10-13-2022

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Abstract. Defense and aerospace industries usually possess unique high-mix low-volume production characteristics. This uniqueness generally calls for prohibitive production costs and long production lead-time. One of the major trends in advanced, smart manufacturing is to be more responsive and better readiness while ensuring the same or higher production quality and lower cost. This study reviews the state-of-the-art manufacturing technologies to solve these issues and previews two levels of flexibility, i.e., system and process, that could potentially reduce the costs while increasing the production volume in such a scenario. The main contribution of the work includes an assessment of the current solutions for HMLV scenarios, especially within the defense of aerospace sectors, and a survey of the current and potential future practices focusing on smart production process planning and flexible assembly plan driven by emerging techniques.

Keywords: High mix low volume manufacturing · Production planning · Lean manufacturing · Robotics · Group technology

1 Introduction

Modern manufacturing is rooted in the Ford Model T production line favoring the mass production strategy to reduce production costs based on the Economies of Scale principle [1]. Its essence is to maximize the production volume based on the foreseeable demand. In this way, the prohibitive manufacturing setup cost and overhead costs can be evenly distributed among many fabricated parts, resulting in the reduction of production costs per unit. Another major effect is the training standardization and work division. The workers are only responsible for working in a certain portion of the manufacturing plant or assembly line. Even though this standardization can reduce the need for high-skill working labor, which could further reduce the production costs, the jobs become repetitive and less creative.

However, mass production has its major weakness when facing the requests for high-mix low-volume (HMLV) products, which becomes more critical with the advent of mass customization during the past few decades, especially in defense sectors and the

K.-Y. Kim et al. (Eds.): FAIM 2022, LNME, pp. 237–245, 2023.
https://doi.org/10.1007/978-3-031-18326-3_24

aerospace industry [2]. HMLV manufacturing is a production scenario when producing a wide variety of parts with small demand [3, 4]. Generally speaking, the products in HMLV cases require complex fabrication processes to meet the harsh condition of usage, especially in defense and aerospace applications. This urges the industry to re-evaluate the production system and processes for a better solution to meet the HMLV demand and, more importantly, lower the production costs and energy consumption [5].

Mass customization allows the original equipment manufacturers (OEMs) or customers, in a general setting, to order the products with specified designs to fulfill their unique functional specifications, which is known as a make-to-order manufacturing strategy [6]. Suppliers also need to provide high-quality products while delivering the desired diversified families of parts in a timely manner to remain competitive in the market. Suppliers have incorporated the flexible manufacturing strategy as a remedy solution to meet these strict requirements. One way to tackle the issue is the just-in-time (JIT) approach, which can assist in increasing manufacturing effectiveness [7, 8]. JIT is an integrated scheduling system that synchronizes suppliers, schedulers, and production teams to reduce inventory and produce parts according to the specifications.

In this paper, we provide a thorough treatment of the previously proposed methods that could potentially remedy the issues and restrictions of mass customization. State-of-the-art solutions are briefly reviewed, together with their pros and cons. The solutions are summarized as the increase of two levels of flexibility: system-level and process-level. Potential solutions that are built upon current technological advancements are proposed. Specifically, mass customization can directly benefit from the major progress in Industrial 4.0/5.0, including robotics, additive manufacturing, big data, etc., based on which data-driven decision making and process planning can provide a more robust and resilient solution to defense and aerospace applications.

The remainder of this paper is organized as follows. In Sect. 2, we present the major characteristics and solutions of the modern manufacturing systems for HMLV scenarios. Major research topics are surveyed with discussions of their advantages and disadvantages. In Sect. 3, several ongoing or potential trends that can potentially further increase the readiness and lower the costs of resources for mass customization are reviewed. This paper concludes with a discussion of the current status and trend in smart manufacturing.

2 Manufacturing Strategies for HMLV in Defense and Aerospace Industries

2.1 Major Issues

In a general manufacturing setting, the widely used way of reducing cost is to connect and outsource manufacturing tasks to the regions closer to the production materials or cheap labor for cost reduction. However, since the designs and products in the defense and aerospace industries are considered sensitive and critical to a nation, inshore manufacturing is generally preferred. As a result, it is critical to provide a robust solution to strengthen preexisting manufacturing capability with smart planning and control while reshoring the high value-added manufacturing industries to keep a resilient supply chain system.

The major issues when applying traditional manufacturing strategies in inshore manufacturing, especially those involving small and medium enterprises (SMEs), with the HMLV scenario are the limited order scales and restricted manufacturing capability. The order volume is generally small for the defense and aerospace industries. In this way, the SMEs are not as profitable as the OEMs, which makes them quite vulnerable to even small demand changes. On the other hand, the small demand for each part design significantly increases the setup cost of the production process and, more importantly, prolongs the production lead time.

