Additive Manufacturing Validation Methods, Technology Transfer Based on Case Studies

Iñigo Flores Ituarte, Niklas Kretzschmar, Sergei Chekurov, Jouni Partanen and Jukka Tuomi

1 Introduction

A firm's supply chain and its interconnected manufacturing processes result in complex systems (Rogers 2002). By definition, a complex system features a large number of interacting components (i.e. agents, processes, etc.) whose aggregate activity is nonlinear (i.e. not derivable from the summations of the activity of individual components) and typically exhibits hierarchical self-organization under selective pressures (Valckenaers and Brussel 2015). In other words, in complex systems, the same input stimulus sometimes has relatively different responses. The literature has explained that a successful outcome of a new technology transfer is dependent on how the new technology is integrated in this complex system. At the same time, the lessons learned and rules derived from successful technology transfer projects cannot be applied exactly into all organizational settings, and therefore the outcomes will generally be different.

Additive Manufacturing (AM) is a cornerstone in the high-end manufacturing scene. To a great extent, the technology is novel for the end-manufacturing of valuable mechanical components, which can be produced by metal, plastic or ceramic materials. Technological projections define AM technologies as an important element of the future of manufacturing (Bogue 2013). The hypothesis is that AM will coexist and in certain cases replace conventional manufacturing techniques based on subtractive and forming methods. By doing so, the technology will reduce the cost of operations and at the same time improve the functionality of products or services. The paradigm change is that mass production will need to become highly flexible to answer individualized needs in a resource-friendly manner (Jiang et al. 2017). The objectives for companies are to be able to serve heterogeneous niche markets as well as the 'long tail' of the customer markets (Khorram Niaki and Nonino 2017). A

I. Flores Ituarte (✉) · N. Kretzschmar · S. Chekurov · J. Partanen · J. Tuomi
Research Group on Advanced Production Technologies, Department of Mechanical Engineering, Aalto University School of Engineering, Espoo, Finland
e-mail: inigo.flores.ituarte@aalto.fi

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recent result of an empirical study with firms concluded that demand-side benefits and compatibility (i.e. the ability to satisfy customer demands due to the possibility of customization) are the main determinants of AM technology transfer (Oettmeier and Hofmann 2016). As a consequence, inter-organizational factors are central for AM technology transfer. In this scenario, the reality is that most of the companies lack knowledge on the possibilities of AM systems in end-manufacturing applications. The technology is continuously tested and improved in different industrial settings. Thus, the supply chain of AM services, machines and materials development activities are under continuous growth. However, the size of the AM industry itself is minimal in comparison to conventional methods of production, and the machine and material costs are still high. Furthermore, companies do not necessarily have the tools and the trained workforce to justify quantitatively and qualitatively the purchase and technology transfer or use of modern AM systems for product development applications and end-manufacturing applications. In this regard, traditional education in universities and applied science schools is still undergoing a transformation in their curricula to integrate an up-to-date view on AM-related knowledge and its role in manufacturing, product design and product development courses.

2 Challenges for Technology Transfer—The Additive Manufacturing Business Ecosystem and Technology Convergence

Originally, the concept of business ecosystems was first presented in an article in the Harvard Business Review. In this work, Moore (1993) defined the concept of business ecosystem as a '*random collection of interconnected or networked elements (i.e. suppliers, lead producers, companies, competitors and other stakeholders) that produces goods and services of value to customers*". Over time, all the ecosystems gradually evolve into a more consolidated and structured community, and the tendency is to be aligned in the direction set by one or more key leading companies. The AM industry has become a networked ecosystem, where the stakeholders obtaining value from the ecosystem are extremely fragmented with no clear 'one-stop-shop' solution provider offering end-to-end solutions. At the same time, the AM ecosystem as a whole is trying to expand and conquer other markets and has become very dynamic and difficult to predict.

The existing body of knowledge presents the AM industry at the expansion stage. Economic data also supports this hypothesis, as the industry has had an average revenue growth of 26.2% every year during the past 27 years (Wohlers 2015). According to the analogies presented by Moore, this stage is presented as the process of bringing a new offer to a large market by scaling up operation and maximizing market coverage. This leads to the conclusion that firms in the AM ecosystem need to defeat alternative manufacturing solutions and establish power relations with other players. Gibson (2017) described this phenomenon as 'technology convergence'. In his work, he mentions that AM would not be of any benefit if not combined with other technologies (e.g. CAD). In addition, the technology has naturally evolved to be used in conjunction with other manufacturing methods. Currently, the industry growth is supported by the fact that key original equipment manufacturers (OEMs) have started to integrate AM systems mostly based on metal or plastic Powder Bed Fusion (PBF) technologies in their manufacturing processes. Moreover, the expansion of the AM industry has also been highly influenced by the expiration of some patents on core technologies, such as material extrusion and vat-photopolymerization, which is described commercially as Fused Deposition Modeling (FDM) and Stereolithography (SLA), respectively.

