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Investigating flexibility as a performance dimension of a Manufacturing Value Modeling Methodology (MVMM): a framework for identifying flexibility types in manufacturing systems

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Abstract

In recent years manufacturing companies have been faced with various challenges related to volatile demand and changing requirements from customer as well as suppliers. This trend is now even accelerating with a direct impact on the value chain. New technological roadmaps and suggested interventions in manufacturing systems try to solve these challenges and solutions such as the German high tech strategy “Industrie 4.0” or the Italian cluster “Fabbrica Intelligente” which often aimed at enhancing the flexibility of manufacturing systems among many other competitive dimensions. However, these approaches often do not provide a detailed definition of flexibility and its different manifestations. Therefore, the question rises if different types of flexibility, that have an impact on the complete manufacturing system, can be better identified with the existing Manufacturing Value Modeling Methodology (MVMM). This question becomes even more important when considering the potential that smart machines interacting with humans, such as cyber-physical systems (CPS), and the possibility to increase connectivity and data access through technologies, such as the internet of things (IoT), offer for increasing flexibility. Especially due to the various possibilities it becomes even more important to understand, which kind of flexibility is needed for a given problem. Implementing flexibility into the MVMM requires a ‘catalog’ that makes use of the MVMM framework presenting an overview of internal and external influence factors in order to support the identification of correct solutions and improvements related to functional areas in the manufacturing environment. Starting from a qualitative literature review on manufacturing flexibility, a ‘flexibility catalog’ is designed, which provides a structural definition of existing flexibility types and their composition as well as providing decision support. In conclusion, the scope of the ‘flexibility catalog’ is to verify that the flexibility demand fits into the market trends and is aligned to the manufacturing and company strategy, in order to help firms to take decisions and delivering value.

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Keywords: value modeling creation, manufacturing flexibility, Industry 4.0

1. Introduction

In the current competitive scenario, manufacturing companies are facing different challenges: global markets, increased competition, customers behavior, accelerated lead times and shorter product life cycles, which are contributing to the increase of uncertainty and variability [1]. In this context flexibility becomes a fundamental weapon to compete [2] and it has been recognized as a strategic manufacturing dimension [3], which needs to be modeled in order to deliver and preserve value.

Various definitions of manufacturing flexibility have been recognized in literature and in this paper manufacturing flexibility is defined as the ability to adapt to changes in the

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environment of the manufacturing system and it is evident that flexibility is a multi-dimensional and situation specific concept [4].

Starting from this definition, a flexibility catalog is designed, presenting a clear definition of the different characteristics of manufacturing flexibility also considering the external and internal factors, which have an impact on the company and manufacturing strategy. In order to include these internal and external factors the Manufacturing Value Modeling Methodology (MVMM) [5] is used. Using MVMM the flexibility catalog is designed in a top down approach, capable of storing identified external market trends and elements of the internal strategy such as a specific functional area and flexibility types. The goal of the flexibility catalog is therefore to provide a framework to support firms to make decisions and to deliver value. In order to develop the flexibility catalog, this work is divided in different sections. In section two a literature review on manufacturing flexibility is used to derive a novel flexibility model. The third section then presents the flexibility catalog itself, before the discussion, conclusions and implications are presented in the last section.

2. Literature Review on Manufacturing Flexibility

Flexibility in manufacturing system is not a completely new topic, but due to the current market situations and the enhancements in manufacturing technology and information systems, in the emergent digitalization process, its importance raises. Since there are many different approaches towards defining and structuring a more detailed analysis of flexibility is needed. Therefore, a qualitative literature review composed of two parts is carried out: first, an explorative and unstructured part that has a number of different origins providing inputs from project management and other areas; and second, a more structured review process involving searching databases using queries and dashboards. Academic papers from four databases are selected: ScienceDirect, Scopus, Emerald and Web of Science. As a result 49 empirical academic papers published between 1990 and 2015 are identified [1,2,4–50]. The distribution of publications over years (Figure 1) shows that in 2007 a peek is reached and that the interest decreases until 2012. After 2012, the same time, in which “Industrie 4.0” was first mentioned, the amount of publications increases again.

