets or discrete-event simulation, this area focuses on generating DT for DMFS directly (while rarely considering simulation). Biesinger et al. show how important data about resources, products and process information is to build a data-driven DT on top (Biesinger et al. 2019). Kumbhar et al. use data in combination with process mining to generate knowledge about process structures. The use SCADA events and argue that these event log data sources provide vital information for such DT. As one of the few works they manages to learn N:1 relationships, including supply parts into their transformation model (Kumbhar et al. 2023). Friederich et al. have the most holistic approach to generate a SBDT for DMFS from our point of view. They use state, event data and condition monitoring data to combine methods from process mining and ML to generate and update a SBDT (Friederich et al. 2022). Liu et al. in contrast use knowledge graphs as a different structure to project data knowledge for a DT. Their insights about updating DT models is valuable (Liu et al. 2023). The last two contributions coin the term of the “digital twin shop floor” when developing a data-driven DT. Zhang et al. use ML models to predict time- and quality models (Zhang et al. 2023). Zhuang et al. on the other hand mention the importance of big data for prediction purposes and develop a framework for comparing simulation and data prediction accuracy (Zhuang et al. 2018).

2.4 ML-based component behavior prediction

The last field we consider consist of process time model prediction, product quality prediction and predictive maintenance. Some work has recently been performed on complex situation-specific process time using ML (Alessandro Rizzuto et al. 2021; Bender et al. 2022; Müller and Grumbach 2023). Besides predicting process time, several researchers use ML to evaluate the quality of products (e.g. Muhr et al. 2020, Jan Lehr et al. 2020, Czimmermann et al. 2020). Often summarized under the term anomaly detection as well, often visual information of cameras or other sensor information is used to assess the quality of a product. The last cornerstone of ML-based component behavior prediction is predictive maintenance. The topic is well studied and results can be used to predict resource unavailability (Nunes et al. 2023).

3 METHOD

For our classification of relevant literature, we conducted a systematic literature review (SLR) according to a proposed framework (Kitchenham et al. 2009) . We approached the following research questions:

1. Which parts of SBDT are learned in the context DMFS?
2. What are the reasons to learn parts of the SBDT?
3. Which methods are being used to achieve this?
4. What are the current gaps in the literature?

3.1 Keyword search and criteria

To cover as much ground as possible, we used Google Scholar to search for journals. Scholar searches a wide variety of databases and sorts them according to their relevance for the provided search strings. The quality of the search is highly determined by the words and synonyms used. As stated, contributions of digital twin learning comes from different scientific areas and uses a lot of different wordings for similar topics (Jones et al. 2020). Thus, we tried to make up for that with a high semantic variance. Combined with logical conjunction and disjunction we used the strings in Table 1.

Table 1: Search strings used (The asterisk tells the search engine to accept anything after the symbol)

"digital twin"	**AND** ("data-driven") **OR** ("data")
	AND ("process mining") **OR** ("simulation")
	AND ("adaptive") **OR** ("update*")
	AND ("synchro*") **OR**("online")
	AND ("process") **OR** ("cockpit")
	AND ("self*")
	AND ("manufacturing") **OR** ("production*") **OR** ("scheduling") **OR** ("iot")" **OR** ("shop floor") **OR** ("cps") **OR** ("cyber-physical*")
	AND ("supply chain") **OR** ("warehouse") **OR** ("assembly") **OR** ("material flow")
	AND ("shop floor") **OR** ("automatic model generation") **OR** ("product system identification") **OR** ("predictive maintenance") **OR** ("product quality") **OR** ("process time")

This way, we researched a total amount of 245 papers. To distill the relevant ones for the classification, we applied the following criteria:

1. The paper was written in English.
2. The paper was published in a journal, conference proceedings, magazine, book.
3. Duplicated papers were only considered once.
4. The paper specifically focusses on the application of digital twins in the context of DMFS.
5. In the context of above applications, all sectors are feasible.
6. The paper provides a building block to learn parts of a SBDT from data in the given context.
7. The paper mentions creation objectives, model components and the methods used.

Following these rules, we identified a total of twenty-two articles to sort into our classification scheme. Lots of papers were excluded because they did not match the learning criteria (e.g. only synchronization) or had no DMFS as application domain.

