

Determining the appropriate degree of autonomy in cyber-physical production systems

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Abstract

Existing factories face multiple problems due to their hierarchical structure of decision making and control. Cyber-physical systems principally allow to increase the degree of autonomy to new heights. But which degree of autonomy is really useful and beneficiary? This paper differentiates diverse definitions of autonomy and approaches to determine them. Some experimental findings in a lab environment help to answer the question raised in this paper.

Introduction

Today's manufacturing systems are large dynamic systems characterized by several machines and a large number of different products. Due to discrete events such as machine failures and repairs or demand fluctuations manufacturing systems are unreliable systems. The control policies of such systems must be able to react to these events and to minimize potentially negative impacts. The related control problem is an extremely complex one. This complexity is mainly due to the unreliability of the systems and the large number of machines and products involved [1]. Traditional approaches try to use different hierarchical planning approaches to address the underlying problems of complexity and lack of time for thorough problem solving. Research on future factory designs shows that a change from competing on cost to competing on value is necessary [2]. This change includes highly individualized products, co-operation of robots with workers and remotely controllable factories, to name only a few. Also, it is necessary to fine-tune the consumption of resources, esp. electrical energy to achieve ecological goals like sustainability [3, 4].

With the dawn of cyber-physical systems it is now possible to delegate a huge amount of decisions to lower levels of the hierarchical structure of the factory. It might be possible to reduce the complexity of the planning problem and to increase the ability of the factory to react to spontaneously upcoming disturbances. Unknown is, to which degree the competence for decisions can be given to the elements of a production system.

This contribution shows advantages of cyber-physical systems, gives an overview about prior and related research in the area of autonomous production systems and explains the gap in existing approaches. After providing a possibility to calculate the existing degree of autonomy, an approach to compare demands and supplies of autonomy is presented. This concept is evaluated using four case studies from manufacturing companies which manufacture products with different characteristics. In the last section, a research environment to further investigate the content is presented.

Traditional production systems

A production system is a complex socio-technical system of performing elements [5] which transforms an input with associated value-adding processes into an output [6, 7]. To fulfill the task of output generation, the organization (hierarchy), resources, humans and methods are needed [8]. A well-defined series of transformations [9] encompasses manufacturing as well as assembly tasks, with the help of additional material [10]. Production systems consist of technical, organizational and human elements [11]. The hull of the factory and the space necessary for production are considered part of the technical description of a production system. Machines and automation and information systems also belongs to the technical dimension of a production system. Organizational components are, beside methods, measures and tools, the organizational structure and the process organization. Human elements are the posts, their keepers and their person-bound knowledge.

Production systems and Cyber-Physical Systems

Cyber-physical Systems (CPS) are software-intensive information systems, embedded in high tech products and components and connected with each other using digital networks [12]. This allows a global usage of their data and services. Cyber-physical systems can be controlled using multi-modal human-computer interfaces. RFID is used for instance to monitor transportation processes. Formerly closed systems are opened up and can be connected with other systems to mashed and networked applications. The physical real world is connected using CPS seamlessly with the world of IT to an internet of things, services and data. Sensors capture physical data and influence physical procedures with actuators [13, 14]. Using the captured and analyzed data the cyber-physical systems interact with the physical world.

Because production systems consists of technical, human and organizational components, the influence of CPS has to be considered in all three dimensions. A consideration focused solely on technology will not cover all aspects and can lead to wrong conclusions because side effects on organization and humans were not noted or considered.

Main effects using CPS are the possibility to span a global network of plants and factories, also of different operating companies, newly available optimally organized processes and an increased adaptability to changes on markets and in supply chains [11].

Global networking

The use of cyber-physical systems can increase the adaptability of the production system. Factory equipment can now react autonomously to changes on markets and in supply chains. Products can be manufactured following individual customer requirements, even with equipment that is not suited specially for the manufacturing of individualized components. The production process can be optimized using a network of cooperating adaptable manufacturing units, to better achieving simultaneously goals in lead time, stock, productivity and cost. The work system can be adapted to the needs of single workers, for instance because of demographic developments (older employees, different language or IT skills).

CPS make objects localizable worldwide and allow a persistent location recognition in real-time. With the help of this technology the injection of counterfeits or duplicates in the supply of medication, raw material or spare part can be hindered. The global coordination of different plants or factories can be used for an overlapping scheduling or stock level planning, for instance by real-time rerouting of refill orders or planning of orders where energy cost are lower.

Process optimization

All elements of a cyber-physical production system know their usage realms, configuration alternatives and general conditions. They communicate autonomously and wireless [15]. These capabilities make it possible that an assembly order autonomously can request missing material and can organize the refill from the supplier which can deliver the fastest. Equipment elements are broadcasting when they are ready for new orders. These new orders can start execution on their own, schedule their needed resources and solve small disturbances, for instance by moving the job execution to another piece of equipment which is not touched by the disturbance.

Adaptability

Cyber-physical elements in the production system are capable of self-organization, at least partially. While full autonomy might be possible at least theoretically, a certain amount of centrally controlled information is necessary to achieve the goals of the production system. Therefore the best achievable solution might be a heterarchical production system [16-18]. These autonomous capabilities help plant equipment to react on changes in the market (e.g. demand) or in the supply chain (e.g. to prevent a rupture of refills) [6]. Another capability is that a higher degree of individualization of products is now possible without cost disadvantages. The individual product properties can be embedded into the product's software. This avoids an increase of complexity of central design and planning procedures.

Product properties, cost, logistics, safety and security, reliability, pass-through time and sustainability now can be adjusted during run-time following individual demands, independent from restrictions from built-time.

An old promise of software vendors of production planning and control [19, 20] now can be fulfilled: Real-time adjustment of production schedules to recent developments. These capabilities can also be used to coordinate inter-company networks of adaptive production units.

Finally it is possible to adjust the work system to the needs of the individual human worker, for instance by changing necessary weights to lift, times to work, user interfaces or human-computer interaction.

The effect of CPS on production systems

The properties and application areas of CPS allow the effects on production systems shown in Fig. 1. These effects encompass all dimensions of production systems and are able to reinforce themselves. It can be seen that an addition of CPS to production systems would have some desirable benefits, like the higher degree of changeability and individualization, both demands from the market side. On the other hand the addition of CPS to a production system comes with possible threats like increased (IT related) vulnerability of the production system's ability to fully operate. Therefore it has to be calculated to which degree the advantages of CPS outnumber the disadvantages.

