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Exploitation of Manufacturing Flexibilities in Decision Methods for Autonomous Control of Production Processes

Findings from Industrial Practice and Theoretical Analysis

Nicolas Gebhardt, Oliver Jeken, Katja Windt

The complexity of nowadays logistics processes calls for new approaches to improve the logistics performance. The recently discussed concept of autonomously controlled logistics processes promises to improve coping with the dynamics and complexity in logistics systems. Autonomous decision making of intelligent logistics objects requires decision alternatives within the processes. Manufacturing flexibility is a provider for decision alternatives as it offers multiple ways to perform a manufacturing process. A key flexibility for decision alternatives can be found in a loose allocation of products and orders during the manufacturing process. In order to gain logistic advantage by autonomous control in production, decision methods are needed capable to disclose the logistic potential of alternatives in manufacturing. This contribution presents the function of flexibility and its utilization by methods of autonomous control in production. For this purpose an analog application in industrial practice is observed to reveal insights of what autonomous control in production can look like.

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Introduction

Nowadays series manufacturing traditionally shows a strict linkage of orders and products. The need to serve a high variance of customer requirements and to decrease internal production complexity at the same time provokes companies to standardize and simplify the processes of order management in production. Quick reactions on unpredicted disturbances (e.g. quality problems, production breakdowns, late order changes etc.) do include the reallocation of goods to customer orders rarely automatically but more as a manual action on emergencies. The fix linkage between orders and products lead to restricted possibilities in production control (Windt and Jeken 2009).

Turning this linkage into a flexible and dynamic factor in production planning and control is one of the potentials that autonomous control in production exploits. It aims at improving the achievement of logistic targets by decentralized, independent and autonomous decision processes in production planning and control. Autonomous control in production utilizes flexibilities inherent to the production system but mostly unused so far. One of these flexibilities encountered is the mentioned dynamic assignment of production parts to customer orders. This additional flexibility is called the flexibility of order allocation (Windt and Jeken 2009).

The main purpose of this contribution is to examine the observed practice in an industrial steel making case study as a good example of what autonomous control in production can look like. The case will be presented in the first chapter which explains the steel making production and the observed practice. The second chapter will then go on to present the theoretical background of autonomous production control, covering basic principle, main potential, and so far developed methods. Special emphasis is put on aspects relevant to the case study. Based on the definitions of autonomous control the third chapter inspects similarity of the phenomenon observed in industry and the principle of autonomous control. Finally conclusions are drawn from the case in line with comparability. In the last section a prospect is given of current and future matters of research regarding the research on autonomous control in production being on the cusp of first applications.

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A present industrial practice akin to autonomous control in production

Even though research on applications of autonomous control methods for production control is still fairly infant, there are systems in current production giving an interesting insight of what applications of autonomous control can look like and what kind of limitations will appear. This chapter will introduce a case study of an industrial management practice comparable to autonomous control in production utilizing the flexibility of order allocation mentioned in the introduction. After a summary of theoretical perspective on autonomous control in the next chapter findings from the case are presented.

The industry of steel making – especially sheet metal production – is characterized by a fairly linear production network and by highly variant products (Figure 1). The main aspects of variety are the steel grade, dimensions, surface aspects and the type of material and coating. Make-to-order is the main strategy of order fulfillment.

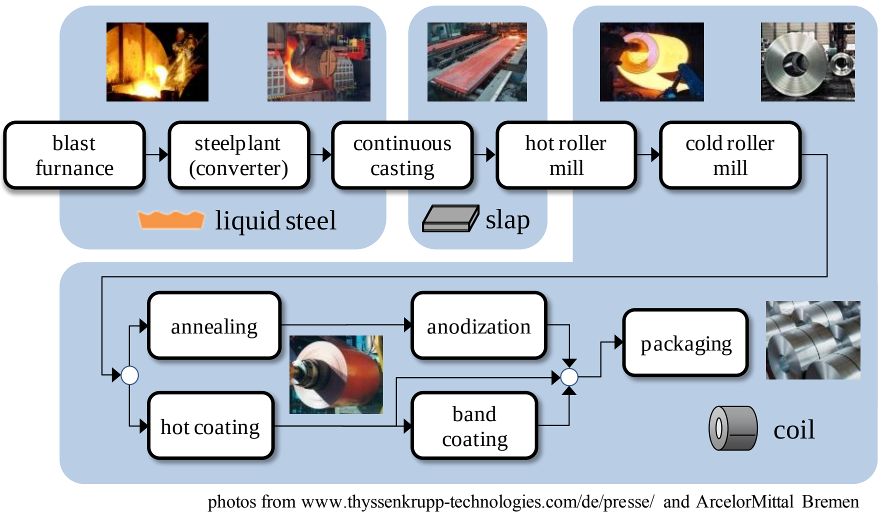

Figure 1: Process steps of steel sheet production (simplified chart)

The single production steps do inherent complex sequencing rules depending on specific material and process parameters. This leads to a structure of produc-

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tion planning and control which exhibits centralized rough planning and order management as well as decentralized short term planning and order sequencing of each production step (Tang 2001).

