Allocation Flexibility - A New Flexibility Type as an Enabler for Autonomous Control in Production Logistics

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Abstract
A so far unused system inherent manufacturing flexibility potential, which is named allocation flexibility, is presented in order to achieve a better fulfilment of logistic targets using autonomous control. The discovery of this new type of manufacturing flexibility demanded for an assessment of already described types of manufacturing flexibility and for development of a new framework of manufacturing flexibility types. For this purpose the basic elements of a manufacturing system are examined to structure and classify the different types of manufacturing flexibility. The result is a criteria catalogue which enables to verify the suitability of a manufacturing system for the application of autonomous control methods.

Keywords:
Classification, Flexibility, Manufacturing

1 INTRODUCTION

Series manufacturing of single items with many variants is traditionally characterized by a fix link between orders and products. Unpredicted disturbances, e.g. unreliable suppliers, short notice due date changes by customers, machine breakdowns, and quality problems, call for a quick and suitable reaction of the production control. The fix linkage between the order and the product locks system inherent flexibility potential, which can be used to enlarge the decision field in order to increase the number of options to cope with the current challenge. Within the Collaborative Research Centre 637 “Autonomous Cooperating Logistic Processes: A Paradigm Shift and its Limitations” at University of Bremen and Jacobs University Bremen autonomous control methods are investigated with the aim of developing these potentials resulting in a higher achievement of the logistic objectives (short delivery times, high due date reliability, low capital tie-up costs, high capacity utilization). The idea of autonomous control in the logistics context is to enable single entities to render information and to make decisions on their own [1]. Logistic objects (e.g. part, pallet, order, or work station) that are able to fulfill these conditions are called intelligent objects.

The central thesis the CRC investigates reads as follow: The implementation of autonomous logistic processes provides a better accomplishment of logistic objectives in comparison to conventionally managed processes despite increasing complexity; more precisely autonomous control presumes a certain level of complexity as a completely predetermined system would not allow implementing any decentralized decision-making. Figure 1 illustrates the relation between level of autonomous control and achievement of logistic objectives. Today’s production planning and control methods allow already a high achievement of logistic objectives, but there is still some logistic potential to be developed. In order to develop the open logistic potential increasing the level of autonomous control is considered to be promising. Despite the assumed improvement in the achievement of logistic objectives a certain degree of autonomous control will probably lead to chaotic system behaviour and results in lower achievement of logistic objectives [1]. One of the current aims in the CRC is the identification of boarders of autonomous control of logistic processes.

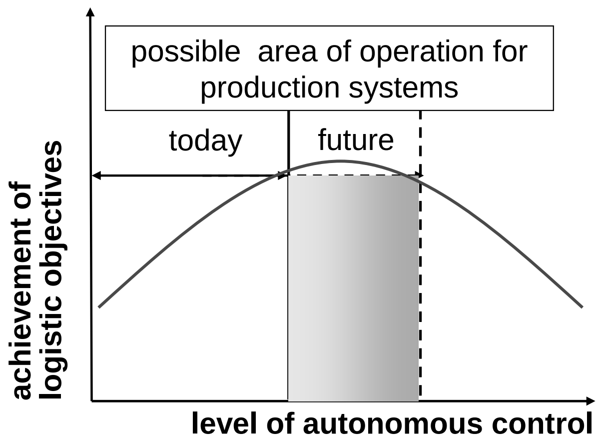

Figure 1: Area of operation for production systems.

Suitable autonomous control methods for logistics can be found in several scientific disciplines. Bio-analogical strategies (e.g. pheromone based ant-algorithms) and rational autonomous control strategies (e.g. rule based decision methods and queue length estimator) are just two examples [2]. Independent from the applied autonomous control strategy the number of possible decision nodes and decision alternatives is crucial for its efficiency.

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. Manufacturing flexibility is a provider for decision alternatives as it offers multiple ways to perform a manufacturing process. Hence, this paper will address the classification of manufacturing flexibility types from an autonomous control perspective.

