Determing the Decentrality of Production Processes Due to Analysis of Their Communication Structure

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Abstract: This paper motivates the benefits of the analysis of the communication structure for process improvement. Therefore first, the paper presents a three-stage model for determining the decentralization of production processes. This is based on the analysis of the communication and decision structure of the process' actors. In addition, it presents a way of visualizing communication relationships. To conclude, this paper presents a practical example and the results of a simulation study. It depicts the advantages of analyzing the communication structure.

1 INTRODUCTION

Decentralized production helps companies to meet today's market requirements (Petschow et al., 2014; Kluth and Storr, 1997; Sundermeier et al., 2020). Positive benefits are an increased speed of response and adaptability (Hichert et al., 1996; Ten Hompel and Henke, 2014) as well as cost advantages by a task integration over centralized production control (Milberg, 1991; Westkämper et al., 1998). They allow a short-term reaction to unforeseen events and thus contribute to an increase in the reaction speed (Mussbach-Winter, 1997). Further advantages include the increase of transparency, a reduction of the forecast shares, the improvement of the planning quality, and a reduction and control of the complexity (Köhler et al., 1997). Characteristics of decentralized production control are few hierarchical levels with homogeneously distributed decision-making authority [10], which independently decide on optimal manufacturing methods, product quality, and the timing of orders (Mussbach-Winter, 1997).

Scientists have been discussing the advantages of decentralized control for over 20 years (see for example (Köhler et al., 1997; Ramsauer, 1997)). However, developments in recent years have created extensive opportunities for technical implementation (Faber, 2019; Huber, 2018; Wang et al., 2017). The transfer of decision-making, execution, and communication capabilities to actors involved enables decentralized production control. These technologies are summed up under the term autonomous technologies. Autonomous technologies are a basis for decentralized production planning (Zeidler et al., 2019).

Although the benefits of decentralized control structures are well known (Windt, 2006; Ramsauer, 1997), it is not possible to make general statements about the best decentralization of a production process. Instead, it is necessary to examine on a process-specific basis which implementation is best suited to achieving the desired goals (Gronau and Theuer, 2016). Therefore, it is important to operationalize the decentrality of a production process.

Though the importance of the communication structure increases, there is no method that uses the communication structure as the basis for operationalizing decentralization. Therefore, the author of this paper suggests a three-stage model. It allows determining decentralization based on the communication and decision structure of the process actors.

Therefore first, the paper presents a three-stage model for determining the decentralization of production processes. This is based on the analysis of the communication and decision structure of the process' actors. In addition, it presents a way of visualizing communication relationships. To conclude, this paper presents a practical example and the results of a simulation study. It depicts the advantages of analyzing the communication structure.

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2 DETERMING DECENTRALITY IN PRODUCTION PROCESSES

The communication and control structure of the actors involved in the process takes an important role in decentralized production control. For determing actor-based decentrality in production processes, it is necessary to define when an actor reaches the maximum or minimum structural centrality and what the mathematical relationship is between the factors and the target value (decentrality) in terms of increase and decrease of distances and number of reachable actors. The focus is on one element at a time. Relevant factors are, according to the social network analysis, the number of elements the considered element reaches, and the steps required for this.

Based on the four forms of control structures (see figure 1), four definitions are necessary (for detailed argumentation and mathematical examination of the definitions, please see (Theuer, 2022)): Dilts et al. distinguish between controlling and executing units. Controlling actors are actively involved in decision-making and can pass on the decisions made to their subordinate units. However, they cannot execute decisions. Executing actors implement the instructions they have received from their upstream entities. They are not involved in decision-making (Boccella et al., 2020). The model presented in this paper removes this separation, as modern technologies enable the unification of controlling and executing activities by one actor.

1. The structural autonomy of an actor is maximal if and only if it reaches all actors in the network directly.
2. The structural autonomy of an actor is minimal if and only if it cannot reach any other actor in the network.
3. The structural autonomy of an actor decreases with an increasing distance to the other actors (given a constant number of reachable actors).
4. The structural autonomy of an actor increases with an increasing number of reached actors (given a constant sum of distances).