3.2 Classification scheme

Our classification scheme is based on the basic model components needed to describe DMFS (Figure 1). DMFS can be described by a set of static and a set of dynamic components (Arnold and Furmans 2006). *Static components* describe the possibility space of the system (e.g. processes that can be performed, resources that can be used), while *dynamic components* define the concrete material flow for a certain part or order (e.g. routing rules). Static components are parts, resources and processes (Simulation Interoperability Standards Organization 2012). Parts are transformed by processes using resources, sometimes based on orders. Transformation can have an impact on physical properties of the parts (*transformation model*), spacial position (*transition model*), the quality of the parts (*quality model*) and takes time (*time model*) and uses resources (*resource model*). Resources have a capacity of handling parts in parallel (*resource capacity model*) and processes have a predecessor-successors relationship (*process model*). The transformation model describes which parts can be transformed into which parts (e.g. assembly, packing, unpacking, forming) and can be based on a 1:1, N:1 or N:M cardinality. The transition model describes the possible movement of the parts from one resource to another or from one spacial position to another. The quality model describes the possible impact on the parts' qualities while the time model describes the process time that passes. Both models can be unconditional probability distributions (e.g. uniform or normal distribution) or conditional probability distributions keeping specific characteristics of the situation into account (e.g. deep neural networks). The resource model describes the resource options that are needed to execute the process (e.g. transport by automated guided vehicle or forklift and driver) and states the standard, exceptional and situation-based availability. The later allowing the prediction of an unavailability in a certain situation (e.g. predictive maintenance). The process model describes the possible process flows for different part types or even individual orders.