Following the preceding introduction to aspects of autonomous control of logistic processes this paper will introduce a new approach to implement autonomous control in production logistics. The idea of this new approach for the implementation of autonomous control methods triggered the discovery of a new type of manufacturing flexibility. Existing approaches to classify manufacturing flexibility will be reviewed in order to incorporate the new type of manufacturing flexibility. A new framework of manufacturing flexibility will be presented which complies with the new findings. In order to assess the implementation potential of manufacturing systems for autonomously controlled processes a criteria catalog will be developed. Finally, the new criteria catalog for manufacturing flexibility types will be illustrated with an example of a manufacturing scenario.

2 AUTONOMOUS CONTROL IN PRODUCTION LOGISTICS

The typical job-shop-scheduling leads to NP-hard problems. These are characterized by the fact that the solution space in the sense of decision alternatives grows faster than the speed of decision-making on the decision nodes. Central control methods rely on heuristics which cause time intense calculations and normally lead to suboptimal decisions. During these time intense calculations the circumstances for which the scheduling is planed, can change and in the end the final schedule becomes obsolete before being implemented. Therefore the production control is challenged to implement constantly changing schedules, facing simultaneous process changes that are neither recognizable nor capable of being influenced. Due to this fact it is not recommendable for non deterministic systems to conduct a complete scheduling for a longer period of time, rather decentralized control methods appear to cope better with such problems. Due to the focus on the particular object less parameter have to be considered and thereby the required number of computer operations can be reduced. Decentralized control methods can apply conventional decision methods which need less computer operations and as a result are time savers [3]. This reduces the probability of simultaneous operation changes. Consequently autonomous control unlocks new logistic potential in the context of complex dynamical changing process structures.

In order to implement autonomous control in production logistics the vision of an intelligent logistic object (e.g. part) is the underlying scenario. The intelligent part is able to select its own construction cycle, meaning to decide about what, where, when, and for whom it gets produced. More precisely that includes selection of resources to be produced on, decision about sequence of manufacturing steps, variation of operations, and allocation to customer orders. These decision alternatives can be described as different types of manufacturing flexibility. Many of these manufacturing flexibility types are not unknown, but a so far unused important flexibility potential is available by using a loose and situational allocation of product variants and customer orders instead of having fixed allocations. This new type of manufacturing flexibility is termed allocation flexibility.

To exploit the potential flexibility a new autonomous control method will be developed, which allows the individual work pieces during their production to make their own decisions. Previous concepts such as product development process, product lifecycle, etc. do not describe precise enough, the idea of this new approach. Therefore, the term autonomous product construction cycle is introduced. A product construction cycle covers the period from order release to completion of a product type and refers to the gradual (relative to the product structure level) and type oriented construction of the product. The adjective ‘autonomous’ characterizes the self-determined development of the component or assembly towards a final product type, which outcome is flexible during this process. Autonomously controlled logistic objects allow for example, that missing parts recognize themselves as early as possible and forward this information directly to the affected logistic objects in the assembly stage. In the assembly stage the logistic object can decide, depending on the degree of assembly, whether it changes for the emergence of another product variant and thus bypasses the issue of a missing part. At the same time it must be taken into account that the missing component of the postponed order is replenished or that the disturbance will be resolved. The method seeks for the best order-product type assignment and provides this for the manufacturing process.

All the different alternatives of the logistic objects can be displayed in a so called product type corridor shown in Figure 2. The product type corridor expresses which product types for a given production stage and a given number of possible customer orders are generally feasible respectively reasonable to be produced. The product type corridor narrows down or in the case of new emerging customer order expands again. Only after a customer decoupling point, which requires the specification for an individual customer, the potential of autonomous control in the sense of a dynamic product-order-allocation is exhausted. Hence, the product type corridor allows logistic objects to choose among different product types, as long as it is possible from the product structure.

Current types of manufacturing flexibility do not allow the use of the logistic potential that the introduction of autonomous control arises. Therefore existing frameworks of manufacturing flexibility types are discussed in the following in order to derive a new framework of manufacturing flexibility types.