Consultancy and academic publications point towards the need to develop a skilled workforce with the ability to utilize and integrate AM technologies with another manufacturing solution (Renda 2015). The required skills need to cover the cycle from advanced and knowledge-intensive design tools (e.g. simulations tools for functional optimization of components, topology optimization, lattice structure generation, manufacturing process simulation, etc.). All the way to the ability to transfer the data to the machines in a digitalized networked manufacturing environment (e.g. e-commerce platforms for manufacturing services, distributed manufacturing models, manufacturing capacity sharing, etc.). New skills will be increasingly needed for quality assurance of AM methods, integration with conventional production methods, STL data conversion and file manipulation as well as post-processing and maintenance. Demand for application engineers and design engineers will surge to fully exploit the advantages of the AM process and to justify technology transfer decisions. To obtain value from AM implementation, companies need to manage complex innovation and sociotechnical processes (Mellor et al. 2014). The role of these newly trained engineers will become crucial to challenge the typical rules of designing and manufacturing within organizations. In this regard, the new workforce will require methods to assess the feasibility of AM technologies from an economic, technical and organizational perspective.

2.1 Economics: Can Additive Manufacturing Compete in Cost?

Hopkinson and Dickens (2003) introduced a breakeven point method to evaluate the economic feasibility of AM compared to conventional methods. For some geometries, it is more economical to use AM methods than it is to use traditional approaches for production. This method helped identify where the major sources of cost for AM are to be found (i.e. machine cost, material cost and labour cost).

In this scenario, Fig. 1 shows the breakeven point analysis to replace conventional manufacturing of a structural mobile phone component in pre-series production (i.e. nominal size of 70 × 37 × 15 mm). The data in this case study was obtained by contacting more than 25 offshore companies, in which case a company in the consumer

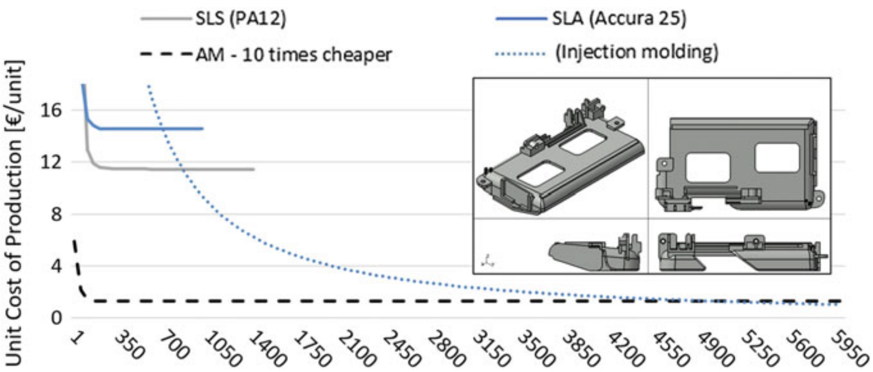

Fig. 1 Breakeven point analysis to replace the conventional manufacturing of a structural mobile phone component in pre-series production. Adapted from (Flores Ituarte et al. 2016b)

electronics sector manufactures and assembles some of its products (Flores Ituarte et al. 2016a, b). This case study allowed for the evaluation of costs and delivery times for injection moulding as well as its AM alternatives (i.e. PA12 and Accura 25, made by SLS and SLA). The data presents a breakeven point around production volumes of 850 units for AM methods. Newly trained design engineers must understand that AM systems would hardly compete in terms of cost with products that are designed to be conventionally manufactured. Even if we consider that AM cost (i.e. those related to material and machine cost) can be reduced by a factor of 10, the breakeven would still be no higher than 5,000 units. Regarding this scenario, it is a mistake to conceive of AM as a mass-production technology rather than as a tool to test and refine the mass-production systems, utilizing the technology in the ramp-up phases of product commercialization or as a bridge manufacturing technology.

