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Axiomatic approach to flexible and changeable production system design

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Abstract

The general increase of products' customization, the reduction of product life cycle spans and dynamically changing markets challenge manufacturers today. Flexible and changeable production equipment addresses these challenges. It is thus necessary to evaluate the flexibility and changeability of alternative production equipment design solutions during the design process. The paper focusses on an appropriate adaption of Axiomatic Design's information axiom. The concept of changeability and the use of Axiomatic Design when designing production equipment are first introduced. Second, design-solution-specific barriers to flexibility and changeability are described. Finally, a detailed presentation of the information axiom adaption follows. The paper concludes with a validation case of an automotive body-in-white gripper system design.

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Keywords: Flexibility; Axiomatic Design; Information Axiom

1. Introduction

The current paradigm of personalized production forces manufacturing enterprises to deal with an ever larger product variety and smaller volumes per variant [1]. Data of the German automotive market illustrate this: the number of passenger car models have risen from 227 in the year of 1995 to around 415 in the year of 2015 [2], while the total number of new car registrations in the same period stagnated at around 3.2 million [3]. In addition, product life cycles become shorter [4], further enlarging the gap between product and production equipment life cycles [5]. As a consequence, production systems need to be designed to produce a wide variety of products and respond rapidly to change to even yet unknown variants, in order to minimize the investment risk.

Automotive manufacturing as of current state of the art is not capable of doing this: Dedicated lines produce very large numbers of certain models with an exactly specified output volume [6]. The concepts of product flexibility and changeability are a means to overcome this insufficiency. Product flexibility is defined as a production system's ability to quickly change over to other product variants [8]. It is achieved by holding available necessary resources for previously known variants [6]. As such, the system is made scalable within a pre-invested range of flexibility. The case of reducing or enhancing the system outside of this so-called "flexibility corridor" [9] is not provided for. On the other hand, the concept of changeability aims to enable the system to move its flexibility corridors when necessary [10] to address future unknown flexibility requirements without pre-investing into possibly unused resources. ElMaraghy and Wiendahl [11] identify both reconfigurability and flexibility as types of changeability on the factory levels of the production system, the cell and the station. Flexibility thus enables changeability.

Many research works have applied changeability in production system design [12–17]. However, only higher factory levels are addressed and mainly with an economical approach. Changeability is not evaluated based on specific characteristics of production equipment and alternatives are not compared. To decide for the best design solution, a production system designer needs to be able to compare alternative production equipment design solutions during the design process in regard to their product flexibility and responsiveness to change for future variants and under consideration of

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investment cost, quality and cycle time restrictions. This paper presents an extension of the axiomatic design methodology's information axiom for this purpose, taking into consideration barriers to flexibility and changeability. The approach was validated with the design of an automotive body-in-white door module assembly cell. The section of body-in-white assembly was chosen as it shows a particularly low degree of existing product flexibility while at the same time, with its high degree of automation, the required investment is relatively high [7]. The validation is presented in the last section of this paper.

2. Axiomatic design of production equipment

2.1. Introduction to axiomatic design

Axiomatic design was developed by Suh [18] as a methodology to guide the design process of complex systems with two fundamental axioms through four design domains: Customer demands (CA) characterize the customer domain, functional requirements (FR) are derived from the CA in the functional domain. The physical domain contains design parameters (DP) as solutions to satisfy the FRs. The process domain holds process variables (PV) relevant for production.