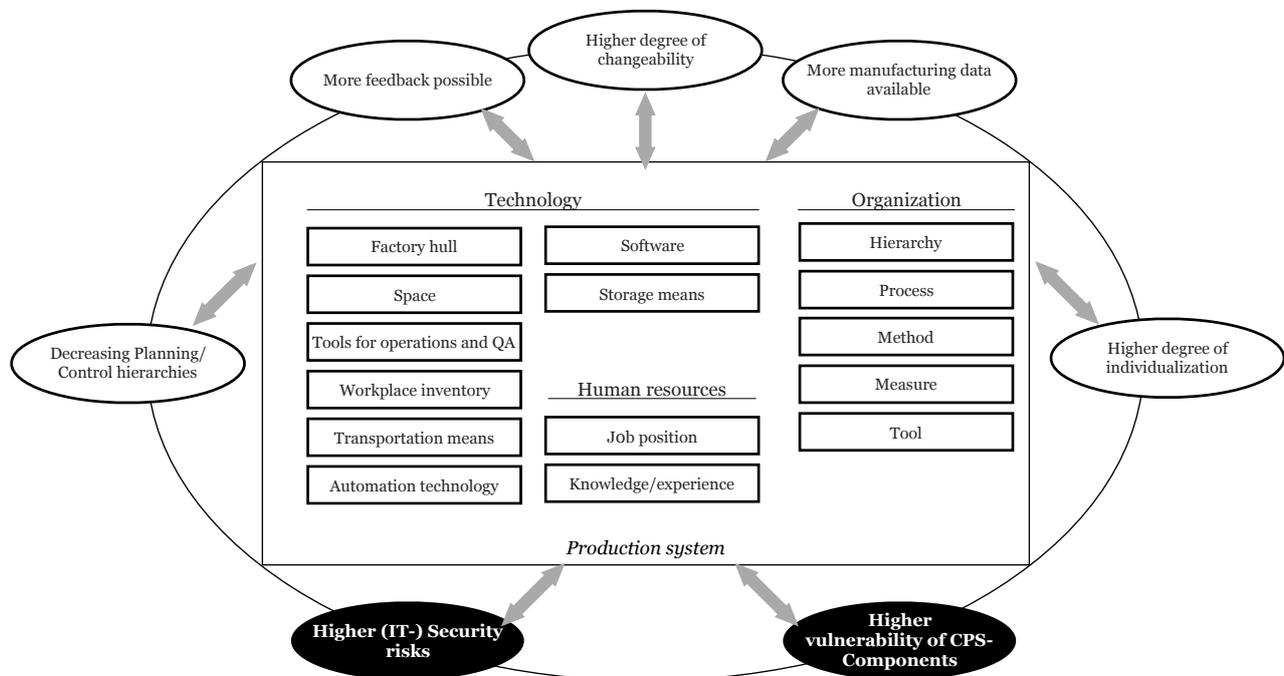


Fig. 1. Effects of CPS on production systems

Adaptability can be achieved mainly by self configuration, self-maintenance and self-organization. CPS help units in production systems to perform self-x functions, so they undoubtedly increase the adaptability of production systems.

Global networking and the possibility to communicate also between workpieces and plant equipment increase the ability to feed back information from the field to the factory (Fig. 2). An analysis of this information helps to adjust the productions schedules for new products and the definition of product features for new generation of products as well.

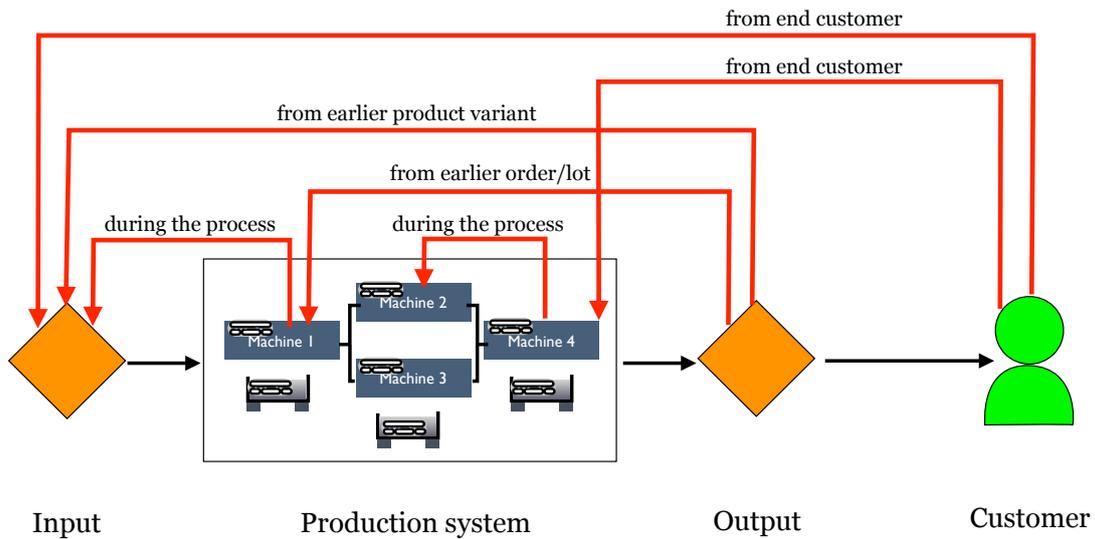


Fig. 2. Possible feedback of field information [21]

It may for instance be possible to use life-time information from the field to readjust the action limits of plant equipment. A change in customer preferences can be used to recalculate the production volume of different product alternatives. Nowadays American car manufacturers use social media analysis to find out the most wanted color combinations of their cars and transfer this information directly into job shop scheduling of the paint shop [22].

All these feedbacks can be directed to their intended recipients directly without passing information up in a hierarchy of information systems and then down to the intended addressee. Unfortunately nowadays no processing capacity exists in the factory control level higher than PLC.

To be able to end the separation of built-time and run-time and herewith to de-serialize the factory (by stronger individualization of products and process paths) additional capabilities are needed to process more data that also can arrive with delays.