3 THREE-STAGE MODEL

This paper presents a three-stage model for the analysis of actor-based decentrality in production processes (see figure 1). Stage 1 analyzes the communication and decision structure of autonomous actors. Social network diagrams visualize the communication structure (nodes and directed edges). Afterward, stage 2

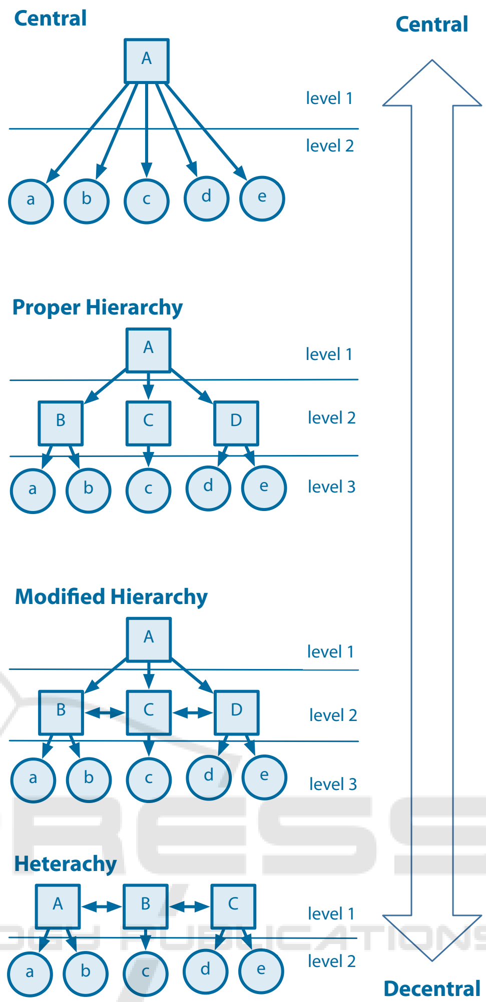

Figure 1: Four Forms of Control Structures (following (Dilts et al., 1991)).

aggregates the results into a key figure that describes the decentralization of the process step. Finally, stage 3 evaluates the decentralization of the process

3.1 First Stage: Actors' Autonomy

The starting point of the model is the three actor classes: human, factory software (software integrated into machines), and operational application system. Their instances fulfill the requirements of autonomous actors (Theuer, 2018): independent information processing, decision making, and decision execution (Windt, 2008).

It is necessary to create an understanding of decentralization of production processes firstly. Four requirements quantify the communication structure. A systematic analysis confirms the suitability of the social network analysis (SNA) key figure, harmonic

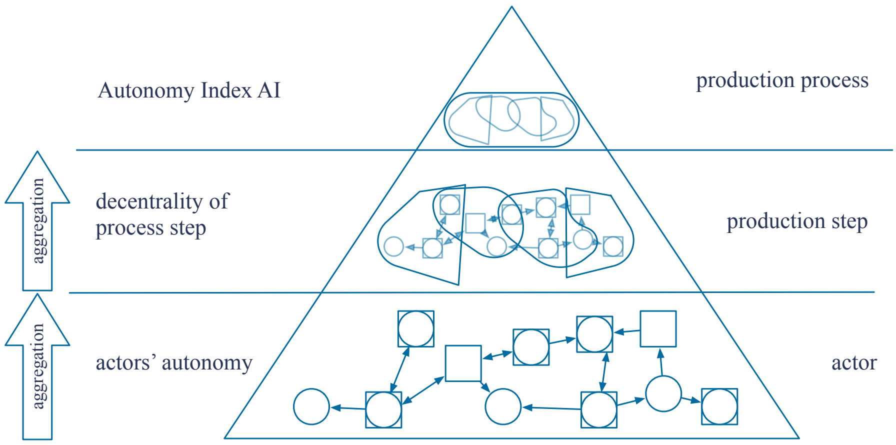

Figure 2: Three-stage model for determination of decentralization of production processes.

closeness, for operationalizing the structural autonomy of individual autonomous actors. A correction factor considers self-executing actors in the calculation. Those combine decision-making and decision-execution and have no directed connection to another actor.

However, because of the possibility of integrating control and execution capabilities in one actor, it is insufficient to only focus on structural relations to determine decentralization. Therefore, the model considers a second value describing the decision structure. It is determined by the ratio of the decision alternatives of the actor to the sum of the decision alternatives in the process step.