The independence axiom seeks for functional separation of FRs and DPs. In accordance to the axiom, a design is ideal, if each DP only influences exactly one FR. The design is detailed by decomposing each DP hierarchically into the next layer of FRs, until an implementable design stage is reached. This iterative mapping process is called zig-zagging. [18]

In addition to FRs, superordinate requirements called constraints (C) set bound to the possible space of acceptable solutions. Quality, cost and production rate are often treated as input Cs, whereas higher level DPs act as system constraints to all its lower layers. Usually, the design needs to be completed before it can be checked regarding its Cs. [18]

The information axiom helps to choose between several possible ideal designs the one that has the highest probability to successfully satisfy respective FRs. The axiom states, that the smaller the information content *I* of a design, the better the design. I_i for one FR_i-DP_i pairing is defined as the logarithm of the inverse of the success probability p_i, see equation (1), and expressed in the unit of bits. The information content I_{Sys} of a complete design is calculated by the sum of all single I_i. Equation (2) shows the derivation for an uncoupled design with *m* independent FRs. [18]

$$I_i = \log_2\left(\frac{1}{p_i}\right) = -\log_2 p_i \qquad (1)$$

$$I_{Sys} = \log_2\left(\frac{1}{p_{\{m\}}}\right) = -\log_2\left(\prod_{i=1}^{m} p_i\right) = \sum_{i=1}^{m} I_i \qquad (2)$$

The success probability *p* depends on the overlap between the design range dr_i and the system range sr_i. Suh defines dr_i as the specification of the allowable tolerance of a design solution in regard to the FR_i. Accordingly, sr_i describes the range between possible lower and upper limit of varying DP_i parameter values. The overlap is the common range *cr*. [18]

The design will only succeed for the DP parameter values inside of *cr*, as only these are inside the allowable tolerance zone [18]. Consequently, the success probability *p* evaluates how much of *sr* is covered by *cr: p* equals the area A_{cr} under the system probability density function within *cr* [18]. This correlation results in equation (3). For the case of a uniform distribution, the calculation of *I* simplifies to equation (4).

$$I_i = \log_2\left(\frac{1}{A_{cr,i}}\right) \qquad (3)$$

$$I_i = \log_2\left(\frac{|sr_i|}{|cr_i|}\right), \quad with \quad p_i = \frac{|cr_i|}{|sr_i|} \qquad (4)$$

The smallest achievable *I* equals zero for *p*=100%, if all possible DP parameter values are inside the acceptable tolerance zone *dr*. If all DP parameter values are outside, it follows $I \to \infty$.

2.2. Limitations of the information axiom for a spread of FR

The calculation of the information content as defined by Suh is only feasible if there is a dispersion of the parameter values of DPs. It is not feasible if FRs are spread with a probability distribution. Helander and Lin [19,20] discovered this problem already in axiomatic ergonomic design. They re-define *sr* and *dr* into *supplied range* and *desired range* and evaluate how much of the *desired range* is overlapped by the *cr* to judge on the success probability of a design solution. The according formula to calculate *I* is given in equation (5).

$$I = \log_2\left(\frac{desired\ range}{common\ range}\right) \qquad (5)$$

Fig. 1 compares the two approaches: The left side shows the correlation between *sr* and *dr* according to Suh [18], the right side shows the correlation between *supplied range* and *desired range* according to Helander and Lin [19,20], both for the case of a normal distribution of each varying parameter values.

2.3. State of the art of axiomatic design of production systems

Axiomatic design has already been applied in manifold production system use cases: Sohlenius [21] and Vallhagen [22] enhance the domain structure to better suit production system design. Cochran and Reynal [23] compare the applicability of different manufacturing systems. Linck [24] and Cochran et al. [25] analyze lean production methods dependencies. Babic [26] designs flexible manufacturing systems out of a knowledge module of manufacturing machines. Reichenbach [27] develops an assembly planning tool with the scope to address market volatility with volume scalability by applying human-robot-collaboration.