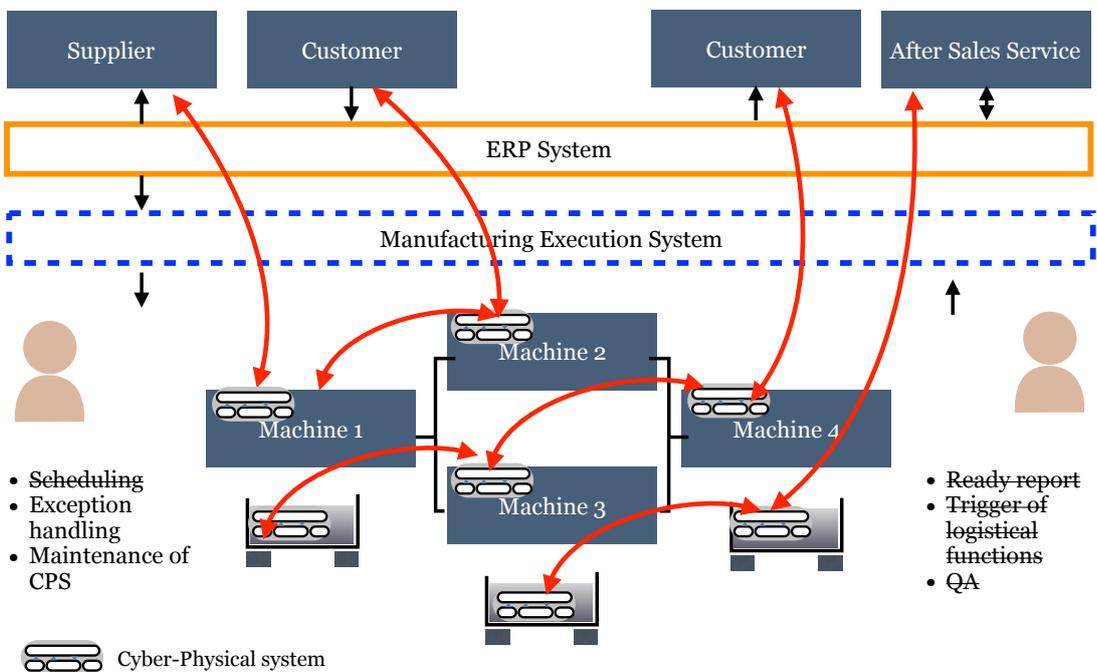


Fig. 3: Increase of individualization, decrease of hierarchy.

This development can also explain another effect of CPS in production systems: For the first time there is enough information available about status and location of every single element of a production system. Data

which is stored nowadays only to fulfill the requirements of traceability can be analyzed now and combined with data from other internal or external sources. This extended ability of analysis of manufacturing data for simulation, optimization and prognosis is called analytic manufacturing [23-25].

The individualization of products can be transferred to the individualization of manufacturing processes. It cannot be taken for granted that two similar products have the same manufacturing process steps.

The increasing degree of self-organization in the factory leads to a decreasing importance of hierarchical approaches of planning and control of production systems (Fig. 3)

Many companies only use an ERP system for planning and to some extent also for controlling the manufacturing process. Every shop floor order is printed out and added with progress information during its processing. Detailed scheduling and disturbance management is carried out by workers. This picture changes with the use of CPS. Human workers will maintain the CPS and work on heavy disturbances. Routine tasks are carried out by the CPS-equipped units of a production system.

Existing factory information systems like MES and to some extent also ERP are a severe barrier for the introduction of CPS-based manufacturing [26]. These older systems do not allow to store data of individual product items nor of mobile factory equipment. In some of these systems not even the location of a machine can be stored. The system would not even notice a relocation of a machine although this would have a severe impact on scheduling decisions.

The author of this contribution sees in these developments some of the revolutionary effects of CPS in production systems.

When a better reaction of the production system is possible the steps of planning in advance will lose much of their importance. When more units in the factory can coordinate their behavior autonomously central planning approaches also will lose their importance. It is at this time very difficult to foresee all consequences of this development. Nevertheless it seems probable that some of the basic principles of engineering and planning of production systems are no longer valid or even reverted into their opposite.

Research situation and research gap

The different approaches from literature can be distinguished as follows: The focus of the application of autonomy could be applied to a single element of the production system, to a subsystem (like the logistic system), or a group of similar elements (workers, machines) or to the production system as a whole. Some approaches don't derive their call for autonomy from the demand, for instance stemming from some qualities of the production systems which are necessary to perform. Other approaches do not show, where the autonomy comes from. If there was made an attempt to gauge autonomy than only as a discriminating property of an approach. Finally the approaches found in literature are judged whether they offer a normative setting, from which recommendations for practice could be derived.

Scholz-Reiter et al. [27] see autonomy as an advantage to control complex logistic systems, but limited when logistic target achievement is very high. Dashkovskiy et al. [28] model autonomous behavior in a production network to avoid the growth of waiting lines. Windt et al. [29] describe a set of criteria how autonomous control increases in a logistic network. Armbruster et al. [30] develop an approach for controlling production networks using a pheromone-based model and a discrete simulation environment. Karimi et al. [31] show how autonomous decision making could help to control local capacity in large production networks.

An early approach to autonomy in production systems is the introduction of multi-agent systems (MAS), which model the behavior of production elements [32]. In a way MAS can be seen as predecessors of nowadays cyber-physical systems. MAS lack the actuators and they are only an abstract representation, not the real elements of the manufacturing system.

Related work in other areas can be found in electricity control in supply grids including micro-grids, where the control of voltage and current is given to every unit of a microgrid. Using this approach it is assured that power generation and consumption is possible also when central control elements are no longer working [33].

Table 1 shows that in recent research activities a normative setting for the determination of an appropriate degree of autonomy could not be found. Therefore this contribution aims to fill this research gap.

