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MASS CUSTOMIZATION AND ITS IMPACT ON ASSEMBLY PROCESS' COMPLEXITY

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Abstract: *It is well known that high level of customer requirements and rapidly changing environment both induce complexity. The main reason for the failure of majority mass customized applications and projects is an increasing overall complexity of the system while relevant solutions for the overall production complexity reduction are still missing. The paper presents an overview of variety induced complexities in assembly operations capable and assessing the impact of assembly variety on performance, and reveals problems arising between quality and complexity. This paper aims to describe the current views to complexity, its measurement and management within assembly processes in mass customized productions and presents proposals for future development in the area.*

Keywords: *Mass Customization, Complexity Management, Assembly Supply Chain, Process Management*

1. Introduction

Mass customization (MC) is quite a new term in customization of products and mass-produced artifacts. On the other hand, product customization is not a new issue in the field of manufacturing management. During last decades, companies all over the world aimed to improve their customization approaches. In order to define this phenomena we can select some characteristics of this production strategy. According to (Blecker *et al*., 2006; Ko, 2008; Martin, 2010), mass customization aims to satisfy the customer`s individual needs with near mass production efficiency. Therefore, a real mass customized production needs make-to-order equipment as well as mass production capabilities at the same time. In principle, mass customization is a production system manufacturing customized goods in high volumes for mass markets. It is able to offer a number of product configurations and variants derived from a single or few core products. While product is mass-produced, customers are asking for the adaption and inclusion of their requirements. There isn’t a car producing or any other company offering only a narrow range of choices. Mass customization principles can be applied to different consumer goods such as computers, clothes, food, furniture or investment goods such as machinery equipment or buildings (Blecker *et al*., 2006). MC brings huge advantage over competitors to producers byoffering special, additional product features. The biggest success of the MC and of mass customized productions (MCP) is in their ability to achieve a flexibility of the specific product or product group while avoiding cost rise for the mass producing facility and in

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the supply chain due to variety and complexity. Therefore, MC affects in almost all aspects of the company production and business processes. While the main company functions as "source-make-deliver-return" remain unchanged, company key enablers such as information systems, or business processes should be able to cope with the higher complexity induced by product variety. Rapid increasing of MC phenomena can be expected in a near future, since its "dissemination" is pulled by the need to pamper the customer. Therefore, managers in all company levels gain broad attention in MC and try to apply it within various industries and markets.

In this paper we will introduce mass customization concept and its base application problem, which is variety induced complexity. In the next section, the mostly used complexity concepts are presented and the appropriate literature reviews is presented. The paper aims to identify and present the currently used types of complexities in terms of mass customization and to identify the metrics for complexity assessment applicable in assembly supply operations and its sub-problems. Section 3 presents commonly used complexity metrics on different platforms and identifies sources of complexity in terms of assembly lines. Section 4 provides a classification of approaches to variety induced complexity from author's perspective. The last section summarizes the overview and brings directions for future research in the area.

2. Mass customization and related complexity issues

Production lines evolved from simple moving lines to complex assembly systems with convergence in the early 1900s. Complete evolution of production can be seen in Figure 1. Wang (2010) for instance stated, that in last decades there has been a need for transformation of productions towards four general dimensions, namely customer demand and requirements, consumption rate and volume, market factors like globalization and technological progress. Mass customization applies to products according to their purchasing frequency and adaptability. Variety, market saturation and distribution are recognized as mass customization enablers.

However, there are still deficits in the practical application of the theory into the practice (Piller and Reichwald, 2002). Transition to and practical application of mass customization is not an easy job either. The complexity of any system is generally based on one of the three complexity variables, namely, number and state`s variety of system elements and relationships among them. These variables then differ between structural (static) and operational (dynamic) complexity. While structural complexity defines the state of a static system, dynamic complexity tries to describe the state of a system in a specific period of time.

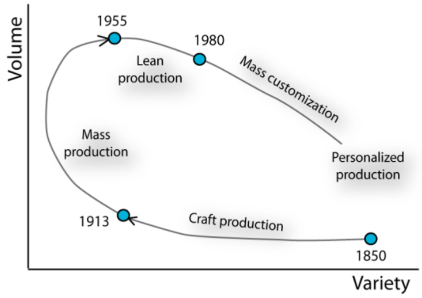

Figure 1. Evolution of production understanding (Piller and Reichwald, 2002)