Actors' autonomy $R_{a,ps}$ is calculated by multiplying the two factors.

$$\begin{aligned} R_{a,ps} &= C'_{a,ps} \cdot d_{a,ps} \\ &= (C_{a,ps} + \frac{1}{n_{ps}-1}) \cdot \frac{e_{a,ps}}{\sum_{a}^{n_{ps}} e_{a,ps}} \end{aligned} \tag{1}$$

with

$R_{a,ps}$: Actors' autonomy of actor a in process step ps

$C'_{a,ps}$: Structural Autonomy of self executing actor a in process step ps

$c_{a,ps}$: Harmonic Closeness of actor a in process step ps

$d_{a,ps}$: Decision autonomy of actor a in process step ps

$e_{a,ps}$: Quantity of decisions of actor a in process step ps

n_{ps} : Number of actors in process step ps

3.2 Second Stage: Decentrality of Process Steps

The calculation of the decentrality of the process step is performed using the graph centrality of social network analysis. The SNA distinguished two different approaches to centrality determination. While other explanations for the analysis of social structures focused on the centrality of individual actors ("local point centrality") (Bavelas, 1950; Flament, 1963; Beauchamp, 1965; Sabidussi, 1966), Freeman (Freeman, 1978) succeeded in his work to consider the whole network ("graph centrality"). He defines such graphs as central, where one point dominates the other points.

For this purpose, the sum of the differences between maximum and all other nodal centralities is first calculated. Subsequently, the ratio of this value to the theoretical maximum value is determined.

Freeman's approach classifies the control structure (homogeneous/heterogeneous) of a graph. Thus, it is suitable for determining the decentrality of production processes. A square root increases the dispersion and allows better discrimination of the results.

$$D_{ps} = 1 - C_{ps} = 1 - \frac{\Sigma\left(R'_{ps} - R_{a,ps}\right)}{n_{ps}-1} \tag{2}$$

with

D_{ps} : Decentrality of process step ps

C_{ps} : Centrality of process step ps

R'_{ps} : max Actors' autonomy in process step ps

$R_{a,ps}$: Actors' autonomy of actor a in process step

n_{ps} : Number of actors in process step

3.3 Third Stage: Decentrality of Process

The third step (second aggregation) combines the previously determined characteristic values for the decentralization of process steps to a characteristic value describing the decentralization of the process: the Autonomy Index AI.

It was developed in accordance with the Lean Index-a key metric of lean production. It compares the value-added time of a process to the total cycle time of a product through the process (Drees and Sack, 2011; Erlach, 2020). During initial research activities, the calculation was based on a binary value (0 or 1) (Theuer, 2011; Gronau, 2016). However, research work has shown that a continuous value (between 0 and 1) is more suitable. The Autonomy Index increases as the process steps become more decentralized. An AI of 1 indicates a total decentralized, an AI of 0 a total central production.

$$AI = \frac{\sum D_{ps}}{n_{ps}} \tag{3}$$

with

AI: Autonomie Index
D_{ps}: Decentrality of process step ps
n_{ps}: Number of actors in process step

4 INDUSTRIAL EXAMPLE

The analysis uses a process from the variant-rich small batch production of an industrial company. The process comprises 13 process steps, with 24 actors of the three actor classes involved; material transported is via trolleys, with a one-to-one relation. Some parts of the process use FIFO (first in first out) lines. The process includes branching. Sometimes there is a need for jumps back and external manufacturer. Information sharing is via paper-based information objects.

The following paragraphs present the analysis of one process step and interpret the results. After, process improvement, based on the analysis of its communication structure, follows.

4.1 Analysis of Process

The analysis of the practice process is based on documentation of the process as extended event-driven process chains (eEPC). Besides the temporal and logical sequence, the diagrams contain the human actors responsible for the work steps, the used information objects, and other technical, non-autonomous actors (e. g. machines).

