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Using a systems approach to model a process digital twin

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Abstract: SME production companies producing high variety/low volume discrete products face challenging customer demands. These result in complex planning issues due to the tension between optimizing a low volume flow and optimizing efficiency parameters. Current planning and control systems do not support this kind of complexity. A process digital twin supports an integral optimization of flow and efficiency in real time. The use of real time data raises new questions such as: what decision-making level does the twin needs to address (e.g., operational, tactical) and what does this mean for the organization. Existing theory does not adequately cover modeling of relations between the shopfloor, total organization and the process digital twin. We suggest a systems approach in which the structure of the digital twin model and the organizational design are both considered. We discuss practical issues and show a systems framework for digital twin modeling.

Keywords: Digital Twin, Manufacturing modelling, Organization Design, Systems approach

1. INTRODUCTION

SME production companies face challenges due to customer demand for a multiplicity of products. For companies in discrete production, these products are made in small quantities before the process switches to the production of a different variant or to a completely different product. Thus, this High Variety, Low Volume (HVLV) demand needs to be met by a HVLV production system.

This type of production system is a challenge for most SME companies. Commonly, they have limited resources and thus are unable to invest in separate and dedicated production flows for each product family. Therefore, products and product variants need to be produced via the same process/system. Consequently, the conflicting demands from different products and production flows bring challenges to the production process planning and control. Current planning and control methods like ERP and MES systems do not support these challenges dynamically and in real time.

The literature reports digital twinning as an approach to supporting decision making in the planning and control of mass customization processes (Stoldt, et al., 2018; Kritzinger, et al., 2018; Uhlemann, et al., 2017). However, while much of this literature describes the concepts of manufacturing digital twins, (Bao, et al., 2019) applications of digital twinning are still at an early stage (Zhuang 2018; Lu 2020).

To close this gap, our paper presents a systems view for developing real-time simulation, based on the results of a longitudinal (2017-2021) case study for a sheet metal company with a HVLV production system. A process digital twin was developed to support the planning and control of their HVLV manufacturing process. At the same time, a systems view theory was developed to support company decision making regarding choices in the process of building and implementing a fit-for-purpose digital twin (DT).

In section 2 we present the methodology used in the case study and the consequent development of the systems view for developing a practical DT. In section 3, we present the case study and the resulting development problems we found for digital twinning. Section 4 describes a systems view and basic systems model to meet these development problems, and in section 5, we discuss the consequences and possibilities, as well as suggestions for further research.

2. METHODOLOGY

In a longitudinal single case study, starting September 2018 and ending October 2021, data were collected at a medium sized sheet metal company. During the research period, a series of research cycles were conducted in two connected development tracks: the company's practical improvement track and the observatory knowledge track.

In the first track, we looked at technology development within the company. In small iterations, the company developed a working digital twin. In the second track, the research group conducted observations and developed knowledge about real time simulation, the development process, and the context in which this development took place. In concentric research cycles, outcomes of earlier stages of the research were used to develop a next set of (real-time) simulation techniques.

This process of research and development cycles is shown in figure 1:

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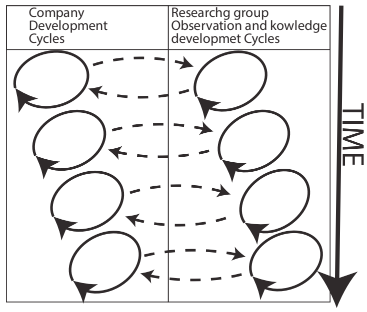

Figure 1: Research and development cycles

At the end of each iteration:

- results were reported and analyzed, and learning points identified;
- the research questions were (re)defined;
- (new) data gathering actions were determined;
- goals were set for the next stages; either extending existing goals, adjusting goals, or setting new goals.

After every research cycle, the systems model for twinning was adjusted and tested.

To ensure validity and reliability (Yin, 1994), multiple sources of data were collected for the production track (e.g., measurements of production, planning data, output) and for the Organization track (e.g., protocols, procedure meeting-minutes, and strategic and operation policy statements). A standardized analysis method was developed including the organization of data collection and information exchange.