In this regard, Modrak *et al*. (2014) stated, that the main reason for the failure of majority mass customization application projects is increasing overall complexity problem in all aspects of production. On the other hand researches examining overall complexity are still missing. Authors are preceding their researches in specific fields of mass customized assembly productions, e.g. layout design, product families, modularity, product configurations, etc. but never search for the complexity framework from all aspects at once.Researches examining complexity depending on case of customization are also missing. Moreover, different authors confuse their results of variety induced complexities achieved in batch, lean or even mass production in order to present the effect on complexity in mass customized production. This is of course not a correct view on mass customized production and its complexity, since it has got its own properties and they should be taken into account when dealing with complexity in different aspects of the production.It is empirically known that he higher the number of product variants, configurations or the overall variety, the more complex difficulties in the production design and operational management of assembly systems or assembly supply chains there are. It has also been proofed by theory,experimental data and simulations that variety itself had a significant impact on the performance (productivity, quality) and complexity, especially in automotive vehicle production, including assembly and parts supply (Webbink and Hu, 2005; Marcora *et al*., 2009). One of the current efforts in the assessment of impact of assembly variety on performance is to reveal or develop a measure for variety-based complexity in the assembly supply chain operations.

Up to this moment, scientists of various disciplines have not found a satisfactory definition of complexity. It has only been admitted, that a complexity is a system attribute depending on the composition of system elements. It is widely discussed in area of system and graph theory. We already know that any system consists of building elements, such as objects and sub-systems, and of relationships between sub-systems and systems of lower order. At the same time it is discussed that a system should have an exact function within the system or higher order and should perform a specific function there. Numbers of authors, e.g. Hu *et al*. (2008) or Zhu *et al*. (2008) explored reasons of high complexity in mass customized productions. There is, however, a little evidence about the key source of complexity in such an environment. In order to effectively manage a complexity, it is necessary to obtain a common framework providing a wide definition of the term. Once we have the definition, we are able to better understand the causes and effect of complexity.

In mass customization literature, the term complexity is mostly used without having been defined first. Furthermore, variety and complexity are often used interchangeably as if they were equivalent terms. It is basically discussed in connection with the system theory and is referred to as a system attribute. A system consists of elements or parts (objects, systems of lower order, subsystems) and the existing relationships between them. Authors from distinct fields of interest see and define the term ’complexity’ in different ways. Some authors look at complexity from a perspective of product or process as Hu *et al*. (2008), some from the perspective of managerial structures as Vujovic and Krivokapic (2011), some from consequences on modeling viewpoints like Arsovski *et al.* (2009), Modrak *et al*. (2012) or Modrak and Marton (2014) and some authors have developed their own information-based theories like Shannon (1948). Andre *et al*. (2009) emphasize that complexity as an internal property of the entity describes the essential characteristic of the system. The evolution of complexity understanding is depicted in timeline of Figure 2.

According to El Maraghy *et al*. (2005) and Zhu *et al*. (2008), complexity of a system is defined with respect to the 3 complexity variables, namely number, dissimilitude and states' variety of the system elements and relationships. The three variables allow us to differ between structural and dynamic complexity. While the first one describes the state of system in a defined time point, dynamic one describes a change of a system in a period of time.

