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Defining Flexibility of Assembly Workstations Through the Underlying Dimensions and Impacting Drivers

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Abstract

The concept of mass customization is becoming increasingly important for manufacturers of assembled products. As a result, manufacturers face a high variety of products, small batch sizes and frequent changeovers. To cope with these challenges, an appropriate level of flexibility of the assembly system is required. A methodology for quantifying the flexibility level of assembly workstations could help to evaluate (and improve) this flexibility level at all times. That flexibility model could even be integrated into the standard workstation design process. Despite the general consensus among researchers that manufacturing flexibility is a multi-dimensional concept, there is still no consensus on its different dimensions. A Systematic Literature Review (SLR) shows that many similarities can be found in the multitude of flexibility dimensions. Through a series of interactive company workshops, we achieved to reduce them to a shortlist of 9 flexibility dimensions applicable to an assembly workstation. In addition, a first step was taken to construct a causal model of these flexibility dimensions and their determining factors, the so called drivers, through the Interpretive Structural Modelling (ISM) approach. In the next phase, a driver scoring mechanism will be initiated to achieve an overall assembly workstation flexibility assessment based on the scoring of drivers depending on the workstation design.

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1. Introduction

Already in the 1990's, with the rise of the globalization, manufacturing and assembly companies started facing rapidly varying product demand and frequent introductions of new products [1]. This made the design of manufacturing systems and assembly architectures a major challenge, because it impacts the performance and flexibility for many years after the factory design. The introduction of mass customization during the last decades further stresses the assembly system' design and operations [2,3]. Mass customization is in fact the state of the art production paradigm that aims to produce individualized, highly variant products and services at nearly mass production costs [4]. A high level of flexibility is needed to cope with this mass customization challenge efficiently and cost effectively [5]. It is estimated that assembly still uses up to 50% of the production time and accounts for almost 20% of the overall cost in the manufacturing of complex products [5]. Flexible assembly workstations could thus already mean a huge improvement towards a flexible factory.

A first step in incorporating flexibility in assembly workstations is understanding what flexibility means and how it can be quantified. A methodology for quantifying the flexibility level of assembly workstations could help to evaluate (and if necessary improve) that flexibility level at all times. That flexibility assessment could even be integrated into the workstation design process. Defining and scoring flexibility is nonetheless a complex matter because it applies to a range of disciplines and sub-disciplines [6]. Its meaning also varies depending on the context. Nevertheless, there is a general consensus among researchers that flexibility in a manufacturing and assembly context is multidimensional and thus consists of different dimensions, each focusing on other aspects: volume, new products etc. [7]. These dimensions at their turn are influenced by measurable factors, so called drivers.

This paper gives an overview of the most common dimensions of manufacturing flexibility and describes the first steps in developing a causal model between these dimensions and their determining factors in the context of assembly workstations. In the end, this causal model will allow scoring the overall flexibility level of an assembly workstation. Section 2 shows the results of a Systematic Literature Review (SLR), conducted to get a full understanding of the current state-of-the-art in manufacturing flexibility. In section 3, the focus is on the specific flexibility of assembly workstations and the related causal model. Finally, conclusions and further research directions can be found in section 4.

2. Manufacturing flexibility

Before looking into the flexibility of assembly workstations, a full understanding of the broader manufacturing flexibility is necessary. Manufacturing flexibility has received a lot of attention in research, resulting in plenty of different types or dimensions of flexibility and various approaches towards the measurement of flexibility [8]. Despite that, there is still a lack of complete understanding and consensus among researchers about the different flexibility dimensions. Research in manufacturing flexibility can be considered fragmented and unstructured, hence the need for a SLR [9].

2.1. Methodology: systematic literature review

Analyzing literature via a SLR is recognized as one of the most efficient and high quality methodologies for identifying and evaluating extensive literatures [10]. It is in fact a research synthesis methodology resulting in the systematic accumulation, analysis and reflective interpretation of the full body of research related to a specific research domain [11]. Because a SLR is not a conventional literature review, the necessary full view on the current state-of-the-art in manufacturing flexibility can be attained. The scope of this SLR is limited to answering the following two research questions (RQ):

- RQ1: How can the flexibility of manufacturing systems be defined?
- RQ2: What are the different flexibility dimensions that define the flexibility of manufacturing systems?

