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Deployment of Additive Manufacturing and Robotics for Increasing Flexibility in Productions

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Abstract. As manufacturing industry seeks different strategies and technologies to respond to the ever-increasing demands in markets that prioritize versatility of products with low-volume productions, certain technologies and strategies gain more attraction and form higher acceptance levels among different sectors. Individual firms are driven by their market requirements. Various factors including product specification, assembly sequence, and manufacturing operations are central to the decisions that are made with respect to the type of technology to respond to market dynamics. Additive Manufacturing (AM) is one of the technology alternatives that has exhibited remarkable strengths in countering market disruptions. Although AM can be utilized along conventional technologies (i.e., subtracting and forming) in a hybrid context to combine advantages and offset weaknesses of each category, the arguments supporting its applications would need to be formulated rigorously to ensure investments are rightfully justified. Another alternative continuously investigated by companies is automation and more specifically, using robotics for various purposes e.g., operations like welding and painting, material handling, machine tending, etc. Both industrial robots and the applications that require a collaboration between humans and robots can be valid in this context. Considering advancements in AM and Automation and their potentials in increasing flexibility, expediting operations, and leveraging cost advantages, this paper explores how AM and automation in tandem could improve flexibility in productions. Results of this study can be used for proposing a conceptual model which will be further developed and then tested on industrial cases in future studies. While this study incorporates raw data about processing requirements in production that has been obtained via interviews with industrial companies, inputs about the technologies i.e., AM and robotics are derived from literature.

Keywords. Additive manufacturing, Automation, Robotics, Flexibility

1. Introduction

The current trend in the market indicates that demands for low volume production of versatile products – otherwise known as high mix low volume or HMLV – is continuously rising [1]. Fierce competition among firms and continuous evolvement of markets merits more research into managing this type of production. This is to not only to acquire an adequate understanding about HMLV productions but develop competitive solutions based on available technologies. The issues surrounding HMLV in industrial

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manufacturing needs to be interpreted in production terms since demand for these customized products is unpredictable, while processing them could be a challenge due to their uniqueness, engineering requirements, and other variations within processes [2]. Therefore, one of the areas that should be explored is flexibility and its prominence in such productions. The intention here is not to define flexibility as a concept, but rather, couple flexibility requirements of productions with some of the promising technologies that are readily available to manufacturers to understand how these technologies can facilitate the need for increased flexibility. The variations across products can be found both in the final product configuration as well as intermediary parts and components. According to [3], a product configuration system (PCS) supports design activities in the early phases of engineering by pre-defining a set of components and their connections while putting certain constraints in place to avoid any infeasible configurations. As the authors in that study argue, there are certain benefits that can be achieved from implementing PCSs, some of which include lead-time reduction for making specifications and product delivery, improving product quality, lowering production costs, controlling product variants, etc. Given that moving from one variation to another variation in the same product could entail making changes to several production resources, the said flexibility needs to address a range of aspects among which manufacturing operations, assembly sequence, process parameters, tooling requirements (e.g., end of arm tooling, jigs, fixtures) can be mentioned. A preliminary search over the literature shows that there are not too many publications that have studied AM, automation, and production flexibility altogether. Therefore, the purpose of this paper is to present an analytic perspective over industrial challenges that deal with final assembly of high mix low volume products through deployment of AM and robotics with the final goal of increasing flexibility in such productions.

2. Flexibility in literature

When it comes to the types of flexibility in literature, it would be difficult to find a consensus among publications, since researchers in this area have used different ways to approach this topic. Two examples can be found in [4], [5]. Given that the purpose of this paper does not revolve around defining the concept of flexibility in manufacturing, nor does it try to provide a review of literature in this specific area, the closest classification that could be found in relation to the conducted interviews with the industrial companies was selected as the theoretical base in the context of manufacturing flexibility. Based on [6], there are eleven types of flexibility i.e., flexibility in equipment (machine), material handling, operation (sequence), process, product, routing, volume, expansion, program, production, and market. The definitions for each type of flexibility can be seen in Table 1.