2.2 Advanced Processing Techniques

Several proposals are available to remedy the issues. The two major tracks of consideration are to (1) increase the production volume by grouping some parts or processes; and (2) utilize a "smart", automated process to increase the process flexibility.

Robotic-aided machining processes have been considered by researchers and practitioners, specifically in the HMLV scenario, to process workpieces in a faster and more reliable fashion than manual operations. Hu et al. [9] proposed an automated robotic deburring and chamfering system, to select features in the piece's computer-aided design (CAD) model with a human-machine interface, then target accurate gear registration and fast collision-free trajectory planning through another human-machine interface. The system also consists of a robotic manipulator, force/torque sensors, pneumatic controls, pneumatic control components, and tool changes with the aim of generating an efficient part processing plan. Similarly, another study shows the development of a flexible and automatic deburring system to process large cast parts, such as aerospace and aircraft components [10], which consists of using robotic manipulators, 3D vision sensors, lasers, and force control sensors.

Part assembly, especially a robot-guided assembly, still shows many gaps in agility, flexibility, automation technologies, and human-robot interaction, as robots require crucial data to operate in the desired manner [11]. With the goal of reducing assembly time for HMLV parts, 3D-vision systems have been developed to provide flexible robotic assembly and precise workpiece positioning. Such is the case where using vision-guided assembly robots provides subtle variations in geometries and workpiece poses rather than only using limiting expensive fixtures [12]. Using matching algorithms, part CAD models and 3D point cloud data of a part position are matched by corresponding points and features to achieve object-accurate pose estimation. Although there is some rotational and translations error, these systems show the possibility of improvement, with more vision guidance and force/torque control, to be applicable for real-life industrial applications.

Another critical advancement is the development of additive manufacturing technologies (AM) [13]. AM processes fabricate parts in a layer-by-layer fashion, which reduces the restrictions on the design geometry and intricate features. Therefore, instead of decomposing the parts into multiple subassemblies, AM provides the capability of fabricating the final product with reduced weight, higher strength, and lower costs [14, 15].

2.3 Make-to-X Strategy

The manufacturing system is conventionally considered to input raw materials and output final products or parts. However, depending on the demand behaviors, many manufacturing and production strategies are available.

The most classic manufacturing strategy is make-to-order. Job-based production system produces customized products according to particular customer demands and functional specifications. The specialized nature of the product requires varied machine setup and skilled, versatile workers [16]. Generally, one set of workers produces a particular type of product as a whole. Material and demand of the products are inconsistent, which compels the planning, and cost-effectiveness of the production to be a challenge. It is also similar to Make to Order (MTO) manufacturing which essentially involves the manufacturer producing a product based on demand placed by the customer. Wastage is low in the particular type of manufacturing; however, utilization of labor and equipment, and setup cost of the machine are challenging.

Make-to-stock is a strategy to deal with the scenario with highly variable demand. This type of production system follows mass production, whose products are generally highly demanded or consumed [17]. Standardized materials, labor, and a process flow are integral parts of this type of manufacturing. The desired product is produced as a direct output of a system, and the product is assembled by production from a different line of the system [18]. The system has significant effectiveness improvement and cost reduction potential due to the generally reduced variability [19]. Production volume demand is highly stable for the product type. In this particular kind of manufacturing, the product is produced and preserved in inventory held in stores which involves the risk of wastage in the case of goods that are not sold according to the demand forecast.

Another widely adopted manufacturing strategy is make-to-assembly. Batch production can be distinguished from job production based on the order quantity. Based on the demand, a higher number of products is produced for a certain period of time in a production facility involving a particular machine group. Batch production is also utilized to manufacture a certain portion of the product or assembly to improve cost-effectiveness and utilization. The type of production involves the make-to-assemble type of manufacturing. The order delivery lead time is relatively lower compared to job-based manufacturing, and the product parts are manufactured to assemble and customer demand relatively faster.

One of the major issues with the above sole make-to-X strategies is that they generally produce a "finished" product, which can be either the final parts or subassemblies that generally do not need further fabrication steps. A mixture of make-to-stock and make-to-order strategies is proposed to solve the unforeseen demand, mass-customization case, as presented in Fig. 1. The full product system is decomposed into two major steps: (1) semi-finished parts are produced in a make-to-stock fashion, and (2) final products are fabricated from the semi-finished parts for make-to-order purposes. The proposed strategy can potentially increase the robustness of the suppliers to the variable demand while providing the capability to produce multiple part families, which share similar manufacturing steps.