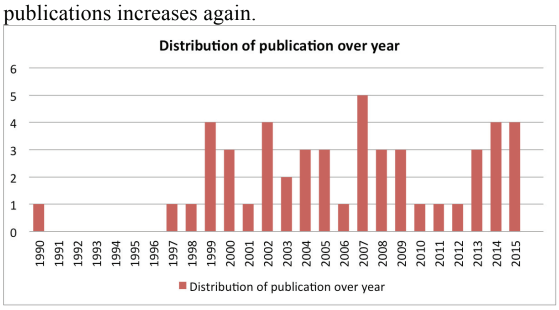

Figure 1: Distribution of publication over years

The distribution of publications over keywords (Figure 2) show that the top five keywords are “flexibility”, “manufacturing”, “empirical research”, “manufacturing systems” and “flexible manufacturing systems”.

Another important finding of the literature review is that a high amount of publications reference the flexibility model presented by Browne et al as well as Sethi and Sethi. that differentiates between basic, system and aggregated flexibility [21,51].

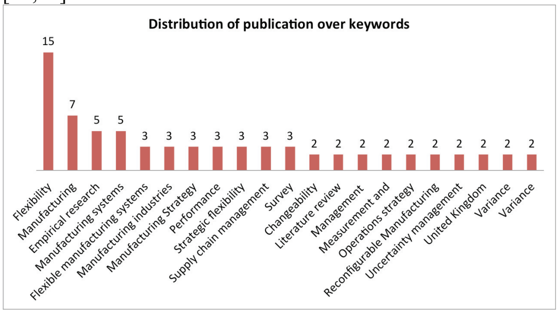

Figure 2: Distribution of publication over keywords

In their work Sethi & Sethi present a hierarchical model consisting of eleven types of flexibility, which are either affecting the important components of the system and the product (machine, material handling, operations) or the system as a whole [21]. Even though the aggregated flexibility already hints at different triggers for the flexibility demand, there are other authors that have a stronger focus on the causes for flexibility.

Kara and Kayis for instance investigate the origin of flexibility demand and state that it can either occur externally from a market point of view or internally from a manufacturing process point of view. Furthermore they also create a mapping between the causes for flexibility demand and flexibility types that are associated with them.[2]

Reviewing the two approaches it becomes clear that a combination of both could support the process of identifying a potential flexibility type candidate for a given manufacturing scenario. While the hierarchical structure of Sethi and Sethi creates an overview of the different impact levels and possible aggregation of flexibility types [21], they lack to highlight the factors, which could cause the need for flexibility. Kara and Kayis on the other hand side present an overview of different causes that can trigger the need for flexibility [2]. However, in their approach the hierarchical structure, which defines the impact levels of these flexibility types, is missing.

Hence both approaches share a common understanding of flexibility types a combination is possible that can overcome the drawbacks of the individual approaches, proposing a new one.

3. Flexibility catalog

3.1. Components of the flexibility catalog

The flexibility catalog uses the structure of external influence factors (market trends), internal influence factors (company objectives), functional areas (practices) from MVMM [52] as components and introduces the flexibility type as a new element for presenting different flexibility manifestations in manufacturing that have an impact on the complete system.

3.1.1. External influence factors

The external view represents the market trends. This component describes the specific environment in which a company operates. Examples for current market trends in manufacturing could be the complexity of supply chains due to decreasing lot sizes and increasing customization [53,54]. However, the market trends can vary from industry to industry and leading to industry specific libraries for presenting the possible market trends. Nonetheless there are global categories which apply to each library. In alignment with Kara and Kayis [2] this categories are the demand, the product lifecycle and the variant spectrum. Each trend can be assigned to at least one of those market related categories.

3.1.2. Internal influence factors

The external view is followed by the analysis of the internal process and strategies. Therefore, the company objectives section of MVMM is used to represent the internal influence factors including the goals and strategies of the manufacturing company. In general the flexibility catalog aims at aligning the internal influence factors according to the dimensions of the iron triangle: performance/quality, time/schedule and cost [55]In general the flexibility catalog suggests aligning the internal influence factors according to the dimensions of the triple constraint method: performance, time and cost. Different internal influence factors can be derived from Porter´s generic strategies of differentiation, cost leadership and focus [56]. In this case, the differentiation strategy fits to the performance dimension, meaning that the most important indicator for differentiation is the performance, which could lead to higher costs. When a cost leadership strategy is favored, the focus should be on the cost constraints while having fewer requirements regarding the performance. However the specific sets of possible strategies can again vary from scenario to scenario, leading to industry specific libraries that contain all possible influence factors. Nonetheless the previously introduced structure is remaining the same and these influence factors should be formulated as cost, performance and time requirements.

3.1.3. Functional area

The functional area defines the position within a primary activity of the value chain (Figure 4). Functional areas can therefore be listed for inbound logistics, operation, outbound logistics, sales and marketing as well as servicing.

