Survey on Flexibility and Changeability Indicators of automated Manufacturing Systems

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***Abstract*—The environment of todays automated manufacturing machines is highly dynamic. Unpredictable changes in customer demands and shorter product lifecycles pose challenges for automated manufacturing systems which usually are designed for a static context. Thus, flexibility and changeability are discussed in order to face the challenges that arise from the dynamic production environment. This paper presents the results of two literature reviews on flexibility indicators and changeability indicators and discusses the determined indicators as well as their usage in the literature over time. A classification of the indicators based on their frequency of usage is also given.**

***Keywords*—flexibility, changeability, manufacturing systems, survey, indicators**

I. Introduction

Shorter product lifecycles and frequently changing demand behaviors of customers pose a challenge for the operators of automated manufacturing systems [1]. In contrast to this dynamic environment, manufacturing systems are usually constructed for an operation period of multiple years or even decades due to their high investment costs [2]. To enable a manufacturing system to cope with events and changes which cannot be completely foreseen at the time of development of the manufacturing system, different approaches and paradigms have been investigated in the literature within the last 25 years like Flexible Manufacturing Systems [3], Reconfigurable Manufacturing Systems [3], Agile Manufacturing Systems [4], Holonic Manufacturing Systems [5] and Cyber-Physical Production Systems [6].

When taking a closer look at these manufacturing system paradigms, differences and similarities can be found. The underlying concepts that are used by these paradigms differ and therefore also the limitations of these paradigms. For instance, while the paradigm of Flexible Manufacturing Systems usually uses a fixed mechanical set-up, the flexibility is achieved by changeable software. To overcome the limitations of static mechanics, Reconfigurable Manufacturing Systems support reconfigurations of hardware and software. However, all paradigms aim at improving the handling of predicted and also unpredicted disturbances and changes in the production environment. This ease of dealing with these disturbances is known under the terms of flexibility and changeability in the literature.

While changeability is defined as “the characteristics to accomplish early, foresighted and economic adjustments of the structures and processes on all production levels in response to change impulses. Changeability serves as an umbrella term and encompasses different types of change according to the levels of production” [7], many different definitions of flexibility exist, for instance [8, 9]. Azab et al. state that “flexibility is achieved by the system ability and potential to realize fast adaptation within narrow corridors of change, both at the operational and strategic levels with low investment, for example to meet demands of customers with low level of volatility” [10]. Sethi and Sethi [9] divide the general term of flexibility into different partial aspects like routing flexibility or operation flexibility.

Due to the nature of the terms *flexibility* and *changeability*, measuring them is not directly possible although various authors propose different metrics for measuring specific aspects of them. Indicators are often used in the literature for assessing non-directly measurable characteristics. An indicator is an operator that can generate an indication. Although the evidence of the indication cannot be proofed, it is more convincing than a guess. Different indicators for flexibility and changeability have been discussed in the literature in the last years and different classifications of indicators have been presented.

This paper describes the results of two literature reviews, one on flexibility indicators (82 publications) and one on changeability indicators (85 publications). The most frequently mentioned indicators are identified and classified according to their frequency of usage. The paper also discusses indicators which have gained more importance over the last years and those which lost importance and gives possible reasons for these changes of significance.

The remainder of this paper is structured as follows: in Section II, different classifications of flexibility and changeability are introduced and different methods for measuring flexibility and changeability are presented. Section III describes the methodology of the literature review on flexibility and changeability indicators. The results of the literature review and their discussion are given in Section IV.

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Finally, the paper closes with a summary and an outlook on future work in Section V.

II. State of the Art

This section introduces different classifications of flexibility and changeability and demarcates both terms. Furthermore, different approaches for measuring flexibility and changeability are described.

A. Classifications of flexibility and changeability

Flexibility indicates the ability of a production system to adapt quickly and favorably to influencing factors [11]. In fact, a general definition of the flexibility of a production system is impossible since a company's production system consists of many subsystems, different components and modules. In order to describe the flexibility of a production system more accurately, the subdivision of flexibility into partial flexibilities is necessary. Using these partial flexibilities, allows to observe the production system from different perspectives and allows to describe each flexibility aspect with the essential parts and characteristics of the flexibility [12].

