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Evaluation of Production Processes Using Hybrid Simulation

Norbert Gronau, Hanna Theuer and Sander Lass

Abstract Changing market conditions, variable customer demands and growing customer requirements are some reasons for producing companies to create flexible and adaptable processes and to fulfil the customer demands in a high quality. For this reason it may be beneficial to change the production system from a centralized towards a decentralized production management approach. It is of high importance to figure out the best mix of centralized and decentralized production control for every company separately, while at the same time ensuring that the process continues running. Comprehensive analyses often turn out to be time-consuming and expensive. Especially small and medium sized enterprises have to avoid these side-effects. This article presents a method for the fast and well-founded evaluation of the best mix of decentralized and centralized production control by using autonomous technologies.

Keywords Decentralized production control · Hybrid simulation · Autonomous technologies · Robust production control

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1 Introduction

Due to various changes of production conditions during the last years—e.g. variable customer demands, growing customer requirements as well as a shift from a seller to a buyer market—global production networks are faced with several exigencies. It is important that companies cogitate about new methods and evaluate those toward the achievements of objectives in consideration of their processes.

Decentralized production control by the use of autonomous technologies seems to be an adequate method to deal with the current requirements on production processes. It would be pointless to make generally applicable statements towards the best degree of decentralized and centralized production control. It is of high importance to figure out the best mix for every company separately, while at the same time ensuring that the manufacturing process continues. Often comprehensive analyses turn out to be time-consuming and costly. Especially small and medium sized enterprises try many times to avoid these efforts. The distribution of such concepts or methods in practice is low. For reinforcing of competitiveness it is important to use modern autonomous technologies. Therefore it is necessary to create a method with low effort to ensure the consideration of all relevant parts of a production system.

The authors perform a research project ("Leistungsfähigkeitsbeurteilung unabhängiger Produktionsprozesse"—LUPO) [1] with the aim of creating a possibility for the fast and well-founded evaluation of the best mix of decentralized and centralized production control by using autonomous technologies [2]. Therefore they develop a hybrid simulation environment that combines the advantages of computer simulation and physical model factory. Production processes are mapped, recreated, simulated and analyzed towards their suitability of decentralized structures. Due to a high flexibility regarding the construction of the simulation environment and the possible integration of miscellaneous autonomous technologies, it is possible to analyze a high variety of scenarios. The integration of a Manufacturing Execution Systems (MES) ensures the consideration of the state-of-the-art information technology.

This article presents firstly, the concept of the simulation environment and secondly the integration of information technology. The third part introduces a key figure for the evaluation of decentral and autonomous technologies. This enables an analysis of benefit and applicability for concrete production processes. The article ends with an outlook for further research activities.

2 Hybrid Simulation Environment

For the evaluation of autonomous production processes it is of high importance to use a suitable method for modeling, simulation and analysis. The most important requirements for the simulation of autonomous production processes regarding the objectives mentioned above are:

- High flexibility of processes
- Quick set up
- Possibility to reproduce physical issues, e.g. antenna orientation

Common methods that are used in coherence with production processes are the Digital Factory and the Model Factory. The analysis of both show that they have their strengths and weaknesses. A combination of the two approaches would fit the requirements of the simulation the best way. The following sections shortly describe both simulation methods.

2.1 Digital Factory

Digital Factory is a planning approach, which is used in product development for modeling suitable versions for future objects in order to visualize and perform analyses. The objective is the optimization of product relevant structures, processes and resources [3, 4]. Real time monitoring and planning support are connected to one system [5] and establish a shared database for all product relevant software systems. Modeling a Digital Factory is often expensive. Despite decreased costs of information technology systems small and medium sized enterprises forego the use of this kind of planning. In the automotive industry this planning approach is used successfully [6]. A digital mockup of a product is used to analyze ergonomic issues and functionality, possible construction methods or mere visualization [7]. Its strength lies within shortening of duration for product development and design at unchanged costs [8]. An optimization of production processes primarily occurs during product development and focuses on the product itself.

But in the early phases of designing manufacturing processes there are no integrated factory and logistic planning methods that allow a structured comparison of different alternatives based on a set of various criteria [6]. The introduction and use of the different technologies in production process are marginally considered. With regard to the stated aims above, physical systems appear only as data provider. In summary, it allows simulation without the use of hardware components through digital mockup, if there is an adequate implementation of a physical model within the software. Otherwise, it has to be implemented. This possibly causes high effort compared with a hardware variant and results in software tools with high complexity. The strength of Digital Factories is the product development. With regard to the given objectives Digital Factories cannot be applied without extending their concepts.