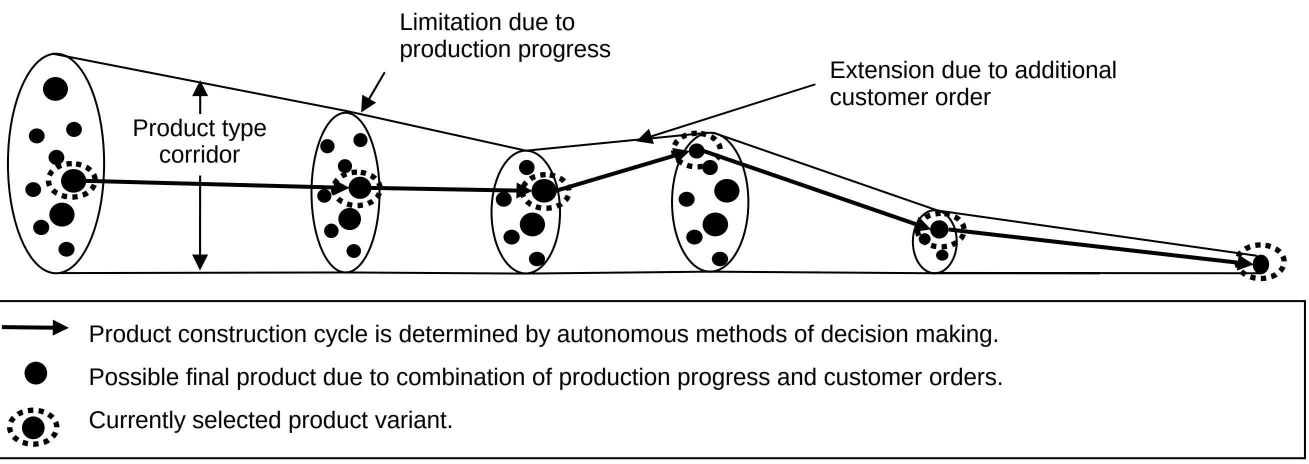

Figure 2: Product type corridor.

3 FRAMEWORK OF MANUFACTURING FLEXIBILITY TYPES

3.1 Definition of manufacturing flexibility

Manufacturing flexibility is a much researched topic according to Wiendahl et al. [4]. Several publications list and classify types of manufacturing flexibility. Apart from the different types of manufacturing flexibility there is also no coherent definition of manufacturing flexibility [5]. Manufacturing flexibility is generally regarded as the ability to adapt. According to ElMaraghy definitions related to manufacturing flexibility follow the idea of adaptability to uncertainties [6, 7]. Upton adds constraints to the definition allowing only little penalty in time, effort, cost and performance [8]. Manufacturing flexibility is therefore not about general availability of alternatives, but about alternatives that suit certain conditions from the outset. A different approach undertakes Chryssolouris by defining the flexibility of a manufacturing system as its sensitivity to change, thus choosing an indirect description of adaptability. According to this definition he proposes a mechanical analogy in order to measure manufacturing flexibility [9]. This analogy of manufacturing flexibility as a damping factor of a system indicating the sensitivity to an external impact is a black box approach. For the investigation of manufacturing flexibility as an enabler for autonomous control this is not appropriate, as it does not reveal the different elements of a system that contribute to the systems flexibility. For this paper manufacturing flexibility is defined as the ability of a manufacturing system to adapt.

3.2 Discussion of existing manufacturing flexibility frameworks

Different attempts have been made to structure various types of manufacturing flexibility into a framework. A survey done by Sethi and Sethi provides a comprehensive overview of manufacturing flexibility [5]. They identify more than 50 different terms for various types of manufacturing flexibility and organize them in 11 different types of manufacturing flexibility. These different types are summarized in Figure 3, showing the linkages among them.

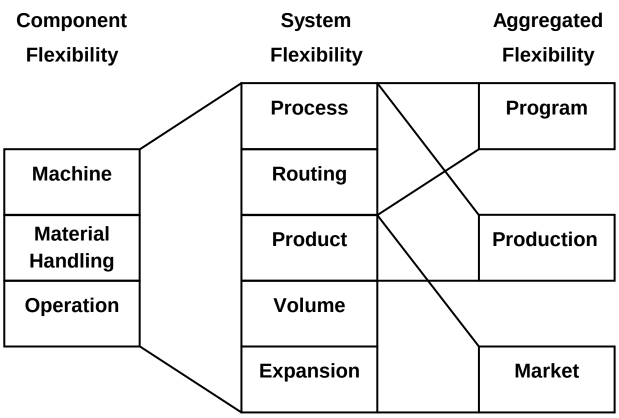

Figure 3: Linkages between various types of manufacturing flexibility [5].