In [12], the classifications of partial flexibilities frequently cited and proposed by the authors Sethi and Sethi [9], Tempelmeier and Kuhn [13], Barad and Sipper [14], Browne et al. [15] and the REFA [16] are considered and summarized. These authors proposed their thoughts on flexibility through different observation methods of the system. Tempelmeier and Kuhn classify partial flexibilities according to certain reference objects, REFA and Barad and Sipper classify it by means of short-term and long-term horizon, and the authors Sethi and Sethi and Browne et al. perform their consideration with the help of components, the system and aggregated sizes. To sum up, a totally agreed classification of partial flexibility does not exist. The selection of a suitable flexibility classification and the application of the classification is also depending on the surrounding context of the manufacturing system (company, strategy etc.).

This paper focuses on the classification based on certain reference objects, more specifically, machine and production system. These flexibilities are: machine flexibility, material handling flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, program flexibility, production flexibility and market flexibility. Machine flexibility refers to the ability of the machine which can switch from one operation to another without high effort, thereby enabling the machine to perform various tasks [12]. Material handling flexibility is a feature of a material flow system that allows different types of components to be moved to the correct position through different routes [12]. Process flexibility describes the ability of the system to process different workpieces with individualized customer requirements even for small batches without high efforts [12]. Product flexibility makes it possible to add new products or replace existing products easily [12]. Routing flexibility enables workpieces to be processed by the system through different routes [15] which means the production system has other machines which can perform the same process, i.e. the product does not need to be processed by a specific machine all the time. Volume flexibility describes the ability of the production system to perform profitably at different degrees of capacity utilization [15]. Expansion flexibility is the ability of the system to easily increase its capacity or quality according to requirements [15]. Program flexibility refers to the stability of a system. A high level of program flexibility means, for example, that a system can run a long time correctly without any human intervention and is able to recognize and correct errors occurring during runtime [9]. Production flexibility describes the ability of production to adapt to changing market conditions without costly conversion [15]. Market flexibility is the ability of a production system to get accustomed to changing market conditions [9].

Changeability is proposed as a new dimension of flexibility in [17]. Changeability is the ability of the production system to adapt to internal or external influences to a limited extent quickly and economically [18]. Through changeability of the production system, the product variance, delivery time and process quality can be changed [11]. In 2002, Wiendahl subdivided the term "changeability" into spatial and temporal, structural and technical adaptability based on different types and dimensions [19]. Spatial changeability includes extensibility and reducibility. Temporal changeability describes the long-term, medium-term or short-term reaction to changes. The change and adaptation of the organizational logistical procedures and processes is taken into consideration inside the structural changeability. Technical changeability is the ability to modify the technical equipment and technological processes. In the literature, changeability is sometimes hierarchically distinguished into primary and secondary changeability enablers [20]. For example, the so-called five primary changeability enablers (*Modularity, Scalability, Mobility, Compatibility and Universality*) are presented in [21]. Besides that, there are also many secondary changeability enablers (e.g. *Neutrality, Customizability, Adjustability, Change rapidity*) referred as supplements to primary enablers in the literature [22].

B. Demarcation of flexibility and changeability

Changeability is different from flexibility in the way that flexibility describes the character or ability of a system to respond quickly and easily to a changed demand. Making a corresponding adjustment to recognized changing requirements is sufficient for flexibility [23]. As for changeability, it describes the potential of a system which has the ability to make modifications reactively or proactively to suit future changing requirements [24].

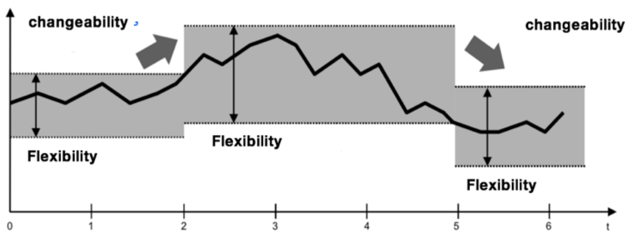

Fig. 1. Demarcation of flexibility and changeability acording to [24]

The characteristics of flexibility and changeability are exposed in Fig. 1. The bandwidth of the flexibility corridor at different points in time may not be exceeded. Within the corridor, for example, the system can adjust itself during runtime without any physical changes. In a changeable manufacturing system, the corridor can be moved up and down and can be broadened by adaptations in hardware and/or software [24]. Thus, the system can handle the changed requirement even if the initial flexibility corridor is exceeded. However, changeability requires a longer reaction time than flexibility [25]. A reasonable combination of flexibility and changeability should try to keep the flexibility corridor as narrow as possible and the reaction time of changeability as short as possible.