We now take a look at the manufacturing applications of AM using metal components. The use of AM is limited to small series production of complex and special parts for aerospace, the automotive industry and med-tech. Figure 2 shows the cost development of AM systems for increased build volume rates (i.e. the material volume being created from the powder over time, which is used as a productivity indicator in AM systems). The model behind this figure accounts for the major sources of cost for AM (i.e. machine cost, material cost and labour cost) and compares the cost development for three different materials. In this regard, the figure shows the result of the cost development for increased build volume rates for rapid manufacture of a timing pulley (i.e. nominal size of 53.8 × 53.8 × 60 mm) in an industrial AM system (i.e. 'EOS M400' with a 1KW fibre laser and a build platform of 400 × 400 × 400 mm). The results of this case study indicate that cost savings are mostly dependent on the cost of the material and to a great extent independent of the achievable build volume rates or productivity issues. In this regard, the justification of AM applications merely in economic terms is not a viable option. Thus, AM technology transfer decisions will need to be accompanied by other parameters, as cost will continue being a barrier for years to come.

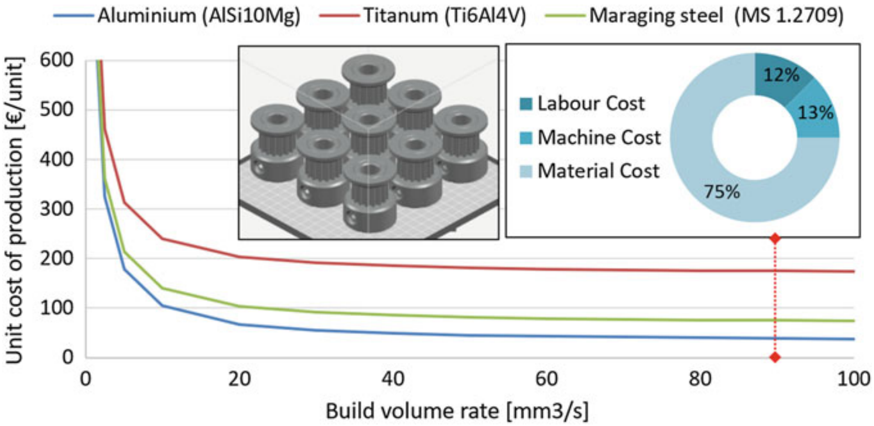

Fig. 2 Cost development for increased build volume rates in metal powder bed fusion systems

2.2 *If Cost is the Barrier, What are the Enablers?*

Conner et al. (2014) defined the key attributes for analysing the suitability of AM applications from a manufacturability standpoint. These are defined as complexity, customization, and production volume. In this regard, engineering decisions to transfer AM technology need to look at these key attributes to assess how likely AM is able to provide advantages over conventional manufacturing. To this end, (1) reduction of lead time and new product introduction enabled by AM for 'manufacturing of few', (2) design modifications, product variations and 'mass-customization' and finally (3) improved functionality or product performance 'complexity advantage' (e.g. topology optimization, part consolidation, etc.) are some of the key enablers that make AM competitive versus conventional methods in traditional manufacturing settings.

In this regard, Fig. 3 shows the delivery time of injection-moulded parts versus AM for the same structural mobile phone component introduced previously. Injection moulding requires at least 25 working days to obtain the first moulded part. In contrast, AM parts are supplied in a matter of days. Currently, the breakeven point in terms of time occurs at production volumes of 900 units. The intrinsic material, energy and process interactions that occur during the SLS or SLA process fundamentally limit AM production speed. Future technologies, such as high-speed sintering, continuous liquid interface production or multi-jet fusion promise to launch a new generation of machines that are much quicker than current ones. Nevertheless, while the service business for OEMs is becoming more relevant and spare parts demand is unpredictable, AM enables production of parts without tooling or tool-less production, generating less inventory and inexpensive design modification, thus increasing availability, reducing service operation costs and making delivery time faster. On the other end, Fig. 4 shows a case study of an AM industrial application enabled