An (external) researcher acted as 'assessor', guarding the research methodology and advising on next steps.

Although this was a single case study and thus external validity (replication possibilities and logic in multiple cases) was difficult, during the research period we communicated and tested our findings in interviews, workshops, and other activities with other companies of similar size and production process parameters. After documenting these activities, the results were discussed.

3. CASE STUDY

3.1 The company

The case-company is a sheet metal processing SME with 30 employees. Their most important production processes are cutting (5 machines) followed by bending (14 machines) working in day-shifts. Other processes include welding, assembly, packaging, and shipment. The bending process is the bottleneck in the process. The company has struggled with short and reliable production lead times, resulting in poor delivery reliability figures. We followed this company over a period of four years from 2018 till 2021 (HAN, 2021).

Step by step, the company moved towards becoming a data-driven company. The focus on (real-time) data improved fact-based control of the production process, resulting in a decrease of production lead time from 13 to 7 days. We developed a first version of a process digital twin aiming to support the loading and sequencing of orders released to the cutting process in such a way that the bending machines were evenly loaded.

3.2 Central problem for digital twinning

In the first step, parts are cut from metal sheets in a flat plane with laser cutters/punching on one of five machines. Parts for different orders can be cut from one sheet. At the same time, parts of one order are sometimes distributed over several metal sheets. The optimization rule is: "*The optimal use of the metal sheets to reduce waste.*"

After the parts are cut, bending presses bend the parts into spatial objects depending on size, larger ones (up to 4 meters) or smaller ones (up to 1 meter). The optimization rules for this process are*: (1) an evenly distributed load of the bending presses (utilization), (2) the start of the single piece/ small batch flow for the rest of the production, and (3) optimal changeover times*.

This defines the *complexity of different optimization rules for different processes*. Planning has to manage the release of the orders at the laser cutting machines with the material efficiency of sheet metal (and different metals etc.) and with the optimization of downstream. Moreover, they also have to deal with rush orders and priority customers.

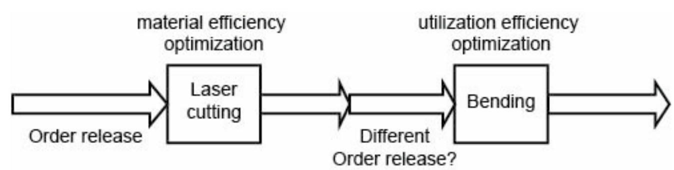

Figure 2: Contrasting optimizations

Thus, the planner faces a complex planning question: "*What order mix do we send to cutting in order to evenly load the bending presses?*".

These optimization issues are not unique to the case company The presence of different production processes with a combination of one of more machines and different optimization rules for each process step is typical for many. Some differences are small (for instance: cycle times differ slightly) while some are large and can even counteract each other (for instance material efficiency and utilization efficiency). These differences interact with each other resulting in process complexity and unpredictable lead times. Mass customization requires short, reliable lead times.

3.3 Process digital twin

A digital representation was built to simulate the process steps and the relations between them. It included the number of machines and their properties. The model's process properties were selected after an analysis of historic production data. The model was validated by the planner.

Digital modelling of these process steps proved valuable. The model provided digitally-simulated order information which was then provided to the planner who used this to gain insights in any conflicting process steps.

3.4 Issues of the use of the digital twin

The first issue to arise during the research cycles was that of data validity. Disturbances, "invisible" to the DT need to be accounted for, as at present, only data is used that can be detected by automated systems and sent as input to the digital representation. Visual information from, for example, an operator, cannot be used in the DT. Moreover, any day-to-day disturbances not in sight of the production manager or planner can highly influence overall production system reliability, as well as reliable and short throughput times.

A second issue is related to modelling and the organizational hierarchy. The "real" problems were not as neat as those presented above and were not only related to optimization or timing. Decisions related to these problems is usually done by operators, logistic personnel and others, and they use their existing flexibility in decision making. The question therefore arose regarding who should be given the DT results to optimize decision making.