The first column refers to manufacturing flexibility types of the important components of the manufacturing system, i.e., machines, material handling system and the parts to be produced. The second column lists manufacturing flexibility types that are related to the system as a whole. The remaining third column lists aggregated types of manufacturing flexibility. The figure shows that the aggregated types of manufacturing flexibility comprise certain manufacturing flexibility types of the system column (e.g. program flexibility comprises process flexibility and routing flexibility), whereas manufacturing flexibility types of the system comprise all types of manufacturing flexibility of the component column.

Rao and Mohanty list 12 different flexibilities and differentiate them in generic flexibilities, which express needs in the system or the system's environment, and coping flexibilities, which are the means by which the needs can be satisfied. Generic flexibilities can be distinguished in external e.g. volume flexibility, and internal e.g. design flexibility. Coping flexibilities are separated in hardware flexibility e.g. machine flexibility and software flexibility e.g. programming flexibility [10]. Even though this classification differentiates between a physical and a logical level of manufacturing flexibility, it does not cover the flexible allocation of customer orders to production orders as it is proposed in this paper.

Shewchunk and Moodie classify existing manufacturing flexibility terms into a scheme consisting of six attributes: level of manufacturing requirements specification, manufacturing system specification, manufacturing environment specification, flexibility dimension, flexibility measurement approach, and time frame [11]. Two of their findings shall be mentioned: Many terms, which are considered to be a single type of manufacturing flexibility, turn out to be composited of multiple manufacturing flexibility types (e.g. expansion flexibility and routing flexibility by Browne et al. [12], or product flexibility by Chryssolouris and Lee [13]). Apart from some manufacturing flexibility terms being consistent in terming and meaning among different authors, some identical terms can be found which have a very different meaning (e.g. machine flexibility by Browne et al. [12] and Carter [14]). They state that their framework cannot be used to identify the various types of manufacturing flexibility and suggest deriving them from a suitable model of a manufacturing system, taking into consideration the elements of the model and their relationships.

3.3 Derivation of new manufacturing flexibility framework

Out of many investigated frameworks for manufacturing flexibility types the one from Sethi and Sethi is the most suitable to be developed further and to implement the newly discovered type of manufacturing flexibility as it contains a view on the elements of a manufacturing system. Based on the discussion of existing frameworks for manufacturing flexibility types the following requirements for a new framework can be formulated:

- systematical structure,
- comprising all perspectives (e.g. order),
- no overlapping of different flexibility types,
- implementation of new manufacturing flexibility type: allocation flexibility.

Systematical structure

In order to develop systematically a new framework of manufacturing flexibility types a general description of a manufacturing system is used. Based on the elements of a common manufacturing system model and their relationships to another, different types of manufacturing flexibility are derived. In general a system consists of its elements and the relations between them. Figure 4 shows the basic elements that are commonly accepted to constitute a manufacturing system: order, product and resource [15]. In the following the elements of the manufacturing system model are described more precisely.

The element order represents the external customer demand for a specific product. It can be a predicted or a confirmed customer order, depending on the stockpiling strategy of the enterprise (e.g. built-to-order, built-to-stock). Furthermore it contains a specific delivery due date. The external customer demand is the driver for the decision about what to produce. During the manufacturing process the order is the logical representation of the final outcome.

The element product is the physical representation of the customer demand, which can be also called work piece, component or part. The product is desired to become the demanded outcome of manufacturing process.

The element resource represents all necessary means of production. That includes apart from the machines also the material handling facilities and the workers operating the facilities.

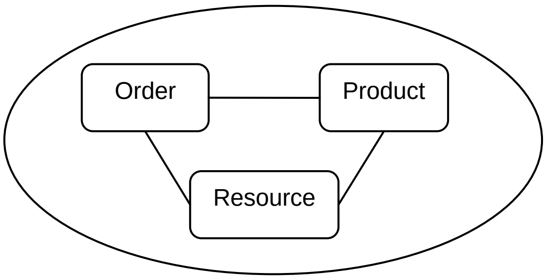

Figure 4: Basic elements of a manufacturing system [acc. to [15]]

Comprising all perspectives

In order to examine different types of manufacturing flexibility the basic elements of the manufacturing system are taken as perspectives on manufacturing flexibility. Figure 5 shows the perspectives on manufacturing flexibility. The clear reference to the basic elements of the manufacturing system avoids an overlapping of different types of flexibility. Further more it is not aspired to implement aggregated types of manufacturing flexibility, as they do not provide additional decision alternatives for autonomous control methods.