C. *Measuring flexibility and changeability*

Because flexibility and changeability of a production system cannot be measured directly, the question arises how they can be measured indirectly. In the literature, many different evaluation models are introduced, e.g. in [30]:

- Indicators
- Decision options
- Economic target criteria
- Capacity-oriented measurement
- Entropy
- Real-options theory

The indicator-based measurement methods measure the flexibility and changeability by means of key figures [26], usually by measuring different partial aspects of flexibility and changeability. This includes either measuring the value of an indicator or by determining the presence of the indicator.

The measurement methods based on decision options represent the flexibility and changeability by the set of options for action which are still feasible after an initial decision [27]. For instance, flexibility can be measured by the amount of follow-up actions which are made possible. In other words, the more options a decision allows, the more flexible it is [28].

The measurement methods based on economic target criteria assess flexibility based on the target effects of different flexibility's potentials [29]. The target usually is a monetary goal, but it can also be another business management goal. This measurement model not only offers flexibility measurement but also an assessment of flexibility potential [30].

In the capacity-oriented measurement method, flexibility and changeability are introduced by quantitative or qualitative overcapacities [31]. The relative degree of the capacity provided to the required capacity reflects the degree of the flexibility. Because the capacity dimensions are relatively easy to be determined, the measurement models are in principle suitable for practical use. However, a disadvantage of the measurement models is that the effort for the measurement will be significantly increased because of the additional determination of required capacity which may change over time [30].

The entropy-based measurement model can measure the flexibility of a production system with the help of using the entropy about parameter values of the system [32]. This measurement originated from thermodynamics and was later applied to information theory for the measurement of flexibility. Due to its very theoretical background, it can hardly be applied in practice.

In the real options-based measurement method, flexibility and changeability can be assessed by calculating the value of a financial or real option [33]. The disadvantage of this measurement is that it cannot measure flexibility or changeability accurately since it solely calculates the value of the option in an economic way.

Compared with other assessment models, one advantage of indicator-based measurement is that flexibility and changeability can be evaluated by real-world characteristics, e.g. the number of possible ways to process one workpiece type in the system can be an indicator for routing flexibility [34]; time and cost required to switch from one product variant to another can be considered as an indicator for product flexibility [15].

III. Review Methodology

Two literature reviews have been conducted, one on flexibility indicators (82 publications) and one on changeability indicators (85 publications). For both reviews, the same five step methodology was applied which is described in this section.

(1) Different indicator classifications were researched for flexibility and changeability, respectively. The mentioned indicators and their definitions in the different classifications have been compared to identify synonymous indicators. The result of this step are two lists with 13 flexibility indicators and 23 changeability indicators.

(2) The first approx. 200 publications from the results of common literature libraries like IEEE Xplore, Google Scholar and Springerlink have been downloaded for the search terms "flexibility, production system, indicator/criteria" and "changeability, production system, indicator/criteria" as well as combinations thereof.

(3) The downloaded papers were investigated whether they really contained information about flexibility and changeability indicators of manufacturing systems. An additional filtering of multiple papers by the same author(s) was performed in this step to ensure that only one paper per author was considered in the following analysis phase. In total, 82 papers dealing with flexibility indicators (years: 1981-today) remained and 85 that deal with changeability indicators (years: 1999-today).

(4) For each of the remaining papers, it was checked whether the previously identified indicators (step 1) are mentioned in the paper. Since many flexibility related papers use the flexibility classification by Sethi and Sethi [9], a mapping between their 11 types of flexibilities and the 13 flexibility indicators has been performed which is displayed in Section IV, Table I. Since some of the investigated papers have been published in German, the translation of the indicator is also given in Table I. It was also noted whether the paper focuses on hardware measures, software measures or a combination of both.

(5) The results of the previous step were grouped by the year of publication to identify trends for the investigated indicators. The total number as well as the relative number of papers mentioning an indicator in a certain time interval was calculated and used for the trend identification.

IV. Results and Discussion

This section describes the results of both literature reviews on flexibility indicators and changeability indicators. A discussion on identified trends regarding the indicators is following the description of the results.

A. *Literature review on flexibility indicators*

As mentioned before, flexibility is often discussed using (partial) flexibilities according to Sethi and Sethi [9]. In our literature review (step 4), we identified indicators for theses flexibilities. Their mapping is depicted in Table I.