To identify relevant publications, the Web of Science (WoS) Core Collection database of Clarivate Analytics was used. The database was accessed in August 2018. The time period selected, was the maximum allowed by the database (1955-2018). The WoS database was searched for keywords in the title of publications, since the title expresses the core information an author would like to convey and provides a reasonably detailed picture of an article's theme [12,13]. The keywords used for the database search are: manufacturing flexibility and flexibility of manufacturing systems. These two keywords combined in an OR-statement give no less than 459 hits. A bibliography of 459 titles appears to be too extensive for a review. Therefore a selection was made based on the abstract. In line with the scope (RQ1 and RQ2) of the review, only publications that have a broad view and aid in defining and classifying manufacturing flexibility are considered relevant. After the database search, the list of publications was completed by results of forwards and backwards reference snowballing to include all relevant work [14]. Eventually 112 publications were analyzed in the final analysis.

2.2. Defining manufacturing flexibility

Different interpretations of flexibility gave birth to a number of derived definitions such as system reconfigurability [15], changeability [16], evolvability [17], adaptability [2,5], agility [15] and transformability [18]. All those terms can be in some way classified under flexibility, but there are numerous connotation differences. In literature there is no general agreement on the definition of manufacturing flexibility [19]. However, a comprehensive and broad definition of manufacturing flexibility is provided by Upton: "the ability of a manufacturing system to change or react to changing circumstances with little penalty in time, effort, cost or performance" [20]. Important to note is that the flexibility of a manufacturing system depends not only on the range of states it can adopt, but also on the ease with which it can change states [21]. The differences in literature partly arise as a result of the fact that today every company perceives flexibility in its own way, since it is multi-dimensional [19]. Therefore it is difficult to summarize manufacturing flexibility in one sentence. It can thus best be defined through a series of dimensions.

A flexibility dimension is a term used to refer to different forms of flexibility. During the SLR no less than 174 different manufacturing flexibility dimensions were discovered. 146 of these dimensions were less than 5 times cited and their definitions typically have a lot in common with one of the more cited dimensions, apart from small differences in connotation. The most generally used and cited classification framework for manufacturing flexibility was proposed by Browne et al [22]. It consists of 8 flexibility dimensions: machine, process, product, routing, volume, expansion, operation and production flexibility. For quite some time, this classification was considered one of the most comprehensible in literature and was fully accepted by various authors [23]. It was later extended by Sethi and Sethi [24] by adding three dimensions: material handling, program and market flexibility. Their proposed framework thus consists of 11 different dimensions that define the flexibility of a manufacturing system. A lot of other frameworks were proposed later in research [25–27]. Table 1 summarizes the 15 most cited flexibility dimensions.

The different dimensions of manufacturing flexibility can manifest themselves at various and distinct operational levels in an enterprise [28]. They can also be categorized in terms of their long- and short-term effects [28]. Figure 1 classifies the 15 most-cited dimensions described in table 1 into different categories based on timing and their level of application. Koste and Malhotra [27] defined five application levels (tiers) ranging from the individual resources to the strategic business unit. In this research these tiers are simplified to only four main levels: company, factory, workstation and product. Some dimensions span across different levels of application. Volume flexibility for example will have its implications on the factory-level as well as on the workstation-level. The classification in figure 1 is based on different frameworks [24,27,29] and definitions found in literature (Table 1).