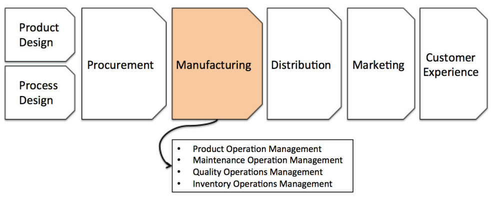

Figure 3: Value Chain

Since this work deals with manufacturing systems, the functional area is limited to the Manufacturing Operation Management (MOM) domain. However, Table 1 presents the possible elements from ISA 95 that represents the functional areas of the flexibility catalog.

Table 1: Functional areas [57]

Functional area	Description
Product operation management	Activities that are used to select, start and move the work units within the manufacturing system, by following an appropriated sequence of operations.
Maintenance operation management	Activities that are used to coordinate, direct and track the functions relevant for equipment and tool maintenance as well as related assets in order to guarantee a certain availability level.
Quality operations management	Activities related to the quality monitoring that includes the coordination, direction and tracking of quality measurement functions.
Inventory operations management	Activities related to managing and tracking product as well as material inventory, which also includes the transfer between work centers and the reporting on material transfer capabilities.

3.1.4. Flexibility Types

The last component is the flexibility type component that represents the novel flexibility model of the flexibility catalog. Four flexibility types with an impact on system level, are identified: variant spectrum, volume, expansion and scheduling (Table 2). The selection of these types is derived from the performed literature review and represents the consolidation of the analyzed flexibility types and their definitions.

The first flexibility type, variant spectrum, is mainly derived from both the process and product flexibility from Sethi and Sethi and therefore it does not only aim at the flexibility to produce similar parts but also new parts within a production line without the requiring major setup effort [21]. Hence the term variant spectrum is used to describe the outcome of different items that can be produced by a production line. Those items can be different variants of the same product or even different products.

The expansion flexibility on the other hand side focuses more on the trend of plug and produce, since it is described as the flexibility that enables the system to easily exchange capabilities in terms of manufacturing technologies [21]. Considering the previous flexibility types this could also be connected to the variant spectrum flexibility in cases were new technologies are needed to extent the current variant spectrum.

Another flexibility type is the scheduling flexibility, which is tightly connected to prioritization and delivery time as well as efficiency and utilization optimization topics. It partly includes the delivery flexibility that Oke defines as “the ability to change planned or assumed delivery dates [5]”. However, scheduling flexibility in the connection with the flexibility catalog is not just limited to the use case of delivery time topics. As mentioned before the flexibility regarding the adaption of production plans can also be used to enhance the overall utilization of the system as well as the optimization regarding other measures such as cost efficiency. An example for that would be the scheduling of production tasks that require an high energy consumptions at times where the energy costs are lower [58,59]. This could be beneficial if there are different prices between day and night.

The last flexibility type deals with the volume. This flexibility characterizes a system which is capable of producing efficiently even though the output can vary between different levels [21]. In contrast to the variant spectrum flexibility, this flexibility type considers the quantity of each good that can be produced in the system. However, in areas where different production mix solutions are compared or evaluated both types of flexibilities have to be analyzed together because the quantity of each item in the variant spectrum could vary.

As mentioned earlier the flexibility model follows the hierarchical structure from Sethi and Sethi [21] and therefore each flexibility type consists of the same set of flexibility building blocks.

Table 2 Flexibility types

Flexibility type	Characteristics	Sources
Variant spectrum	Amount of different final products that can be produced by a manufacturing system, compared to the required effort (operational and invest)	[10]; [34]; [41]; [13]; [26]; [43]; [47]; [12]; [46]; [11]; [1]; [49]; [14]; [18]; [20]; [4]; [44]; [22]; [5]; [32]; [2]; [37]; [27]; [39]; [28]; [8]; [7]; [9]; [25]; [17]; [21]
Expansion	Capability to arrange production mix and production order in different ways compared to required effort (operational and invest)	[10]; [41]; [46]; [4]; [22]; [2]; [27]; [28]; [8]; [7]; [9]; [17]; [21]
Scheduling	Output range in which the manufacturing system can be operated profitably, compared to required effort (operational and invest)	[10]; [41]; [13]; [50]; [40]; [47]; [48]; [18]; [4]; [22]; [5]; [32]; [2]; [27]; [28]; [8]; [7]; [9]; [25]; [21]
Volume	Amount of additional manufacturing capabilities that can be added to the manufacturing system, compared to required effort (operational and invest)	[10]; [41]; [13]; [47]; [12]; [46]; [48]; [11]; [1]; [49]; [14]; [18]; [4]; [44]; [22]; [5]; [32]; [2]; [19]; [27]; [28]; [8]; [7]; [9]; [21]