TABLE I. Mapping between Flexibilities according to [9] and indicators

Flexibility	**Indicator (with German translation)**
Machine flexibility	Convertibility (Umrüstbarkeit)
Material handling flexibility	(Re-)Routability (Umsteuerbarkeit)
	Storage ability (Speicherfähigkeit)
Process flexibility	Versatility (Vielseitigkeit)
Routing flexibility	Redundancy (Durchlauffreizügigkeit)
Product flexibility	Substitutability (of products, Nachfolgbarkeit)
Volume flexibility	Capacity adaptability (Leistungsfähigkeit)
Expansion flexibility	Expandability (Erweiterungsfähigkeit)
Production flexibility	Diversity (Vielfaltigkeit)
Program flexibility	Error resilience (Fehlerelastizität)
Market flexibility	Market adaptability ((Markt-)Anpassbarkeit)
none	Integrability (Integrierbarkeit)
none	Robustness (Robustheit)

Table II shows the absolute and relative number of papers mentioning the flexibility indicator according to their year of publication. Besides that, the indicators are classified into 3 categories. The indicators which are mentioned by less than 20 papers are assigned to category C. If the amount of the papers referring to the indicator is over 20 and less than 40, then the corresponding indicator is assigned to category B. The indicators mentioned by at least 40 papers are assigned to category A.

The percentage of indicators in the figure is the ratio of papers that refer to the corresponding indicator in relation to the total number of papers under investigation during the time period. In order to make reading the table more intuitive, the share of each is indicated by color.

The four most frequently used indicators *Capacity adaptability*, *Versatility*, *Diversity*, and *Routability* are classified into category A. *Diversity* make it possible that companies can compete in changing markets which often need new products. Implementation time for new products or major adaptation of existing products is also minimized by Diversity [35].

Survival strategies, such as maintaining existing markets and profitability, can be achieved by *Capacity adaptability*. As the table depicts, this indicator has always occupied a high proportion from 1981 till now. Most of the investigated papers in the recent years have mentioned it. This shows that *Capacity adaptability* is seen as a key factor to deal with uncertain demand levels.

Machines can be shared through *Versatility*, which minimizes the demand of duplicate or redundant machines so it satisfies the strategic need of being simultaneously able to offer customers a range of product lines [37].

(Re-)Routability and *Storage ability* are both indicators which enable material handling flexibility. *Routability* is used more frequently and focuses on increasing availability of machines and thus increases their utilization, reduces throughput times [36] by means of sending parts to new paths in cases of blocking and machine breakdowns. The use of this indicator has a gradual upward trend within the analyzed time span, which is also consistent with the general trend that production efficiency is becoming more and more important.

TABLE II. Results of literature review on Flexibility indicators, clustered by year of publication

Indicator	**1981-1985**	**1986-1990**	**1991-1995**	**1996-2000**	**2001-2005**	**2006-2010**	**2011-2014**	**2015-2018**	**Sum**	**Cat**
Capacity adaptability	3	9	9	10	13	6	7	5	62	A
	50.0%	*81.8%*	*69.2%*	*62.5%*	*92.9%*	*75.0%*	*77.8%*	*100%*		
Versatility	3	9	11	10	10	4	7	4	58	
	50.0%	*81.8%*	*84.6%*	*62.5%*	*71.4%*	*50.0%*	*77.8%*	*80.0%*		
Diversity	3	9	8	12	11	6	5	3	57	
	50.0%	*81.8%*	*61.5%*	*75.0%*	*78.6%*	*75.0%*	*55.6%*	*60.0%*		
(Re-) Routability	2	4	9	10	8	4	7	4	48	
	33.3%	*36.4%*	*69.2%*	*62.5%*	*57.1%*	*50.0%*	*77.8%*	*80.0%*		
Redundancy	2	3	7	8	7	4	5	3	39	B
	33.3%	*27.3%*	*53.8%*	*50.0%*	*50.0%*	*50.0%*	*55.6%*	*60.0%*		
Expand-ability	3	6	7	7	6	4	2	3	38	
	50.0%	*54.5%*	*53.8%*	*43.8%*	*42.9%*	*50.0%*	*22.2%*	*60.0%*		
Market adaptability	0	6	6	5	6	2	4	3	32	
	0.0%	*54.5%*	*46.2%*	*31.3%*	*42.9%*	*25.0%*	*44.4%*	*60.0%*		
Converti-bility	3	4	5	5	4	3	4	3	31	
	50.0%	*36.4%*	*38.5%*	*31.3%*	*28.6%*	*37.5%*	*44.4%*	*60.0%*		
Substitut-ability	1	4	5	5	6	3	3	3	30	
	16.7%	*36.4%*	*38.5%*	*31.3%*	*42.9%*	*37.5%*	*33.3%*	*60.0%*		
Storage ability	1	2	6	5	4	3	4	3	28	
	16.7%	*18.2%*	*46.2%*	*31.3%*	*28.6%*	*37.5%*	*44.4%*	*60.0%*		
Error resilience	2	2	3	6	5	3	2	3	26	
	33.3%	*18.2%*	*23.1%*	*37.5%*	*35.7%*	*37.5%*	*22.2%*	*60.0%*		
Integrability	0	1	3	3	1	4	2	0	14	C
	0.0%	*9.1%*	*23.1%*	*18.8%*	*7.1%*	*50.0%*	*22.2%*	*0.0%*		
Robustness	0	2	0	3	0	4	1	0	10	
	0.0%	*18.2%*	*0.0%*	*18.8%*	*0.0%*	*50.0%*	*11.1%*	*0.0%*		
Sum of	**6**	**11**	**13**	**16**	**14**	**8**	**9**	**5**	**82**	