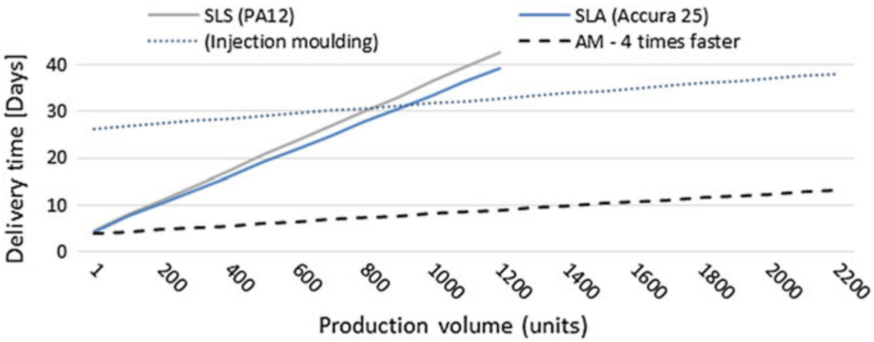

Fig. 3 Delivery time of conventional manufacturing versus AM to produce a mobile phone structural component in pre-series production. Adapted from (Flores Ituarte et al. 2016a, b)

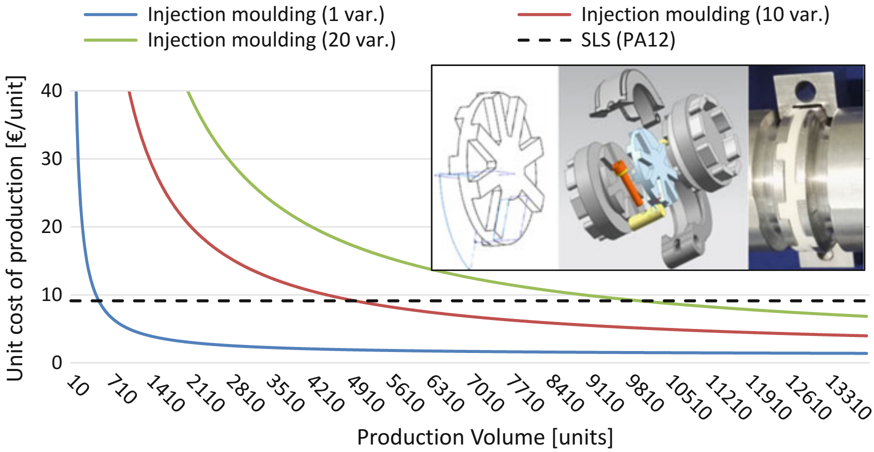

Fig. 4 Economic impact of product variations in conventional manufacturing versus AM

by 'mass-customization'. The object of the case study was the redesigned joint of a novel customizable gripper system, responsible for holding large components during the transportation of car body parts in a factory line—more specifically, the AM component element that adjusts the positioning angle of the gripper allowing multiple configurations by means of a parametric CAD model of the coupling and its digital manufacturing using SLS.

The data shows that the unit costs of AM-produced parts remain constant regardless of the amount of variations. In the case of injection moulding, the cost of the final component depends on the number of necessary moulds to produce all variations of the part. During this case study, the designer and factory estimated the need to produce more than 10 coupling variations. To this end, design engineers should have a holistic perspective to evaluate the impact of product variation and be able to justify AM applications based on it (Schroder et al. 2015). In conclusion, AM

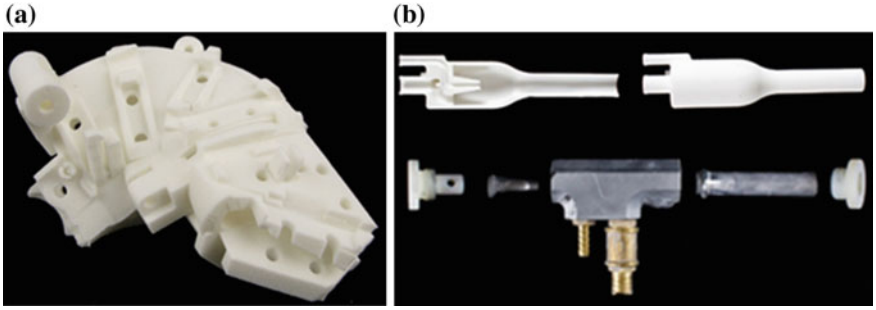

Fig. 5 Case studies. Part consolidation. Adapted from (Flores Ituarte et al. 2016a)

can reduce the capital tied to inventories and its carrying cost, as well as its part's obsolescence, by a build-to-order scheme (Khajavi et al. 2014).

On top of the mentioned enablers for AM technology transfer (i.e. reduction of lead-time enabled by AM for 'manufacturing of few' and design modifications, product variations and 'mass-customization'), newly trained design engineers should take full advantage of AM to be able to improve the product overall functional behaviour using the 'complexity advantage' of AM methods. This process can be distinguished into two areas. First, to simplify product assemblies by means of part consolidation and be able to integrate all the complexity of the mechanisms into a minimal set of elements while maintaining its functionality (Rosen 2014). Second, by topology optimization (i.e. structural optimization using lattice or cellular structures) to decrease weight and maximize stiffness (Tang and Zhao 2016) or to optimize mass and heat transfer efficiency in industrial applications (Aslam Bhutta et al. 2012).