Table 1

Related research on autonomy in production systems

Approach	Focus	Demand of autonomy	Supply of autonomy	Measuring of autonomy	Normative setting
Calculation of autonomous control (Windt et al. [29])	logistic subsystem	-	Decision, information, execution	-	-
Control with pheromones (Armbruster et. al. [30])	decentralized coordination and individual routing	-	-	-	-
Cope with time delay (Karimi et al. [31])	large networks	-	-	-	-
Influence of autonomous control on logistic performance (Scholz-Reiter et al. [27])	logistic subsystem	high complexity, medium logistic target achievement	-	Set of criteria	Which priority heuristics is best for use
Modeling autonomy (Dashkovskiy, et al. [28])	production network	-	-	seen as given	-
Multi-Agent systems (Caridi & Cavalieri [33]):	Adapting to changing environments	-	-	-	-

Normative settings from existing research for this purpose are very rare and seldom cover the whole variety of elements in cyber-physical production systems. An important characteristic during the planning of new factories or the upgrading of existing factories is the adaptability to fluctuating demands from the market side. The supply delivered by the factory has been planned with upper and lower limits, out of them the factory would not be able to operate efficiently. As an analogy to this comparison between demand and supply, this paper aims to determine the right amount of autonomy by comparing demand and supply of autonomy and to find a balance between them. The demand for autonomy can be derived from the characteristics of the production system. Autonomy is supplied by the increasing capabilities of the cyber-physical systems to act, based on their experience, their information input by sensors and their ability to locally coordinate their tasks with other CPS. As a first step, the existing degree of autonomy has to be measured.

Autonomy and ways to measure it

There are different ways to describe and measure autonomy [34, 35]. Basically, autonomy is defined as the ability of an entity to structure its own action and its environment independently and without unwanted influence from the outside. Protocols measuring autonomy nowadays are widely used in medicine [36] and psychology [37]. In Artificial Intelligence autonomous agents pursue goals independent from the goals of other agents [38]. Agent autonomy means that agents have control over their internal state and their behavior [39].

These definitions of autonomy cannot be applied on production systems unchanged, because they either reflect the behavior of an individual, not of a system or solely define autonomy without differentiating different grades of it. In this contribution two approaches to define the autonomy of a production system are presented, a descriptive approach and an approach which is based on the simulation of behavior of entities on a market. Autonomy is adjustable, following van der Vecht [39], when the agent is able to choose a distinctive style of decision making and of coping in an agent organization. There are several ways to achieve coordination within an agent organization. Approaches range from emergent coordination, where the actors are autonomous and the coordination is implicitly implemented, to explicit coordination, such as a hierarchical organization where the actors have no decision autonomy but just follow the orders from their superiors.

In the context of logistics processes autonomous control describes processes of decentralized decision-making in heterarchical structures [29]. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of autonomous control

is to increase robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity. Autonomy in production systems gained in importance during the last years. Autonomous production objects like (semi-finished) products, machines, tools or transportation means that are able to proceed information, make and execute decisions on their own are one core capability for Industrie 4.0 (a term mainly used in Germany) or Smart Production [40, 41].

This paper suggests two approaches to determine the appropriate degree of autonomy, following the characteristics of a given production process. The research on agents cannot be transferred fully to production systems due to the fact that in production systems there are by design designated elements (agents) with no degree of autonomy, with some extent of autonomy and with a high degree of autonomy. Therefore instead of a unified determination of the optimal degree of autonomy a specialized determination with different results for different production systems instantiations is necessary.

Table 2
Classification of manufacturing systems [42]

Attribute	Attribute values			
Product range	Specification by customer	Serial products with customer-specific variations	Standard products with variations	Standard products without variations
Product structure	One-piece-product	Multiple-piece-products with simple structure	Multiple-piece-products with complex structure	
Order trigger	Manufacturing on demand with single orders	Manufacturing on demand with blanket orders	Manufacturing on stock	
Disposition	Following the customer's order	Mainly following the customer's order	Mainly MRP-based	MRP-based
Demand planning	No relevant external supply	Relevant external supply	Huge external supply	
Manufacturing process	Unique manufacturing	Unique and small lot manufacturing	Serial manufacturing	Mass manufacturing
Manufacturing organization	Construction site	Shop floor	Group-/ line assembly	Line production
Share of self-manufactured parts	Low	Medium	High	

To be able to differentiate between production systems, a classification system stemming from Schomburg [42] is used (Tab. 2). The model to determine the right degree of autonomy is depicted in fig. 1. Based on similar concepts to adjust the fitting degree of adaptability in turbulent environments [43-45] there might be a discrepancy between the necessary amount of autonomy in a certain environment and the actual degree of autonomy.

The optimal degree of autonomy can be calculated by comparison of the least necessary degree of autonomy with the actual degree of autonomy delivered by the production system (Fig. 4). The actual deliverable degree of autonomy can be calculated using one of the approaches described in this contribution. First, the descriptive and the market-based approaches are explained. Using two brief case studies the way to determine the necessary degree of autonomy depending from manufacturing characteristics is then outlined.

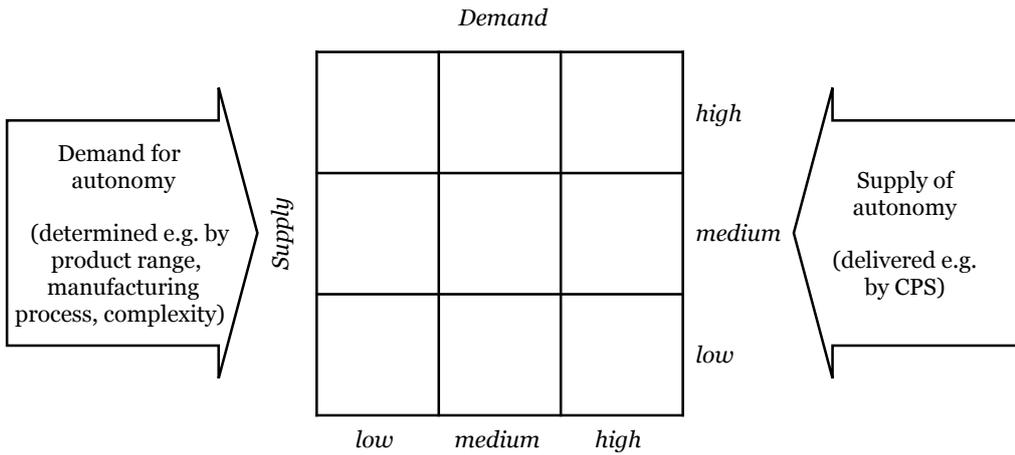


Fig. 4. Model to compare demand and supply of autonomy

Descriptive approach

The core element of this method is the Autonomy Index AI which is based on value stream consideration and puts autonomous part of the considered value stream into relation to the entire value stream [34].