Due to high product variety – the steel grade by itself offers several hundreds of options to choose from – and customer individual order properties the single customer orders are considered to be unique combinations of customer relevant attributes. Nevertheless, flexible handling of material consignment is a common practice in the industry of sheet steel production. Production steps are usually performed on consigned parts only but the order management can change the allocation of products to customer orders in between production steps. This additional flexibility in production originates from the need of quick reactions on schedule violations, quality issues etc. In such a case the order management can interchange the consignments of steel slaps or coils to improve over all order compliance.

Triggering incidents of allocation changes come from different aspects. Reasons that appropriate an allocation change can be driven by

- aspects of the item (cast, slap or coil) and its current order allocation, e.g. quality issues and rejects due to defects; they cause a violation of the order requirements by the item and the need to detach the item from the order,
- the production status of the currently allocated order, e.g. excess of safety surplus of material, order changes by the customer at short notice and
- the production statuses of all customer orders with special regard to deficient orders, e.g. shortfall quantities, scheduling delay, high prioritized orders.

Figure 2 illustrates the process of allocation change. The affected objects and the information the allocation change is based on are highlighted. The main objective of performing order allocation changes is to increase the logistic targets achievement and order compliance. The logistics targets are short lead times, high due date reliability, high utilization, and low inventory (Nyhuis and Wiendahl 2008).

In the present case study the main objective of material allocation changes is reduced to increasing order lateness. This is due to features of the production system which was examined. On the one hand non-time related logistic targets have not been the main focus and current necessity of order allocations. On the other hand they are as well not affected heavily enough by changes of item allocation to orders.

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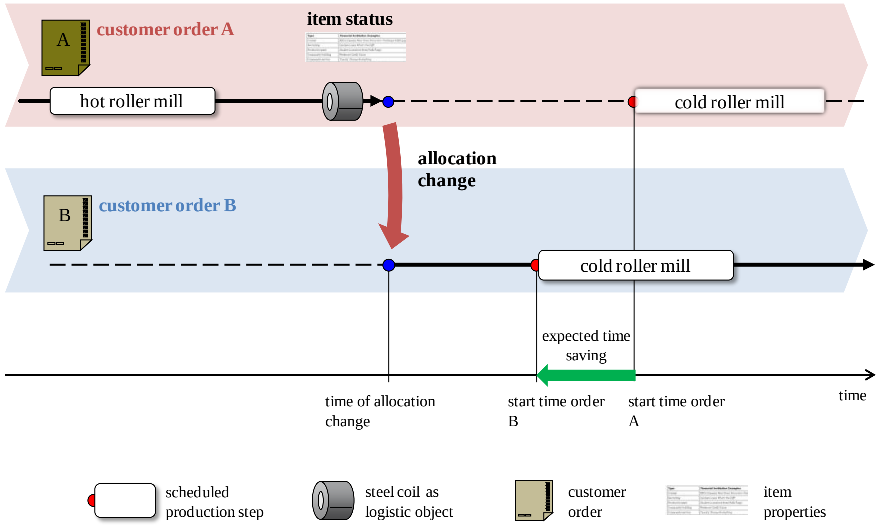

Figure 2: Allocation change of production items to customer orders

Referring to the example shown in Figure 2 the production item is processed while being consigned to the customer order ‘A’. At any time after the preceding process and before the start of the next pending process the consignment of the item can be changed. Customer order ‘B’ might show shortfall in the number of steel coils or might be tied by a coil far behind the order production schedule. Any reason mentioned above concerning the properties of the former assigned order ‘A’ or the item itself may interfere as well. In the example of Figure 2 a saving in throughput time of the item can be achieved by swapping items. Considering the objective of lowering throughput times in the observed case the potential of time saving and thus processing an item faster is the main target of allocation changes.

The examined practice of changing allocations of the production items from one customer order to another represents an action by the order management to reduce interruptions in the value flow within production. This case gives a good example of what a practical application of autonomous control in production can look like. The observed practice utilizes the additional flexibility of order allocation in a way that exhibits many of the characteristics of autonomous control. The

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total number of allocation changes per production output is large enough to draw significant conclusions[1].

For the research of autonomous control in production two interesting question arise:

- First, to what extent does the practice of allocation changes in the steel industry comply with the idea and definitions of autonomous control in production?
- Second, do the findings of allocation changes in the steel industry increase the level of achievement of the logistic objectives in production?

These questions are attended in the chapter "Comparison of the order allocation practice in steel making and autonomous control " unterhalb. First, the following chapter presents the theory of autonomous control in production and autonomous control methods.

[1] Due to reasons of secrecy obligation of the observed production company more details cannot be exposed.