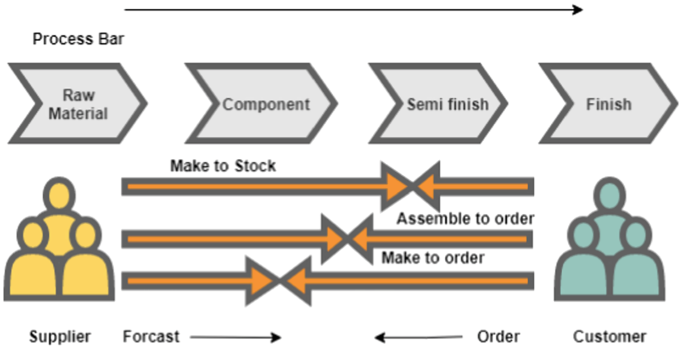

Fig. 1. A mixture of make-to-stock and make-to-order manufacturing strategies.

2.4 Group Technology

Group technology is a method that decomposes the manufacturing system into multiple subsystems by organizing different products into different clusters based on the similarities of their design and required processes. Conventionally, a cluster of products can be produced via a cellular manufacturing system, also known as a manufacturing cell [20]. This manufacturing cell can produce the final products from bulk material while remaining reconfigurable and flexible enough for this cluster of products. A more decentralized planning and control production architecture has been recently proposed to allow for better control in case of uncertainties or changes within product mix and volume via vertical integration of different production modules within the corporation [21].

2.5 Lean Practices

Mass production has been improved through lean manufacturing practices since the 1980s. The particular manufacturing type thrived with high volume, however, low mix. The dramatic changes in the market, availability of a product, and competitiveness warrant product manufacturers to increase customization suitable to customer demand. The transformation in consumer demand has resulted in low volume higher volume manufacturing practices which have brought about the need for revaluation of the manufacturing and supply chain system as a whole. Companies are renovating existing equipment with the capability to produce complex products in optimum amounts of time and reduce unnecessary waste [22, 23]. Value stream mapping is developed to improve different system components of the processes by detailed categorization of the system and finding areas for improvement [24]. Kaizen to improve existing equipment and reduction of change over time through process improvement have emerged.

Lean thinking has changed the world of manufacturing for the better and is characterized as one of the most successful approaches [25]. A fundamental part of Toyota's production system is the Kanban production system which means "to look closely." Pull and push systems are always considered superior as less inventory is involved in the system [3]. Kanban is a type of pull system where material and flow are synchronized to produce exactly what is necessary and to stock only the amount required during replenishment. Even though Kanban is a primitive process, however, the ideology is effective for continuous production and flow control. Powell showed the application of the Kanban system in the HMLV environment [25].

3 A Smart Manufacturing Solution

With the advent of new manufacturing technologies, especially smart manufacturing and artificial intelligence, new solutions are emerging to solve the major issues in mass customization.

3.1 Automation in Manufacturing

One major trend in smart manufacturing is to utilize collaborative robot technology and skilled labor to manufacture diverse parts in the same machine to cater to demand. The improvement effectiveness in HMLV is accomplished by careful inspection of current practices and through improvement initiatives driven at each step. High mix environment results are higher setup and change over time in a production line involving various repetitive tasks. The repetitive tasks and assistance for the pre-planned work process can be accomplished by introducing collaborative robots into the system. There are several techniques to enable and match the skill of the robot's task for the particular task with workers. The Cobots have the ability to learn through hand-guided teaching and programming [26]. The ease of programming and highly accurate task completion of the collaborative robots enables them to a competitive choice.

Aligning with the dynamic shift in manufacturing technological advancement to tackle the challenges has also ensued [27]. Flexible manufacturing equipment capable of unique customized product manufacturing has been gracing the factory environment. The introduction of the HMLV production scenario has ushered in the need for the inclusion of robots in manufacturing assembly. The repetitive tasks executed with the help of automation can increase accuracy, reduce time and increase the effectiveness of the system. The collaboration of lean principles with robotic automation is called lean automation. The ease of reprogramming the software to accommodate the change in product specification brings in the required flexibility to cope with the market. 3D vision and AM are often considered to be the ultimate solution to the customization landscape. The 3D printing software offers a unique customer experience, and 3D printing adapted businesses will be ahead of the competitors due to the sheer flexibility achievable. The technology allows the whole assembly or product to be manufactured together, increasing accuracy and reducing lead time. Regardless of the variations, the product will be manufactured as a whole without slowing down product flow. The paper explores the effectiveness and scrutinizes the method as an effective solution.