2.2 Model Factory

A model is a simplified representation of a planned or existent system build up to reduce complexity [7]. A Model Factory represents concrete production processes in a simplified way under lab conditions. There is no standard or universally agreed definition for the term Model Factory which is mainly used for educational and teaching purposes, for example at the RWTH Aachen [9] or the Technical University Darmstadt [10]. The components in a Model Factory are a physical implementation of their real counterpart and works the same way e.g. machines or production islands. In most cases the specialized model elements have a small field of operations. Their application is limited to simple products and scenarios. Due to the inflexibility of model factories, the analysis of new ideas and concepts are restricted to cases with similar usage. The limitation to a concrete production process impede the use for different production situations and prevents the implementation of the model into various processes. The evaluation of alternative scenarios is difficult. The obtained results subsequently have to be transferred from this special application to other applications. To sum up, a Model Factory allows a quick realization of physical problems with low effort, but it has a low degree of flexibility concerning different production scenarios. Thus, it is not an adequate solution for the objectives stated in the introduction.

2.3 Hybrid Simulation

In the Hybrid Simulation environment there are physical models for the relevant production objects. They are used for the representation of the existing system by deploying a combination of software and hardware components. For every single part of simulation, the most appropriate way of simulation can be identified. The implementation of original equipment in the digital model, opens the possibility of testing physical effects e.g. detection rate, field intensity or antenna pointing of AutoID-elements with minimal effort [11]. Neither the purely physical nor the purely digital simulation can offer this advantage. The hybrid approach is suitable for the realization of the started objectives.

The LUPO simulation environment consists of the work piece and machine tool demonstrators as well as transport lines that connect the various machine tool demonstrators. The demonstrators with their ability to communicate in different ways and the flexible transport system do provide an effortless integration of hardware components into the overall system. The software is designed for a quick integration of sensors and other devices using standard communication protocols. The hardware section provides the interfaces for an easy connection. The system supports the integration of hardware-components by design. This is an important advantage compared with sole software models which are supplemented by some hardware parts. For an investigation of receiving characteristics in a RFID scenario, for example, it is not sufficient to connect merely a reader device, but in addition it is necessary to realize moved work pieces with a kind of conveyer. A cost intensive construction of further hardware parts is imperative for good results. Thus, the presented approach avoids these efforts.

A demonstrator consists of a box which is configured with the parameters of a certain production object. The interaction of demonstrators allows the setup and

Fig. 1 Machine tool demonstrator—schema and original

simulation of a whole production process. Relevant environmental information is delivered for input by various sensors. Some interface and communication modules allow the connection of different types of sensors and enable the interaction with other components. Thus, it is possible to configure demonstrators and complete them with further pieces of hardware. Figure 1 illustrates the setup as a matter of principle as well as a picture of the existing demonstrator. The illustrations of the parts to be worked on are displayed as a 2D or 3D model on both sides of the demonstrator. The monitoring display is on the top side reporting the relevant product, process and job information. All of this information is up to date at every time during the simulation. The diverse machine center demonstrators are aligned by transport lines. To ensure a high level of flexibility and adaptability to the simulation environment transport, several line elements like switch plates, circular shelves as well as entry points and gates are used. Various factory layouts with sequences, parallelism or repetition can be represented. For process control of the simulated production processes, it is necessary to use corresponding software tools (described in the following section).

2.4 Integration of Information Technology

The LUPO simulation environment distinguish between two types of software: the LUPO operation system (LOS) and the MES. The tasks of the LOS are the control of the different types of demonstrators and the transportation lines as well as the internal communication of demonstrators. Additionally it provides the user interface that enables the configuration of demonstrators and the input of relevant process parameters.

It distinguishes between the simulation operation level and simulation application level. All technical adjustments for the configuration of demonstrators are made in the simulation operation level. In the simulation application level the concrete process is displayed. All settings that are necessary for the configuration of the real process are made.

The MES is used for the control and analyses of processes. An exchange of the default parameters of machine center and work piece demonstrator has to be ensured. This includes the production plan, relevant-related key figures like process time, set up time or transport times as well as data on possible breakdowns of the simulated process. This enables a control of relevant process parameters.

3 Evaluation of Decentral and Autonomous Production Processes

Autonomous technologies are one possibility for the realization of a decontrol controlled production. Therefor In the following the focus is on this kind of production control. It is necessary to have a suitable method for the documentation and analyses of simulation runs of autonomous processes at the LUPO hybrid simulator. There should be an opportunity for creating an easy overview, whether a process acts autonomously or not. A comparison of different processes towards their degree of autonomy is possible. A modeling method had to be selected for the documentation of different scenarios being simulated in the hybrid simulation environment. In accordance with criteria different methods, e.g. Value Stream Design (VSD) and Event driven Process Chain, were compared.