Those building blocks are the workstation flexibility, the transport flexibility, the flow control flexibility as well as the flexibility provided by the ICT system. Each of the four system level flexibility types can be realized with different characterizations of the system components (Figure 5). However, the concrete flexibility of those components strongly depends on the given scenario. On the one hand side, variant spectrum flexibility could be realized with a set of highly flexible workstation connected through a rigid transport system. But it might also be possible to reach the same flexibility with less flexible workstations that are connected via a more flexible transport system. Additionally, the most flexible machine, transport system or flow control does not provide any improvements if their flexibility potential cannot be processed by the ICT systems that are responsible for planning and executing the manufacturing processes.

Depending on environment and the existing internal influence factors the characterization of each building block can differ. Hence the building blocks are necessary to define the solution template that describes the flexibility demand of the manufacturing system.

3.2. Relationships in the flexibility catalog

Besides the general description of the flexibility catalog framework, it is mandatory to explain the application of the catalog itself. Since the general approach is derived from the MVMM approach it is also possible to create relationships between the different components.

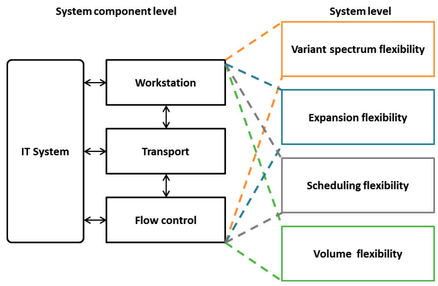

Figure 4: Flexibility demand

There is the possibility to create a relationship between external influence factors (market trends) and the business strategy (internal factor) that is used to tackle them. This means there is a certain set of internal influence factors that fit to a certain external factor.

Continuing with this approach the MVMM also defines a relationship between the internal factors and the functional area. This relationship is used to further specify the solution space by specifying, which internal factor relates to which ISA 95 pillar. With the flexibility catalog an additional relationship is introduced that shows the relationship between an internal influence factor and a system level flexibility type.

Based on those relationships it is then possible to identify the corresponding flexibility type for a given problem statement consisting of the identified market trend as well as the identified internal actions for dealing with it.

However, since those input factors depend strongly on the different production use cases it is mandatory to create a scenario specific set of external factors (market trends) and internal factors (business strategies) before the relationships to the functional area and the flexibility domain can be created.

4. Conclusion and further research

The purpose of the paper was to investigate the topic of manufacturing flexibility to develop a framework, which allows companies to identify the impact of flexibility on their environment and processes. The performed literature review has shown that the topic is extensively covered but there is a lack in identifying the factors, which could cause a flexibility demand. In this paper the MVMM is used to close this gap. The MVMM structure allows identifying the external impact factors and internal strategy that drive the flexibility demand. By adopting the aforementioned structure a flexibility catalog is developed, showing a possible identification of the four main flexibility types for manufacturing systems, which can be clearly defined and delimited from each other. It also shows that a general framework could be used to highlight the relationships between flexibility demand and flexibility type. The flexibility demand can be derived through the MVMM and the consideration of internal and external factors, leading to a better understanding of the concrete type of flexibility that is needed for the given scenario. Therefore, the hierarchical structure of the MVMM allows to identify pressure and challenges, in terms of flexibility demand that has an impact on the company environment. And starting from these trends, define specific flexibility types and capabilities that are essential for driving companies to reconfigure their processes. Especially at this point it necessary to highlight again that these objectives highly depend on the specific scenario under study, however a set of general objectives for industry are provided as a starting point for the assessment with a company. The goal is to offer a first set of objectives that can be discussed with a company and to sharpen the understanding in order to add more scenario specific objectives that follow the same structure and definition.

There are some limitations to the flexibility catalogue. The model is mainly qualitative and does not allow a detailed quantitative analysis. To overcome this limitation further research could build on different approaches towards measuring flexibility in manufacturing systems [60–63].

Additionally, a validation with real use cases is needed to verify and improve the catalogue. Finally, the definition of reconfiguration and technological solutions for each type of flexibility starting from an analysis of potential improvements of current manufacturing systems, could also be included in further research.

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