Table 1 – Different types of flexibility and their definitions, according to [6].

Type of flexibility	Definition
Machine (Equipment) flexibility	Refers to various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another. The prohibition is usually expressed in terms of costs and time. While a machine redesign is ruled out, tool changes in the magazine could take place.
Material handling system flexibility	The ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves. This includes loading/unloading, transporting between machines, and storing parts.
Operation (Sequence) flexibility	Refers to its ability to be produced in different ways. It is a property of the part, meaning that the part can be produced with alternate process plans, where a process plan means a sequence of operations required to produce the part.
Process flexibility	Relates to the set of part types that the system can produce without major setups.
Product flexibility	The ease with which new parts can be added or substituted for existing part mix without incurring huge amounts of cost and time.
Routing flexibility	The ability to produce a part by alternate routes through the system using different machines, operations, or sequences of operations.
Volume flexibility	The ability to operate profitably at different overall output levels which are feasible.
Expansion flexibility	The ease with which capacity and capability can be increased when needed. While capacity refers to output rate per unit of time, capability concerns to characteristics such as quality, technological state, etc. This flexibility makes it easier to replace or add machinery by providing for such flexibilities in the original design.
Program flexibility	The ability of the system to run virtually untended for a long enough period.
Production flexibility	The universe of part types that the manufacturing system can produce without adding major capital equipment. This excludes minor resources such as new tools. In contrast to product flexibility, production flexibility may allow considerable setups but not major capital investment.
Market flexibility	The ease with which the manufacturing system can adapt to a changing market environment.

As it can be seen, the classification in Table 1 incorporates several factors that are important for a company's flexibility. Depending on the industrial sector, market requirements, and the type of products, companies might prioritize one over the other to be able to integrate the concept of flexibility within their operations.

According to [7], there are four main themes in literature that can support definition of flexibility: flexibility to enable change, perspectives on flexibility, flexibility types, and flexibility dimensions. The study characterizes flexibility of AM based on its internal capabilities which are:

- Flexibility for on-demand manufacturing
- Design freedom
- Production of a wide range of parts
- Fabrication of complex geometries
- Versatile materials processing
- Tooling freedom
- Exploiting process variables in efficient production

The interest towards studying the links between flexibility and AM is of course increasing in literature [8]–[10], but most of them are concerned with the supply chain impacts. It would thus become even more interesting to evaluate how adopting AM for increasing flexibility could go beyond supply chain and include aspects that have stronger effects within manufacturing processes and assembly operations.

On the other hand, AM is not the only technology that can provide the much-needed flexibility in productions. Automation in general and robotics in particular has a significant potential to improve flexibility in manufacturing [11]. When it comes to implementation of robotics in industrial manufacturing, there are several parameters and components that need to be considered. They can include robots' kinematics and dynamics, actuators, control systems and computer interfaces, mechatronics, end-effectors, sensors and intelligence, languages and programming methods, and even the application-dependent considerations [12]. One component in particular which is more than others discussed both in literature and industry is the design of end-effectors or grippers. Given their role as the single point of contact between the manipulator and the workpiece as well as their application-dependent designs (resulting in high customization), they need to be able to grasp the object in a relatively stable position without compromising its structural integrity. The human hand is considered to be the universal gripper which can grasp items in the following ways [13]: cylindrical, lateral, palmary, spherical, between ends, and as a hook. So, it is reasonable to assume that a gripper should be designed in a way to be able to mimic these functions as a minimum requirement. There are several research papers which have delved into this area. For example, the paper by [14] studies grippers based on their configurations, type of actuation, application, size, and stiffness. In another study, the authors categorize grippers based on their applications into industrial situations, fragile object gripping, medical applications, micro and nano grippers, and soft fabric grippers [15]. Another study takes a statistical approach and provides a review over characteristics of pneumatic, parallel, two-finger, and industrial grippers by studying certain parameters including stroke, force, weight, and performance index [16].