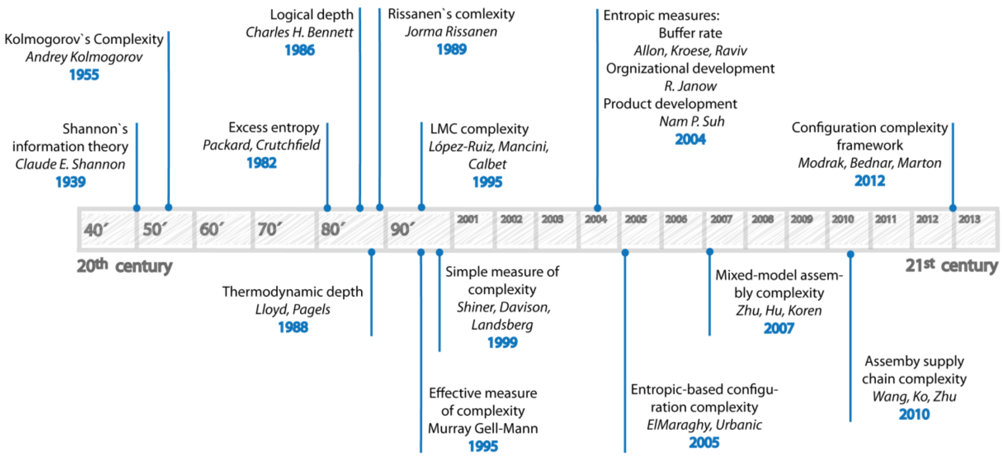

Figure 2. Review of important milestones in complexity management

If we, for example, take a production layout solution of a mass type consisting of a number of product configurations at a certain time point, the number of all product configurations and variations determines the structural complexity of a system. Dynamic complexity on the other hand relies on the size and frequency of changes in the system. The complexity is even higher if a product is eliminated or introduced. Papakostasa *et al*. (2009) have defined a metric for system complexity on the basis of both, dynamical and structural complexities. According to them, a system is simple if both complexities are low. On the other hand, if only a structural or dynamic complexity is low (high), a system is considered to be complicated or relatively complex. System is very complex only if the both complexities are high. Definition of a companies' complexity according to Piller (2006) says that "…it is a systemic effect that numerous products, customers, markets, processes, parts, and organizational entities have on activities, overhead structures, and information flows." The crucial problem of complexity is in its hidden extra cost that may come up during the process. They advise to describe a complexity by decision-making process at a customer's side and the one on the market side.

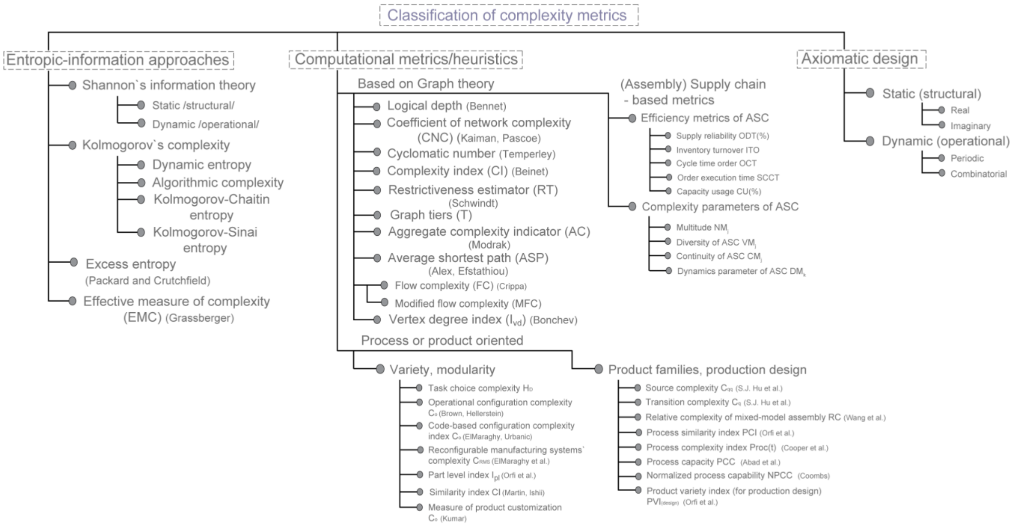

Figure 3. Classification of complexity metrics in terms of production

Frizelle and Efstathiou (2002) have introduced the former "good complexity" and the latter "bad complexity" and presented them on a number of case studies. Wildemann (2006) introduced three individual complexity measures, namely: complexity reduction, complexity prevention and complexity control. Complexity reduction aims to make process or product structures simpler by elimination or even introduction of a new product variant in order to eliminate the priceless product variants. Complexity prevention aims to prevent the high local structural and dynamical complexities by developing a so called Complexity prevention action plan. Complexity control takes care of the rest of complexities. They cannot be managed or reduced because of market requirements or turbulences of the market.

Rother and Toyota (2009) and Loffler *et al*. (2012) reminded that complexity management is only possible if we distinguish between different complexity tools and techniques for product, process or layout complexity reduction. Reiss (2011) and Holger (2005) propose to differ between complexity decreasing and complexity increasing measures. Bliss and Haddock (2008) developed a concept consisting of four phases. Theircomplexity management concept is based on the theoretical analysis of a production systems and case studies.

3. Relationship between complexity and quality

Product quality and/or quality product is generally understood as the measure of customer requirements satisfaction. A measurement of quality level required by customer and delivered to customer is extremely sensitive activity, as it allows us to uncover the degree of conformance to customer specification only partially. According to El Maraghy (2009), quality is inversely proportional to variability resulting from the manufacturing system as designed and/or as a result of changing capability. Despite of various existing tools for product quality assessment in the manufacturing system, there is only a limited number of authors concerned with the impact of manufacturing system design complexity on final product quality. Moreover, there is rather no research concerned with the issue of mass customized production complexity impact on final product design, or at least on how the mass customized product conforms to the customer requirements. Much of the recently developed metrics for the prediction of product quality are applicable rather in on-line production management. Those methodologies developed for the design/structural complexities are still limited.