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Theoretical perspective of autonomous control in production

Basic principle of autonomous control in production

The Collaborative Research Centre 637 "Autonomous Cooperating Logistic Processes: A Paradigm Shift and its Limitations" at University of Bremen and Jacobs University Bremen underlies a main hypothesis to autonomous control: A higher level of decentralized and heterarchical decision making can result in a better achievement of logistic objectives compared to conventionally managed processes despite increasing complexity (Windt et al. 2008). Conventional methods of production planning and control manage complexity in manufacturing by mostly inflexible scheduling and centralized computing processes. Regarding all available information in a centralized scheduling task will often lead to a very complex calculation. Schedule optimization usually leads to NP-hard problems where solution space grows faster than the speed of decision-making. Due to this fact central heuristics are used which cannot achieve optimal solutions or react on quick changes.

The idea of autonomous control in production tries to break this tie. Decisions are taken on the level of single parts and only regarding confined spaces of information and consequences. The decision capabilities are shifted from a central control to the system elements (Krallmann 2004). Distributed heuristics that operate on local knowledge can result in low decision complexity and acceptable performance. Single decisions are taken independently of each other on the basis of only a fraction of the global data. The range of impact is limited to only a few of the production steps pending next and to only one logistic object. Thus the logic functions of decision making become fairly simple – compared to centralized control methods – and can be executed much faster. The decentralization and the independence of decision making are main criteria of autonomous control. The processes of decision making are performed by the logistic objects or their agents (Scholz-Reiter et al. 2004).

> **Autonomous control in the field of logistics** is defined as "… the ability of logistics objects to process information, to render and to execute decisions on their own. (…) Logistic objects (e.g. part, pallet, order, or work station) that are able to fulfill these conditions are called **intelligent objects**." (Windt et al. 2008)

The idea includes the assumption that this strategy of decentralized and at first glance egoistic decision making will have a beneficial impact on overall logistic

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objectives of the whole system. Due to distributed and consequently more flexible decisions autonomous control can react better on high dynamics and complexity and thus increase system robustness (Hülsmann and Windt 2007).

To make this possible the deciding functions must regard not only their own state and the state of surrounding logistic objects like production systems but also the basic figures of an incorporated parameter set of business objectives. Furthermore the current aim of the production system – i.e. the production program or order book – must be part of the information the decisions are based on. The concept of autonomous control in production is in line with such approaches as "intelligent products" (McFarlane 2003) and "product-driven control" (Gouyon 2008), but extends these by a loose link of products and orders.

Manufacturing flexibilities as the main potential of autonomous control in production

A conventional production system will not provide decision alternatives in the meaning and suitable extend of autonomous control in production. However, the number of possible decision nodes and decision alternatives is crucial for the efficiency of autonomous control in logistics. The more decision nodes with a high number of decision alternatives exist within a logistic system, the higher is the logistics potential that can be realized with autonomous control methods. Alternative options in regard to the decision capacity of autonomous control in production systems can be provided by the degree of manufacturing flexibility as it offers multiple ways to perform a manufacturing process (Windt and Jeken 2009).

Manufacturing flexibility is generally regarded as the ability to adapt. Definitions related to manufacturing flexibility follow the idea of adaptability of a manufacturing system to uncertainties (ElMaraghy 2006), (Mandelbaum 1978).

"**Manufacturing flexibility** is (…) about alternatives that suit certain conditions from the outset." (Windt and Jeken 2009)

In order to implement autonomous control in production logistics the vision of an intelligent logistic object (e.g. part) or its representing agent is the underlying scenario. From the point of view of a single logistic object within a production system possible decisions can be categorized into selections of

- the allocation to a suiting customer order,
- the product variant within the remaining scope,

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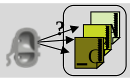
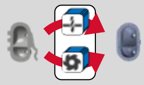
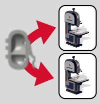
- the resources to be processed by, and
- the sequence of manufacturing steps.

The research results of the CRC 637 include a catalogue of manufacturing flexibility types that represents the decision space of autonomous control in production. By this it will even be possible to derive a set of indicators for the degree of autonomous control flexibility provided by the production system. The catalogue of five types of manufacturing flexibilities was established in a systematical structure incorporating all common elements constituting a manufacturing system. The catalogue represents a set of independent measures for manufacturing flexibilities useable in autonomous control in production as a provider for decision alternatives (Windt and Jeken 2009). Table 1 shows the catalogue of manufacturing flexibility types including degrees of freedom which can be formulated to operationalize manufacturing flexibility.

Table 1: Catalogue of manufacturing flexibilities (Windt and Jeken 2009)

Level	Element	Flexibility Type	Degree of Freedom
logical	order	Allocation Flexibility	convertible orders 
physical	resource	Machine Flexibility	different operations 
		Material handling Flexibility	multiple system paths 
		Volume Flexibility	workload variation 
	product	Operation Flexibility	different processing plans 

From the orders as logical element a new type of manufacturing flexibility arises, called allocation flexibility. It describes the flexibility of an order to be allocated to a different product or its unfinished precursor during a manufacturing process. An order specifies one or more product variants and due dates for the production. A product variant is a set of features where some features have slight-

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ly different specifications compared to the set of features of another product (Hribernik 2010).