Papers										

These four indicators, (*Diversity, Versatility, Capacity adaptability* and *Routability*) put their focus on the efficiency of the production process as well as on the diversity of products. Due to their high number of mentions in the literature, these two factors are seen as key factors in order to respond to changing market conditions.

From the table, it can be seen that the usage frequency of three indicators in category B is increasing over time: *Redundancy, Substitutability* and *Storage ability*. With aid of storage capacity in the transportation system, reasonable use of the machine is possible. Optimizing the dimension of storages and buffers is increasingly discussed in the literature. *Redundancy* reflects the ability of system to produce a component by alternate routes in case of a machine breakdown. Additionally, redundant components allow the production system to have an efficient scheduling through better balancing of machine loads [9]. One possible reason of *Redundancy* becoming more and more emphasized is the decrease in costs of components, which allows to add redundant components to the production system without high extra capital investment in order to increase Routing flexibility.

Because of the shorter product lifecycles and frequently changing demand behaviors of customers and in order to save investment costs, the ability that system components like production equipment or software can be reused is becoming more and more important during the production of new and improved products. This makes *Substitutability* as an indicator for evaluating product flexibility to be used more and more frequently.

In addition, there are four indicators other *Market adaptability, Expandability, Error resilience, Convertibility* in category B. Rapid technological innovations, changing customer tastes, short product life cycles, uncertainty in sources of supply, etc. all consist of environment changes [38]. With help of *Market adaptability*, a company can respond to these changes. Besides, market flexibility enables the company to easily grasp new business opportunities [9]. This may be increasingly important since new business models like Software-as-a-Service have been introduced within the last years.

Expandability can be measured by the ratio of the cost of doubling the output of the system to its original cost [15]. It is important for companies with growth strategies such as venturing into new markets, since it permits step-by-step adaptation of the system for expansion.

Error resilience describes the stability of the system. It allows the system to run faultless without any human intervention for a long time, which can increase both productivity and quality of the production system [9]. However, the higher the *Error resilience* is, the higher the requirements on sensor amounts as well as on hardware and software of the system are, which can greatly increase its costs. This may be the reason that *Error Resilience* is relatively less used.

Convertibility describes the diverse use of the machine and its ability to convert from one use to another. Production batch can be decreased by Convertibility [36], which can save storage costs, improve machine utilization [38], produce complex components or to shorten the time to launch new products [35]. *Convertibility* can be measured by the number of tools or programs which machines can use and the ratio of the total output to the idle costs of the machine for a given period, which also can be a measurement factor of *(Re-)Routability*, *Capacity adaptability*, *versatility* or *Redundancy*. Therefore, in some papers, *Convertibility* is tend to be replaced by *(Re-)Routability*, *Capacity adaptability*, or *Redundancy*, which may be the reason that *Convertibility* is relatively less used in comparison to the indicators in category A.

Although *Market adaptability, Expandability, Error resilience*, *Convertibility* are classified into category B, their usage rate has reached 60% in recent years, which is enough to indicate that they are also important indicators for evaluating flexibility.