3.2 Smart Production Planning and Control

The dynamic art of sharing the flow of types of machinery among different cells in a factory is also an effective solution to address the HMLV scenario. Flow path design manages the flow of a product among different cells and derives the optimized flow path to share the suitable outcome. Peng et al. [28] derived a mathematical programming model from designing the flow of material in a small and mid-sized company with a higher variation. Simulation techniques, such as discrete-event simulation [29] and agent-based modeling [30], also provide a numerical solution for path, policy, and facility layout planning.

Theory of constraint (TOC) is the accumulation of managing and deriving solution based on different constraints. The physical constraint may be equipment and space; non-physical constraint can be management style, process, and demand. The limitation of the theory of constraint problem is that it is suitable for small scenarios. However, to tackle the problem genetic algorithm (GA) is formulated to work with a sample of the problem and increase throughput.

Similar to the genetic algorithm (GA) method, the evolutionary algorithm-based layered encoding cascade optimization approach is also applied to tackle the problem. The evolutionary algorithm essentially follows the survival of the fittest methodology, and the iterative method is executed with the closest to the goal batch of solution. Particle swarm optimization is a stochastic-based approach looking for a solution by searching through the objective. Neoh et al. [31] investigated and addressed the problem by combining the different methods discussed above. In the research, it was observed that the integrated GA-PSO model could efficiently solve the problem faster compared to any other model.

4 Concluding Remarks

A broad range of technologies, especially smart manufacturing techniques, can be utilized to remedy the unique characteristics in high-mix low-volume manufacturing scenarios, especially in defense and aerospace applications. This paper reviews state-of-the-art solutions to this problem, ranging from process-level to system-level. Both are critical to reducing the costs and lead time while maintaining the capability of producing a variety of products in a low volume setting. Further research studies are needed to incorporate both to further improve the performance and the capability of smart manufacturing systems in the HMLV scenario.

Another trend lies in the development of artificial intelligence and machine learning-driven methodologies, equipped with advanced metrology to further improve the smart decision making in process selection, path planning, and flexible assembly, i.e., to further reduce the restrictions on rigid tolerance design via part matching and efficient material handling.

Acknowledgment. The work of Tanjida Tahmina, Mauro Garcia, and Zhaohui Geng was financially supported by the Department of Defense (DoD) MEEP Program under Award N00014–19-1–2728.

References

1. Alizon, F., Shooter, S.B., Simpson, T.W.: Henry Ford and the Model T: lessons for product platforming and mass customization. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, pp. 59–66. Elsevier, Brooklyn, NY (2008)
2. Lyons, B.: Additive manufacturing in aerospace: examples and research outlook. The Bridge **44**(3), 13–19 (2014)
3. Zhang, Q., Tseng, M.M.: Modelling and integration of customer flexibility in the order commitment process for high mix low volume production. Int. J. Prod. Res. **47**(22), 6397–6416 (2009)
4. Rajgopal, J., Bidanda, B.: On scheduling parallel machines with two setup classes. Int. J. Prod. Res. **29**(12), 2443–2458 (1991)
5. Hu, G., Wang, L., Chen, Y., Bidanda, B.: An oligopoly model to analyze the market and social welfare for green manufacturing industry. J. Clean. Prod. **85**, 94–103 (2014)
6. Thürer, M., Stevenson, M., Silva, C., Land, M.J., Fredendall, L.D.: Workload control and order release: a lean solution for make-to-order companies. Prod. Oper. Manag. **21**(5), 939–953 (2012)
7. Swanson, C.A., Lankford, W.M.: Just-in-time manufacturing. Bus. Process. Manag. J. **4**(4), 333–341 (1998)
8. Cleland, D.I., Bidanda, B.: Project management circa 2025. Project Management Institute, Newtown Square, PA (2009)
9. Hu, J., Kabir, A.M., Hartford, S.M., Gupta, S.K., Pagilla, P.R.: Robotic deburring and chamfering of complex geometries in high-mix/low-volume production applications. In: 2020 IEEE 16th International Conference on Automation Science and Engineering (CASE), pp. 1155–1160. IEEE, Hong Kong, China (2020)
10. Onstein, I.F., Semeniuta, O., Bjerkeng, M.: Deburring using robot manipulators: a review. In 2020 3rd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS), pp. 1–7. IEEE, Gjovik, Norway (2020)
11. Johansen, K., Rao, S., Ashourpour, M.: The role of automation in complexities of high-mix in low-volume production–a literature review. Procedia CIRP **104**, 1452–1457 (2021)
12. Ogun, P.S., Usman, Z., Dharmaraj, K., Jackson, M.R.: 3D vision assisted flexible robotic assembly of machine components. In: Eighth international conference on machine vision (ICMV 2015), pp. 98751O. International Society for Optics and Photonics. SPIE, Bellingham, WA (2015)
13. Bidanda, B., Narayanan, V., Billo, R.: Reverse engineering and rapid prototyping. In: Dorf, R.C., Kusiak, A. (eds.) Handbook of Design, Manufacturing and Automation, pp. 977–990. John Wiley & Sons Inc, Hoboken, NJ (1994)
14. Najmon, J.C., Raeisi, S., Tovar, A.: Review of additive manufacturing technologies and applications in the aerospace industry. In: Frobes, F., Boyer, R. (eds.) Additive manufacturing for the aerospace industry, pp. 7–31. Elsevier, Cambridge, MA (2019)
15. Geng, Z., Bidanda, B.: Medical applications of additive manufacturing. In: Bártolo, P.J., Bidanda, B. (eds.) Bio-Materials and Prototyping Applications in Medicine, pp. 97–110. Springer, Cham, Switzerland (2021)
16. Chua, T.J., Cai, T.X., Low, J.M.: Dynamic operations and manpower scheduling for high-mix, low-volume manufacturing. In: 2008 IEEE International Conference on Emerging Technologies and Factory Automation, pp. 54–57. IEEE, Hamburg, Germany (2008)
17. Tien, J.M.: Manufacturing and services: from mass production to mass customization. J. Syst. Sci. Syst. Eng. **20**(2), 129–154 (2011)