Production resources and products are on the physical level of the manufacturing system. Related to the element resource are machine flexibility, material handling flexibility and volume flexibility.

The element product refers to operation flexibility. The design of the product directly causes a certain limitation in possible alternatives of production steps. Process planning and scheduling deduce production plans from the product data and thereby form a critical stage in the exploitation of manufacturing flexibilities for autonomous control in production.

Further details of the flexibility of order allocation

In general these manufacturing flexibility types are not unknown but fairly well researched, listed and classified (Wiendahl 2007). Nevertheless the allocation flexibility of products to orders is so far rarely used but an important potential to autonomous control in production.

> "**Allocation flexibility** is related to the order as it describes the flexibility of an order to be allocated to a different product or its unfinished precursor." (Windt and Jeken 2009)

Allocation flexibility depends on the availability of orders that a certain product can be allocated to. That means that a product, component or part in an early production state will most likely find a higher amount of suiting orders since it is less specified by further production processes. The amount of orders that a product can be allocated to at a certain point of time does depend on static and dynamic information. The product structure and the production system layout are static whereas the status of the order book and the features of the regarded part are dynamic. Altogether these types of information define the decision alternatives concerning order allocation. Supporting the utilization of allocation flexibility for autonomous control in production the variant corridor has been developed. The variant corridor is an approach providing each item with all combination of product variant and customer orders it can currently be allocated to. In short, the variant corridor assembles all decision alternatives of a part or component for each manufacturing step. It then draws off any alternative not obtainable anymore due to an advanced process stage of the product or not included in the current orders. Thus the product variant corridor represents the range of possible production alternatives for a given production stage and matches them with the actual customer orders.

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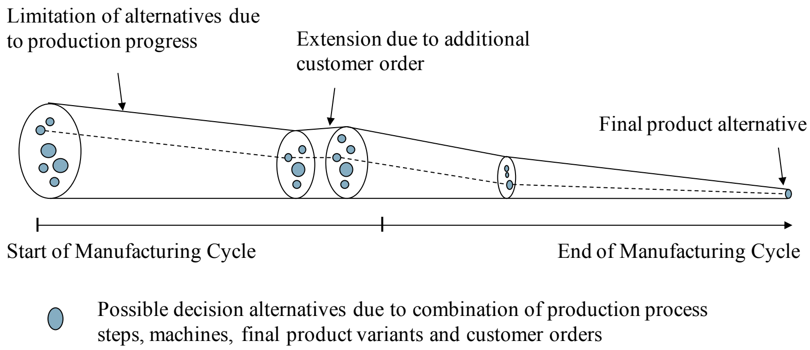

Figure 3: The Product Variant Corridor as a representation of allocation flexibility (Windt and Jeken 2009)

Each production step applies more features to the product parts or components. A feature is a property that is added to a product (geometries, mechanical behavior, mounting etc.). Thus a production step can only decrease the amount variants possible to be met by the product, part or component and the corridor narrows down along production progress. However, it can expand again in the case of new emerging and obtainable customer order. Only after a customer decoupling point, the potential a dynamic product-order allocation is exhausted (Hribernik 2010).

Methods of autonomous control in production

The principle of autonomous control in production leads to two separate fields of prerequisites of practical application. First logistic objects need to have the technological capability to be identified and traced within the production system and to share information with the system environment. Secondly the fully decentralized scheme of decision making calls for the technical and methodical capability of processing data and rendering decision. This chapter discusses the methodical requirements of autonomous Control for logistic items in production systems.

The actual execution of logistic decisions requires the capability of the production system to act upon the items' commands. In order to execute a decision alternative the product has to communicate the decision to the material flow system, which then organizes the necessary processes (Hribernik 2010). The ability of logistic items to autonomously navigate through a production system becomes more and more possible since recent developments (e.g. information and communica-

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tion technologies, e.g. radio frequency identification, global positioning system or universal mobile telecommunications system) (Böse 2005).

Studies on computing times of the decision making process show that autonomous control methods derive decisions faster than conventional approaches can do (Windt 2008). Nevertheless a boundary of autonomous control that needs to be dealt with in future will be the calculating capacity of logistic objects. Running times of single decisions in autonomously controlled systems increase with the system complexity and level of autonomous control. These two aspects in combination can lead to decision times too long for the dynamics of the certain system. The question is how much computing capacity can be fitted under economically reasonable conditions. Autonomous control might suffer in the possible level of computing capacity due to practical and economical reasons.