Table 1. The fifteen most cited flexibility dimensions discovered during SLR

Flexibility dimensions	Explanation	Times cited	Explanation based on
Volume flexibility	Volume flexibility is the ability to cost-efficiently vary output levels in response to customer demands and promised delivery dates without sacrificing quality or other competitive criteria.	77	[30–32]
Routing flexibility	Routing flexibility is the ability to manufacture a product using several alternative routes between the units and machines in the system without actually changing the sequence of operations.	42	[19,22,24,33,34]
Mix flexibility	Mix flexibility is the ability of the system to produce a variety of products simultaneously while also being able to switch, quickly and without major reconfigurations, between products in the current product mix.	40	[35–37]
Machine flexibility	Machine flexibility is the ability of a machine or tool to perform different operations without requiring a prohibitive effort in time and cost to switch between operations. It indicates how multifunctional a machine or tool is.	39	[24,38]
Process flexibility	Process flexibility is the ability of a workstation to quickly and without major reconfigurations produce a variety of products from the current product mix. This flexibility allows workstations to reduce the required batch sizes, but also to easily adapt to various changes in production (balancing, schedule changes, machine breakdowns, random access of product mix…).	37	[33,39–41]
Product flexibility	Product flexibility is the ability to inexpensively and rapidly (without major reconfigurations) change the current product mix, i.e. adding new products. Product flexibility applies to both the workstation and manufacturing system level.	36	[24]
Expansion flexibility	Expansion flexibility is the ability of the system to handle a long-term increase in capacity or change in the product range. This can be accommodated by a modular and expandable design of the system which allows to easily add or change resources (machines, labor, new technologies etc.).	25	[21,33,42,43]
Production flexibility	Production flexibility reflects the variety of products the manufacturing system can produce without adding major capital equipment and scores the ease with which they can be produced (major vs. minor set-ups). It gives an answer to the question: 'How flexible is the current production plant?'	25	[19,21,24,38]
Modification flexibility	Modification flexibility refers to the ease of producing minor alternations in products to meet customization or differentiation requests. The addressed product changes are less involved than the development of entirely new products and major upgrades to current products. The changes may often be accomplished through engineering change orders.	21	[27,35,44]
Material handling flexibility	Material handling flexibility is the ability of a material handling system to efficiently move several product types and parts from one point to another for proper positioning, processing or storing.	20	[24,33]
Operation flexibility	Operation flexibility is a property of the product and reflects the ability to change (the sequence of) operations required to produce/assemble the product, while complying with different restrictions imposed by its design, safety regulations etc.	18	[45,46]
Labor flexibility	Labor flexibility is the ability of a company to possess a flexible workforce. This means having a workforce able to handle a wide range of tasks, together with the ability of the company to easily deploy additional staff and vary working hours (e.g. overtime, third shift etc.).	18	[16,33,47]
New product flexibility	New product flexibility is the ability of the company to quickly and successfully introduce new products from design to production.	18	[7,21,27,48]
Delivery flexibility	Delivery flexibility is the ability of the system to respond to changes in delivery requests such as changed delivery dates, changed content of the orders, rush orders etc.	16	[42]
Material flexibility	Material flexibility is the ability of the workstations and machines to deal with unexpected variations in the processed products and input materials (e.g. tolerances, metallurgical properties etc.), but material flexibility is also the ability of the product design itself to accommodate small deviations in the necessary parts and their material properties.	11	[21,49]

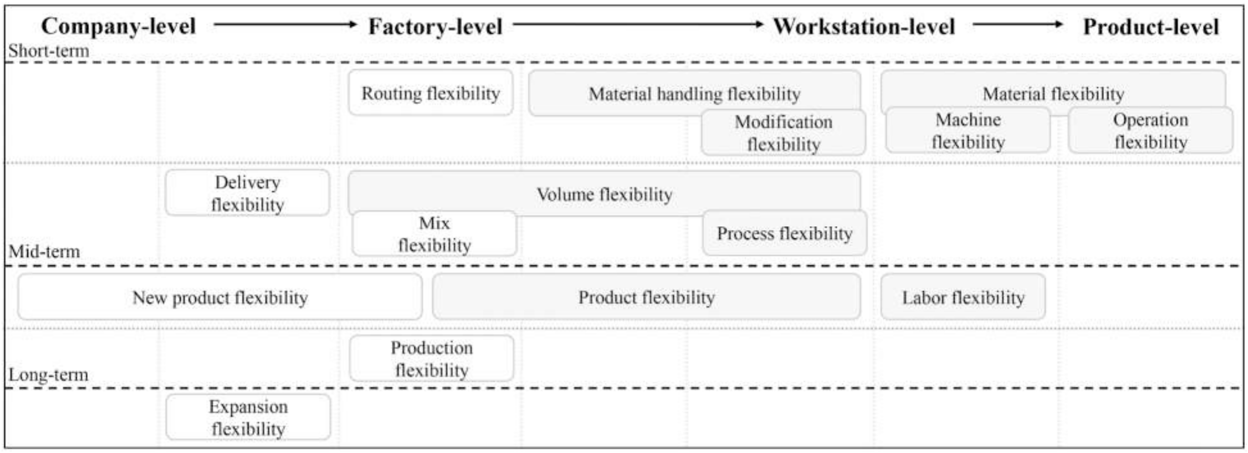

Fig. 1. Manufacturing flexibility hierarchy: time vs. application-level

3. Assembly workstation flexibility

Since assembly is only one part of the production, specific flexibility dimensions apply. Together with 8 cooperating manufacturing companies from the Flemish industry, the relevant flexibility dimensions for assembly workstations were defined through a series of interactive company discussions. These discussions also resulted in an overall definition of assembly workstation flexibility. Next, the first steps were taken to define a causal model between these dimensions and their corresponding drivers.