The Autonomy Index

The Autonomy Index [46] specifies the degree of autonomy used in the production process. The term was chosen following the term Lean Index used in Toyota's Value Stream Design [47]. While defining the index the basis for the comparison had to be determined. There are various possibilities, e. g.:

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

The number of autonomous process steps is the most suitable of the named possibilities. Relevant data can be collected on the shop floor without disturbing the actual production processes.

Autonomy in production systems can be allocated to hardware on automation level, to software on the production planning and control or manufacturing execution level and to humans in the factory [48]. In accordance to typical multi-level-models of factory automation these are stacked in three levels. These three enablers of autonomy are used to calculate the Autonomy Index. The Autonomy Index AI describes the proportion between autonomous process steps and the total amount of process steps. Two additional key figures were defined to characterize the autonomy of a production system in more detail: the Interaction Index II and the Communication Index CI. The Interaction Index II describes the proportion of autonomous process steps executed with the help of communication of actors on the same level to the total amount of process steps in this level. The higher the II the more interaction takes place between actors of the same kind (automation, software, humans).

The Communication Index CI roughly describes the proportion of autonomous process steps executed with the help of communication of actors on the same level to actors on another level to the total amount of process steps that are executed in this level with the help of communication to actors on another level. The CI indicates which autonomous process steps needs help from other levels to maintain its autonomy. The Autonomy Index increases when the Interaction Index or the Communication Index rise.

While the descriptive approach focus on the autonomy of a production system as a whole, the market-based approach concentrates on the behavior of the single elements of a production system.

Autonomy as the result of acting on markets

The market approach [49] relies on the following abstract understanding of a CPS's degree of autonomy (DoA): The CPS acts autonomously if it decides completely self-determined (DoA = 100, autonomy). If its decisions are solely determined by others, its autonomy is zero (DoA=0, heteronomy). The CPSs are interpreted as participants of a cyber-physical market on which each individual CPS interplays with its environment. A CPS might be a work piece, a machine or workplace or a logistic element. Even workers could be considered as CPS when they are connected to the flow of information and decisions in the production system, for instance by a tablet or smart wearables. The similarity to real market mechanisms can be used to find the optimal setting for each production component and optimization dimension.

The market autonomy model is built up on the following assumptions:

Assumption 1: Any CPS can communicate with any other CPS so that a fully meshed communication structure exists. Each CPS as a market player is able to access all information on the market. No market anomalies with regard to information deficits distort the ideal market model.

Assumption 2: The determination of the CPS specific optimum is based on the interplay of the individual CPS and its environment, which can be seen as market equilibrium.

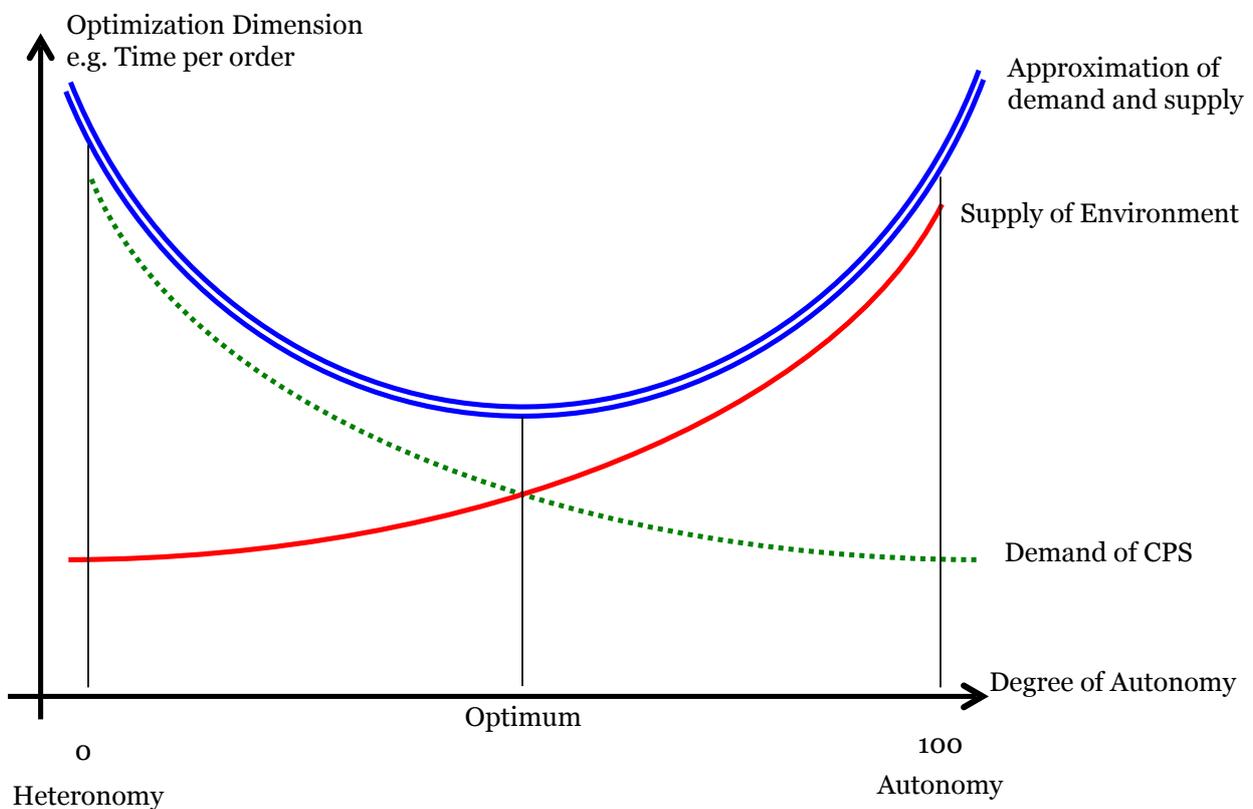


Fig. 5. Supply and Demand of each CPS

In Fig. 5, this equilibrium can be seen at the intersection of the plain and dotted curve. The dotted curve shows the demand of a single CPS. For example, this could be a work piece that is in the search for a milling machine. It intends to minimize its general time per order. The more self-directed (or egotistically) it can select the required offer combination to be milled given by the manufacturing environment, the smaller will be its time per order. The more those offers selected by the environment are favoring other CPS, the longer will be the CPS's time per order. This is because other CPSs have to be considered as well and they may be preferred.