This issue arose at the different hierarchical planning and control levels where the results were used for decision making The production manager needs the output for an overview of the total production. The sheet metal manager and the planner need the output to specifically deal with the cutting-bending problem. To ensure that process optimization is within acceptable limits, group managers require the output. The machine operators had visual information, not known to the DT and needed flexibility in decision making. Figure 3 shows possible allocations of decisions in organizational functions.

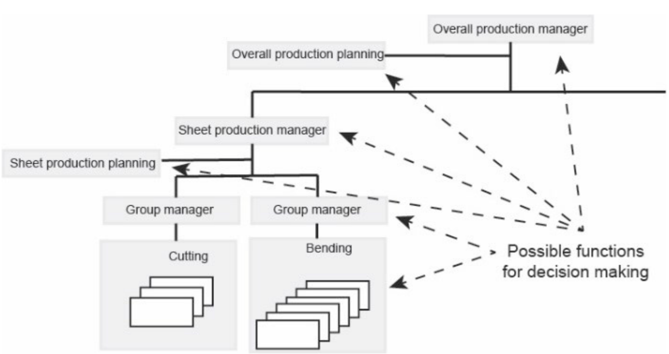

Figure 3. Detailed organization chart: Decision making in relation to the hierarchy of the production organization.

Related to the second issue, is that of the scope of the real time simulation. We used the Manufacturing Planning & Control (MPC) framework (Chapman, et al., 2017) to demonstrate this (Fig.4).

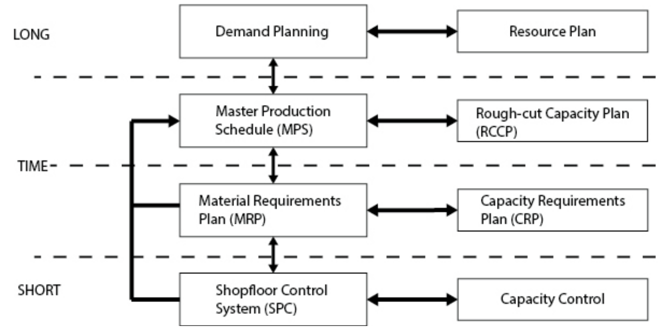

Figure 4. MPC framework with planning and control hierarchy (Chapman, et al., 2017)

The MPC framework shows the production planning and control function hierarchy. The DT, of course, deals with the shopfloor control system, but also gives results that influence the Material Requirements Plan (MRP) and the loop between MRP and Shopfloor Control System (SPC), and even incidentally touches the Master Production Schedule (MPS).

In our case study, the modeling choices proved useful at some levels but hindered the use of the DT at others. The scope of the results, and therefore that of the DT modelling needed to be addressed, not only in a production context but also in an organizational and a planning hierarchical context.

These three issues were mirrored in the development of the company's real-time simulation models. A wide array of questions and problems, sometimes with contrasting demands and lacking the right input data, resulted in a fuzzy set of simulation parameters, with resulting challenges for model development.

When modeling the DT, choices are made to fit one level of the MPC framework for specific uses in the organization. However, it is necessary to deal with output that is contrary to solutions required at other MPC levels and organization departments.

We aimed to use a real-time simulation to ensure a more effective control of the production process. The solution had to deal with the *challenges of effective control of the production process*, given the different and sometimes opposing needs of the production organization and the planning and organization hierarchy.

4. PROPOSED SYSTEMS APPROACH

3.2 Ashby's law of requisite variety

We propose a systems approach to address the modelling challenges of dealing with the opposing interests of different organizations. functions, and digitally unmeasurable shopfloor exceptions.

Ashby (1957) defined rules for effective process control. He stated that if the output of a system is out of its defined boundaries (or norm), a counter action is required. A commonly used systems model is shown in Figure 5. The model includes a measurement of the output, and a regulator that initiates a counter measure to regulate the process.

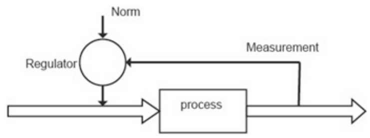

Figure 5. Basic input-process-output model with regulator.