18. Iravani, S.M., Liu, T., Simchi-Levi, D.: Optimal production and admission policies in make-to-stock/make-to-order manufacturing systems. Prod. Oper. Manag. **21**(2), 224–235 (2012)
19. Quante, R.: Management of Stochastic Demand in Make-to-Stock Manufacturing. Peter Lang International Academic Publishers, Bern, Germany (2018)
20. Billo, R.E., Bidanda, B., Tate, D.: A genetic cluster algorithm for the machine-component grouping problem. J. Intell. Manuf. **7**(3), 229–241 (1996)
21. Didden, J.B., Dang, Q.V., Adan, I.J.: A semi-decentralized control architecture for high-mix-low-volume factories in Industry 4.0. Manufacturing Letters **30**, 11–14 (2021)
22. Bidanda, B., Kadidal, M., Billo, R.E.: Development of an intelligent castability and cost estimation system. Int. J. Prod. Res. **36**(2), 547–568 (1998)
23. Martinez, S.E., Smith, A.E., Bidanda, B.: Reducing waste in casting with a predictive neural model. J. Intell. Manuf. **5**(4), 277–286 (1994)
24. Seth, D., Seth, N., Dhariwal, P.: Application of value stream mapping (VSM) for lean and cycle time reduction in complex production environments: a case study. Prod. Planning Control **28**(5), 398–419 (2017)
25. Powell, D.J.: Kanban for lean production in high mix, low volume environments. IFAC-PapersOnLine **51**(11), 140–143 (2018)
26. El Zaatari, S., Marei, M., Li, W., Usman, Z.: Cobot programming for collaborative industrial tasks: an overview. Robot. Auton. Syst. **116**, 162–180 (2019)
27. Duray, R.: Mass customization origins: mass or custom manufacturing? Int. J. Oper. Prod. Manag. **22**(3), 314–328 (2002)
28. Peng, Y., Guan, Z., Ma, L., Zhang, C., Li, P.: A mathematical programming method for flow path design in high-mix and low-volume flow manufacturing. In: 2008 IEEE International Conference on Industrial Engineering and Engineering Management, pp. 1169–1173. IEEE, Singapore, Singapore (2008)
29. Balaban, C., Sochats, K.M., Kelley, M.H., Bidanda, B., Shuman, L.J., Wu, S.: Dynamic discrete decision simulation system. U.S. Patent No. 8,204,836. U.S. Patent and Trademark Office, Washington, DC (2012)
30. Wu, S., Shuman, L., Bidanda, B., Kelley, M., Sochats, K., Balaban, C.: Agent-based discrete event simulation modeling for disaster responses. In: Fowler, J., Mason, S. (eds.): Proceedings of the 2008 Industrial Engineering Research Conference, pp. 1908–1913. Institute of Industrial and Systems Engineers (IISE), Atlanta, GA (2008)
31. Neoh, S.C., Morad, N., Lim, C.P., Aziz, Z.A.: A layered-encoding cascade optimization approach to product-mix planning in high-mix–low-volume manufacturing. IEEE Trans. Syst., Man, Cybernetics-Part A: Syst. Humans **40**(1), 133–146 (2009)