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Procedia CIRP 41 (2016) 105 – 110

www.elsevier.com/locate/procedia

48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015

The relevance of manufacturing flexibility in the context of Industrie 4.0

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Abstract

Manufacturing companies have to withstand a growing global competition on different strategic dimensions like production costs, product quality and product innovation. To cope with this increased competition, companies in high-wage countries often employ a differentiation strategy to meet individual customer needs, as it becomes increasingly challenging to justify higher production costs through superior product quality. Manufacturing flexibility as a strategic orientation has been discussed in engineering and management literature for several decades with growing interest in the recent past. As a result of this development, scientific literature has focused on a multitude of topics including flexibility as a reactive and proactive strategy. This paper summarizes the different research streams associated with production flexibility, building on the groundbreaking work of Donald Gerwin [1], who introduced flexibility as a strategic perspective and developed a framework that illustrates the relationship between manufacturing strategy, environmental uncertainty and methods for delivering flexibility.
To the best of our knowledge, this is the first study to identify the relationships between flexibility and performance by systematically charting empirical findings from the literature and to link this development to the advancements of manufacturing schemes of Industrie 4.0. We use our findings to allocate the literature stream of production and manufacturing flexibility in the framework of Industrie 4.0, proposed by Schuh et al. [2]. The relevance of the discussed relationships are verified with different research groups in the Cluster of Excellence "Integrative Production Technology in High-Wage Countries" of the RWTH Aachen University.

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Keywords: Flexibility; Mass customization; Manufacturing

1. Introduction

Flexibility is widely accepted as one of the four operational capabilities of a firm amongst quality, dependability and costs [3]–[5]. While quality has been the top priority of German manufacturing firms for a long time, flexibility has recently gained increasing attention. A persistent trend of globalization supports competitive pressure, while significant market fluctuations and increasing demands for individualized products prevail. Increasingly heterogeneous markets accompanied by shorter product lifecycles are provoking the need of companies to provide great product variety, while at the same time maintaining excellent product performance at low costs [6].

One of the biggest challenges within these boundaries is sustainable competitiveness. The complementary theories of Cumulative Capabilities and Trade-Offs within the Operations Management field provide a solid basis for the analysis of the strategic importance of flexibility for producing companies [7], [8]. Recent developments in production technology increase the focus on flexibility means by producing companies and question the boundaries of the traditional production theory. Our approach of integrating the key aspects of Industrie 4.0 into the production theory development shows an increased need to advance our understanding of flexibility on the production context.

This paper aims at presenting a comprehensive overview over the development of flexibility literature in Operations Management. In a second step, the authors transfer the key-

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Peer-review under responsibility of the scientific committee of 48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015
doi:10.1016/j.procir.2015.12.047

findings towards the implementations of iterative product lifecycles as a result of the technology advancements of Industrie 4.0. The paper closes with a discussion and concluding remarks.

2. Theoretical foundation

Unlike other research fields, Operations Management does not build on a common set of theories for which it is famous. However, it applies theoretical frameworks from adjacent research fields like management science, microeconomics and natural sciences [8]. One of the major frames used to derive theory in Operations Management research is the Resource Based View (RBV), which states that valuable, rare, inimitable, and non-substitutable resources can lead to competitive advantage [9], [10]. In the corporate context, a firm controls a variety of resources like organizational processes, capabilities, assets, knowledge, attributes etc. to implement strategies and to secure its competitive position [11], [12]. According to the contingency theory, which builds on the RBV, the optimal set of a corporation's resources depends on its specific internal setup and environment [13]. This assumption challenges the neoclassical production