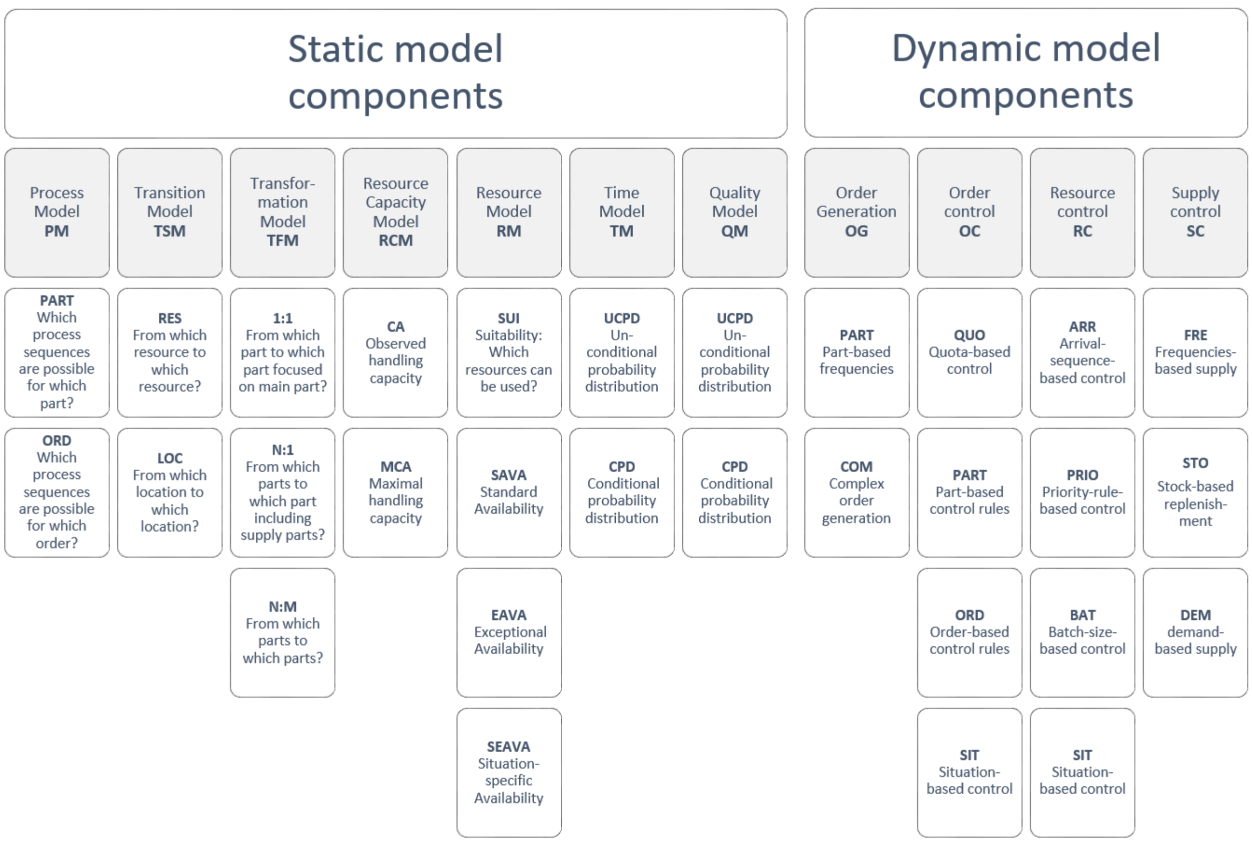

Figure 1: Classification scheme

Dynamic components are used to define the concrete dynamic material flow within the DMFS. There are four components *order generation*, *order control*, *resource control and supply control*. Order generation defines the load the system must process. We differentiate between part-based frequencies at that are defined at the sources of a system and complex order generation, which generates high-variant orders based on historical customer demand data. Order control defines how parts are processed, sometimes referred to as routing rules (Milde and Reinhart 2019). There can be simple quota-based mechanisms (e.g. 30 % of the parts go to process 1 and 70% to process 2), there can be rules based on part types for parts with low variants or order-specific routings for high-variant parts. The most complex routing would be situation-based since they take e.g. resource and part availability as well as delivery dates into account. Resource control defines how resource decide to handle processing request, also sometimes referred to as priority rules (Milde and Reinhart 2019). The control can be based only on the arrival sequence of the request (e.g. FIFO, LIFO). It can be based on priority rules based on attributes of the part or order (e.g. shortest-job-first, due date) including combinations of these simple rules. It can describe a batch-based processing defining batch sizes for different part types or can be situation-specific trying to optimize the processing based on defined objectives. Supply control describes how supply parts are provided. It can be based on frequencies (e.g. 500 per hour), based on stock monitoring (e.g. Kanban) or demand-based (e.g. JIT).

The specific realization of the respective model component can be read as a complexity degree from top to button (e.g. a description is less complex that assigns an unconditional time probability distribution as time model to a process than an unconditional one, where it is possible to predict the process lead time for a specific situation).

4 RESULTS

The proposed classification scheme was applied on a collection of texts identified with the mentioned literature technique (Kitchenham et al. 2009). In Table 2 we present the main findings. The relevant papers are classified on the one hand with respect to the reason why model learning was used (reduce creation effort (R1), update the twin (R2), improve prediction accuracy (R3)) and on the other according to the static and dynamic components that are learned from data and which degree of complexity the learned model component has.

Table 2: Summary of the literature review

	R1	R2	R3	PM	TSM	TFM	RM	RCM	TM	QM	OG	OC	RC	SC
Bano et al. 2022	✓			PART	RES	1:1	SUI		UCPD					
Biesinger et al. 2019	✓	✓				1:1	SUI		UCPD					
Charpentier and Vejár 2014	✓	✓		PART	LOC	M:N			UCPD			PART		
Choueiri et al. 2020			✓	PART	RES				UCPD					
Denno et al. 2018	✓	✓		PART	RES	1:1	EAVA	CA	UCPD			PART	ARR	
Evermann et al. 2016	✓											SIT		
Friederich et al. 2022	✓	✓	✓	PART	RES	1:1	SEAVA		UCPD					
Goodall et al. 2019		✓							UCPD					
Kumbhar et al. 2023	✓			PART	RES	N:1	SUI		UCPD					
Liu et al. 2023		✓		PART	RES	N:1	SUI							
Lugaresi and Matta 2021	✓			PART	RES	1:1	SUI		UCPD		PART	QUO		

Martin et al. 2015	✓										PART			
Martin et al. 2016	✓						EAVA							
Martin et al. 2017	✓			PART									BAT	
Milde and Reinhart 2019	✓			PART	RES	1:1	SUI		UCPD			PART	BAT	
Moon et al. 2021	✓											SIT		
Pourbafrani et al. 2020	✓					1:1	SUI		UCPD					
Rozinat et al. 2009	✓			PART		1:1	SUI		UCPD		PART	PART		
Smith 2015	✓			PART	LOC			CA	UCPD			QUO		
Tax et al. 2016	✓								CPD			SIT		
Zhang, J. et al. 2023			✓						CPD	CPD				
Zhuang et al. 2018			✓						CPD	CPD				
SUM	**17**	**6**	**4**	**12**	**9**	**11**	**11**	**2**	**16**	**2**	**4**	**8**	**3**	**0**