The curves of the individual CPS's can be consolidated. When there are several CPSs as consumers of manufacturing services, so their individual demand curves can be added to a cyber-physical market demand

curve. In the same way the cyber-physical market supply curve can be created based on the supplies of other CPSs (see plain curve in Fig. 5).

The equilibrium can be found at the intersection of the plain and the dotted curve. It is referred to a pareto optimal degree of autonomy and describes the situation where no possibility to improve the situation of an individual CPS exists without worsening the situation of another CPS.

Assumption 3: CPSs as demanders and suppliers consider the cost of their optimization dimension as given. This means, that the CPSs do not recognize their actions to influence shop floor cost parameters and they try to realize the best possible actions for a given market price. This situation can be interpreted as a competitive market.

Assumption 4: The elasticity of the supply is decreased by an increasing degree of autonomy while the elasticity of the demand is increased by an increasing degree of autonomy. On the supply side a small degree of autonomy is characteristic to have a lower value because there is less flexibility for optimization than a greater degree does have. On the demand side it is vice versa.

From the perspective of a machine, these curves can be interpreted as follows: The dotted curve shows the demand of a single milling machine that is in search for CPS-equipped workpieces to be milled. The machine intends to minimize the time per order. The more self-directed it can select the required offer combination given by its environment, the smaller will be its time per order. The more other-directed those offers are influenced by other players on the market, the greater will be the CPS's time per order. This is because the influence of other CPSs can lead to a fulfillment of their preferences.

The plain curve stands for the market supply curve and represents the specific offers of the machine's environment. More self-determined selections do show higher times per order since the fulfillment of more CPS specific needs to come along with the disregard of others. More other-directed selections do show a lower value for optimization because the solution was found centrally and no specific needs had to be considered. Again, the pareto optimal degree of autonomy can be found at the intersection of those two curves since both the individual and system wide perspectives are considered. Here, the CPPS is not dependent on the evaluation criteria of only one system and the strengths of an harmonic CPPS can be realized efficiently.

Assumption 5: The demand and supply curves can be approximated with the help of a squared curve. Based on this assumption, only three points are needed to specify the approximated curve, in Fig. 5 depicted with a double-lined curve.

Since those optimization curves are expected to be influenced by the elements of CPS, further assumptions have to be formulated with regard to the CPS itself. This includes assumptions about the processor(s), sensor(s), communicator(s) and the actuator(s), as well as its environment, based on disturbances (e.g. machine erosion, work piece defects, human motivation, conveyor bottlenecks, loading equipment lost, etc.) and enhancements (e.g. machine processor speed up, work piece sensor updates, human qualification, conveyor technique innovations, optimization of the shape of loading equipment, etc.).

The appropriate degree of autonomy

On the demand side the necessary degree of autonomy is calculated using a formula, where a high coordination effort and a dynamic variance of requirements during manufacturing lead to a higher degree of autonomy, while no need for coordination and strictly predictive requirements lead to a very low demand for autonomy.

Table 3
Characteristics of the case studies

Attribute	Attribute values			
	Rating key: ++ = 1, + = 0,67, 0 = 0,33, - = 0			
Product range	Specification by customer ++	Serial products with customer-specific variations +	Standard products with variations 0	Standard products without variations -
Company 1 (whole)		✓		
Company 2(whole)			✓	
Product structure	One-piece-product -	Multiple-piece-products with simple structure 0	Multiple-piece-products with complex structure +	
Company 1 (whole)		✓		
Company 2(whole)				✓
Order trigger	Manufacturing on demand with single orders ++	Manufacturing on demand with blanket orders +	Manufacturing on stock 0	
Case Study 2		✓		
Case Study 2	✓			
Company 1 QM	✓			
Company 2 paint shop	✓			
Disposition	Following the customer's order ++	Mainly following the customer's order +	Mainly MRP-based 0	MRP-based -
Company 1 (whole)			✓	
Company 2(whole)				✓
Company 1 QM	✓			
Company 2 paint shop				✓
Demand planning	No relevant external supply 0	Relevant external supply +	Huge external supply ++	
Company 1 (whole)		✓		
Company 2(whole)				✓
Company 1 QM	✓			
Company 2 paint shop	✓			
Manufacturing process	Unique manufacturing ++	Unique and small lot manufacturing +	Serial manufacturing 0	Mass manufacturing -
Company 1 (whole)		✓		
Company 2(whole)			✓	
Company 1 QM		✓		
Company 2 paint shop			✓	
Manufacturing organization	Construction site +	Shop floor ++	Group-/ line assembly +	Line production -
Company 1 (whole)		✓		
Company 2(whole)				✓
Company 1 QM				✓
Company 2 paint shop		✓		
Share of self-manufactured parts	Low 0	Medium +	High ++	
Company 1 (whole)		✓		
Company 2(whole)	✓			

In Tab. 3 four case studies from two companies are shown. Company 1 is a medical technology company manufacturing artificial knee joints in flexible batch jobs while company 2 manufactures tractors where the lot size is 1 and all products are assembled on a single assembly line with AGVs driving the product from start to finish of the assembly process. For all case studies a rough calculation of the necessary degree of

Attributes	Company 1		Company 2	
	Whole production system	Quality management station	Whole production system	Paint shop
Product range	0,67	0,67	0,33	0,33
Product structure	0,33	0,67	0,33	0,67
Order trigger	0,67	1	1	1
Disposition	0,33	1	0	0
Demand planning	0,67	0	1	0
Manufacturing process	0,67	0,33	0	0
Manufacturing organization	1	0	0	0,67
Share of self-manufactured parts	0,67	0,67	0	0
Sum	5,01	4,34	2,66	2,67
Autonomy demand	62,6 %	54,3 %	33,3 %	33,4 %

autonomy is provided in table 4.