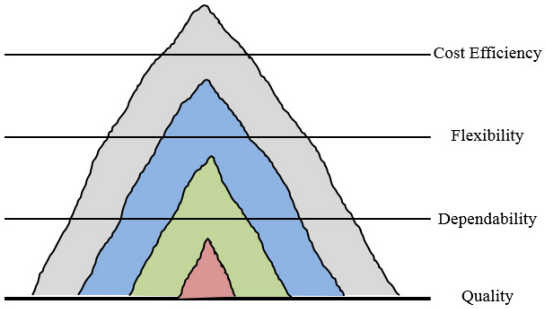


Fig 1: Sand cone model [4]

functions as it claims that there is not a universal function that holds for all eventualities and can be applied to different companies [14]. In the Operations Management literature, two conflicting research streams dealing with cumulative capabilities and trade-offs have evolved [8]. The theory of trade-offs, also known as the theory of competitive capabilities, is based on the observations of Wickham Skinner, that there are trade-offs to be made in designing or operating a production system [15], [16]. A given state of technology defines an outer boundary of where a production system can operate. Hence, one system cannot provide the highest level in various operational dimensions like quality, flexibility, delivery and cost at the same time [17]. Especially when decisions for initial designs of green-field plants are made, several dimensions conflict with each other like the flexibility to produce high product variety and cost effectiveness, or the implementation of lean or agile manufacturing systems [15]. As a result of these trade-offs, the manufacturing strategy should always be aligned with strategy of the overarching corporation [18].

In contrast to the theory of trade-offs, the theory of cumulative capabilities describes the achievement of high performance in multiple capabilities at the same time, because the simultaneous pursuit of capabilities can lead to superior overall performance [8], [19]. This theory is based on the observation, that certain manufacturing plants outperform their rivals in multiple dimensions at the same time. The underlying assumption is, that improvements in certain manufacturing capabilities are a prerequisite for further improvements in other capabilities [4]. The widely cited sand cone model (Fig 1) of Ferdows and de Mayer suggests quality as a foundation for all other capabilities, as less rework and waste facilitate delivery dependability, speed and cost efficiency [4]. Whereas the supporting influence of quality and dependability on speed and quality has been subject of several empirical studies, it is questioned whether there is a cumulative relationship between high cost and flexibility performance [14].

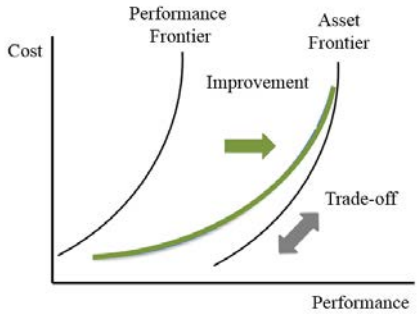


Fig 2: Theory of frontiers [8]

The theory of performance frontiers (Fig 2), also referred to as the theory of production function frontiers, subsumes the law of cumulative capabilities and trade-offs. In contrast to the production functions or frontiers known from neoclassical production theory, the theory of performance frontiers differentiates between performance and asset frontiers. Further, the dimensions of product variety, quality and cost effectiveness are incorporated as outputs. The performance frontier is defined as the maximum performance achieved by a manufacturing unit, given a set of operating choices whereas the asset frontiers represent the technical maximum output of a system [11]. The shape and position of the performance frontier are affected by the firms' business policy and thereby depend on business environment and available resources. On a given performance frontier, companies can only improve one dimension by trading-off the degradation of another. Hence, improvements result out of a firms' choices about its competitive priorities and are bound by the available unique resources and the environment, specific to a firm [12]. In order to escape these trade-offs, the asset frontier needs to be advanced by introducing new production technology. Integrated machines or additive production technologies enable revolutionary short value chains and dramatically enable iterative product lifecycles [20], [21].

3. Development of flexibility literature

There has been a growing interest for flexible manufacturing and mass customization in the recent years [22]–[24]. Literature has focused on various aspects of the topic like definitions of manufacturing flexibility, dimensions [25]–[27], classifications and taxonomies[28], [29], measurement of flexibility [30], the relationship between uncertainty, flexibility and performance [3], [31], [1], or the dimension of supply-chain flexibility [32], [33]. Groundbreaking contributions to the topic of manufacturing flexibility have been made by Gerwin [1] through the development of a conceptual framework based on the proposal of Swamidass and Newell [3], who have introduced flexibility as a manufacturing strategy. Gerwin shows the interdependencies between environmental uncertainty, manufacturing strategy, manufacturing flexibility, and performance [1] (Fig. 3). Manufacturing strategy is the core of the framework as it is the place where the other elements are put into context. Swamidass and Newell define manufacturing strategy as the effective use of manufacturing strengths as a competitive weapon for the achievement of business and corporate goals [3]. Generally the manufacturing strategy literature comprises the following four dimensions: cost, quality, flexibility and dependability [3], [5].