From the table, it is easy to see that *Integrability* and *Robustness* have been rarely used. The reason may be that the majority of authors divides flexibility into partial flexibilities and then evaluate partial flexibility by their corresponding indicators. However, *Integrability* and *Robustness* do not have corresponding partial flexibilities (cf. Table I). *Integrability* reflects the ability of a system to link to other devices or to be expanded with new functions. Some authors use the *Integrability* as an indicator for evaluating changeability rather than flexibility. On the other hand, *Robustness* reflects the ability of system to respond to accidental and unpredictable problems, such as machine breakdowns, delivery problems or staff shortages. Robustness consists of multiple dimensions and can be achieved by the presence of other flexibility indicators such as *Redundancy* or *Error resilience*.

In general, due to the introduction of partial flexibilities in the earlier English literature, the indicators corresponding to partial flexibilities are often mentioned in papers related to manufacturing flexibility. Since *Integrability* and *Robustness* do not correspond to a specific partial flexibility, their number of usage in this literature review was determined as smaller.

B. Literature review on changeability indicators

In the literature review on changeability indicators, 23 different indicators have been determined. The 85 investigated papers were published between 1999 and 2018. A small number of papers published before 1999 was not considered since changeability was put into focus of research in the beginning of the millennium. Accordingly to the flexibility indicator review, the investigated indicators were classified into three categories. Indicators which were mentioned in more than 50 papers were classified into category A, indicators mentioned 10 to 49 times were classified into category B and indicators with less than 10 mentions were classified into category C. In Table III, the results of the literature review are given in form of a table which displays the absolute and also relative number of mentions of an indicator within a certain time interval.

Five indicators were classified in category A. Among these most frequently mentioned changeability indicators are: *Modularity*, *Scalability*, *Mobility*, *Compatibility* and *Universality*. Due to early mentions in German literature on changeability, e.g. by Reinhart [17], the usage of these five indicators was supported and has lasted over the last decades.

TABLE III. RESULTS OF LITERATURE REVIEW ON CHANGEABILITY INDICATORS, CLUSTERED BY YEAR OF PUBLICATION

Indicator	1999-2001	2001-2004	2005-2007	2008-2010	2011-2013	2014-2018	Sum	Cat
Modularity	2	8	15	18	17	21	81	A
	100%	*100%*	*88.2%*	*100%*	*94.4%*	*95.5%*		
Scalability	1	6	15	17	18	22	79	
	50.0%	*75.0%*	*88.2%*	*94.4%*	*100%*	*100%*		
Mobility	1	5	13	14	16	21	70	
	50.0%	*62.5%*	*76.5%*	*77.8%*	*88.9%*	*95.5%*		
Compatibility	0	2	13	12	17	19	63	
	0.0%	*25.0%*	*76.5%*	*66.7%*	*94.4%*	*86.4%*		
Universality	1	1	9	11	16	21	59	
	50.0%	*12.5%*	*52.9%*	*61.1%*	*88.9%*	*95.5%*		
Interoperability	2	3	7	9	7	5	33	B
	100%	*37.5%*	*41.2%*	*50.0%*	*38.9%*	*22.7%*		
Neutrality	0	3	4	6	6	9	28	
	0.0%	*37.5%*	*23.5%*	*33.3%*	*33.3%*	*40.9%*		
Standardization	0	2	3	4	4	8	21	
	0.0%	*25.0%*	*17.6%*	*22.2%*	*22.2%*	*36.4%*		
Decentralization	1	4	5	2	2	5	19	
	50.0%	*50.0%*	*29.4%*	*11.1%*	*11.1%*	*22.7%*		
Self-organization	0	2	5	4	2	2	15	
	0.0%	*25.0%*	*29.4%*	*22.2%*	*11.1%*	*9.1%*		
Self-similarity	1	2	2	5	1	3	14	
	50.0%	*25.0%*	*11.8%*	*27.8%*	*5.6%*	*13.6%*		
Redundancy	0	2	2	4	1	4	13	
	0.0%	*25.0%*	*11.8%*	*22.2%*	*5.6%*	*18.2%*		
Knowledge about the ISA	0	3	2	3	1	1	10	C
	0.0%	*37.5%*	*11.8%*	*16.7%*	*5.6%*	*4.5%*		
Customizability	1	1	1	2	3	1	9	
	50.0%	*12.5%*	*5.9%*	*11.1%*	*16.7%*	*4.5%*		
Change rapidity	1	1	0	2	2	2	8	
	50.0%	*12.5%*	*0.0%*	*11.1%*	*11.1%*	*9.1%*		
Convertibility	1	0	2	2	2	1	8	
	50.0%	*0.0%*	*11.8%*	*11.1%*	*11.1%*	*4.5%*		
Adjustability	0	1	1	2	3	0	7	
	0.0%	*12.5%*	*5.9%*	*11.1%*	*16.7%*	*0.0%*		
Diagnosability	1	0	1	2	2	1	7	
	50.0%	*0.0%*	*5.9%*	*11.1%*	*11.1%*	*4.5%*		
Independence	0	0	3	4	0	0	7	
	0.0%	*0.0%*	*17.6%*	*22.2%*	*0.0%*	*0.0%*		
Availability	0	0	1	4	0	1	6	
	0.0%	*0.0%*	*5.9%*	*22.2%*	*0.0%*	*4.5%*		
Automation	0	0	1	1	1	2	5	
	0.0%	*0.0%*	*5.9%*	*5.6%*	*5.6%*	*9.1%*		
Self-Awareness	0	0	1	1	1	0	3	
	0.0%	*0.0%*	*5.9%*	*5.6%*	*5.6%*	*0.0%*		
Granularity	0	0	1	1	1	0	3	
	0.0%	*0.0%*	*5.9%*	*5.6%*	*5.6%*	*0.0%*		
Sum of Papers	**2**	**8**	**17**	**18**	**18**	**22**	**85**	