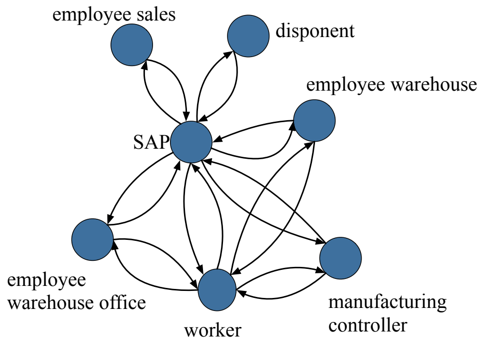

Figure 3: Visualization of the communication relationship of the considered process step 6.

First, the communication relationships are determined and next visualized in figure 2. Rules for the consideration of non-autonomous actors and information objects are applied.

The figure depicts that SAP occupies a very central structural position. Every other actor is a direct neighbor. From and to the worker, there are communication relations to the actor employee warehouse office, employee warehouse, and production controller. Table 1 presents the results of the first stage of the presented evaluation model.

Table 1: Characteristics of process step 6 (central scenario).

actor	$d_{a,6}$	$c_{a,6}$	$R_{a,6}$
disponent	0,091	0,583	0,053
manufacturing controller	0,045	0,667	0,030
employee warehouse	0,045	0,667	0,030
employee warehouse office	0,045	0,667	0,030
employee distribution	0,045	0,583	0,027
SAP	0,682	1,000	0,682
worker	0,045	0,833	0,038
		D_6	0,196

Analogously, the further twelve process steps of the practice process are examined. Table 2 shows the number of autonomous actors involved #a, the number of actors #$c_{ca,ps} > 0$ and decision-making autonomy $d_{a,ps} > 0$, and the decentralization of the process step D_{ps}. It also includes the Autonomy Index AI as a characteristic value, describing the decentrality of the process.

It shows varying decentralization of the process steps. While process step 4 (warehouse preparation) has the lowest decentralization of 0.065, process step 2 (creation of production order) has the highest value of 0.470. The resulting Autonomy Index is 0.224. Overall, decentralization is rather low, e.g. a central authority largely controls the process.

Table 2: Characteristics of the industrial process (central scenario).

	process step	$\#a$	$\#c_{a,ps}$	$\#d_{a,ps}$	D_{ps}
1	creation planned order	3	3	3	0,084
2	creation of production order	5	5	5	0,470
3	purchasing	3	3	3	0,138
4	storage preparation	2	2	2	0,065
5	storage preparation	4	4	3	0,353
6	manufacturing component A	7	7	7	0,196
7	manufacturing component B	7	7	4	0,161
8	manufacturing component C	7	7	6	0,196
9	manufacturing component D	7	7	7	0,173
10	assembly	3	3	3	0,214
11	testing	5	5	5	0,213
12	varnishing	5	5	4	0,277
13	shipping	4	4	4	0,373

4.2 Process Improvement

The visual representation of the communication relationships can provide clues for improving the process in terms of decentralization. It allows the identification of very central and very distant actors that can only be reached via a long communication path. The possibilities of cyber-physical elements offer a basis for the development of alternative scenarios. Besides the flow of information and the decision-making structure, it is also important to consider the implementation of the material flow. Therefore, the mobility of processing actors, workpieces, and tools as well as the design of the material flow (for example, rigid transport routes, flexible transport routes (human-controlled/unmanned)) have to be analyzed.

The previously described process was analyzed based on the visualizations of the communication relationships and process alternatives were developed. Figure 3 shows the resulting communication diagram.

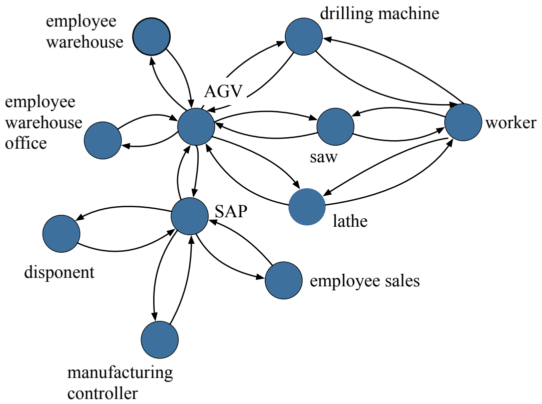

Figure 4: Visualization of the communication relationship of the decentralized process step 6.