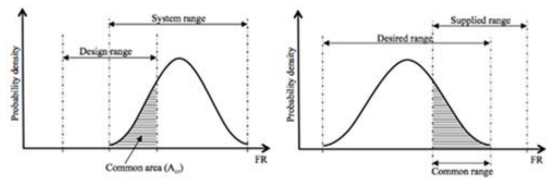

Fig. 1. Information axiom components acc. to [18] (left) and [20] (right)

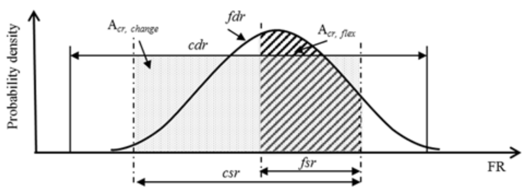

Fig. 2. Information axiom components for changeability and flexibility

Al Zaher [28] applies axiomatic design principles to map product-design driven flexibility into the design of automotive body-in-white framing manufacturing systems. Matt [29] and Foith-Förster and Bauernhansl [30, 31] apply axiomatic design to design assembly systems with a focus on flexibility and changeability. All mentioned research works focus on the independence axiom, the information axiom is not applied.

Bahadir and Satoglu [32] use both the information axiom as defined by Suh and the enhancement as of Helander and Lin (see sections 2.1 and 2.2 of this paper) for the selection of a robot arm during robotic system design. However, they do so for a specific planning case without particular focus on flexibility and changeability.

In the following, the use of the axiomatic design information axiom for the comparison and selection of production equipment is described

3. Flexibility- and changeability-oriented selection methodology of production equipment

3.1. Adaption of the information axiom

Product flexibility of production systems is needed if properties of produced parts change. Typical changes are a change of material and a change of geometrical properties. Varying quality requirements, regarding i.e. surface finish or visibility of joints, eventually also leads to the utilization of product flexibility.

The upmost FR of the here presented production system axiomatic design is to perform the production process for a defined group of products. With this arises the need to deal with different part properties as requirements. Consequently, there is a dispersion of FR parameter values.

(Flexible) production equipment responds as DP to these FR. As discussed in section **Fehler! Verweisquelle konnte nicht gefunden werden.** of this paper, flexibility is associated with a corridor defined by a lower and an upper limit of a certain system characteristic. This flexibility corridor corresponds to a flexibility system range (*fsr*). The respective requirement is accordingly called flexibility design range (*fdr*). In an analogical manner, the changeability design range (*cdr*), as well as the changeability system range (*csr*), are introduced. While *fdr* and *fsr* address known ranges of current flexibility requirements and system-flexibility, *cdr* and *csr* stand for future flexibility ranges that are still unknown in average and width. Even though changeability is understood by some as a system characteristic without predefined limits (e.g. [33]), the introduction of the *cdr* seems reasonable, as otherwise the calculation of a changeability information content would always lead to $I_{change} \to \infty$. Limits of required changeability are thus set based on scenarios. Fig. 2 shows *fdr*, *fsr* as well as *cdr* and *csr* and their respective common ranges for the case of a normal distribution of the flexibility requirement and a uniform distribution of the changeability requirement. In reality, these distributions depend on the volume mix of produced variants.

Other than conventional, flexibility requirements and solutions can be associated with several discontiguous ranges. Equation (6) states the example of *fdr* consisting of n independent fdr_i. In discrete cases, a set of singular points replaces these ranges. Each point stands for a certain value of a flexibility characteristic. Equation (7) shows the example of *fdr* with a discrete distribution of n singular points. In the extreme case of no flexibility, the cardinality of such a set equals 1: The *fdr* has become a flexibility design point *fdp*.

$$fdr = \bigcup_{i=1}^{n} fdr_i \qquad (6)$$

$$FDR = \{a, b, ..., n\} \qquad (7)$$

I_{flex} and I_{change} are again computed according to equation(8). The calculation of p_{flex} and p_{change} is derived from the calculation logic of Helander and Lin (see section 2.2) and enhanced depending on the formation of requirements and design solutions: If both flexibility requirement and design solution are defined by one or several steady ranges, *p* computes with n common ranges and m flexibility design ranges as given in equation (9) exemplarily for the simple case of uniformly distributed *fdr*. If the flexibility requirement is defined by one or several discrete *fdp*, the design solution can either be discrete or steady, as well as a combination of steady ranges and discrete points. Equation (10) shows the calculation of the respective *p* with uniform distributed *fdp*.