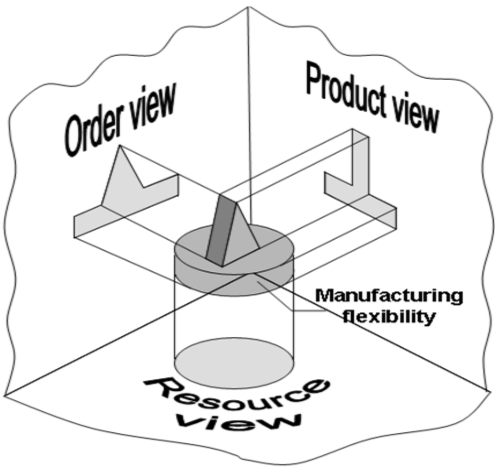

Figure 5: Different perspectives on manufacturing flexibility of an item. [on the basis of Wiendahl, H.-H.]

No overlapping of different flexibility types

Sethi and Sethi have differentiated the various types of manufacturing flexibility in component flexibility, system flexibility and aggregated flexibility (Figure 3) [5]. Component flexibility refers to the types of manufacturing flexibility that are related to the elements of a manufacturing system. It comprises machine flexibility, material handling flexibility, and operation flexibility.

'Machine flexibility (of a machine) refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another' [5][1]. According to the definition it is the ability of the machine to adopt and therefore it can be classified as a type of manufacturing flexibility related to the resource of the manufacturing system.

'Flexibility of a material handling system is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves' [5][2]. As this type of manufacturing flexibility clearly refers to the characteristics of the material handling facilities, it can also be related to the resource perspective on manufacturing flexibility.

'Operation flexibility of a part refers to its ability to be produced in different ways' [5][3]. As the definition states operation flexibility refers to the characteristics of the part. The part is an unfinished product according to the definition of the basic elements of a manufacturing system and therefore operation flexibility is related to the product perspective of manufacturing flexibility.

Implementation of new manufacturing flexibility type: allocation flexibility

After reallocating the different types of manufacturing flexibility on the component level of the manufacturing system the newly defined allocation flexibility can be integrated in the structure. 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. Figure 6 shows the link of the basic elements of a manufacturing system to the respective types of manufacturing flexibility related to the element including the newly defined type of manufacturing flexibility, termed allocation flexibility.

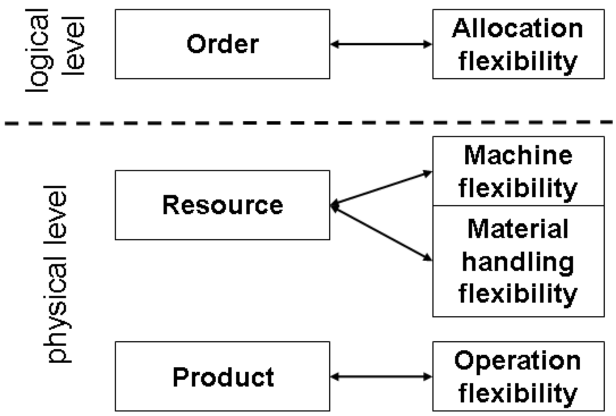

Figure 6: Basic elements of a manufacturing system linked to types of manufacturing flexibility.

In order to complete the new framework of manufacturing flexibility types, the types of manufacturing flexibility that are assigned to the system level have to be examined to identify whether they are aggregated types of manufacturing flexibility that can be deduced from manufacturing flexibility types on the component level or contain additional types of manufacturing flexibility. Sethi and Sethi have defined process flexibility, routing flexibility, product flexibility, volume flexibility, and expansion flexibility as manufacturing flexibility types of the manufacturing system. In the following each of them will be discussed whether they provide additional decision-making alternatives and therefore need to be

[1] p. 298

[2] p. 300

[3] p. 301

implemented in the framework of manufacturing flexibility types.

'Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups' [5][4]. Sethi and Sethi state that this type of manufacturing flexibility derives from the three types of manufacturing flexibility on the component level. Hence, it is not an additional source of decision alternatives and therefore not to integrate in the new framework of manufacturing flexibility types for autonomous control.

'Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system' [5][5]. Sethi and Sethi note that different machines, different operations, or different sequences of operations are required to find alternative routes. As operation flexibility already includes the option of interchanging operations or substituting operations by other operations to find alternate process plans, no additional decision alternatives for the application of autonomous control can be provided by routing flexibility.

'Product flexibility is the ease with which new parts can be added or substituted for existing parts' [5][6]. This type of manufacturing flexibility clearly refers to the manufacturing system as a whole, because it deals with the ability of the manufacturing system to handle new parts. Therefore it is not applicable as a source for autonomous control decision alternatives.

For the two remaining types of manufacturing flexibility related to the system level Sethi and Sethi do not explicitly note the relation to manufacturing flexibility types on the component level. 'Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels' [5][7] and 'Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed' [5][8]. Both types of manufacturing flexibility deal with ability to handle variations of the workload of the manufacturing system. Volume flexibility is related to variation of workload within the current capacity of the manufacturing system, whereas expansion flexibility refers to the variation of the capacity and the capability of the manufacturing system. The later is for strategic decision-making which is not part of the decision making of autonomous control methods at present. Volume flexibility on the other hand enables the manufacturing system to operate cost-effective on different workloads. This can be done by the variation of operating hours of the manufacturing system, for the short term by build-up or downsizing of overtime, internal exchange of workforce and for the middle term by additional shifts or short-time work. Volume flexibility can therefore be seen as a source for decision alternatives for autonomous control methods as it provides the ability to vary the workload and therefore enables the use of additional machines. Hence, it is a type of manufacturing flexibility related to the element resource.

Figure 7 shows the framework of manufacturing flexibility types related to the elements of a manufacturing system. On the logical level one can find the new type of manufacturing flexibility allocation flexibility related to the order. The elements resource and product 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.

Level	Element	Flexibility Type
Logical	**Order**	**Allocation flexibility**
Physical	**Resource**	**Machine flexibility**
		Material handling flexibility
		Volume flexibility
	Product	**Operation flexibility**

Figure 7: Framework of manufacturing flexibility types.

3.4 Criteria catalogue for decision alternatives

Many ways have been proposed to quantify manufacturing flexibility. Some have tried to grasp manufacturing flexibility in only one measure; others developed different measures for each single type of manufacturing flexibility. In order to determine the applicability of the introduced approach to implement autonomous control in production logistics manufacturing flexibility is considered as a provider for decision alternatives. Therefore criteria to assess the potential have to be focused on the decision alternatives that can be generated from the type of manufacturing flexibility. Allocation flexibility as the ability of an order to be linked to another product depends on the availability of orders that can be converted. That means that a part in an early production stage can change its desired final outcome and be allocated to the order. Hence, convertible orders are an indicator for the number of available decision alternatives. Machine flexibility refers to the ability of a machine to perform different operations. The ability to perform different operations allows machines to process different parts. To identify different decision alternatives the number of the number of different operations is a key indicator. The material handling flexibility describes the various parts and paths that can be operated by the manufacturing system. As an enabler for other types of manufacturing flexibility it provides connectivity among different machines. Hence, the number of system path is the criteria to assess this type of manufacturing flexibility. Volume flexibility is as material handling flexibility an enabler for other types of manufacturing flexibility as it allows to increase or to decrease the workload and created therefore additional options to produce parts. Therefore the workload variation is an indicator for the additional decision alternatives generated by volume flexibility. Operation flexibility refers to the ability of a part to be produced in different ways. This can mean a change in the sequence of the operations or the substitution of an operation by another operation. The total of these decision alternatives is represented by the number of different processing plans. Figure 8 shows the framework of manufacturing flexibility types enlarged by the criteria to assess the availability of decision alternatives for the implementation of autonomous control methods in production logistics.

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[4] p. 302

[5] p. 305

[6] p. 304

[7] p. 307

[8] p. 309

Level	Element	Flexibility Type	Criteria
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

Figure 8: Catalog of criteria for types manufacturing flexibility on the element level.

4 APPLICATION OF NEW CRITERIA CATALOG FOR MANUFACTURING FLEXIBILITY TYPES

In the following first the framework of manufacturing flexibility types will be related to certain steps within a manufacturing process. Second the catalog of criteria to assess the provision of decision alternatives for autonomous control related to different types of manufacturing flexibility is described considering as example a simple scenario of a three-stage jop-shop manufacturing.