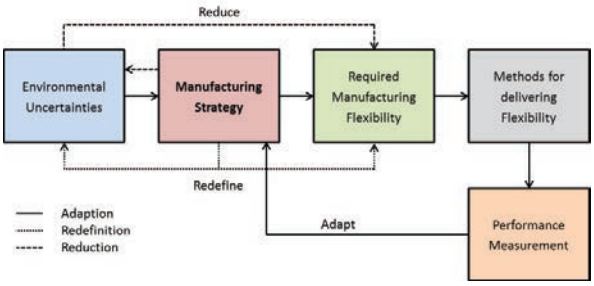


Figure 3: Conceptual Framework, adopted from Gerwin [1]

In the context of his framework, Gerwin introduces three generic strategies, classified into whether they are defensive or proactive in use. Adaptation, the reactive use of flexibility, refers to the adjustment of the manufacturing setup as a reaction to perceived uncertainty, meaning that more random changes in the environment lead to higher investments in the abilities to vary the production process. A proactive approach, however, is the redefinition of market uncertainties meaning, that companies can try "bend the environment to its will" [1]. A company can for example create additional uncertainties for its competitors by making their customers getting used to a faster introduction of new products. The third strategy is the reduction of uncertainties leading to a decreased need of flexibility. Such a reduction of uncertainties can be achieved for example by long-term contracts with customers, with the effect of lower fluctuations in demand or through preventive maintenance

While Gerwin [1] identified four different strategies, the flexibility literature stream focuses on the two aspects of reactiveness or adaptation (Fig 4). Building on the theoretical framework of Gerwin, several researchers have composed empirical investigations on manufacturing flexibility as a strategy to cope with environmental uncertainty.