The most important criteria for the selection are:

- Suitability for production processes
- Good opportunity to evaluate and compare various production processes towards relevant objectives
- Basis for discussion
- Consideration of special requirement of autonomous technologies.

The comparison revealed that Value Stream Design is the most suitable method for the aims of the LUPO simulation environment. This method fulfills the first four of the requirements mentioned above.

3.1 Value Stream Design

Originally designed by Rother and Shook for mass production in automotive industry, the VSD method took on significance even for small batch production in recent years as for many companies Lean Production came into the focus of attention [12]. By distinction of value-adding (non waste) and non-value-adding (waste) processes it is a simple way to analyze the current situation of a production towards lean aspects. Sources of waste can be discovered—the basis for improvements is given. Based on the findings, different production scenarios for improvement can be compared and analyzed. Therefore VSD and Lean Production are a good combination for long lasting improvements [12]. For modeling, the method offers a clearly defined set of symbols that considers different properties of a supply chain such as production processes, inventory, customer, supplier and material flow. Furthermore relevant key data (e. g. lead times, waiting times, set-up times, number of persons at one process, stock) are mapped. Information flow is also of interest but the focus of this method is on material flow [12, 13].

The relation of value-adding and total process time is called Lean Index. It is expressed in x:y (x to y with $x =$ value-adding times, $y =$ total process time). The more similar both numbers are, the less (time) waste can be found in the production. A Lean Index of 1:1 presents a perfect piece flow with no waiting times for the products, and complete adjusted cycle times. Nowadays the Lean Index in many companies is bigger than 1:$y > 100$ [12, 13].

3.2 Extended VSD

The original Value Steam Design method does not consider the special requirements for the analyses of processes using autonomous technologies. As this is of high importance for the analyses of production processes in the LUPO simulation environment it is necessary to extend the method by details of the information flow. By an additional documentation of data which is relevant for autonomous control, traceability increases. Furthermore a reproducibility of the process is given. For the process evaluation an index that measures the degree of autonomy is introduced. Since Value Stream Design is easy to understand and to practice directly at the workflow without great effort, the extension should be likely.

Set of Symbols In order to create an easy overview as to whether a process acts autonomously or not the symbolism of processes has to be extended. An autonomous process is marked with a black triangle on the right corner. During Value Stream Mapping the author of the diagram can decide whether a process is autonomous or not and mark the process, if necessary.

Figure 2 shows an example of a Value Stream Map of a production site with three processes. While Process A and B and non-autonomous controlled, Process C its autonomous controlled. The supplier delivers the goods to a production supermarket. From there Process A takes them in. After finishing the procedures at Process A the goods are given into a FIFO line to Process B. Another FIFO line connects Process B and Process C. After Process C is completed all goods are put into stock where they have to wait for a certain time. From there the products are delivered to the customer. All customer and supplier processes are like a black box. They exist but no further information is known. External processes are similar. The only figure that is known is the total process time for the external process [13].

Data Dictionary For the reproducibility of the autonomous process it is necessary to document all data that is relevant for process execution. This includes all data that is exchanged between production objects which are involved in the process as well as data that the process needs to decide how to act. The relevant

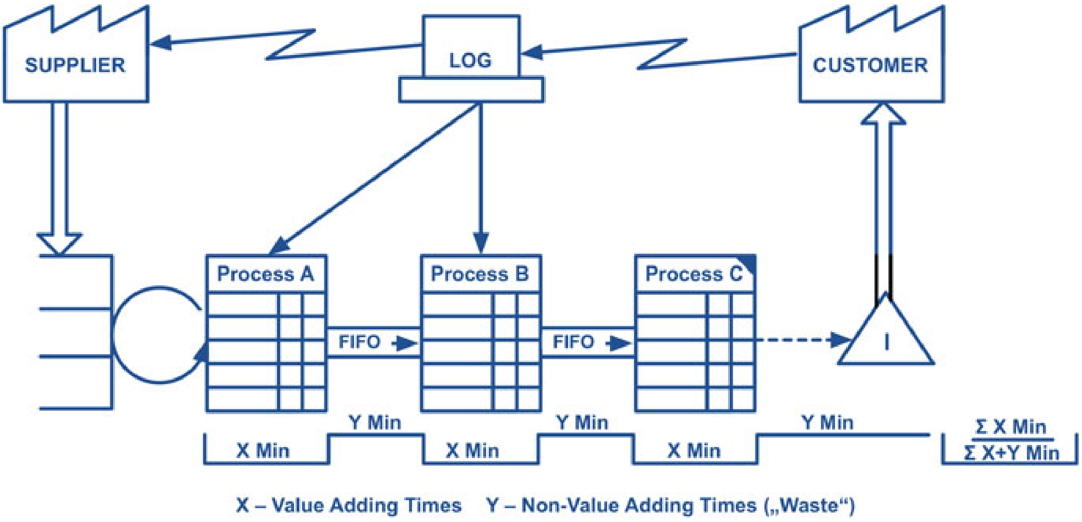

Fig. 2 Example of a value stream map with three processes connected by FIFO lines