$$I_{flex;change} = \log_2\left(\frac{1}{p_{flex;change}}\right) \qquad (8)$$

$$p_{flex} = \frac{\sum_{i=1}^{n} |cr_i|}{\sum_{j=1}^{m} |fdr_j|} \qquad (9)$$

$$p_{flex} = \frac{|\{cp_1, ..., cp_n\}|}{|\{fdp_1, ..., fdp_m\}|} \qquad (10)$$

Per definition, $I_{flex;change} \to \infty$ if one or several steady *fdr* are addressed with a discrete flexibility system range (*FSR*). Similarly, discrete points can be ignored in both requirements and solutions as soon as they are combined with a steady range in the same domain, as the values of the steady ranges will always by far outnumber the discrete points.

3.2. Distinction of flexibility and changeability system ranges

It has already been stated in section 3.1 that flexibility ranges are associated with current and known flexibility, while changeability represents future flexibility ranges. Precisely, an *fsr* specifies the present flexibility corridor hold available by the system, which may include change-over of available system elements. The *csr*, on the other hand, specifies the absolute application corridor of the system.

As an example, a fixed installed drilling machine with a non-exchangeable chuck is given as DP to an FR stated as: drill holes with a diameter of 4mm to 6mm, i.e *fdr* = [4, 6]. The chuck is capable of holding drills in the range of 1,5mm to 13mm. The system is currently equipped with three drills with the diameters of 4mm, 5mm and 6mm, i.e. *fsr* = {4, 5, 6}. However, new drills can be bought if a change of variants require a new flexibility corridor – the limitation is the chuck range of the drilling machine, i.e. *csr* = [1.5, 13].

3.3. System flexibility and changeability information content

According to Suh (see section 2.1), the design solution's information content needs to be calculated at each decomposition layer. This is also valid for the flexibility and changeability information content respectively. However, when it comes to flexibility, the total system is only as flexible as its lowest flexible subsystem. In the example of the drilling machine given in section 0, a relevant product property that is subject to change for different variants might be the height of the component to be drilled. Both the chuck as well as drill are subsystems of the drilling machine, modeled in lower level layers of the decomposition. As the chuck and the drills might reduce the maximum possible component height, this *fdr* can only finally be judged upon once the complete design is mapped.

Therefore, to judge on the flexibility and changeability information content, an overall system information content needs to be calculated per branch of the decomposition tree, taking into account all relevant layers at once instead of just summing up all independent I_i. To do so, *fsr* and *csr* per relevant flexible system characteristics need to be related to the overall system *fdr* and *cdr*.

3.4. Change barriers analysis

As the first step of the evaluation, relevant flexible system characteristics need to be identified. All alternative design solutions are analyzed with regard to their change barriers. Change barriers are here defined as classification criteria, under which the limits of use of a technical system can be quantified in categories. Those categories essentially match with the system's flexibility corridors and thus equal a system's *fsr*. Examples of change barriers are e.g. processible material, dimensions of reachable joining locations, maximum dimensions of processible parts. A system's change barrier correlates to variant-dependent product properties.

Alternative design solutions are compared regarding flexibility and changeability only in the categories of the change barriers. This has the advantage that a relatively smaller number of system characteristics need to be evaluated, instead of comparing all possible system characteristics. As change barriers and their quantification are inherent attributes of a system, it may be possible that some barriers found in one design solution are not relevant to others. To be able to nevertheless compare those design solutions to each other, design solutions with no relevance to a certain change barrier are quantified with $fsr \to \infty$ in regard to this barrier, which results in an information content of *I*=0.

3.5. Comparison of cost, production rate and quality

The so far presented approach compares alternative design solutions based on their flexible and changeable functionality. Furthermore, I_{change} and I_{flex} do not assess a surplus of flexibility or changeability that a certain production system design solution bears, as it rightly compares against set requirements. Such a surplus, essentially a redundant design, could nevertheless hold opportunities as defined future flexibility needs naturally carry the risk of being incorrect.