The following general considerations underlie the process improvement:

- transport carriage, drilling machine, lathe and saw are designed as autonomous actors (actor class factory software) by integrating smart technologies. This empowers them to take part actively in decision- making and promotes the benefits of decentralized production control. That reduces the strong centrality of the SAP system.
- transport carriage is a driverless transport system that independently determines the route to the next processing step. Manual operation becomes obsolete so that the human actors involved in the process can pursue value-adding activities.
- an operable display at transport carriage enables its operation by human operators. The human operator can directly assign processing results or annotations to the workpiece on-site (1:1 relationship of transport carriage and workpiece). This avoids the need to enter data via production data acquisition (PDA) terminals connected to the central SAP.

Besides these general considerations, there are two changes to the process considered:

- the SAP operational application system notifies the transport cart of the order data at the beginning of the process step. After competition of all process steps, the transport cart reports back to the system. This parallelizes the material and information. Also, it significantly reduces the number of communication relationships from or to the SAP system.
- the transport carriage independently schedules the processing sequence and times by communicating with the autonomous actors drilling machine, lathe, and saw. Thus, the decentralized decision-making process can always consider the current situation, which increases flexibility in the face of

deviations compared to planning by a central controller.

Table 3 lists the characteristic values of the decentralized scenario. It highlights an increased centrality of the transport trolley and a decreased centrality of the SAP system. The ERP solution now only has bidirectional communication relationships with employee sales, production controller, and scheduler. These three human actors perform tasks upstream and downstream of the actual value-added manufacturing process. SAP and shop floor communicate exclusively via a communication relationship between SAP and AGV.

Table 3: Characteristics of process step 6 (decentral scenario).

actor	$d_{a,6i}$	$c_{a,6i}$	$R_{a,6i}$
AGV	0,296	0,800	0,237
disponent	0,074	0,442	0,033
drilling machine	0,074	0,220	0,041
employee distribution	0,037	0,442	0,016
employee warehouse	0,037	,0533	0,020
employee warehouse office	0,037	0,533	0,020
lathe	0,037	0,550	0,020
manufacturing controller	0,037	0,442	0,016
saw	0,074	0,550	0,041
SAP	0,259	0,683	0,177
worker	0,037	0,525	0,019
		D_6	0,556

The actor characteristics are more homogeneous in the improved process than in the original process. It shows that the decentralization of the process step has increased in comparison. Additionally, the structural and decision-making autonomy and the resulting autonomy of the actors are more balanced.

In conclusion, more actors are involved in decision-making in the improved process than in the original process. This is due in particular to the endowment of previously non-autonomous actors with the criteria decision making, information processing, and decision execution.

Table 4 presents the results of process adaptation for all 13 process steps. The number of actors involved has increased in most process steps. The decentralization of the process steps has risen significantly because of shifting away from a few central actors and a more even distribution of decision-making authority. In summary, the Autonomy Index increases to 0,511.

The comparison of alternative scenarios and theirs' effects is very time-consuming and cost-intensive. Therefore, presented industrial example could not highlight the effects of decentralization on the production process (model's stage 3). To perform the complete model with all three stages and to so show the impacts of the process changes, the author carried out a simulation study with two scenario (central and decentral control) at the Center Industry 4.0 Potsdam. The next section presents the results.

5 SIMULATION STUDY

The simulation process is the production of optical lenses. It was conducted at Center Industry 4.0 Potsdam (LSWI, 2022). It comprises the four process steps of grinding, marking, dyeing, and quality control. There are two parallel machines for grinding. Figure 5 visualizes the value stream diagramm of the process. The communication relationships are recorded, stored in a database, processed, classified, filtered, and aggregated with SQL. Subsequently, an R script evaluates them. Additionally, an assignment of the decision alternatives to the actors takes place. This Evaluation also includes the decision structure.

The process under consideration starts with the regular operation of lens production. A workpiece carrier transports a batch of lenses. After a short time, a rush job is set up. The goal is to produce the rush order in the required time of two minutes and fifteen seconds. At the same time, the regular operation is to be produced with the shortest possible lead time.