Process Data	Information Flow Data	Product Data
Predefined rules stored Set-up time matrix Amount of different products beeing worked on the specific process Process times for different products beeing worked on the process	Data-On-Tag or Data-On-Network Used technology of data exchange Frequency of data exchange Amount of data per exchange Mission critcal index - what happens in case where the data needed is not availbale	Type of product Relevance (express or not) Planned completion data Additional information

Fig. 3 Relevant data for data dictionary in extended value stream design

data can be divided into three super classes: process data, information flow data and product data.

Process data is specific for the process. It includes all information that is necessary to enable the process to make decisions on its own. Information flow data specifies the data exchange of the production objects at the process (e.g. process and product). This data is necessary to rebuild the technological settings of the process. Product data specify the product that is worked on in the process. Process data and information flow data require particular values. As there may be various products in one specific process product data are of Boolean type. It is necessary to know what product data is exchanged without a concrete definition. Relevant data may be (but is not limited) as shown in Fig. 3:

Autonomy Index For the evaluation of value streams with autonomous technologies the introduction of a key performance figure is necessary. To underline the interest it is named Autonomy Index. It specifies the degree of autonomy used at the value stream and thereby give the possibly to compare different production systems. In coherence with the Lean Index the Autonomy Index should clarify the amount of autonomy in comparison to the whole value stream. When defining the index the basis for the comparison has to be specified. There are a number of possibilities:

- number of autonomous processes: number of all processes
- autonomous controlled process time: total cycle time
- quantity of autonomous data: total quantity of data

Due to high importance of data exchange in autonomous production control the decision was made in favor of the third possibility. The Autonomy Index AI is calculated as shown in Eq. 1. With an orientation to the Lean Index AI is noted as *DEaut: DEall*. The range is between 1:X (X means number higher 1) and 1:1. The low AI the higher the degree of autonomy at the value stream. For documentation purpose AI is written down on every Value Stream Map.

$$AI = \frac{\sum_{i=1}^{n} F_i \cdot A_i}{\sum_{j=1}^{m} F_j \cdot A_j} = \frac{DE_{aut}}{DE_{all}} \tag{1}$$

with:
AI: Autonomy Index
DE_{aut}: total amount of autonomous data exchange
DE_{all}: total amount of data exchange
F: frequency of data exchange
A: average amount of data volume per exchange
$i \epsilon I$ with I: amount of autonomous data exchanges
$j \epsilon J$ with J: amount of all data exchanges
$I \subset J$
n: number of autonomous data exchanges
m: number of all data exchanges

It has to be considered that the amount of data exchange does not include all exchanged data but only the relevant. For example not the file size of a picture is relevant (as it may vary strongly depending on the kind of file, e.g. jpg, tiff or bmp), as well as the resolution or quality. Instead the relevant data, e.g. color or size of the product, has to be measured.

3.3 Evaluation

The calculation of AI enables an evaluation of the correlation of the Autonomous Control and another key figure, e.g. total process cost or Lean Index, in a specific value stream. Based on this information it is possible to generate statements about the concrete benefit of decentral production control. It is possible to compare different mixture of decentral and central production control configurations and thereby gain knowledge about the applicability of decentral production control by autonomous production processes for this specific process.

The graphical representation results in a scatter plot since there are different ways of achieving the same value of DE_{aut}. Additionally same values of DE_{aut} can result in different grades of the regarded key figure. The plot may indicate the best degree of Autonomous Control for the considered value stream.

It is possible to analyze which processes have major or minor impact on the decision towards an autonomous control. Based on this, a cost-benefit analysis can be indicated. The reciprocals of both data are put into a scatter plot. An example is depicted in the following chapter.

4 Case Study

This section provides an example for the usage of extended Value Stream Mapping in connection with simulation of production processes in the LUPO laboratory. The analyzed production consists of five processes (process A to E). The production sequence is predefined and identical for all products produced. The process can be classified into two sections that are linked by an interim storage. This storage is the point of product individualization also called order decoupling point. The first section consists of process A and B. Both produce non-individual intermediate products. Products handled at process B are put in an interim storage. There are two variants produced in this section. Processes C to E produce customer individual products. Intermediate products are taken from the storage and then handled in process C. There are three variation possibilities in process C and D, two in process E. All of those possibilities are combinable, so that there are $2 \times 3 \times 3 \times 2 = 36$ variants of the end product.