Ashby concluded that if a process needs to be in control, the regulator has to be able to counter all possible disturbances in order to deal with all possible outputs. Thus, for a system to work well, the variety of regulation options must be at least as large as the variety of possible disturbances. Ashby's Law of Requisite Variety states that if a single disturbance cannot be resolved, it is not possible to control a process. Requisite variety is necessary for effective control for all control mechanisms and thus for the system that regulates a production process by a DT.

3.3 In 't Veld's Steady state model

To determine whether the variety can be controlled, we need to expand the systems model to describe production and regulation functions in full, especially if we take the MPC framework into account. In 't Veld (1988) developed a practical systems model for production processes. We applied this model to explore this systems view further (Fig 6).

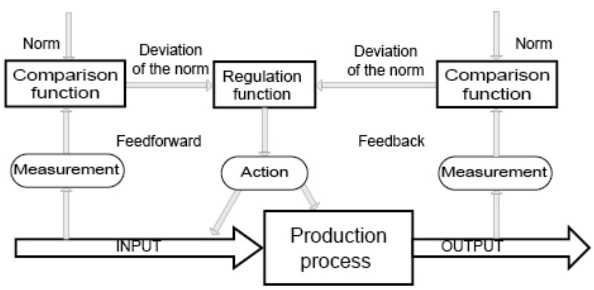

Figure 6. Basic model of In 't Veld (1988)

In 't Veld distinguishes control loops with:

- measurement of the in-and/ or output;
- comparison of this measurement with the norm (how this in- or output should be);
- notification of the deviation between the real and norm situation to a regulation function that determines a counter measure;
- notifications of this counter measure to an actuator ("action" in fig.10, being a person, technology or combination).

In 't Veld adds a second regulator loop. An evaluation function compares a higher-level output and the environmental influences (e.g., planning changes) with the present system norms. Deviations are presented to an adjustment function which in turn sets new productions norms. The adjustment function gets input from the evaluation function, as well as from a higher order control loop (e.g., the rest of the company). This provides a production systems model in "Steady State" accordingly termed *The Steady State model* (Fig.7).

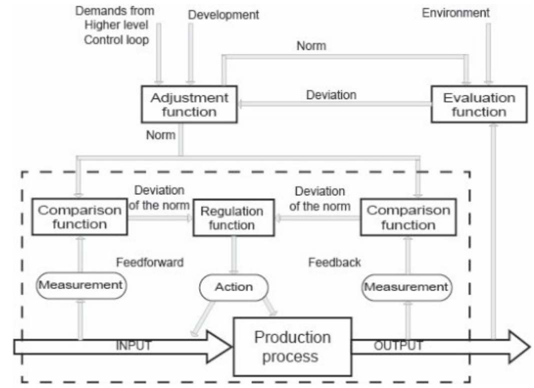

Figure 7. In 't Veld's steady state model (1988) with evaluation and system adjustment functions.

The steady state model is not a stand-alone system, it can be used to zoom out to a higher-level control loop, for instance from a small part of the production to a company-wide system as shown in figure 8.

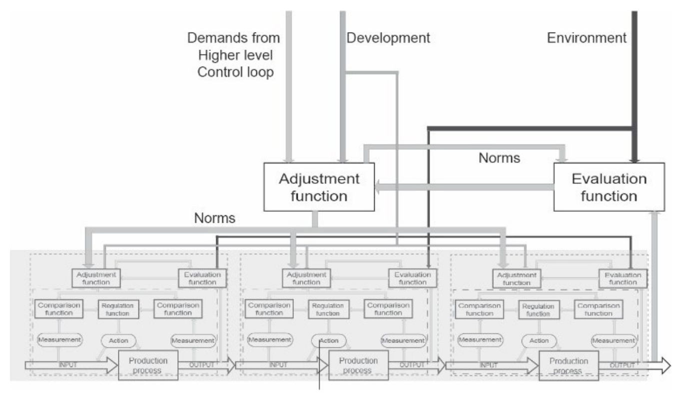

Figure 8. Multiple processes in the steady state model

3.4 Place of the digital twin in a steady state model

We used this steady state model to explore the use of a DT to support production planning and control.