Two scenarios are simulated: a central and a decentral one. In the central scenario, the Control Center performs production planning, the control commands are passed on to the other actors. Ten actors are involved. The decentralized scenario distributes decision-making among 14 autonomous actors. For this purpose, the decentralized actors have local intelligence. The example process is suitable for the validation of the developed evaluation model, since the differentiation of centralized and decentralized control is possible. The communication relationships and the distribution of the share in the decision-making process per actor can be varied. Thus, the parameters relevant for the model can be changed, so that the effects can be analyzed. Each simulation run considers a normal and a rush order. Twenty simulation runs were executed from both scenarios. The communication structure and the decision structure are recorded. Additionally, lead time is collected as a metric to evaluate the benefits. Table 5 presents the results.

The analysis highlights that the decentralization of the process step is much more homogeneous in the decentralized scenario. The autonomy index AI increases significantly from 0.175 to 0.680. Decentralization lowers lead time both in normal order and in rush order. The robustness (standard deviation of the

Table 4: Characteristics of the industrial process (decentral scenario).

	process	# a	$\#c_{a,ps} > 0$	$\#d_{a,ps} > 0$	D_{ps}
1	creation planned order	3	3	3	0,084
2	creation of production order	5	5	5	0,437
3	purchasing	4	4	4	0,353
4	storage preparation	3	3	3	0,684
5	picking	5	5	5	0,476
6	manufacturing component A	11	11	11	0,556
7	manufacturing component B	11	11	11	0,556
8	manufacturing component C	10	10	10	0,559
9	manufacturing component D	10	10	10	0,548
10	assembly	4	4	4	0,608
11	testing	6	6	6	0,652
12	varnishing	6	5	5	0,552
13	shipping	5	5	5	0,571

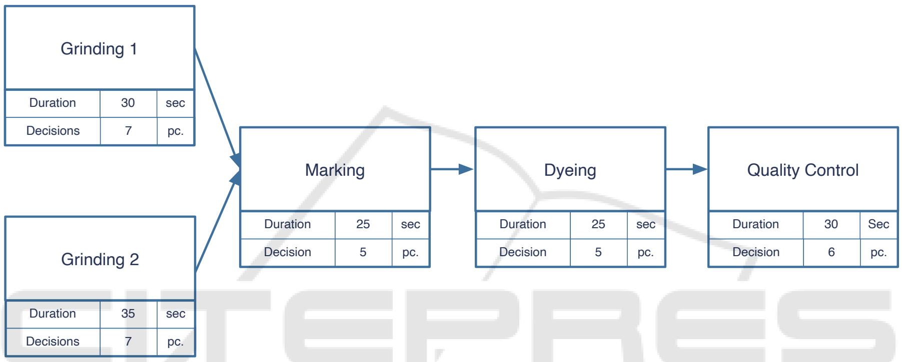

Figure 5: Value Stream Diagram of Process Used in Simulation Study

collected lead times) rises. Thus, decentralization improves process planning and the adherence to delivery of this process.

6 CONCLUSIONS AND LIMITATIONS

This papers presents a model that, for the first time, focuses on the autonomy of the actors for technically dominated systems. Therefor it considers both the structural and the decision-making autonomy of each actor. The model enables an evaluation of the overall system through 2-level aggregation.

An industrial process was used to show how visualization of the communication structure can serve as a basis for process improvement. The presented model was run under laboratory conditions in a simulation environment. Transfer and application of the model in a real production environment bear the risk that the data acquisition is incomplete. Experience shows that the interaction of human actors with each other and with the technical components of the production process is characterized by actions reacting to the individual situation. These can be short agreements and shouts or even smaller manual interventions in the process flow, such as the alignment of a workpiece. Complete monitoring requires a great deal of effort, especially with spatially distributed processes - either by human observers or by technical instruments such as cameras and microphones, although legal restrictions must be expected here regarding the monitoring of individual persons and their work performance.

Another challenge of practical application concerns the operationalization of decision autonomy. Both the complete identification of decision alternatives and their allocation to the actors involved is difficult to realize in reality. Reasons are especially decisions with continuous values, such as processing durations, which theoretically contain an infinite number of decision alternatives. It is necessary to make a reasonable discretization - a wrong choice distorts the model's results. Further challenges may be the assignment of actors to decision alternatives, especially because it is not always possible to assign decisions unambiguously.