There is a huge number of metrics and tools to assess quality of the final product within a manufacturing system. But there is only limited research efforts not a successful tool to study impact between product quality and production system design. It would be of course essential to use such a tool for development of new production system/layout even in the development stage of the system. The methodologies and procedures dedicated to assess final product quality and their interaction with current manufacturing system are rather limited. In terms of MCP, a manager is faced with specific number of product configurations and their variants, and with other expected or unexpected system changes. Then a quality manager in terms of MCP should be able to decide, with help of mathematical models, and choose, what decision affects the final product quality the most. Until the research work of El Maraghy (2009), there have not been efforts in finding the relationship between manufacturing system layout (structural complexity of a system) and final product quality. There has not been any research undertaken in the field of MCP vs. quality. Researchers of various directions are only finding the most applicable tool to describe MC system in a structural way, so the structure of any system is analyzed with focus on single or multiple structure property and a calculation of static „complexity“ is performed.

Despite of serious efforts to develop and verify a quality measure, most metrics can neither predict the final product quality in terms of manufacturing system parameters, norare theyapplicable in the facility/production design stage. Serious efforts have been done during the last decade in the field of general manufacturing complexity to develop a quality approach based on the relation between manufacturing system design and manufacturing complexity.Researches of Nada *et al*. (2006), Sivadasan *et al*. (2010) proofed, that final product quality in the changeable manufacturing environment is very sensitive to operational system changes. Variety induced complexity has been presented as an indicator or changing system to point out the dependencies or relations applicable in final product quality.

Shibata *et al*. (2003) developed an assembly defect rate - quality of an assembled product tool applicable yet in the assembly design stage. His research showed a strong correlation between the presence of assembly defects and his manufacturing complexity measures, based on the system design parameters. His approach called Global assembly quality methodology consists of assembly complexity using only two manufacturing measures. The first one is estimated assembly time which can be easily calculated from the bill of product material (BOM) and estimated assembly operation times. The second measure used in the complexity metrics is own rating for ease-of-assembly, so that each assembly operation gets its own rating. Applying the two measured together using a simple equation, the assembly complexity is then obtained. Unfortunately, his metric only counts with the two mentioned measures and no other production parameters are taken into account.

Other authors focused on reliability of a production system. Young and Jionghua (2005) stated that the reliability of any system (including mass customized system) and its building components and sub-systems affects final product quality. A calculation model has been developed to describe the complex relationship between the system components reliability and the resulting product quality. The model was verified in terms of various production types, such as machining, assembly, welding, sewing productions and in service sector. It is evident, that that the introduction of quality customized products involves two specific views. One angle of view is related to the customized product design. In mass customized productions, it is the customer who defines the quality level by choosing the desired product "quality" design, so that all the customer`s requirements and conditions on design are satisfied.

The other aspect of quality in terms of mass customized production is related to the production with minimum deviation of all features, diameters or other properties. Therefore it is necessary to develop a production system that is able to produce within the predefined quality criteria. Assessment of the production quality capability through the complexity of a manufacturing system (ideally in the early stage of its development) is a challenging issue.

4. Complexity Measurement Approaches

A number of research paper has been published on the topics of supply chain and assembly system complexity. Grussenmeyer and Blecker (2013) proposed a pilot methodology to study an operational complexity in a single-supplies-customer system. Sivadasan *et al*. (2010) and (2013) developed a complexity which is a measure of variety and uncertainty linked to a desired system. Based on the previous statement, they were able to transform the complexity of any supply chain into structural complexity at a certain time point. Such a static complexity is linked to a product variety, and the operational complexity is then linked to uncertainty of a dynamic system. Later, Frizelle and Woodcock (1995) transformed and used the entropy function to measure and describe the complexity of different manufacturing processes, layout and different machinery. Reiss (2011) presented a variety-based complexity depending on the current product mix (structure of product mix). He found that there is a negative correlation between any manufacturing system performance and its complexity, right in the case study. El Maraghy *et al*. (2005) presented their complexity metric on the basis of product mix and product structure using entropic measures at different levels of product structure on the basics of process planning. Subsequently, Fujimoto (2007) presents and entropic complexity measure to be applied for different part mix, especially in job shop scheduling.

Thereare only a limited number of approaches to complexity in the today's technical literature. Some of them are focused on partial complexity problems and reflect a kind of subjectivity when finding the right complexity solution for problems. On the other hand, there are approaches that pretty much cover as many different problems, as possible.

There is only a few publications and scientific work done on the development of measures relating to the objective complexity assessment. There is kind of a failure present in the area of complexity, or the lack of adaptability of different complexity metrics suggested by the authors. However, Sivadasan *et al*. (2010) and (2013) developed an entropy-based measure able to assess a complexity of any manufacturing system.