Figure 9 illustrates the different types of manufacturing flexibility related to the elements of a manufacturing process. In this conceptional model there are 3 steps remaining to complete a product. For the first step (step A) three identical machines (machine 1-3) are available and connected via the material handling system. This provides machine flexibility as well as material handling flexibility and therefore the part can decide according to the implemented autonomous control method on which machine it wants to get manufactured. The target system of the decision is based on the achievement of the logistic objectives (short delivery times, high due date reliability, low capital tie-up costs, high capacity utilization). In case of high capacity utilization and therefore resulting long queues at the machines additional shifts (machine 1') can be introduced. This provides volume flexibility and enables therefore the fast processing of parts. If instead of step A the alternative step C is operated the part would change it final outcome from product variant type 2 (P_{var2}) to product variant type 1 (P_{var1}). This decision is based on the current set of customer orders and the production stage of the part and is termed as allocation flexibility. In the current case the link between order and product continues. If the part was allocated to the other order alternatively step D_1 could be executed before step C as the operations are interchangeable. This type of manufacturing flexibility is called operation flexibility.

Following the illustration of the different types of manufacturing flexibility as enabler for decision alternatives for autonomous control methods Figure 10 shows the application of the catalog criteria on a simple scenario of a 2x3-stage job-shop manufacturing. The illustrated job-shop manufacturing scenario has three steps, whereas the first two steps are production steps and the last one is an assembly step according to the previously described conceptional model (Figure 9). For each step two identical machines are available, which are capable of different operations. From the receiving area (Ra) the raw material is transported via a fork lifter to the machine. After the first production step is accomplished, the parts can be transported to the next machine or to final assembly step, depending on performed operation and the required outcome. The different criteria to assess the decision alternatives are exemplarily shown in the figure.

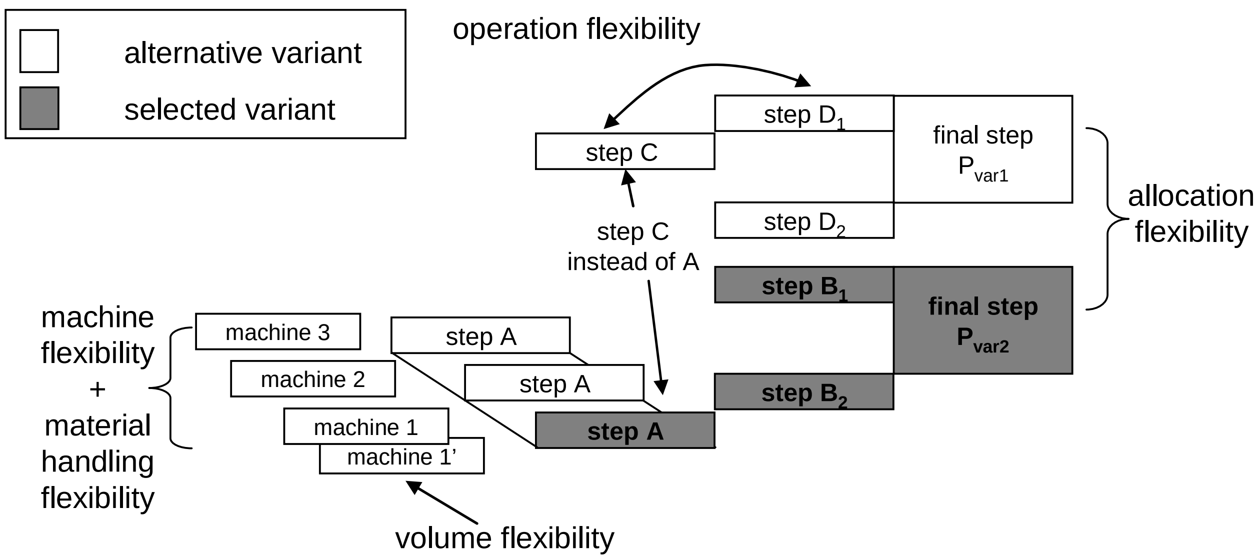

Figure 9: Illustration of manufacturing flexibility types.