Accordingly, out of several design solutions that are equally suitable in terms of independence and information axiom, the one design with the highest cardinality of *fsr* and *csr* respectively should be chosen – however, only if there is no negative influence on the constraints of cost, quality and cycle time. Thus, the last step of the comparison of alternative production system design solutions must be the examination of the complete designs in regard to these three constraints.

4. Designing a changeable body-in-white production cell

To validate the here presented adaption of the information axiom, a changeable automotive body-in-white production cell was designed with axiomatic design. In the use case, an adhesive is applied on the inner assembly of the body in white door module and placed in correct position into the outer assembly. The production cell was required to be designed to flexibly handle two different existing door types and targeted for continued use for follow-up models which are still unknown in design and dimensions.

Fig. 3 shows the decomposition of the assembly process and production cell. Due to the paper's page limitation, only the comparison of gripper systems, as part of the handling subsystem of the cell, is presented in detail in the following.

4.1. Analyses of the gripper systems' change barriers

A prehension process is made up of the subprocesses of establishing the contact, holding the contact during manipulation and placing precisely the manipulated component. It is carried out by a grab guide manipulator equipped with a gripper system. [34]

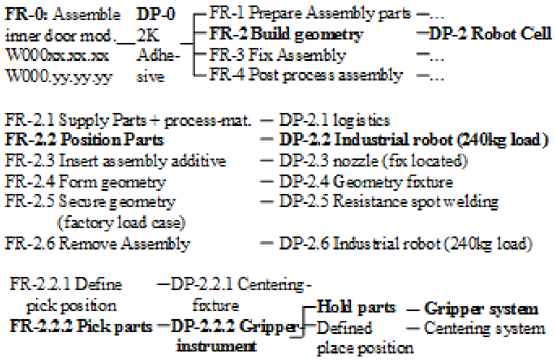

Fig. 3 Decomposition use case production process and cell

Gripper systems consist of gripper modules who possess a certain gripping principle (i.e. mechanical gripping, magnetism) and other automation components [35]. Based on a review of relevant engineering standards, the change barriers given in Table 1 were identified. They are listed with corresponding product properties in the second column.

Table 1: change barriers of gripper systems and product properties

Change barrier of gripper system	Product property
Load limits	Weight of parts
Number of gripping modules	Min number of gripping-points
Grab-position (x,y,z,) of each gripping module (common coordinate system)	Position of gripping-points
Gripping principle	Material / Elasticity
Effective force at gripping point	Hardness / Surface finish
Geometrical contact principle (jaw)	Geometrical shape in gripp.-point

4.2. Use Case: Selection of gripper system

In the use case, three different gripper system designs built up of clamping gripper modules as illustrated in Fig. 4 were compared: An inflexible solitary solution (left), a quick change system armed with two solitary gripper systems (right) and an adaptable gripper system with automatically shiftable gripper modules (middle).

All DP equal in their number of gripping modules, gripping principle and effective force in the gripping point with sufficient values for the requirements. The current geometrical contact principle used in the environment of this use case are form-specific counterparts. As all door modules provide areas to grab with flat surface gripper jaws, the geometrical contact principle is not investigated. Thus, only the change barriers of load limit and grab-positions are further examined.

The *fdr* is derived from the two existing door types named in the use case description (see the beginning of section 4). To determine the *cdr*, planners and designers of the division were consulted. They agreed that they would feel comfortable to be well equipped for future flexibility requirements, if the current distance between gripping point positions of the *fdr* was enlarged by +/-40mm and if the maximum weight limit was increased by the factor of 1.5. The weight was not expected to be significantly smaller. So, the current smallest weight is simply rounded down. As the load limit of gripper modules and the gripper system is higher than the limit of the chosen manipulating robot, the weight system ranges are associated with the robot load minus the weight of the respective gripper system. Table 2 shows the calculated information content for the three gripping systems. As expected, the solitary solution has the worst I_{flex} as it is only suitable for one door type. Both the change system and the adaptable solution fulfill the flexibility requirements. For all three systems, the same industrial robot with a load limit of 240kg was chosen. All three solutions thus have the same weight *csr*. As the gripping system can be exchanged on the robot, the possible *csr* of gripper positions was determined with respect to a reasonable size of a gripping system to prevent collision of the robot. The changeability requirements are fulfilled by all three solutions.