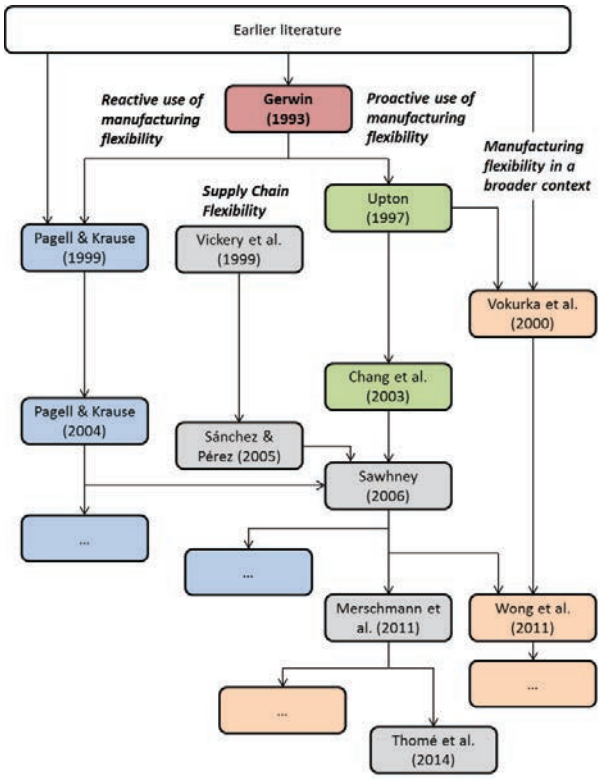


Figure 4: Development and correlations of literature

Pagel and Krause suggest on the basis of empirical data, that not environmental uncertainty is the key driver for flexibility but rather the products a company produces [31], [34]. More recent results of a study analyzing flexibility in a supply chain context however suggest in line with the framework of Gerwin, that companies should achieve a fit between their flexibility strategy and the level of environmental uncertainty in order to reach high levels of performance [35]. Wong et al. provide empirical evidence, that environmental uncertainty positively moderates the relationship between several integration practices and production flexibility [36]. Criticizing that studies like the one of Gerwin solely focus on the relationship between environmental uncertainty and manufacturing flexibility, Vokurka and O'Leary-Kelly recommend to expand the scope of analysis by also focusing on three additional variables influencing manufacturing flexibility, namely strategy, organizational attributes and technology [24]. The latter implicates, that technology advancements can be used to provoke a shift in the customers' expectations towards the degree flexibility of goods offered. Feigenbaum and Karnani suggest, that flexibility is an advantage especially of small firms [37] meaning that smaller companies can realize greater performance gains as a result of output flexibility than large corporations. In order to increase their benefit, large corporations can assimilate certain proponents of process management from small companies [38].

According to Upton there is a significant link between the vintage of process technology, the experience of workers and manufacturing flexibility, suggesting that production flexibility can be increased by technology upgrades and the employment qualified staff [39]. Kuzgunkaya and ElMaraghy give a comprehensive overview over the economic implications of flexible manufacturing systems [40]. Further there is a positive relationship between production and supply chain flexibility, operational performance and firm performance [41], [42]. The effect of flexibility on performance however is dependent on the fit between the manufacturing flexibility with the overall strategic orientation. Parthasarthy and Sethi claim that the flexibility impact on performance is larger if its incorporated as part of the company's strategy and Chang et al. suggest in accordance with the trade-off theory, that companies have to derive flexibility means in line with their strategic positioning [43], [44].

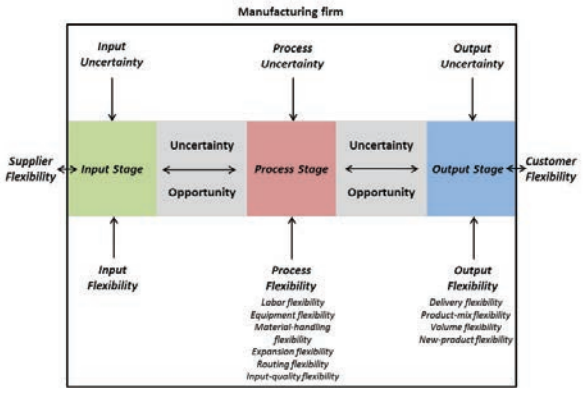


Figure 5: Transformation framework of flexibility [45]

In the year 2000, Sawhney proposed a framework that the two strategies of adaptation and redefinition can be employed simultaneously to encounter uncertainty and to open up opportunities at the same time [45] (Fig 5). Wong et al. built on this framework and introduced the aspect of supply-chain integration to the research field of production flexibility [36]. According to their empirical findings, both supplier integration and customer integration lead to an increased production flexibility performance. Further they show evidence, that this relationship is positively moderated by environmental uncertainty suggesting, that companies aiming to provide high product variety as means to cope with uncertainty, need to integrate both with their suppliers and with their customers.

4. Iterative product lifecycles to drive flexibility in Industrie 4.0

Advanced manufacturing techniques allow radically short lifecycles and an intensified customer orientation with individualized products [21]. For many years additive manufacturing technology was used in the context of rapid prototyping, where products are not produced for end customers but rather for the use in an internal product development process [46]. However, in the recent past there has been a development of the employment of additive manufacturing techniques from rapid prototyping towards rapid manufacturing as a result of increasing process rates and thereby falling marginal production costs [47]–[49]. The advancement of these technologies lays ground for iterative development processes, based on incremental product adjustments. With additive manufacturing technologies products can be developed on the basis of existing parts with the aid of digital design tools such as 3D scanners or altered by the simple variation of digital drawings [50]. Weller et. al. give a comprehensive overview on the economic impact of additive manufacturing technologies based on a payoff function [20]. In comparison to the traditional deterministic product lifecycle, consisting of the phases, development, introduction, growth, maturity and decline, an iterative development process includes an evaluation phase with the possibility to integrate with customers and thereby to gather field data (Fig 6) [51], [52].