As it was mentioned before, robotics comprises various components, and depending on the type of product, production system, and manufacturing requirements, certain aspects of flexibility might need to be fulfilled by focusing on one or several components.

3. Flexibility requirements of industry

To get industrial insights for this research paper, semi-structured interviews were conducted with four industrial companies. The main purpose was to understand the most prominent features of productions at the facilities of the participating companies. While the interviews were organized separately with each company, the researchers stayed completely impartial to the overall flow of the conversations. The interview method was selected based on the requirement to have a certain level of control on the overall flow of the discussions while providing the interviewees with the freedom to address and explore several themes that were of interest. A summary of the interviews with the companies is going to be discussed in the following.

A total of four companies which were all positioned in the fields of automotive and motion control technologies participated in a round of interviews. The end-customers for some of them are quite similar which results in in an extremely competitive and calculated approach in their interactions. Furthermore, the high number of variations in their produced models and variable production volumes turns them into great candidates for this type of research. The interviewees who were representatives of the companies assumed different roles and responsibilities in the following areas: production engineer, manufacturing technology manager, technical expert, automation expert, and project manager. This wide spectrum of positions would allow for the study to collect opinions from multiple levels and avoid biases that could otherwise result from talking to like-minded expertsin the same organization. The questions posed to the interviewees were mainly concerned with the production and assembly operations at their respective facilities. All interviews were started by asking the representatives to give an overview of their respective facilities as well as their own job descriptions and responsibilities. In case there was a need for further clarification, they would be asked to provide more information on the spot. A thorough discussion over this part allowed for obtaining useful insights about the production layout, processes at different stations, flow of parts and components, means of transportation between stations, as well as equipment, tools, jigs, and fixtures. Following a verbal approval for further investigation between the researchers and the companies, another follow-up round of interview was conducted to examine the shopfloor through photos and videos that had been prepared by the interviewees. It must be mentioned that this research was performed during Covid-19 pandemic and so, in-situ observations were not possible to perform. While a wide range of topics were brought up by the representatives of the participating companies as the most remarkable features in their daily productions, there were some areas where a higher level of consensus among all of them could be noticed, and this can be seen in Table 2. Given the different fields of industry that the companies were positioned in, and their varying levels of investment in automation leading to green field and brown field projects, seeing commonalities among the responses was an interesting observation that could not be easily dismissed.

Table 2 - Prominent features of the companies' production operations.

Features	**Commonality among companies (4 in total)**
Changes in future product designs	High consensus (shared by all)
Heavy equipment, handling postures, and hazards	
Kitting challenges	
Manual assembly	
Material and parts delivery to line	
Screwing operation	
Test and quality checks	
Capital investments in automation	
Many components in assembly of products	Medium consensus (shared by 2-3)
One-piece flow solution	
Inconvenience of personal protective equipment (PPE)	
Variations among products	
Design challenges for electricity hazards	
Cell design for material supply	Low consensus (shared by 1-2)
Assembly sequence and speed	
Difficulty of assembly automation	

Looking more closely at table 2, one would realize that the most common features (high consensus) are general in their nature and not specific to any particular field of industry. In fact, even though the four interviewed companies are positioned in automotive and motion control technologies, it is through their assembly operations and complexities of implementing automation in them that a common ground for research can be realized. Taking these features out of the current context of companies and placing it on any other companies that are involved with assembly, the features could still be relevant. However, the other two levels (medium and low consensus) are more customized to the type of activities that are performed within assembly operations of the companies. In the current case, the automotive companies have a great concern (among others) for assembly of components that carry high voltages, while productivity of one-piece flows and the way of presenting parts/components to the line is more tailored to the requirements of motion control technology suppliers. It should also be noted that all of these features need to be interpreted in the context of implementing automation technologies and the overall objective of increasing flexibility in productions.