To change from one to another variant process setups are necessary. As set up times vary from initial state to target state, there are setup matrixes for all five processes. Process times differentiate from process to process as well as from variant to variant. For satisfaction of the customer requirements it is of major importance that the right product is manufactured at the right time. In the case analyzed the delivery performance deteriorated and stock rose. It is for this reason that all processes should be reconsidered. Additionally to the mentioned problems it should be analyzed how to deal with express orders, that ensure a highly shortened delivery time to customers. At the current state all five processes are central controlled. While there is a push control installed at the first section there is a pull control at the second section. The produced amount of both basic variants in the first section is planned due to a sales forecast. The production program for the next week of the second section is planned due to concrete customer orders. Difficulties arose due to missing intermediate products. All five processes with their relevant characteristics have been recreated and simulated at the LUPO laboratory.

Table 1 Characteristics of processes

Process	Average amount of data volume per exchange	Frequency of data exchange
A	1	3
B	2	3
C	3	3
D	3	3
E	2	3

After the validation of simulation results with the existing processes variations of the type of control are made. In addition to a completely centralized or decentralized control mixed control concepts are analyzed. Therefore the first section is set decentralized controlled while the second is central controlled and in a second trial the other way around. Substancial differences are perceived at lead times and stock building. For each set-up a value stream map was created and a value stream analysis performed. Lean and Autonomy Index were calculated. As second quantity the Lean Index is used exemplarily.

Assuming that as well the average amount of data volume per exchange as the frequency of data exchange are identical in all scenarios the relevant data for the scatter plot can be determined with Table 1 and 2:

The reciprocals of both data are put into a scatter plot. The evaluation of the correlation between Autonomy and Lean Index is shown in the scatter plot in Fig. 4. The numbers refers the belonging scenario.The scatter plot indicates that there is no correlation between Autonomy and Lean Index in the specific production analyzed.

It is obvious that the lowest Lean Index is realized with AI = 1:1,5. This situation occurs if the first section is controlled central and the section decentralized controlled. The worst Lean Index is achieved by a decentral controlled first section and a central controlled second section (AI = 1:3,67). The change of a complete central production (AI = 1:∞) to a complete decentralized production (AI = 1:1) only causes marginal differences in consideration of the Lean Index. For all decentral controlled processes a supplementary analysis is realized. Its results are recorded at the data dictionary. This enables a later reproduction of the process and therefore the usage of identified advantages in the real production. Additionally the extended value stream maps enable a well-founded discussion with company internal and external persons. The best mix of central and decentral controlled production has been determined. The problems of the original process mentioned above were reduced to a minimum. Due to a well arranged and completely documentation regarding lean production aspects, a successful implementation of simulation results in real production processes is provided.

Table 2 Characteristics of scenarios

Scenario	AI	LI
1 (completely decentral controlled)	1:1	1:50
2 (completely central controlled)	1:∞	1:45
3 (first section decentral, second section central controlled)	1:3,67	1:70
4 (first section central, section decentral controlled)	1:1,5	1:10

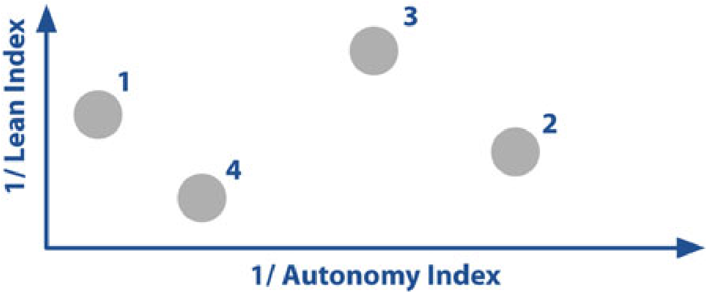

Fig. 4 Scatter plot for the analysis of the correlation of autonomy and lean index

5 Outlook

After the installation of the MES as well as the finalization of the construction of the hybrid simulation environment, it has to be analyzed how to record data relevant for the analysis presented from the MES. It would be possible to compare the results of several processes simulated. A template for the data dictionary is necessary. On this account a number of different autonomous processes have to be analyzed firstly. All relevant information will be extracted and documented separately. A comparison allows the recognition and filtering of recurring data. With the creation and comparison of numerous scatter plots regularities are worked out. It is examined whether it is possible to define rules regarding specific industries or manufacturing techniques.

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