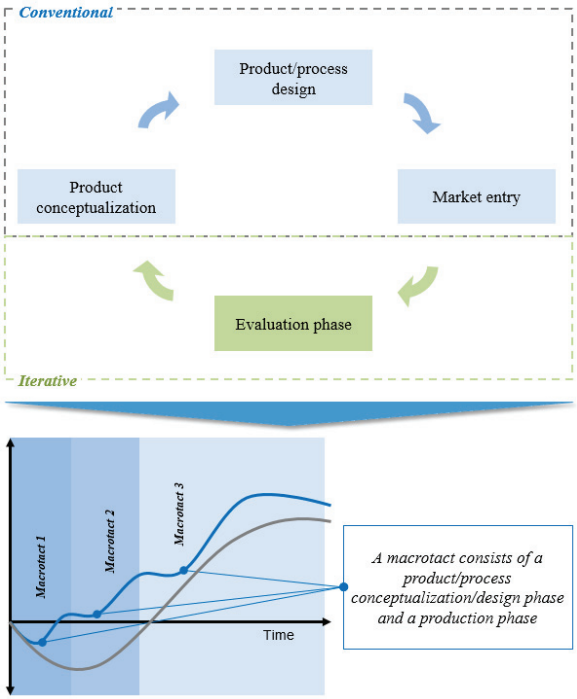


Figure 6: Macrotacts on the basis of iterative product lifecycles

The iterative product-lifecycle is divided into several steps called macrotacts, each consisting of two development phases, namely product conceptualization and product and process design, and a market entry step. The stages of growths, maturity, and decline are seen as intermediate steps of the evaluation phase and as a pre-step of the next macrotact. Iterative and agile product development processes increase the development productivity and allow to handle high complexity under uncertainty [53]. The approach to develop products on the basis of customer feedback is very similar to the lean startup approach known to provide high productivity

at very limited resources [54]. According to the reference system of collaboration productivity, both return on engineering and return on production are positively affected by the iterative product lifecycle [2]. Additive manufacturing technologies as a basis for the iterative approach reduce the cost of producing a minimum-viable-product to enter the market for data generation and thereby increases the return on engineering. Implementing the gained market knowledge and experience into further product variants, enables gains in the return on production as wastage is reduced to a minimum.

This transformation towards iterative product lifecycles has several implications both for reactive and proactive flexibility strategies as proposed by Gerwin [1]. The establishment of the evaluation phase as an integral part of the product lifecycle decreases the risk of missing market trends and thereby increases the responsiveness to changing market needs. Ideally there is a constant assimilation of market based feedback in the sense of customer integration which allows companies to direct their manufacturing processes towards the market changes [36]. Further, the employment of agile technologies like additive manufacturing can be seen as a proactive flexibility strategy. The employment of additive manufacturing techniques has significant effects on the cost structure of manufacturing companies, as they enable companies to develop product varieties at very limited marginal costs [20]. This change in cost structure can be used according to Gerwin's framework to apply pressure on competitors on the market in the sense of redefining the product lifecycles and degree of product individualization the customers in a specific market are used to [1].

5. Discussion

We have shown that the Operations and Production Management literature offers a variety of literature, dealing with the strategic relevance of flexibility. In particular, we have presented the development of a research stream dealing with reactive and proactive flexibility strategies, based on a framework proposed by Gerwin in 1993 [1]. In high-wage countries, where quality and dependability merely function as order qualifiers, the dissolution of the flexibility costs dilemma is of vital strategic importance. The theory of performance frontier illustrates the need, to move the asset frontier to break free of the trade-off between these two dimensions. With additive manufacturing techniques as key-stones of Industie 4.0 in combination with iterative development processes, we present an approach to employ manufacturing flexibility both as reactive and proactive manufacturing strategies.

Acknowledgements

The authors would like to thank the German Research Foundation "Deutsche Forschungsgesellschaft" (DFG) for the kind support of this research project, which is part of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University.

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