3.1. Dimensions of assembly workstation flexibility

Figure 1 shows that there are eight dimensions that apply to the workstation-level: product, modification, process, volume, labor, machine, material handling and material flexibility. During interactive group discussions with the Flemish manufacturing industry, the companies agreed with those eight dimensions. The outcome was however that operation flexibility, a product-level dimension, also needs to be included into the model. After all, it directly impacts the workstations. It also became clear that these nine dimensions can be split up into two different levels. First, the so called base dimensions that directly relate to the basic resources of a company (personnel, equipment and material [50]): labor, machine, material handling, material and operation flexibility [27,31]. Next, the other dimensions: product, modification, process and volume flexibility. These top-level dimensions depend on the base dimensions and can on their turn be bundled into the overall 'assembly workstation flexibility' (Figure 2). A comprehensive definition of assembly workstation flexibility can be defined as: Assembly workstation flexibility is a multidimensional concept, based on a two-layered hierarchy, that reflects the ability of an assembly workstation to adapt or react to changing circumstances without any unanticipated loss in performance, quality or other competitive criteria.

3.2. Causal model

The causal model is the next step in defining a methodology that will allow the evaluation of the overall flexibility level of an (existing) assembly workstation by scoring all identified flexibility drivers. The drivers are the factors that have a direct impact on the flexibility dimensions. For example, labor flexibility as a dimension can describe the ease of switching operators. Labor flexibility can be obtained through drivers such as high quality work instructions, customized assistance via smart glasses and the necessary ergonomic provisions. The causal model will reveal the structure and interaction of all drivers towards the dimensions (Figure 2).

Flexibility is a complex matter. Therefore the following approach will be taken: The analysis will be based on three iterations in consultation with a representative set of companies of the Flemish assembly industry which will incrementally refine the causal model. During the first iteration process flexibility together with labor, machine and material handling flexibility will be analyzed. In the second iteration the causal model will be extended with volume, material and operation flexibility. During the last iteration, the focus lies on embedding product and modification flexibility and improving the overall causal model.

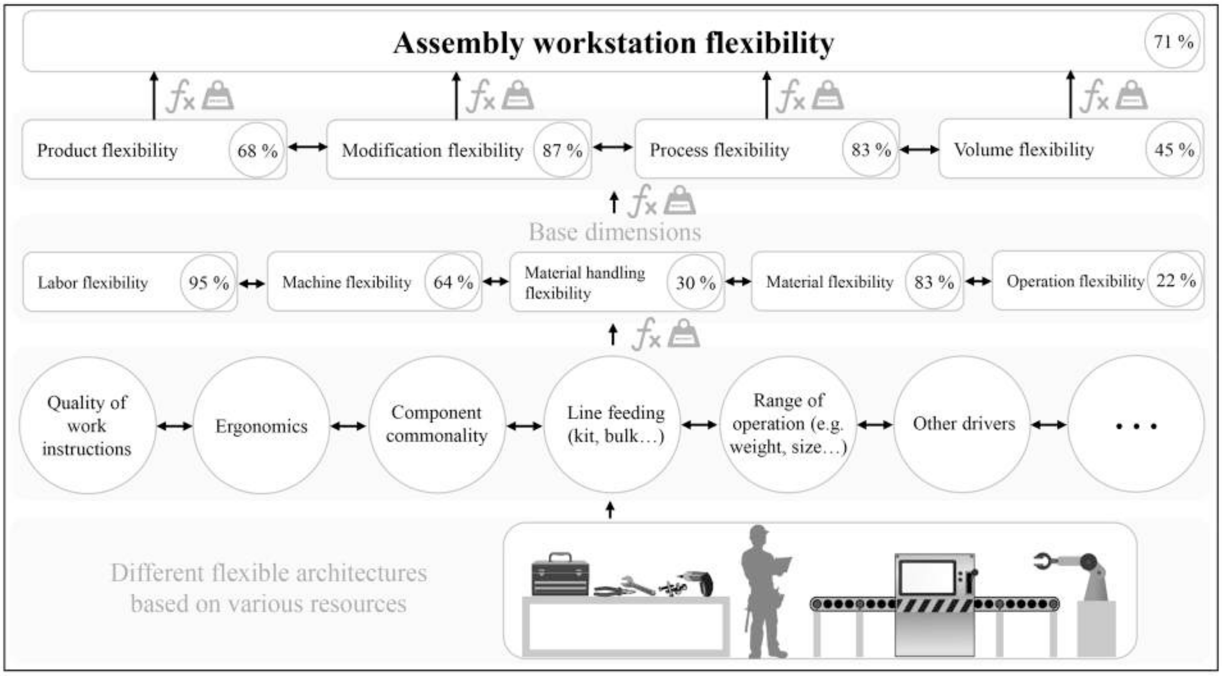

Fig. 2. Assembly workstation flexibility: conceptual causal model (percentages are just indicative examples)

3.2.1. Methodology: interpretive structural modelling

The data will be gathered through a series of interactive company workshops with the use of Interpretive Structural Modelling (ISM). Today, every company perceives flexibility in its own way [19], which makes ISM a suitable methodology because it transforms "unclear and poorly articulated models of systems into visible, well-defined models" [51]. ISM is an interactive learning process in which a set of varied, but directly related, elements are structured into a comprehensive, systemic model. ISM is interpretive because the judgment of a respondent group determines whether and how variables are related [52]. Since its inception, ISM has been applied by a number of researchers in various fields to develop a better understanding of complex systems. Raj for example used ISM in the manufacturing flexibility context [53].