In an autonomously controlled system each system element has to be a decision unit equipped with decision-making competence according to the current task (Frese et al. 1996). Concerning the available options provided by the manufacturing flexibilities shown in Table 1 the decision process of a logistic item taking autonomous control has to fulfill the following set of tasks. According to decision theory the process of decision making incorporates five sub processes (Laux 2007) which are

- describing the problem,
- defining the target system,
- generating decision alternatives,
- evaluating the decision alternatives according to target system and
- executing the decision alternative with the best target contribution.

Concerning a typical job-shop manufacturing the logistic items have to be able to decide about the next production process step, according to which product variant it decides for, on which machine and for which customer order it will get manufactured. The decision space derived by these tasks is shown in figure unterhalb.

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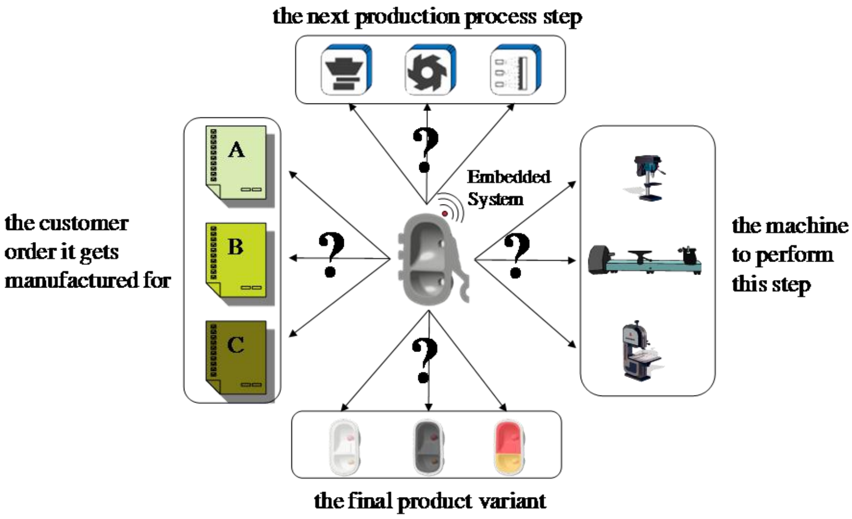

Figure 4: Decision-making of autonomously controlling logistic items in a typical job-shop manufacturing (Windt et al. 2010d)

Within the decision-making, gathering the decision alternatives is critical to the performance of autonomous control in production. As described above each decision is taken by or for a single item and before each production step. The decision alternatives are especially available for product structures with many variants, as one component of a product can precede for different final products variants and for different customers. Generating decision alternatives requires the necessary information from the relevant environment of the item. In addition to generating the alternatives there is a need for further information in order to evaluate these alternatives. All this information encompasses

- the amount of obtainable final product variants,
- the possible production processes,
- the accessible machines for the different available production steps,
- the current situation at the available machines (capacity, work in progress, planed idle times, machine breakdowns etc.), and
- the current demand situation.

In the research work of the CRC 637 several different autonomous control methods have been developed and tested. Others were invented without explicitly naming them autonomous control methods and have been integrated into the ap-

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proaches of the CRC 637. Several studies comparing the performance and behavior of autonomous control methods have illustrated that autonomous control can realize a higher logistics target achievement in comparison to conventional production planning and control (Rekersbrink et al. 2009), (Scholz-Reiter et al. 2009), (Windt et al. 2010c).

“Autonomous control methods describe the logistic objects’ target systems, the way they interact and how and when decisions are taken.” (Windt and Becker 2009).
“An **autonomous control method** is a generic algorithm that describes how logistics objects render and execute decisions by their own.” (Windt et al. 2010c)

A key demand on autonomous control methods is the lack of influencing the basic functionality of the production process in terms of process structure, elements and tasks. There are many different ways an autonomous control method can operate. Always it will have to be designed or at least adjusted to an existing logistic process. In this volume, the article “A Comparative View on Existing Autonomous Control Approaches” presents simulation results comparing the performance of several autonomous control algorithms. In (Windt and Becker 2010b) and (Windt et al. 2010c) one can find simulation studies analyzing the behavior of the most advanced and promising methods so far.

The table unterhalb lists examples of autonomous control methods along with their principles.

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Table 2: Selected examples for autonomous control methods from a simulation approach on a car terminal (Wind et al. 2010c)

Name	Description
Ant Pheromone	After an item is processed at a work station it leaves a fixed amount of pheromones which add up with the already existing amounts at the station; over time the pheromones slowly evaporate. Stations with higher pheromone levels are stations with better throughput and are therefore preferred by the following items.
DLRP	Parts request a route from machines; machines communicate best routes to a destination.
Holonic	Two agents bargain over the next item to be processed. Agents are machines and management; the management punishes machines for delays and machines bid to get jobs from management.
Queue Length Estimation	Choose work station with lowest queue length (number of items)
Simple rule based	Compares estimated waiting time at buffers using future events. The parts are rated in estimated processing times and current buffer levels are calculated as a sum of them. Parts choose the machine with the lowest processing time buffer.