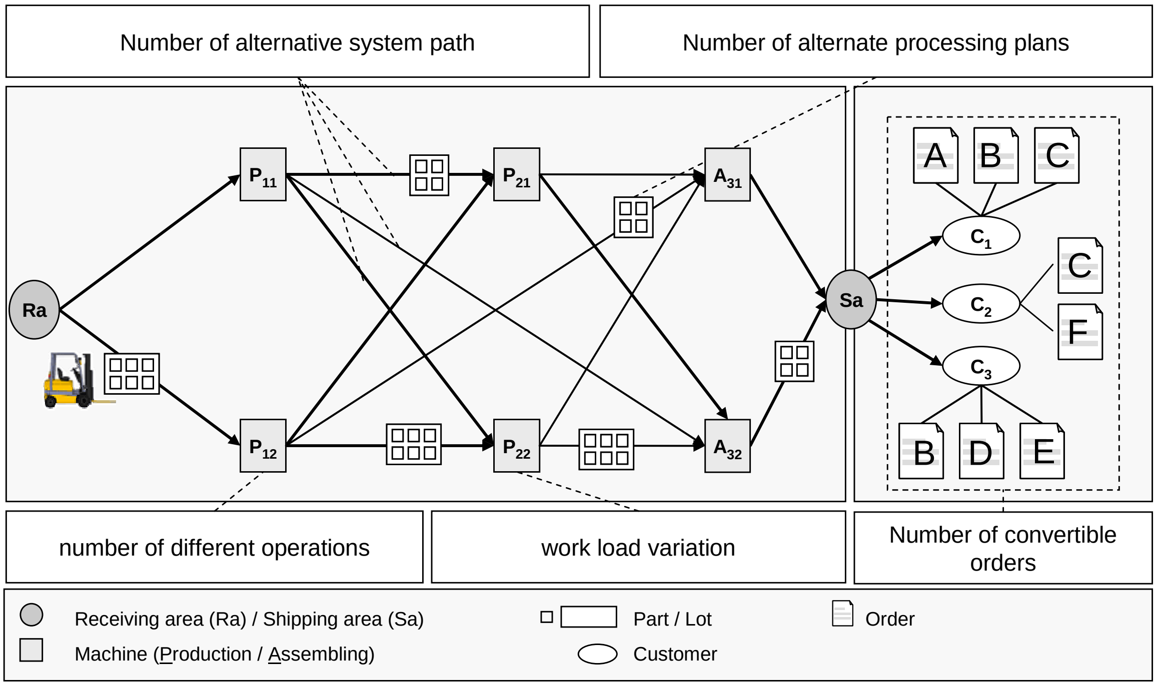

Figure 10: Manufacturing flexibility potentials in a simple job-shop manufacturing scenario.
[on the basis of Böse, F., Windt, K.]

The number of alternative system paths for example is highest after the first production step and decreases from then with each further production step until the part is finished and is brought to the shipping area. If a product has multiple processing plans and the machine flexibility allows performing the required operations it can be send directly to the final assembly after the production of Machine P_{12}. The variation of workload is a criterion for volume flexibility, which is required to adjust output of the machine according to its occupation. Finally the number of convertible orders indicates, to what extend the current order pool allows to change the linkage between orders and products.

5 CONCLUSION AND FURTHER RESEARCH

Autonomously controlled logistic processes are an appropriate approach to cope with the challenges of present manufacturing systems. To develop new approaches for autonomous control in the manufacturing context it is necessary to investigate the availability of decision alternatives within the manufacturing processes. This is essential as the successful implementation of autonomous control methods highly depends on the number of alternative options to perform operations. A new approach to implement autonomous control has originated a so far unknown type of manufacturing flexibility. Existing frameworks to structure and classify different types of manufacturing do not cover this new type of manufacturing flexibility. Hence, a new framework of manufacturing flexibility types, derived from a basic model of a manufacturing system, has been developed and is presented in this paper. Furthermore the new framework is enlarged by criteria to assess the implementation potential of manufacturing systems for autonomously controlled processes. Further research will focus on the operationalization of the criteria. Especially the newly defined type of manufacturing flexibility, allocation flexibility, with its criterion convertible orders is more difficult to determine, as the customer orders are variable in the course of time.

6 ACKNOWLEDGMENTS

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