Modularity has been in the focus of research for many decades and is investigated for hardware [39] as well as for software [40]. A modular structure of a production system is regarded as a key factor for changeability in production systems since modularity allows the reuse of components or software and also allows to handle complex systems by dividing them into smaller modules.

Scalability has also often been mentioned as a changeability indicator within the investigated time span. However, its use seems to be slightly increasing over the last years and the indicator is now mentioned in each of the investigated papers since 2011. This might be due to the fact that customer demands became more and more unpredictable because of the individualization of products that is discussed lately. Thus, the need for scalable production systems increased.

Mobility is another indicator that has become more popular over the last few years, probably because of advances in technology in general and specifically in wireless communication. Dynamic manufacturing environments which are depicted in the discussions about “Industrie 4.0” are also enabled by mobile production units.

The usage of the indicator *Compatibility* has also been increasing over the last few years. Discussions about the Industrial Internet of Things where “Things” from different vendors form an overall system might have fueled this trend. Since it is not known at the design time of the system which “Things” might be used in the overall system, *Compatibility* is essential for changeable manufacturing systems. The term *Compatibility* is increasingly used instead of *Interoperability* (category B) and also supports the indicator *Standardization* (category B).

Universality of system components and structures allows to use them in different production scenarios and enables changeability directly. However, depending on the use case, not all system components and structures can be designed universally under an economical point of view.

Among the seven indicators in category B are: *Interoperability*, *Neutrality*, *Standardization*, *Decentralization*, *Self-Organization*, *Self-Similarity* and *Redundancy*. While some indicators like the already discussed *Interoperability* and *Standardization* are partly replaced by other indicators, also new aspects are being raised by these moderately mentioned indicators.

Although *Neutrality* is required to enable other indicators of Category A like *Universality*, *Modularity*, *Compatibility* and *Scalability*, it is less frequently discussed in the investigated papers of the literature review. As an enabler of these other changeability indicators, it plays an important role in the design of changeable manufacturing systems.

Decentralization is decreasingly used although the main idea behind it is still relevant. However, the indicator has been partly replaced by the related aspects *Interoperability*, *Compatibility* and *Modularity*.

Self-X properties like *Self-Similarity*, *Self-Organization* and *Self-Awareness* (category C) are also discussed as changeability indicators since they include functionalities that a changeable manufacturing system can make use of. For instance, it can be determined that a reconfiguration is necessary by the *Self-Awareness* ability. This reconfiguration can subsequently be performed by using the *Self-Organization* property.

Redundancy is mentioned in some papers as an indicator for changeability. However, most authors support the opinion that it is an indicator for flexibility (e.g. routing flexibility, volume flexibility…) and not for changeability.

In category C, eleven less frequently used indicators were classified. Since their relevance seems to be smaller, the discussion of these indicators will be given in a more compact form.