4. AM and robotics as enablers for flexibility

In this part, a discussion over the role of AM and robotics as the enablers for flexibility requirements of industry is presented.

From Table 1 [6], it is reminded that there are different types of flexibility, namely: machine flexibility, material handling system flexibility, operation (sequence) flexibility, process flexibility, product flexibility, routing flexibility, volume flexibility, expansion flexibility, program flexibility, production flexibility, and market flexibility. Corresponding this list with the specific features of the interviewed companies in Table 2, one can notice the relationships between some of the items that can be traced between the two tables. For example, "changes in future product designs" can be a function of "product flexibility". There may of course be some overlapping between *types* and *features* for more than one item from each table. An overview of the connections between flexibility types and production features can be seen in Table 3. The intersection has been marked by "x" in the table.

Having laid out the basic links among flexibility and manufacturing operations in industry (in this case the identified features from the interviews), the next step would be understanding how AM and robotics could facilitate flexibility particular features. The features themselves may not necessarily be the challenges that the industry is facing, but as the name suggests, they are the day-to-day circumstances that a firm deals with both at the operational and organizational level. There is currently no standard or fixed guideline to identify each technology's best applications. But reviewing capabilities [7] mentioned earlier would provide some hints on the overall application of these technologies. For example, while use of collaborative robotics in screwing operations could provide a good substitution for torque runners that are manually operated in the line, AM can be utilized to quickly design and test different types of grippers that could be deployed for this kind of operation. This can be further motivated by testing over the whole range of design variations pertaining to the company's products to verify whether a further investment would be reasonable. By corresponding all the capabilities with the requirements in similar contexts, companies can evaluate which technology can be useful for their current needs and assess its applications in a verifiable way.

Table 3 – Correspondence of different types of flexibility with some of the specific features of operations in industry.

Features of operations from the interview study	**Type of flexibility [6]**										
	Machine flexibility	Material handling system flexibility	Operation flexibility	Process flexibility	Product flexibility	Routing flexibility	Volume flexibility	Expansion flexibility	Program flexibility	Production flexibility	Market flexibility
Changes in future product designs	x				x	x	x	x	x		x
Heavy equipment, handling postures, and hazards		x									
Kitting challenges		x			x	x	x				
Manual assembly			x			x	x	x		x	
Material and parts delivery to line		x				x					
Screwing operation	x						x		x	x	
Test and quality checks			x			x			x		
Capital investments in automation	x						x	x			x
Many components in assembly of products				x			x				
One-piece flow as a solution				x		x				x	
Inconvenience of personal protective equipment (PPE)	x					x					
Variations among products					x		x	x	x		
Design challenges for electricity hazards			x		x						
Cell design for material supply		x				x		x		x	
Assembly sequence and speed	x		x			x	x		x		
Difficulty of assembly automation				x			x				

5. Conclusions and future work

Flexibility in the context of industrial manufacturing includes a broad range of areas. While it may not be easy to arrive at a single accepted definition or categorization in literature, many aspects of it resonate with the requirements of industry. A standard definition of flexibility within a manufacturing company could facilitate structuring the strategies and the decision-making process. However, an even more important subject would be exploring methods and tools by which the flexibility requirements can be fulfilled at manufacturing companies. This paper presents an analytic study over the subject of flexibility with a particular focus on industry's needs, and then, explores the use of robotics and AM to understand how they can be utilized to overcome the challenges and improve flexibility in a broad range of areas. The capabilities of AM and robotics specially in the context of enablers of flexibility in industry were briefly described in this paper. Furthermore, the need for identifying each technology's most promising potentials in the context of flexibility was identified. Apart from some basic suggestions that were made in Chapter 4, future research could be a further exploration of these technologies and designing models or guidelines through which companies could make their decisions more rigorously and based on verifiable information.

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