The phenomenon of entropy in well known in the area of information theory and in thermodynamics. Entropy provides us with the amount of information in bits associated with the amount of uncertainty of a system, originally information systems. It offers a measure of the amount of information linked to the occurrence of all states of a system. Based on the previous statement, it is clear that the fewer processes, fewer states, fewer variations and configurations, the lower is the entropy. Wildemann (2006) brought one of the first publications concerning the complexity in mass customization. Ulrich and Eppinger (2011) assigned performance parameters to product configurations, product variations, the development, purchasing, production, logistics, information technology, practically to every sub-process. They have further applied a key complexity metric to each of the above mentioned performance parameter. All the performance metrics are further presented in a summarizing model for better understanding of the relationship between different complexity metrics.

The model presents the metrics allowing us to measure complexities within a mass customized productions or systems. On the other hand they don't offer a direct measurement of customized complexities. Summarizing classification of complexity metrics (including the reviewed ones) is depicted in Figure 3.

Recapitulating, mass customization is a strategy that not only increases complexity in the enterprise system but also with some potential to decrease many complexity aspects. On the one hand, it can yield high level of complexity at the configuration, the planning and scheduling as well as the production program levels. We call these aspects complexity drivers or sources, and they are depicted in Figure 4.

5. Classification of Approaches to Variety Complexity in Assembly

We are able to differ between variety management strategies at the product level and its variants and at the process or manufacturing level, as can be seen in Figure 5.

Different strategies can be used in order to manage variety-based complexity on the product level. These are namely: component commonality, product modularity, platforms, component configurations and product variations. Strategies applied in the level of process are namely: component families/cell manufacturing, process modularity, process commonality and delayed differentiation.It is evident that even if most variety management literature argues the potential of these strategies to reduce and/or avoid complexity (Moscato, 1976), it is not clear what kind of complexity they can cope with.

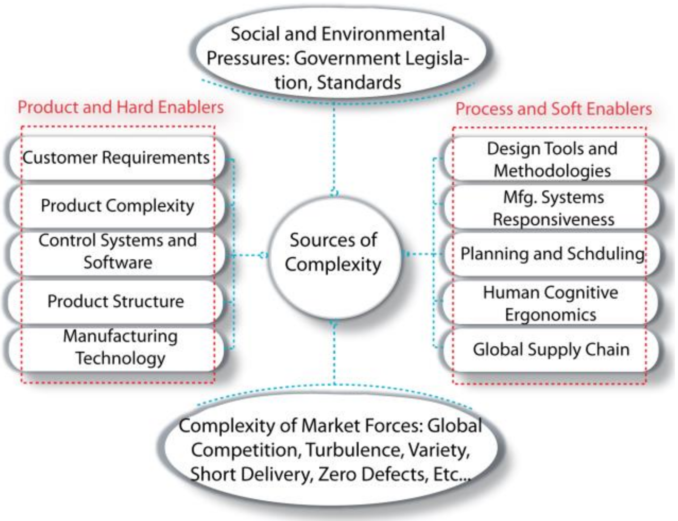

Figure 4. Product, process, social and market sources of complexity

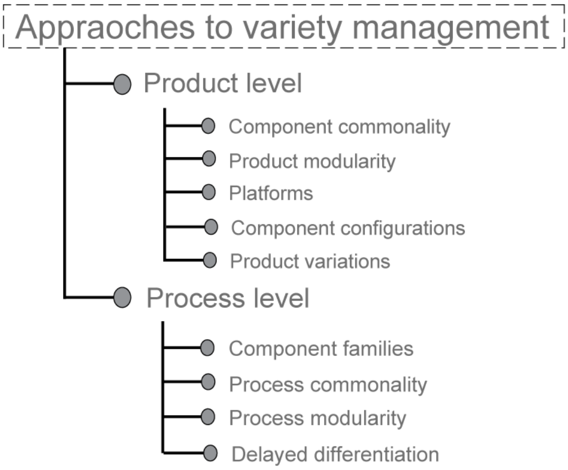

Figure 5. Approaches to variety induced complexity

Component commonality aims to use a few components in as many products and its variations as possible, and as long as it is economically possible.