The “Ant Pheromone” method for example is inspired by ants’ foraging behavior. It uses virtual pheromones emitted by the parts at a station when they are processed by it; pheromones add up with the already existing amounts at the station; over time the pheromones slowly evaporate. Stations with higher pheromone levels have better throughput and are therefore preferred by following items. The “Simple Rule Based” method represents an example from a group of methods. In this method each semi-finished part chooses the next production step by preferring the machine with the lowest number of waiting items in front of it.

Autonomous control methods showing similar attributes in design and principles can be pooled in an autonomous control strategy.

> “An **autonomous control strategy** is a generic term that summarizes multiple autonomous control methods which have common design patterns.” (Windt and Becker 2009)

Examples for autonomous control strategies are “Rational Strategies” which use statistical approaches in order to predict future states of the logistic system for taking decisions (Scholz-Reiter et al. 2007). This could be calculating the past average throughput time or queue lengths for each process step. “Bounded Rationali-

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ty" is an autonomous control strategy deciding with help of simple heuristics without performing large data collection or intensive calculation (Simon 1997). The category of "Combined Strategies" summarizes approaches combing autonomous control methods from the other categories in parallel and using a weighted average of the different decision results (Scholz-Reiter et al. 2007.).

The decision function of a product in an autonomously controlled production system will operate in a decision space based of the manufacturing flexibilities described above (refer to Table 1 and Figure 4). Consequently, the physical results of a single decision will be the next production step of an item and the allocated machine or other kind of logistic resource. Informational results are the allocation of the item to a certain product variant as production outcome and to a certain customer order (Windt et al. 2010d). Decision criteria on the other hand can be derived from the available information listed above.

The decision criteria taken into account incorporate information from local and global domains of the production system. Each system element in an autonomously controlled system is characterized by target oriented behavior. This means that global objectives – e.g. provided by the corporate management – can be modified independently by the decision functions in compliance with the objectives of the autonomous item. The decision functions of a specific autonomous control method can derive an individual set of weighting coefficients for each item and decision, consequently blending the strategic positioning of a company and the ideal decision from the items' perspective (Windt et al. 2010a)

Table 3 shows a selection of autonomous control methods developed and tested so far. Studies on the topic of autonomous control methods classification show that the existing methods mainly differ from each other in terms of performance and applicability. The most important distinctions have been discovered in the following criteria.

- **Temporal data** can be used by the method from the past, future, or both.
- Methods exhibit different **number of planning steps**, i.e. the number of considered production steps in the future.
- The decision process can create **artificial values** (apart from external information), e.g. pheromones or virtual costs, and then use or pass this data.
- The **type of communication** of items, machines and data bases differ.
- Methods will use various **data scopes** for decision making,
- The decision itself can be calculated by different **actors**, e.g. the items, machines, agents etc., and

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- the place of **data storage** can alter.

These criteria form a set of parameters eligible to classify autonomous control methods (Windt et al. 2010c). In this volume, the article "A Comparative View on Existing Autonomous Control Approaches" simulation results are presented which show the differences in performance of several autonomous control methods in an industrial application. The study shows that autonomous control methods will have to be carefully chosen, adapted or even completely designed for a specific application scenario. Tailor-made solutions will be the first way of implementation for a considerable long time.

Autonomous control in production rests upon flexibilities of a production system. These flexibilities have been limited or left unused so far for the sake of simplifying the centralized production planning and control. The decentralized and autonomous decision strategy of autonomous control is restricted to local precincts. This enables autonomous control to exploit the inherent flexibilities in order to improve the system performance.

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Comparison of the order allocation practice in steel making and autonomous control in production

From the case study presented in the oben chapter "A present industrial practice akin to autonomous control in production" conclusions can be drawn concerning autonomous control. In this chapter the question of comparability and generalizability of the case will be dealt with (as stated at the beginning of this article). After that the findings and conclusions are presented.

In order to find to what extent these conclusions are valid for autonomous control first the compliance of the observed phenomenon with the idea and definitions of autonomous control in production has to be identified. If there is a certain scope of compliance the findings about the phenomenon can be generalized to autonomous control within the extent of this scope (Atteslander 2003). The performance of allocation changes in the steel industry can give an indication of the performance of autonomous control if they are proven to be similar.

Similarity of observed phenomenon in steel industry to autonomous control

The similarity of the observed practice and autonomous control is tested by applying the main definitions of autonomous control to the case. The definitions are presented in the chapter "Theoretical perspective of autonomous control in production" oben. The resulting test questions are listed in Table 3. The findings of the assessment questions are discussed below.