As we can see from the summary, almost all publications learn components of the twin from data to reduce manual modelling effort. Only six paper focus on updating the model components and just four paper deal with improving prediction quality. The most holistic update approaches is performed on a semantic web-based DT (Liu et al. 2023). A memorizing-forgetting model is used to classify new data points over time in long-term and short-term knowledge. Another approach is based on constant update of a genetic programming population considering SCADA events as individuals (Denno et al. 2018). The other approaches either focus on updating probability distributions with new data ((Goodall et al. 2019); Friederich et al. 2022) or integrate or delete components of the model based on a delayed reaction to changing event logs (Biesinger et al. 2019; Charpentier and Véjar 2014). All but one paper that have a focus on improving the prediction qualities choose this as the only reason to learn the model component from data. The reason here is surely the complexity of integrating ML into a DT framework without increasing manual work that must be done for data preparation, feature selection and meta parameter optimization. The only approach that integrates automated ML into a DT framework conceptually (Friederich et al. 2022), only validates it on predicting resource unavailability due to disruptions.

Looking at the static model components, for the process model all contributions focus on part type-based process graphs, which can only work for low variance products. The transition model is normally described by possible resource-to-resource connection (usually workstations). Only two contributions use spacial locations since they use not only event log but spacial data from autonomous moving vehicles. For the transformation model the vast majority only focuses on simple 1:1 part transformation. Two paper focus on more complex transformation with supply parts und only one paper considers general M:N relationship. For the resource model normally the suitability of resources for a certain process is learned. Two paper focus also on standard and exceptional availability, adding data about resource status changes into their algorithms. Only one paper focusses on using ML-based availability prediction. The Resource capacity model is considered by only two contributions focusing on the capability of parallel processing as observed. No paper addresses to learn the maximal capacity of resources. The time model is the most common component, but the focus is nearly always on simple unconditional distributions. Only two papers focus on ML- process time prediction. The same papers are the only ones that integrate product quality prediction.

The dynamic components are far less considered in the contributions. Order Generation is done based by learning part-wise frequencies. Complex order generation is not considered. Order control is learned on nearly all levels: Quota-based, Part-wise and also based on the current situation in the field of process prediction using Deep Learning (Large language models, recurrent neural networks or long short-term memories). Resource control is done only by three contributions: one based on arrival sequences learning FIFO and LIFO behavior and two based on batch control, learning the batch size used for a process by a resource. We found no work for learning supply control behavior.

5 DISCUSSION

To summarize the findings: there is still work to do until all components of SBDT for DMFS will be generated automatically taking advantage of the maximal prediction quality. One big challenge is surely the data availability and quality. Approaches based on standardized event logs (like process mining) or smart factory environments have demonstrated the power of good data quality for the learning of model components. It would be interesting to switch the task of process mining from "What can I get from as little data as possible?" to "Which data do companies need to capture to be able to learn the whole SBDT?". Even though the results show that for a lot of model components building blocks are already available, there is the need of an integrating the building blocks into one framework – especially dealing with the issue of automating the ML process completely to not only improve prediction quality but reduce manual expert labor as well. Furthermore, more complex smart manufacturing (e.g. job shop, matrix-production) environments with high-variant products are still underrepresented. Most work is based on standard parts with a single process sequence, ignoring supply parts and complex product structures. Especially the business process focus of the process mining area lacks the complexity of DMFS (Denno et al. 2018). Finally, there is need for more work on the dynamic components. While order control is covered quite well order generation, resource control and especially supply control needs to be focused in the future.

6 CONCLUSION AND OUTLOOK

This paper focuses on the learning SBDS for DMFS. After introducing the numerous relevant scientific areas that contribute to this overall objective, we introduced a novel classification scheme based on breaking down DMFS to static and dynamic components and their possible realizations. These realizations served as a reference of what could possibly be learned in the context of these systems. Conducting a systematic review of respective literature, we analyzed why learning was applied, which parts components were learned to which degree and had a look at data requirements and the methods applied. Some of the details of the analysis could not be addressed within the limitations of this paper. The main findings are as follows:

1. Since a lot of building blocks for the learning model components exist, the task at hand is to create frameworks that integrate all the building blocks, focusing on automation of the ML process.
2. More work should be dedicated to the learning of dynamic system behavior. Especially order generation, resource control and most of all supply control are still blank spaces.
3. With a lot of work being available on flow job based MFS with standardized low-variant products, more work should be dedicated to complex job shop environments with high-variant products.
4. As data standardization (as with event logs) boosts the advances in the field of learning models, future analyses should be focused on what kind of data would be necessary to fully automate the generation and update of SBDT.

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