Table 5: Results of the simulation study.

process step	central			decentral		
	$\#c_{a,ps} > 0$	$\#d_{a,ps} > 0$	$\#D_{ps} > 0$	$\#c_{a,ps} > 0$	$\#d_{a,ps} > 0$	$\#D_{ps} > 0$
1	7	1	0,437	12	5	0,768
2	5	1	0,051	9	4	0,529
3	7	1	0,127	9	6	0,721
4	4	1	0,087	5	5	0,703
AI	0,175			0,680		
lead time	3'07" (normal order) — 3'05" (rush order)			3'02" (normal order) — 2'14" (rush order)		
σ	15" (normal order) — 12" (rush order)			5" (normal order) — 2" (rush order)		

Table 6: Results of the simulation study.

process step	central			decentral		
	$\#c_{a,ps} > 0$	$\#d_{a,ps} > 0$	$\#D_{ps} > 0$	$\#c_{a,ps} > 0$	$\#d_{a,ps} > 0$	$\#D_{ps} > 0$
1	7	1	0,437	12	5	0,768
2	5	1	0,051	9	4	0,529
3	7	1	0,127	9	6	0,721
4	4	1	0,087	5	5	0,703
AI	0,175			0,680		
lead time	3'07" (normal order) — 3'05" (rush order)			3'02" (normal order) — 2'14" (rush order)		
σ	15" (normal order) — 12" (rush order)			5" (normal order) — 2" (rush order)		

Another restriction of the practical feasibility is the realization of different scenarios of a real process in the factory because high time and financial effort are expected for the restructuring in each case. The scenarios allow the effects of different control strategies to be compared. In addition, production downtimes occur, resulting in further financial losses. Particularly in the case of existing processes (brownfield), the benefit of the evaluation model, therefore, lies in the retrospective evaluation of implemented restructuring measures. In the case of newly planned processes (greenfield), the model can help in designing process control.

The limits of the developed model are therefore the determination of the real input data and the high effort for implementing different scenarios of a production process. Examining the processes in suitable simulation environments such as Center Industry 4.0 Potsdam can reduce the risks. However, a prerequisite here is also a suitable abstraction of the real process and the modeling based on it.

Based on the results of the work on which this paper is based, there is a need for further research, which relates in particular to the practical application of the model in a real production process with the challenges described in the previous section. Another research approach is to apply the model to different types of production processes - for example, classified by different types of manufacturing and organization or industries.

Comparing the results makes it possible to answer the questions of whether it is possible to classify the benefits of decentralized control structures according to certain criteria and if there are best practices.

In this context, a comparative study with other evaluation models is possible as well.

REFERENCES

Bavelas, A. (1950). Communication patterns in task-oriented groups. In *The Journal of the Acoustical Society of America*, volume 6, pages 725–730.

Beauchamp, M. A. (1965). An improved index of centrality. In *Behavioral Science – Journal of the Society for General Systems Research*, volume 10, pages 161–163.

Boccella, Centobelli, P., Cerchione, R., Murino, and Riedel (2020). Evaluating centralized and heterarchical control of smart manufacturing systems in the era of industry 4.0. *Applied Sciences*, 10:755.

Dilts, D., Boyd, N. P., and Whorms, H. H. (1991). The evaluation of control architectures for automated manufacturing systems. *Journal of Manufacturing Systems*, 10:79–93.

Drees, J. and Sack, C. (2011). Produktionsoptimierung durch kennzahlen der wertstrom-modellierung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 106(6):466–470.

Erlach, K. (2020). *Wertstromdesign - Der Weg zur schlanken Fabrik*, volume 3. Springer Vieweg.

Faber, O. (2019). Digitalisierung–ein megatrend: Treiber & technologische grundlagen. In *Management 4.0–Unternehmensführung im digitalen Zeitalter*, pages 3–42. Springer.

Flament, C. (1963). *Applications of Graph Theory to Group Structure.* Prentice-Hall Series in Mathematical Analysis of Social Behavior.

Freeman, L. C. (1978). Centrality in social networks conceptual clarification. *Social Networks*, 1(3):215 – 239.

Gronau, N. (2016). *Handbuch der ERP-Auswahl*, volume 2. GITO mbH.