Table 3: Test of similarity between the observed allocation practice in steel industry and autonomous control

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No.	Subject	Testing question	Finding
1	Exploited flexibility	Is the exploited flexibility within scope of autonomous control in production?	Yes
2	Autonomy	Do the logistics objects process information, render and execute decisions by themselves?	No
3	Structure	Is the planning and controlling decentralized and heterarchical?	Mostly not
4	Impact	Is the range of impact limited to only the production step pending next?	Yes
5		Is the range of impact limited to only one logistic object?	Mostly yes
6	Information	Are decisions taken only regarding confined spaces of information?	Yes
7	Decision making	Decisions are taken independently of each other?	Mostly yes
8		Are the functions of decision making are fairly simple compared to a centralized strategy?	Yes

Question number one in Table 3 refers to the manufacturing flexibilities which are seen as the underlying potential which can be utilized by autonomous control in production. However, a positive answer to this question is not mandatory to prove similarity of the case and autonomous control since finding a new flexibility cannot be foreclosed. In this case the exploited flexibility matches the idea and definition of the allocation flexibility described above (refer to chapter "Further details of the flexibility of order allocation"). For the new allocation of items only the shortfall quantities of existing manufacturing orders are taken into account.

The second question aims at one of the main objectives of autonomous control in production which is the shift of planning and scheduling tasks to the logistic items. Of course this is not the case in the observed phenomenon. Hence no conclusions will be valid related to the physical implementation of decision making. The question is, though, if the discovered processes of decision making equals to the idea of autonomous control. The following checks number three to eight consider this aspect and therefore answer this question.

The process of production planning and controlling is not decentralized. However, changing the allocation of items can be performed by the local control of workstations.

Questions number four and five deal with the effects on the production throughput that a single decision of an allocation change have. The parts in production are consigned to a certain order. Changes are not taken back after the upcoming production step and the new allocation will remain until the next change

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or finishing of production. The production sequences only depend on the specific customer order. Concerning the allocation change itself the decision does only affect the production plan of a single item. Nevertheless, if the reasons leading to an allocation change described above apply to more than one item, the conditions allow considering this as an accumulation of single events.

The question number six in Table 3 addresses information processing. In autonomous control only a limited amount of information shall be taken into account in each decision process. By this the decision complexity remains low and the decision speed can be maintained. In the observed case the space of information consists of the current production state of the item, the attributes of the order it is allocated to and the orders showing any applicable deficiency.

Concerning the decision function of allocation change the independence and the simplicity are to be assessed. The characteristics of the observed practice cover a broad range of these attributes. Compared to a complete and central optimization of all items' allocation the decision making is fairly independent and simple.

The comparison of the allocation practice in the steel industry and autonomous control shows that findings from the case study can be transferred regarding most aspects. Conclusions about facts based on the independence of decisions are to be seen invalid in the first instance, as well as conclusions about the technological application of autonomous control. Certainly the attributes of independence and decentralization are vital aspects of autonomous control. As a result this case study can give a good insight and incitement to the development of autonomous control but cannot achieve the preconditions of an example application.

Observed benefits of dynamic order allocation practice in steel making

As described above the main intent of the allocation changes in steel industry is to improve due date reliability and order compliance in production. Non-time related logistic targets are not affected heavily enough by changes of item allocation to orders.

The following Figure 5 shows a summary of the findings about the order allocation changes.

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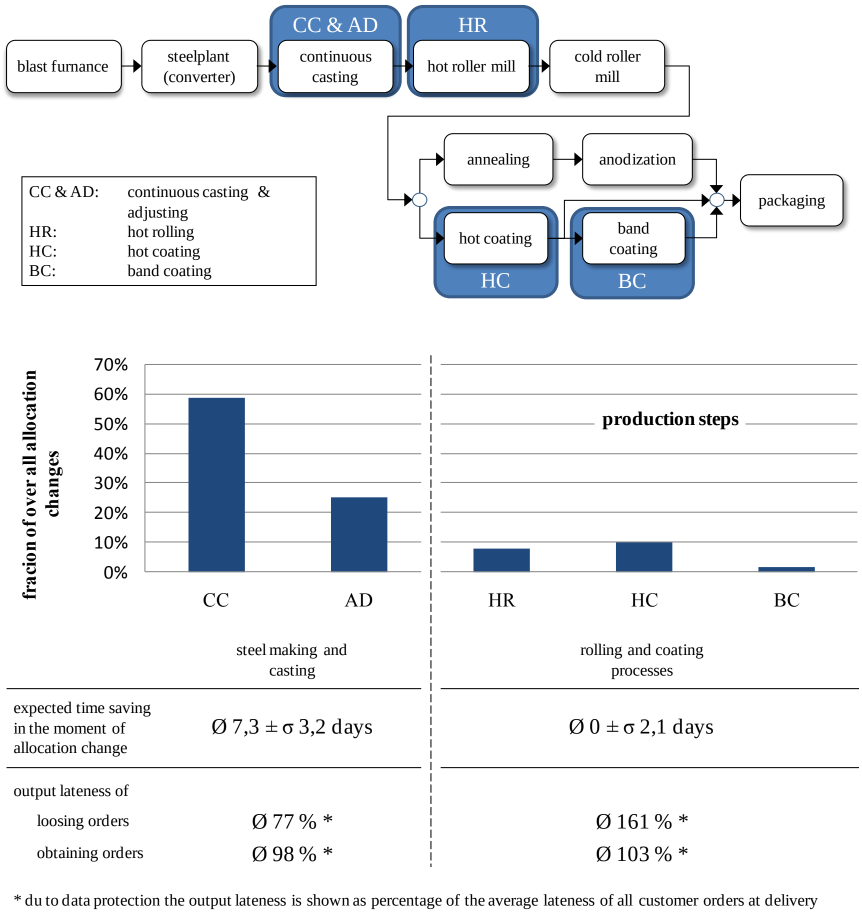
Figure 5: Figures of allocation change performance