The DT uses real-time measurements, and provides real-time production changes (or suggestion for changes). The DT's boundaries are shown in figure 9 in the dotted rectangle:

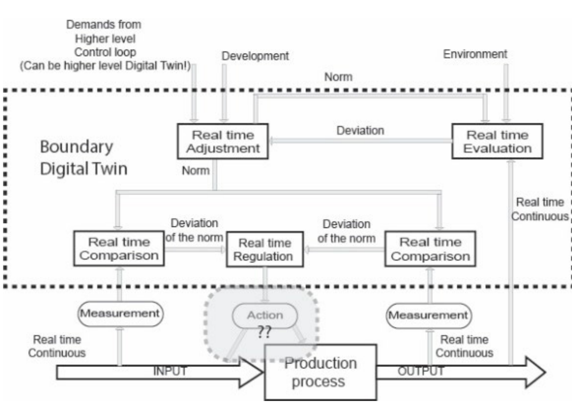

Figure 9. Basic steady state model showing DT boundaries

5. DISCUSSION

5.1 Fixed or flexible settings for digital twinning

The DT's purpose is to deal with real-time short- or medium-term changes in production. In our case, these changes could be due to customer demand, for example the calculation of the influence of a rush job on cutting and bending, or to a temporary change in machine use due to employee illness, or to a delay caused by a worn blade on a press.

We can differentiate in real-time:

- Measurements of the process and its environment including the disturbances to be dealt with. This both in the first order loop of direct production measurements, but also in a higher order of the evaluation and adjustment functions.
- Changes in demands of the system itself, so those related to fixed DT settings and its relation to the production. These fixed settings are in the evaluation and adjustment function.

However, fixed settings for the shopfloor control in the MPC Framework can be set by the MRP planning. So 'flexible' for the MRP planning is 'fixed' for the shopfloor planning. Thus, the term "Fixed" relates to the level in the MPC framework. The time horizon of decision making sets the boundary between "Fixed" and "Flexible" and is related to choices and activities, for instance whether a breakdown of a bending press can be solved immediately (flexible) or can last several days or longer (fixed in settings, and the MRP needs to change).

In both situations, the DT needs regulation flexibility as described by Ashby. Thus, a decision needs to be made at every hierarchical level of regulation in the MPC framework and the relevant output of the DT needs to be presented. *How this works, and the exact distinction between "Fixed' and "Flexible" is subject of further research.*

5.2 Functional organization and the DT

In our case company, planning applied the DT for the order release of the total production. The complexity of opposing optimizations of the cutting and bending processes on the shop floor caused instable and long production lead-times. The DT-model boundaries were set to this subsystem and comprised these two process steps only. *Thus, the problem focus defines the subsystems' boundaries*.

At the start of each day, both the cutter and the benders received a list of orders to process. They could manually change the presented order sequence for their own process. Although this was sometimes counteractive, it was needed based on insights into the current shopfloor conditions. Not all conditions can be automatically detected and sent to the DT. *Questions thus remain about how to deal with disruptions that cannot be detected automatically, and with conflicting needs of different organizational functions.*

5.3 Desired feedback options

As Ashby states, the control variety of a (sub) system should match its variety of disturbances. This suggests that the results of a DT should be at the lowest organizational level possible, preferably at that of the production process.

The desired level of presenting DT information and regulating demands for the shopfloor is an important issue for further research.

5.4 The use of the steady state model

As described earlier, different needs and occurrences can be mapped in the systems model. The steady state model can be used for analyses, for the development of a DT model including its boundaries and functions, the design of production organization including allocation of decision-making functions, the determination of interfacing and much more.

In our model, we mapped the production problem of optimizing cutting and bending. The complexity of optimizing cutting (gaining material efficiency) and bending (gaining resource efficiency) increased due to the variety of materials used. Change over times of the bending presses were also dependent on these varieties (thickness, type of metal, etc.).