Automation has been used as an indicator for changeability before the investigated timespan. Nowadays, it is seen as state of the art and is therefore hardly noticed. This also applies for *Diagnosability*, which marks the ability of the system to detect faulty workpieces by means of sensor-based quality assurance. *Adjustability* describes the ability of a system to be reconfigured, usually by changes of the software or by parametrization. This can also be seen as state of the art in current manufacturing systems. *Availability* is nowadays seen as a must-have for changeable production systems and not as a specific indicator.

The indicator *Granularity* is often interrelated with *Modularization* since the definition of an appropriate level of granularity [41] has a direct influence on the reusability of a module.

Convertibility describes the ability of the system to detect the ideal mode of production and to subsequently perform the quick adaptation of the system. The idea is partly related with the *Self-X* properties discussed above.

Customizability and *Change rapidity* are indicators that are enabled by other indicators like Modularity. Both are mentioned separately in some papers but mostly are not seen as relevant in the literature.

Independence is seen as the ability of a (sub-)system to act independently from other (sub-)systems. This can be achieved by Modularization, Compatibility and Neutrality. It was discussed as a separate term especially between 2008 and 2010.

With the publication of ANSI/ISA-95 in the beginning of the 21st century, the *Knowledge about ISA* was also mentioned as a changeability indicator by some authors. As Table III shows, the interest in this indicator has decreased some years after the publication of ISA-95.

V. Summary and Outlook

This paper presented the results of two literature reviews on (1) flexibility indicators (82 papers from 1981 to 2018) and (2) changeability indicators (85 papers from 1999 to 2018) for automated manufacturing systems. Using a five-step literature review methodology, the database for the discussion of the indicators was generated.

In the field of flexibility, the four most often mentioned indicators are: (1) Capacity adaptability, (2) (Re-) Routability, (3) Diversity and (4) Versatility. The most frequently mentioned indicators in the field of changeability are: (1) Modularity, (2) Scalability, (3) Mobility, (4) Compatibility and (5) Universality.

The literature review revealed that the discussion about flexibility is usually carried out by using partial flexibilities like used for instance by Sethi and Sethi [9]. It was shown that these partial flexibilities can be mostly mapped to flexibility indicators as depicted in Table I. While most indicators can be mapped one-to-one, there are some exceptions which required further discussion. The subject of manufacturing flexibility has been researched for more than 40 years with a peak in interest around the year 2005 (see Fig. 2). Since then the number of published papers in this field is slightly decreasing. In contrast to flexibility, the number of published papers regarding changeability in manufacturing systems is still increasing although the number of papers is still five to ten times smaller. Following the current trend, changeability will be put more into focus of research in the next years. Many research works in changeability are based on early publications from Germany where changeability is known as “Wandlungsfähigkeit”. For this term, the number of papers in Google Scholar has tripled since 2000.

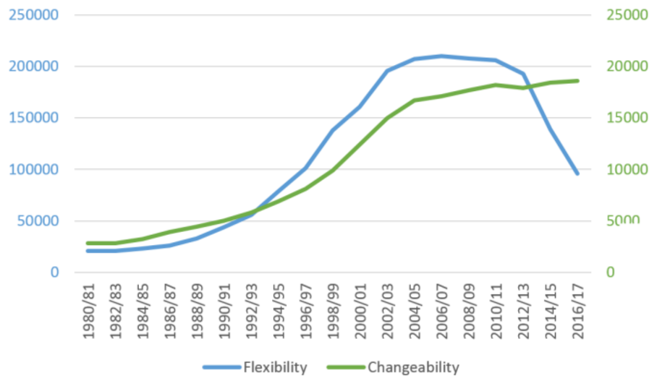

Fig. 2. Number of papers published for “flexibility manufacturing systems” and “changeability manufacturing systems” in Google Scholar

A discussion on all identified indicators and the development of their relevance was given in this paper. The review revealed that the use of indicators for assessing flexibility and changeability is common and allows deeper understanding of single aspects of these multidimensional terms. The use of indicators was also applied for assessing Cyber-Physical Production Systems lately, e.g. in [43].

Future works will focus on the development of a methodology to increase flexibility and changeability of existing production machines. Using an agent-based assistance system [42], the engineer shall be guided through the planning process. The assistance system will make proposals for the adaptation of the system and will evaluate these proposals in cooperation with the engineer.

For this evaluation, different aspects of flexibility will be considered. Currently, a graphical metric for comparing flexibility aspects of two or more manufacturing machines based on the partial flexibilities according to Sethi and Sethi [9] is developed.

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