Gronau, N. and Theuer, H. (2016). Determination of the optimal degree of autonomy in a cyber-physical production system. In *Proceedings of 49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016).*

Hichert, R., Roos, A., Ziegler, J., Reichwald, R., Möslein, K., Meitner, H., Schweiggert, F., and Eberspächer, J. (1996). Information und kommunikation in dezentralen strukturen. In Bullinger, H.-J. and Warnecke, H.-J., editors, *Neue Organisationsformen im Unternehmen*, pages 657–752. Springer-Verlag.

Huber, W. (2018). *Industrie 4.0 kompakt–Wie Technologien unsere Wirtschaft und unsere Unternehmen verändern*. Springer.

Kluth, R. and Storr, A. (1997). Hohe produktivität durch werkergerechtes, situationsorientiertes informationsmanagement. In für Fertigungstechnik, G., editor, *FTK'97: Fertigungstechnisches Kolloquium*, pages 325–349.

Köhler, A., Lämmle, C., and Wiendahl, H.-H. (1997). Dezentralisierung und vernetzung der produktionsplanung und -steuerung. In für Fertigungstechnik, G., editor, *FTK'97: Fertigungstechnisches Kolloquium*, pages 199–217.

LSWI (2022). Center industry 4.0 potdam – a worldwide unique opportunity for an encounter with the future. Webseite.

Milberg, J. (1991). Wettbewerbsfaktor zeit in produktionsunternehmen. In *Wettbewerbsfaktor Zeit in Produktionsunternehmen*, pages 11–31. Springer.

Mussbach-Winter, U. (1997). Dezentrale produktionsplanung und -steuerung. In für Fertigungstechnik, G., editor, *FTK'97: Fertigungstechnisches Kolloquium*, pages 420–431.

Petschow, U., Ferdinand, J.-P., Diekel, S., and Flämig, H. (2014). Dezentrale produktion, 3d-druck und nachhaltigkeit. *Schriftenreihe des IÖW*, 206:14.

Ramsauer, C. (1997). *Dezentrale PPS-Systeme Neue Strukturen bei hoher Innovationsdynamik*. Gabler Verlag.

Sabidussi, G. (1966). The centrality index of a graph. *Psychometrika*, 31(4):581–603.

Sundermeier, J., Gehlhoff, F., and Fay, A. (2020). Development of a simulation model to analyze the performance of decentral rescheduling algorithms in production systems. *Simul. Notes Eur.*, 30(1):15–22.

Ten Hompel, M. and Henke, M. (2014). Logistik 4.0. In *Industrie 4.0 in Produktion, Automatisierung und Logistik*, pages 615–624. Springer.

Theuer, H. (2011). Extension of value stream design for the simulation of autonomous production systems. In ElMaraghy, H., editor, *Proceedings of the 4th International Conference on Changeable, Agile, Reconfigurable and Virtual production (CARV 2011)*, pages 586–591. Springer Verlag.

Theuer, H. (2018). Autonome akteure in der dezentralen produktionssteuerung. *Industrie 4.0 Management*, 34(6):41–44.

Theuer, H. (2022). Communication in decentralized production system (accepted). In *Proceedings of 31rd International Conference on Flexible Automation and Intelligent Manufacturing*.

Wang, Y., Anokhin, O., and Anderl, R. (2017). Concept and use case driven approach for mapping it security requirements on system assets and processes in industrie 4.0. *Procedia CIRP*, 63:207–212.

Westkämper, E., Wiendahl, H.-H., and Balve, P. (1998). Dezentralisierung und autonomie in der produktion. *ZWF – Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 9(93):407–410.

Windt, K. (2006). Selbststeuerung intelligenter objekte in der logistik. In Vec, M., Hütt, M., and Freund, A., editors, *Selbstorganisation – Ein Denksystem für Natur und Gesellschaft*. Böhlau Verlag, Köln.

Windt, K. (2008). Ermittlung des angemessenen selbststeuerungsgrades in der logistik – grenzen der selbststeuerung. In Nyhuis, P., editor, *Beiträge zur Theorie einer Logistik*, pages 349 – 372. Springer-Verlag Berlin Heidelberg.

Zeidler, F., Müller, D., Ten Hompel, M., and Henke, M. (2019). Wip-balancing by autonomous control using flexibility oriented decision-making. In *Proceedings of 48th International Conference on Computers and Industrial Engineering, CIE.*