As a starting point, 8 companies from the Flemish assembly industry will take part in the company workshops. To ensure a result applicable to a wide range of assembly industries, the selected companies operate in a diverse range of industries: heavy-vehicles, small electronics, HVAC, automobile, industrial equipment etc. To avoid an unwanted biased result, having more than two or three companies from the same industry is not desirable. Each company will be asked to select 6 workstations with a great variety in perceived flexibility. This will result in 48 different assembly workstations covering a wide range of different flexibility levels and types of assembly workstations (small components, large vehicles etc.). If necessary, additional workshops will be organized to increase the input data set. Zeltzer et al [54] recently identified the drivers of complexity. They used the data of 76 workstations obtained from 5 different manufacturing locations [54].

3.2.2. Next steps

Before developing the actual causal model through ISM, a list of drivers has to be defined. Once the first iteration has revealed the structure and interaction of the identified flexibility drivers towards the dimensions, the driver scoring mechanism will be initiated. The scoring of the drivers will be influenced by the different resources and control architectures in the assembly workstation. This scoring mechanism will allow to propagate the driver scores through the different flexibility dimensions towards the overall assembly workstation flexibility.

To embed the methodology for quantifying the flexibility level of assembly workstations into the design process of workstations, a structured model of resources and control architectures is necessary to define their impact on the drivers and thus the overall flexibility. In a next phase, resources will be clustered or categorized based on the functionality they provided. Flexible assembly architectures will be proposed as logical combinations of (interconnected) resources orchestrated within a control architecture. A meta-model will describe the relevant concepts (e.g. architectures and their characteristics), constraints (e.g. connectivity requirements) and objective functions (e.g. reconfiguration cost), providing a formal representation of the workstation design space [55,56].

Given the objective measure of flexibility, it will thus not only be possible to score an existing assembly workstation, but also during the design process itself, it will be possible to predict the flexibility level, based on the included resources and architectures. Changes in the workstation configuration will immediately be reflected in the flexibility score, enabling the comparison of multiple designs. Even more, since designs can be readily evaluated, Computational Design Synthesis (CDS) could assist the designer in exploring viable workstation alternatives, by considering the trade-off between cost, throughput and flexibility [57]. Designs can be started anew, or minimal changes to existing setups can be considered [58]. It is impossible to capture all (non-)functional requirements formally, so generated designs will still need to be validated by a design engineer. Nevertheless, integrating the flexibility measure into the CDS framework can help directly in identifying worthwhile workstation improvements.

4. Conclusion and outlook

A Systematic Literature Review (SLR) was conducted to discover the state-of-the-art in defining manufacturing flexibility through its underlying flexibility dimensions. The SLR confirms that there exist a tremendous amount of studies on manufacturing flexibility. This results in more than 170 defined flexibility dimensions, most of which are redundant. Only the relevant research on manufacturing flexibility was analyzed and a summary of the 15 most cited dimensions is compiled. It is assumed that these dimensions define all aspects of manufacturing flexibility. It is also clear that manufacturing flexibility dimensions have a wide range of application: from the management/company level to the workstation and product-level, in the short- or long-term. The flexibility dimensions relevant to assembly workstations are specified through extensive discussions with several companies from the Flemish assembly industry. These dimensions can be subdivided into two levels: top-level dimensions (product, modification, process and volume flexibility) and base dimensions (labor, machine, material handling, material and operation flexibility). The base dimensions are those dimensions directly related to the basic resources of a company (personnel, equipment and material). This paper further described the first steps in developing a causal model between the flexibility dimensions of assembly workstations and their corresponding drivers. A series of company workshops will provide the necessary data set to create a well substantiated causal model through the Interpretive Structural Modelling (ISM) methodology. Thereafter a driver scoring mechanism will be developed that allows the creation of a framework for scoring the overall assembly workstation flexibility of different workstations based on their design. This framework will later on allow integration into an (automated) design procedure (e.g. Computational Design Synthesis (CDS)) for assembly workstations.

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