Table 4
Calculation of autonomy demand

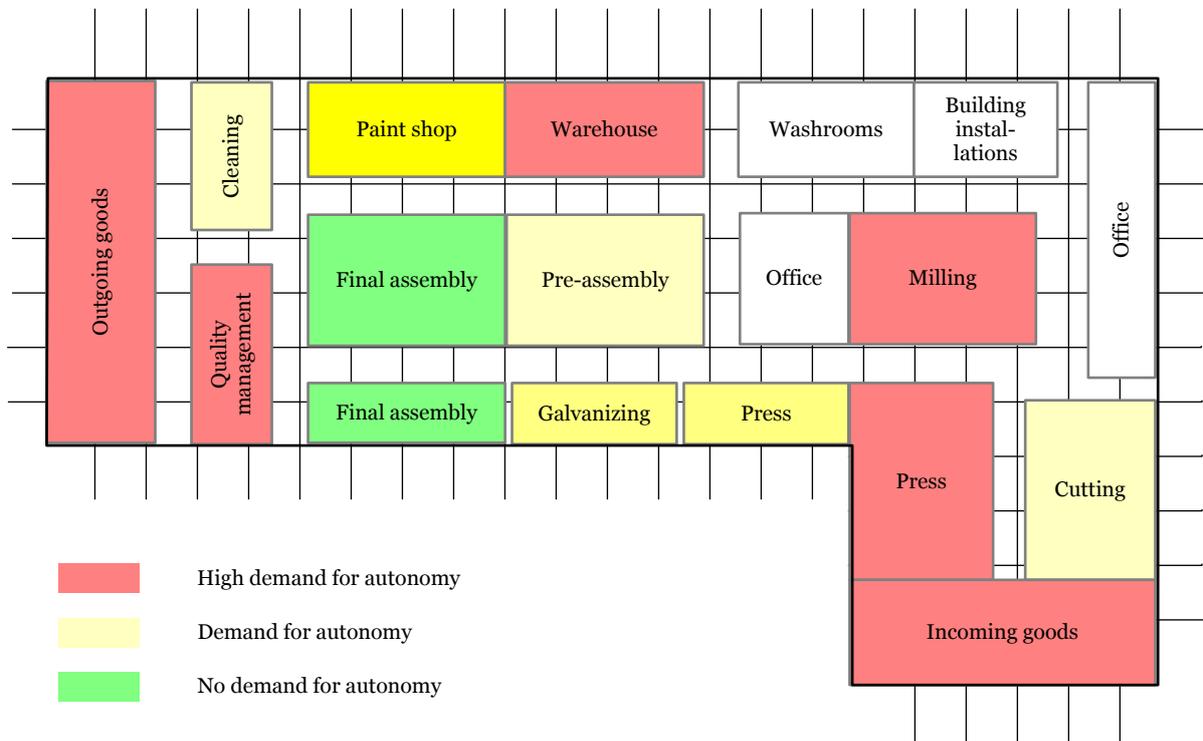
Discussion of results

Both case studies reached a very different degree of autonomy on the level of the production system as a whole. This comes because its manifestation in the production system is different. In case study 1 the factory organization could benefit from autonomous job order execution. Especially this is irrelevant in case study 2, where the main focus of autonomy should lie on product pre-assembly and customer order processing. In case study 2 the actual lot size 1 assembly comes with very long frozen times, where the orders could not be changed anymore. Improvements in the degree of autonomy will allow for a much shorter frozen time. The market approach could be used to find out the pareto optimum for a given market situation.

Evaluation in industry

The results from investigating the whole production system of company 1 and 2 were discussed with responsible persons for investments in the production system, in company 1 with a member of the executive board, in company 2 with the factory manager. Both agreed that the approach gives a correct assumption where an investment in CPS might be useful. Both managers stressed that their production system consists of subsystems and areas with very diverse properties. Therefore a disaggregation of the calculation was conducted in both companies, in company 1 in the quality management department where all finished goods were checked manually and in company 2 in the paint shop. This resulted in a map of autonomy demand which can be projected onto the factory layout. Fig 6 shows a mock-up of such a map.

The approach presented above is based on a couple of assumptions. It is useful, although in most cases not possible in actual production systems to validate these assumptions. Actual production systems have a very limited ability to change the degree of autonomy on other than the human level. Also the stress of investigation could postpone the actual manufacturing process.



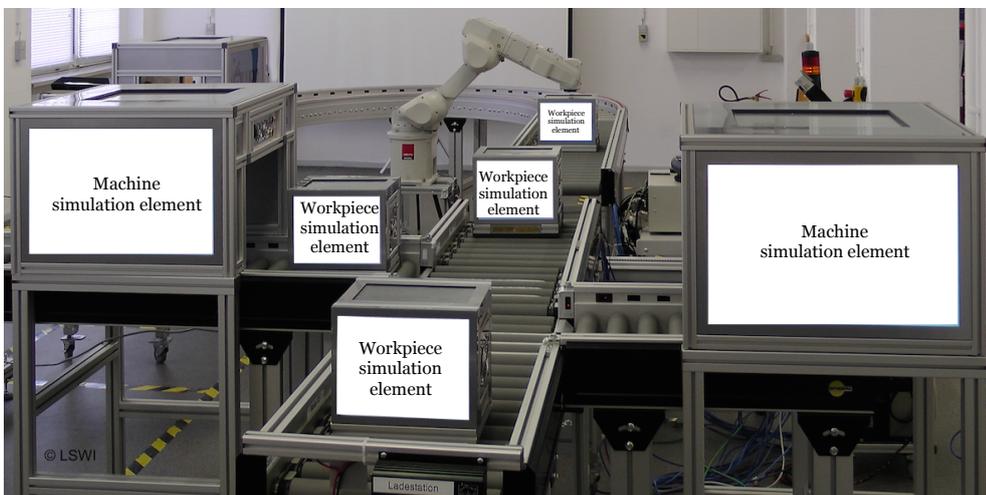
Therefore a further investigation without disturbing the actual manufacturing process is necessary. The transformation of traditional production systems to the optimal CPPS depends on the specific situation of a production setting, this underlines the importance of a systematic approach and real test runs.

Fig. 6: Autonomy map of production system's areas

For that purpose a simulation environment was created, where realistic manufacturing and assembly processes could be tested using CPS with freely changeable degrees of autonomy. Based on this requirement, the simulation approach of the research and application center „Industrie 4.0“ in Potsdam, Germany, is described in the following section.

Validation of assumptions

The simulation environment [49, 50] consists of a composition of physical and computer based models.



The main components are mobile work piece demonstrators and fixed machine tool demonstrators which are

connected by conveyor belt units. The demonstrators are able to communicate in different ways like described above. The transport system provides an effortless integration of actual hardware components into the system. The software in the demonstrators is designed for a quick integration of sensors and other devices using standard communication protocols [51]. The system supports the integration of different hardware components by design.