The study includes the five process steps with the highest number of order allocation changes as illustrated in Figure 5. Altogether, theses five production steps raised nearly all of the allocation changes.

Most of the allocation changes happen in earlier production steps. The high product variety of the steel coil industry shifts a high number of allocation changes in the very beginning of the production where many product variances can still

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be fabricated from each single item. Each production distinguishes roughly the same portion of final product features. Thus the variant corridor of the steel production will constantly shrink along the production process (refer to Figure 3). New customer orders are released by introducing new items into the production, thereby leaving no shortfall quantities right away which could be assigned by the production items along the process. Due to reasons of secrecy obligation in this case the total number of allocation changes per production output cannot be released. However, the amount of events is large enough to draw significant conclusions.

Figures show that together with the diminishing amount of decision alternatives the number of allocation changes abates quickly along the production sequence. At late production steps less time remains to meet the customer orders in terms of quality and quantity. A smaller number of decision alternatives give less potential of improvements by reallocating the product items.

The potential of order allocation changes becomes evident in the expected time saving measured as shown in Figure 2. The decision of the new allocation is primarily based on a comparison of the production schedules of the considerable orders. The aim is to process the items as fast as possible by allocating them to the most urgently pending one among the suitable orders. The allocation changes performed in the early production steps of steel making feature much higher time savings. The allocation changes conducted in late production steps hardly show any time saving at all. Apart from the fact that less decision alternatives can be expected and exploited in late production, these steps exhibit a lower variance of throughput times – thus lessening the need for compensation of lateness by allocation changes.

Finally, in Figure 5 the lateness of all orders affected by the allocation changes in the certain production levels are shown. Interestingly enough, orders that where influenced by an allocation change in early production steps were finished on time or even early. Orders affected by allocation changes at the end of the production sequence, however, show a significant lateness. These findings correspond to the observed expected time savings and to the industry experts' anticipations on the topic.

The observed practice of order allocation strategy similar to autonomous control is qualified as a good perspective on autonomous control in production. Dynamic and decentralized reallocation of production items is successfully used in the steel industry for improving due date reliability. Nevertheless, the later the changes in allocations are performed, the less the effect on the objectives. As a possible conclusion for the research of autonomous control in production the find-

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ings indicate boundary conditions for the exploitation of allocation flexibility as a potential for autonomous control. Furthermore the case shows the applicability of the catalogue of manufacturing flexibilities (refer to Figure 4) as a basic set of measures for autonomous control potentials.

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Prospects on current research of autonomously controlled logistic systems

Research work of autonomous control in production is currently passing the cusp of application. Several studies show that autonomous control utilizing flexibilities in logistic systems as new decision alternatives can improve the achievement of logistic targets.

At the same time simulations have been conducted that display the divergent properties and behavior of methods of autonomous control in production. This raises the necessity of focusing future research on the limitations and characteristics of single methods of autonomous control in production since their diversity will place new dimensions in the research of autonomous control. They all will have to be analyzed with their own impact on the limitations of autonomous control. The contribution in this volume “A Comparative View on Existing Autonomous Control Approaches” represents a first access into this field of research.

The presented case of dynamic order allocation practice in industry gives a good example of what an application of autonomous control in production can look like. The case emphasizes the potential of autonomous solutions that act on sub processes of production or sub tasks in planning and control. At the same time the case demonstrates that autonomous control in production strongly depends on manufacturing flexibilities as elementary prerequisites. Flexibilities that can be exploited by autonomous control can be classified by the established catalogue of manufacturing flexibilities. In order to design an economically reasonable application of autonomous control in production these flexibilities will have to be identified in the specific system. They are determined not only by the production system but by the product structure and design as well as they majorly restrict process design in production and thus the potentials of autonomous control. In future research enhancing the performance of autonomously controlled production will have to be focused on the collaborative identification of manufacturing flexibilities that can support autonomous control performance. Autonomous control solutions coming from an integrated perspective on the production resources, products, planning and control are most promising for offering the high potentials of increasing the achievement of logistic targets in production by autonomous control.

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