In effect, according to Anderson (2004), large product variety need not necessarily yield a large number of internal parts. If we try to increase commonality of a production between products, it may result in over-designed production composition. According to Blecker and Abdelkafi (2006), such functional makeovers may result in extra or hidden costs. It is apparent that the fewer part variety and lower overheads may be beneficial. Moreover, commonality brings risk pooling, which in turn leads to more accurate volume and stock forecasts on the fixed components in stochastic demand environments. Product modularity is a property of any product or product variant understood as the possibility of a module to be mixed and matched with independent and interchangeable product modules or building blocks with standard or fixed modules in order to create different product variants and configurations. The one-to-one mapping between functional elements and physical building blocks is desirable. However, it refers to an extreme and an ideal form of modularity is generally difficult to achieve in practice according to Ulrich and Eppinger (2011). Pine (1993) defines the term modularity as a strategyallowing the firm to minimize the physical changes required to achieve a functional change. It also enables the production of variety while facilitating the achievement of both economies of scale and scope (Agard and Penz, 2009; Brun and Pero, 2012).

A product platform is simply a basic fixed module which can be implemented into a number of variants of certain product family. Wu (2007) and Wu *et al*. (2010) proofed, that platforms have linked costs and are developed to function as the base components for long period of time. They support the concentration on core competencies, while decoupling the life cycles of the product family variations.

There are also component families present at the process level. A method of grouping product components into families is a strategy of a variety management successfully applied and identified in cellular manufacturing. Concept of cellular manufacturing has been developed from group technology philosophy. The aim is at grouping parts of a similar design features or manufacturing processes into part and product families. In accordance with the main objective, e.g. Jiao and Zhang (2005) or Ong *et al*. (2006) reduced the total setup time by decreasing the total number of changeovers Process commonality reflects the degree to which products can be manufactured or assembled on the basis of a few number of processes. The number and diversity of processes give indications of the difficulty of planning and controlling internal production. MacCormack *et al*. (2006) and Ahnert *et al*. (2010) examined the relationships existing between process and component commonality. While component commonality necessarily increases process commonality, the reverse is not true since different component parts can be manufactured on the basis of a small number of processes.

Process modularity according to Parlaktrk (2010) and Yayla-Kullu (2013) aims to transform the system consisting of smaller sub-systems that can be designed independently and can function together as a whole. It is now clear that the process modularity simply divides large processes and process structures into small sub-processes. These small sub-processes may still run independently while making sure that the original process fulfills the objectives of the system. Holtta-Otto *et al*. (2008) offers a more general statement: “modular process is one where each product undergoes a discrete set of operations making it possible to store inventory in semi-finished form and where products differ from each other in terms of the subset of operations that are performed on them. Any discrete assembly process would classify as modular.” Tang and Tomlin (2008) think, that product modularity had a lot to do with process modularity. They proofed that individual product modules may be manufactured and tested in an independent and decoupled process. This way they were able to decrease production lead times.Delayed product differentiation is aimed to redesign of products and processes in order to delay the point at which product variant and configurations assume their unique identities. In this way, Gabriel (2013) proofed, thatthe process would not commit the work-in-process into a particular product until a later point.

6. Direction For Future Research and Conclusion

A direction for future research may be to use quantitative models in order to evaluate the complexity of a mass customization system. It can be useful to examine the sensitivity of an eventual measure of complexity with respect to possible variety and number of configurations. It is also interesting to see whether the complexity of mass customized system is less or more sensitive to variety levels. However, complexity may increase exponentially, which makes the system unpredictable and difficult to manage. Therefore, simulation techniques coupled with the use of complexity measures are appropriate instruments to determine the optimal product variety that can be handled by a specific mass customization system. Some research is also necessary in the field of complexity related to final product quality.

Finally, it can be concluded that the maingoal of this paper was to introduce some features of mass customization in last decades.

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References:

Agard, B., & Penz, B. (2009). A simulated annealing method based on a clustering approach to determine bills of materials for a large product family. *International Journal of Production*

Economics, *117*, 389-401.

Ahnert, S.E., Johnston, I.G., Fink, T.M.A., Doye, J.P.K., Louis, A.A. (2010). Self-Assembly, modularity and physical complexity. *Physical Review E*, *82*, 026-117.

Anderson, D. (2004). *Build-to-order & Mass customization – the ultimate supply chain management and lean manufacturing strategy for Low-Cost On-Demand Production without Forecasts or Inventory*. Cambria, California: CIM Press.

Andre, P.M., Afgan, N.H., & Carvalho, M.G. (2009). Management system sustainability: Based on QMS, EMS, H&S and business indicators. *International Journal for Quality Research*, *3*(5), 113.

Arsovski, Z., Arsovski, S., Mirović, Z., & Stefanović, M. (2009). Simulation Of Quality Goals: A Missing Link Between Corporate Strategy And Business Process Management. *International Journal for Quality Research*, *3*(4), 317-326.