We can demonstrate the use of our systems view to support the modeling of the DT. Suppose the case company has an order mix of three types of material, each with four different thicknesses. This results in 12 different possible combinations. Changing a press from one thickness to another and from one material to another requires change over time. For ease of presentation, we assume that changing from one metal to another takes the same time.

At the start, planning has 12 choices of material/thickness combinations, then 11 other material/thickness combinations remain, i.e., 12!: almost half a billion options (Fig. 10). In general, the 80/20 rule applies: 20% of combinations will occur 80% of the time. But these 20% are still too difficult to calculate by hand or to deal with by intuition. And of course, planning still has to deal with the remaining 80%.

	To:		*Steel*				*Stainless Steel*				*Aluminium*		
From:	With	*1*	*1,5*	*2*	*3*	*1*	*1,5*	*2*	*3*	*1*	*1,5*	*2*	*3*
	1		3	6	9	10	12	13	16	5	7	9	11
Steel	*1,5*	3		6	9	10	12	13	16	5	7	9	11
	2	6	6		9	10	12	13	16	5	7	9	11
	3	9	9	9		10	12	13	16	5	7	9	11
	1	10	10	10			3	6	9	5	7	9	11
Stainless Steel	*1,5*	12	12	12		3		6	9	5	7	9	11
	2	13	13	13		6	6		9	5	7	9	11
	3	16	16	16		9	9	9		5	7	9	11
	1	5	5	5	5	5	5	5	5		3	6	9
Aluminium	*1,5*	7	7	7	7	7	7	7	7	3		6	9
	2	9	9	9	9	9	9	9	9	6	6		9
	3	11	11	11	11	11	11	11	11	9	9	9	

479,001,600
Change Over Possibilities

Figure 10. Change over table for bending press

Figure 11 shows a simplified systems view of the case company's cutting and bending process. The top dotted rectangle represents the DT, the bottom dotted rectangle the activities and processes of the shopfloor.

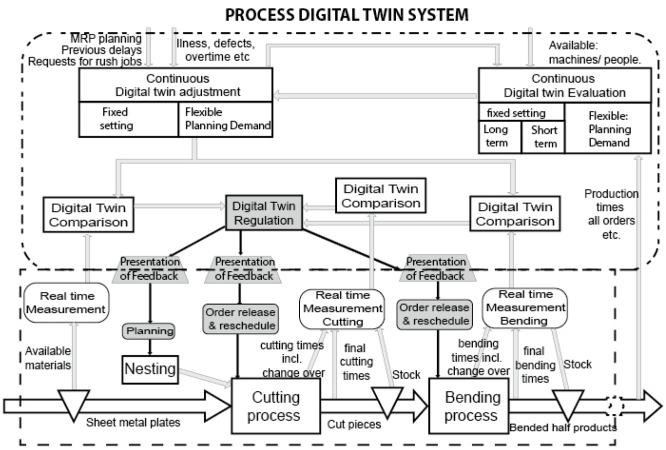

Figure 11. Steady state model for the analyses of production modelling with process digital twinning

Note that choices about the physical appearance of the interfaces (measurement, presentation etc.) are not made, these depend on the situation in a company, as are choices about manual alterations to automated interfaces.

The selected problem with their related processes (lower dotted rectangle) in combination with the possibilities for *effective* control within the organization, determines the DT model (upper dotted rectangle). This also determines real-time measurements the parameters.

Thus, DT modelling and the design of effective control influence each other and need to be developed in conjunction.

5.5 Final remark about types of twins

In this paper, the DT was used specifically for planning and control. As noted in the introduction, a DT can be used for a variety of purposes and thus needs to represent different *aspects of a process*. Bao et. al (2019) for instance, distinguish between product, resource, process, and operation DTs, with the latter describing interactions. The steady state model in this paper was used to determine short and reliable lead times. The question of which process aspects need to be described has to be further detailed, i.e., not only for lead times, but also for aspects like maintenance, quality control, network optimization, and others.

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