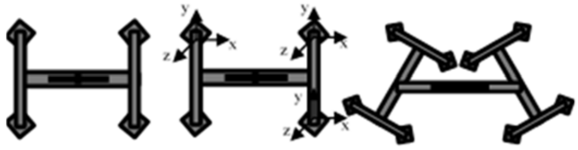

Fig. 4 Three different schematic gripper system DPs

4.3. Comparison of cost and cycle time ability

As input constraints, minimal achievable cost and a cycle time of maximum 76 sec for a part by part production were identified. The process time for the prehension process was estimated to 22 sec. As such, with an estimated changeover time of the quick change system of 30 sec as well as the time for automatic adaption of the adaptable gripper, estimated to around 5 sec, part by part production is possible in both cases.

An estimation of the investment cost (design concept, construction, purchasing and commissioning) per gripping system showed that the quick change system solution cost (including two solitary grippers) sum up to about 210% of one solitary gripping system. The adaptable system was about 5% less costly than the quick change system.

Overall, the adaptable gripper system solution has the lowest information content of all alternatives and is also the economically best solution to satisfy current and future flexibility requirements. It can be noted, that its *fsr* is rather overdesigned and it should thus be investigated if a further reduction of cost could be achieved by downsizing the system with regard to *fdr*.

5. Conclusion

The paper illustrated how to enhance the axiomatic design information axiom to compare different production system design solutions in regard to flexibility and changeability. The validity of the approach was verified with the excerpt of the axiomatic design of a body-in-white assembly cell. Further research work will go into the direction of building morphologies of design parameters for all standard elements of body-in-white production cells.

Table 2 Flexibility and Changeability Information Content to compare Gripper Systems solutions

				Flexibility						Changeability					
				Solitary		Quick Change		Adaptive		Solitary		Quick Change		Adaptive	
		fdr	*cdr*	fsr	I	fsr	I	fsr	I	csr	I	csr	I	csr	I
Part mass [kg]		{5.1, 5.9}	[5, 8.85]	[0, 156]	0	[0, 103.7]	0	[0, 104]	0	[0, 240]	0	[0, 240]	0	[0, 240]	0
Position	x	{-252;-277}	[-317,-212]	{-252}	1	{-252;-277}	0	[-302,-202]	0	[-400,0[	0	[-400,0[	0	[-400,0[	0
Gripper 1	y	{0}	{0}	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0
	z	{80;120}	[40,160]	{80}	1	{80;120}	0	[30,130]	0	[0,250]	0	[0,250]	0	[0,250]	0
Position	x	{327}	[287,367]	{327}	1	{327}	0	{327}	0	[-400,0[	0	[-400,0[	0	[-400,0[	0
Gripper 2	y	{0}	{0}	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0
	z	{-268}	[-308,-228]	{-268}	1	{-268}	0	{-268}	0	[-350,0[	0	[-350,0[	0	[-350,0[	0
Position	x	{260,238}	[220,278]	{260}	0	{260;238}	0	[210,310]	0	[0,400]	0	[0,400]	0	[0,400]	0
Gripper 3	y	{0}	{0}	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0
	z	{-263;-240}	[-303,-200]	{-263}	0	{-263;-240}	0	[-313,-213]	0	[-350,0[	0	[-350,0[	0	[-350,0[	0
Position	x	{315}	[275,355]	{315}	1	{315}	0	[265,365]	0	[0,400]	0	[0,400]	0	[0,400]	0
Gripper 4	y	{0}	{0}	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0	{0}	0
	z	{130;182}	[90,222]	{130}	1	{130;182}	0	[80,180]	0	[0,250]	0	[0,250]	0	[0,250]	0

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