Blecker, T., & Abdelkafi, N. (2006). *Modularity and delayed Product Differentiation in Assemble-to-Order Systems: Analysis and Extensions from a Complexity Perspective*, in Mass Customization: Challenges and Solutions, T. Blecker and G. Friedrich, Eds., Springer Publishing, New York et al.

Blecker, T., Friedrich, G., Kaluza, B., Abdelkafi, N., & Kreutler, G. (2006). *Information and Management Systems for Product Customization*. Boston: Springer Science + Business Media, Inc.

Bliss, C., & Haddock, R. (2008). *Integrating China into Your Global Supply Chain: Lessons Learned from Global Supply Chain Integrators*. Booz Allen Hamilton.

Brun, A., & Pero, M. (2012). Measuring variety reduction along the supply chain: The variety gap model. *International Journal of Production Economics*, *139*(2), 510-524.

El Maraghy, H. A. (2009). *Changeable and Reconfigurable Manufacturing Systems*. London: Springer Verlag London Limited, 435, ISBN 978-1-84882-066-1.

El Maraghy, H. A., Kuzgunkayaa, O., & Urbanic, R.J. (2005). Manufacturing systems configuration complexity. *Annals of the CIRP*, 54, 445-448.

Frizelle, G., & Efstathiou, J. (2002). *Seminar Notes On Measuring Complex Systems. Resource document*. The London School of Economics and Political Science. Retrieved from http:// www. psych. lse.ac.uk complexity/ PDFiles/ Seminars/ Gerjan April02lastversion.pdf. Accessed 12 May 2014.

Frizelle, G., & Woodcock, E. (1995). Measuring complexity as an aid to developing operational strategy. *International Journal of Operations & Production Management*, 15, 26-39.

Fujimoto, T. (2007). Architecture-Based Comparative Advantage – A Design Information View of Manufacturing. *Evolutionary and Institutional Economic Review*, *4*(1), 55-112.

Gabriel, T.J. (2013). Common Attributes of Manufacturing System Design on Performance.Academy of Information and Management Sciences Journal, *16*(1), 75-97.

Grussenmeyer, R., Blecker, T. (2013). *Complexity and Robustness Influence on Production Performance – A Theoretical Framework*. In W. Kersten, J. Wittman (Ed.), Kompetenz, Interdisziplinaritat und Komplexitat in der Betriebwirtschaftslehre (5769). Springer Fachmedien Wiesbaden.

Holger, R. (2005). *Organisatorische Segmentierung – Ein Instrument zur Komplexitätshandhabung*. Wiesbaden: Gabler Verlag.

Hölttä-Otto, K., Tang, V., & Otto, K. (2008). Analyzing module commonality for platform design using dendrograms. *Research in Engineering Design*, *19*(2-3), 127-141.

Hu, S.J., Zhu, X., Wang, H., & Koren, Y. (2008). Product Variety and Manufacturing Complexity in Assembly Systems and Supply Chains, *Annals of CIRP*, *57*(1), 45–48.

Jiao, J., & Zhang, Y. (2005). Product portfolio identification based on Association rule mining. *Computer –Aided design*, 37, 149-172.

Ko, J., Hu. S. J., (2008). Balancing of manufacturing systems with complex configurations for delayed product differentiation. *International Journal of Production Research*, *46*(15), 4285-4308.

MacCormack, A., Rusnak, J., & Baldwin, C.Y. (2006). Exploring the Structure of Complex Software Designs: An Empirical Study of OpenSource and Proprietary Code. *ManagementScience*, *52*(7), 1015-1030.

Marcora S. M., Staiano, W., & Manning, V. (2009). Mental Fatigue Impairs Physical Performance in Humans. *Journal of Applied Physiology*, *106*, 857-864.

Martin, R. (2010). The Age of Customer Capitalism. *Harvard Business Review*, January-February. *15*, 58-65.

Modrak, V., & Marton, D. (2014). Configuration complexity assessment of convergent supply chain systems. *International Journal of General Systems*, *43*(5), 508-520.

Modrak, V., Marton, D., Kulpa, W., & Hricova, R. (2012). Unraveling Complexity in Assembly Supply Chain Networks. *In: Proceedings of the 4th IEEE International Symposium on Logistic and Industrial Informatics 2012, Smolenice, Slovakia*, 151-155.

Moscato, D.R. (1976). The application of the entropy measure to the analysis of part commonality in a product line. *International Journal of Production Research*, *14*(3), 401-406.