Fig 7. Components of the hybrid simulation environment [52]

This is an important advantage compared with sole software models which are supplemented only by isolated hardware parts. For an investigation of possible variations of the degree of autonomy in a production system with RFID, it is not sufficient to connect merely a reader device, but in addition it is necessary to realize the movement of work pieces with a conveyer as well. Fig. 7 shows a sample of the hybrid simulation environment, consisting of immobile units for machines and mobile units for work pieces or work piece carriers. The degree of autonomy of all elements of the production system (mobile and fixed units, conveyor, robots) can be controlled from Zero to fully autonomous behavior.

Example of an experiment

In an experiment the descriptive definition of autonomy was used to compare a fully autonomously acting work piece („smart work piece“) with a degree of autonomy of 1 against a strictly central controlled („dumb“) work piece with a degree of autonomy of 0 [34]. Both work pieces (artificial knee joints) went through the same manufacturing process simultaneously. The logistic infrastructure was set to respond to commands of the smart work piece and of the central dispatcher for the dumb work piece. For this experiment no disturbances were implemented. The whole communication between the components in the factory was logged and analyzed later. The experiment was repeated 70 times to get proper values for the communication between the factory components.

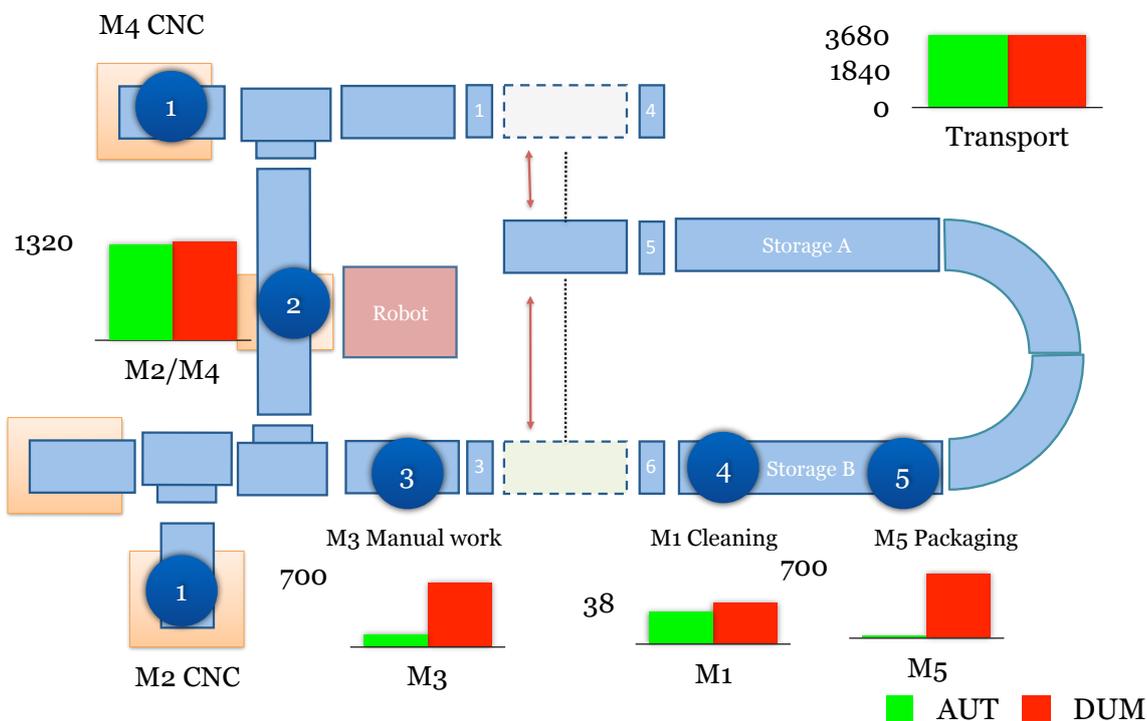


Fig. 8. Results from a comparative run between „dumb“ (DUM) and „smart“ (AUT) work pieces

The results are shown in Fig. 8. Due to the fact that transport tasks are real and therefore equal for both work pieces, differences in this experiment only can occur when a work piece is waiting for processing. In Fig. 8 one can see the different amounts of time needed for processing stations M3 and M5. The „smart“ work piece is typically faster there. This can be explained with additional waiting time for the dumb work piece in front of the unit, while the smart work piece only moves when it is guaranteed that it will be

processed immediately after arrival. When pieces of equipment are available twice, there is only a very short difference in processing time, because (in this scenario) no waiting time occurs.

Tab. 5 shows some key figures collected during the experiment.

Table 5

Key figures from the autonomy experiment.

Property	Autonomous	Centrally controlled
# „waiting for worker“ (per job)	0	5
# of information exchanges with central control	54	980
Successful job simulations	36,4 %	32,5 %

Practical implications and conclusions

In factories all over the world there is a heavy investment in digitalization [53]. Machines, logistical units and also some high tech work pieces are equipped with high performance computing power and an interface to humans and the internet. Although these basic ingredients would allow for an emergent behavior of the production system, these investments are isolated, random and no motivated by improving the capability of the production system as a whole.

Up to now it was no possible to plan investments in CPS with regard to the possible improvements for the whole production system. The approach presented here aims at influencing investment decisions in that manner not only to improve single elements of the production system but to add the capability of complexity cope by showing the very areas of the production system where the necessary degree of autonomy should be improved. Using this approach in the phase of planning a new or refurbishing an existing production system exactly the appropriate degree of autonomy could be taken into account. Autonomy is a tremendously important capability for changeability [54]. Additionally it is possible to fulfill the wish for higher changeability of the production system by improving especially these elements which are necessary for the right amount of autonomy. The additional capability for changeability could be invoked when the demand for it occurs. By comparing investments between classical and appropriately autonomous production systems the cost for additional changeability could be calculated first time.

An even bigger role plays the addition of autonomy when using the production system. Autonomous behavior allow an easier reaction to turbulences [55] as well as a faster ramp-up after disturbances [56]. Both are highly valued properties of production systems. Without an approach like the one presented here there is no benchmark for the additional amount of money to invest. The alternative to equip all available elements of the production system with CPS capabilities has to be ruled out due to the immense costs of such an investment. Also there now exists an alternative to the often-used maturity models with the distinction that maturity models typically do not allow a disaggregation onto subsystems or elements of the production system. So the calculation of the appropriate degree of autonomy helps to realize the vision of the self-organizing factory in the future.

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