Nada, O.A., El Maraghy, H.A., & El Maraghy, W.H. (2006). Quality Prediction in Manufacturing System Design. *Journal of Manufacturing Systems*, *25*(3), 153-171.

Ong, S.K., Lin, Q., Nee, A.Y.C. (2006). Web-Besed Configuration Design System for Product Customization,. *International Journal of Production Research*, *44*(2), 351-382.

Papakostasa, N., Efthymioua, K., Mourtzis, D. (2009). Modeling the Complexity Of Manufacturing Systems Using Nonlinear Dynamics Approaches. *Annals of the CIRP*, *58*(1), 437-440.

Parlaktrk, A.K., Swaminathan, J.M. (2010). *Mass Customization.Wiley Encyclopedia of Operations Research and Management Science*, John Wiley & Sons, Inc.

Piller, F.T. (2006). Mass Customization. 4thed. Wiesbaden: DUV/GWV.

Piller, F.T., & Reichwald, R. (2002). *Mass customization*. In L. Zheng, F. Possel-Doelken (Ed.), Strategic Production Networks, 389-421, New York: Springer.

Pine, II, B.J. (1993). *Mass Customization: The New Frontier in Business Competition, Harvard Business School Press*, Boston, Massachusetts.

Reiss, M. (2011). Komplexitätsmanagementals Grundlagewandlungsfähiger Produktionssysteme. *Industrie Management*, 27, 77-81.

Rother, M., & Toyota, K. (2009). *Managing People for Improvement - Adaptiveness and Superior Results*. USA: Rother& Company.

Shannon, C.E. (1948). A Mathematical Theory of Communication. *Bell System Technical Journal*, *27*(3), 379-423.

Shibata, H., Cheldelin, B., Ishii, K. (2003). Assembly Quality Methodology: A New Method

For Evaluating Assembly Complexity in Globally Distributed Manufacturing. Proceedings of ASME International Mechanical Engineering Congress and Exposition, November 2003, Washington, D.C.

Sivadasan, S., Smart, J., HuachoHuatuco, L., & Calinescu, A. (2013). Reducing Schedule instability by identifying and omittingcomplexity-adding information flows at the supplier - customerinterface. *International Jornal of Production Economics*, *145*(1), 253-262.

Sivadasan, S., Smart, J., Huatuco L. H., & Calinescu, A. (2010). Operational complexity and supplier-customer integration: case study insights and complexity rebound. *Journal of the Operational Research Society*, *61*(12), 1709-1718.

Tang, C.S., & Tomlin, B. (2008). The power of flexibility for mitigating supply chain risks. *International Journal of Production Economics*, *116*(1), 12-26.

Ulrich, K., & Eppinger, S. (2011). *Product design and development – 5th edition*, Boston: McGraw-Hill/Irwin, ISBN-10: 0073404772.

Vujovic, A., & Krivokapic, Z. (2011). Intelligent Systems for decision-making support based on BCM approach. *International Journal for Quality Research*, *5*(1), 47-53.

Wang, H. (2010). *Product Variety Induced Complexity and itsImpact on Mixed - model Assembly Systems and Supply Chains. PhD Dissertation*, Michigan: University of Michigan.

Webbink, R.F, & Hu, S.J. (2005). Automated Generation of Assembly System DesignSolutions.IEEE Trans on Automation Science and Engineering, *2*(1), 32-39.

Wildemann, H. (2006). *Leitfadenzum Einsatz von E-Technologien in der Wertschopfungskette*. Munich: TCW-Transfer-Centrum-Verlag, ISBN 978-3-934155-36-7.

Wu, L. (2007). Toward an Understanding of the Product Variety Decision: In Integrative Model. *International Journal of Management*, *24*(3), 256-264.

Wu, L., De Matta, R., Lowe, T.J. (2010). Consumer influence on product variety decisions. *Proceedings of IEEE International conference on Management of Innovation and Technology (ICMIT), June 2010*, 444-449, ISBN 978-1-4244-6565-1.

Yayla-Kullu, M.H., Parlaktrk, A.K., & Swaminathan, J.M. (2013). Multi -Product Quality Competition: Impact of Resource Constraints. Production and Operations Management, 22(3), 603614.

Young, C., & Jionghua, J. (2005). *Quality-reliability chain modeling for system-reliability analysis of complex manufacturing processes*. IEEE Transactions on Reliability, *54*(3), 475-488.

Zhu, X., Hu, S. J., Koren, Y., Marin, S. P. (2008). Modeling of Manufacturing Complexity In Mixed-Model Assembly Lines. *ASME Journal of Manufacturing Science and Engineering*, *130*(5), 051-013.

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