Figure 5 shows two cases of AM applications and technology transfer enabled by part consolidation. For example, Fig. 5a presents a structural element of a coin-sorting system in ticketing systems for public transport. The functional behaviour of the structural elements required multiple connection points for the assembly of sensing, optics and servomotors, as well as other mechanisms that provide the final performance of the product. Figure 5b shows the manufacturing for end-use applications of a nozzle for an air flushing application. The new constructions reduced the amount of components and simplified its topology to fulfil its intended function, drastically reducing the amount of parts and assembly operations. The original designs were assemblies of multiple components (i.e. aluminium and plastic moulded components). In both examples, the parts are redesigned for AM and produced additively by SLS using nylon (PA12) material.

As shown in the previous two cases, the simplification of mechanical systems using part consolidation can become a factor in technology transfer. There are many other commercial examples, for instance, the firm Kuhn-Stoff reduced the number of components in a complex mechanical gripper from twenty-one to a single element (Kuhnstoff 2012), or Boeing, who uses simplified air ducting systems in commercial aircraft applications produced by SLS (Lyons 2011). These new consolidated solu-

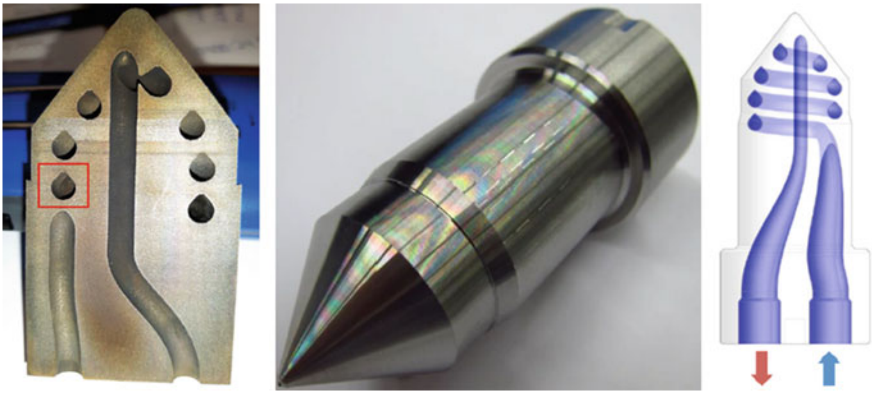

Fig. 6 Case studies. Optimization of geometry for mass and heat transfer applications. Injection moulding metal tooling application

tions have become viable since AM allows the simplification of the overall system and at the same time reduces the need for assembly operation and inventories with a positive impact on cost. In addition, the new designs are lighter and its technical performance was enhanced. With this in mind, newly trained design engineers should focus on mapping AM-compatible systems and components that can be improved in terms of functionality by reducing the number of assembly parts and consolidating the design into primary key elements, while keeping the overall functionality intact. The benefits of this idea are substantial. For example, the aerospace and aeronautical industry achieved improvements in the Buy-to-Fly ratio (i.e. reducing the weight ratio between the raw material used for a component and the weight of the component itself). This is especially relevant for precious materials such as titanium. In addition, the weight reduction of other metal and plastic parts by optimization is technically and economically beneficial over the lifecycle of the aircraft.

Figure 6 shows case studies of AM applications and technology transfer enabled by topology optimization to enhance heat transfer. Figure 6 describes an exploratory case study to manufacture a metal tooling application with integrated conformal cooling for plastic injection moulding (i.e. internal manufacturing complexity). The study was performed to replace an obsolete tooling set manufactured by conventional methods and to use PBF in the context of conformal cooled injection moulding tools. The test results in this regard were favourable, and the new tool was able to improve efficiency of the tool due to lower cycle times in the injection moulding process. However, to achieve the desired final form, PBF-produced parts are rarely usable without post-machining, as tooling components in most cases require a good surface quality only achievable with fine machining. Therefore, AM technology transfer often requires its integration with conventional manufacturing and quality control methods.

The second case, Fig. 7 presents wilful ignorance of traditional manufacturing restrictions to create a heat exchanger that maximizes the benefits of the AM com-

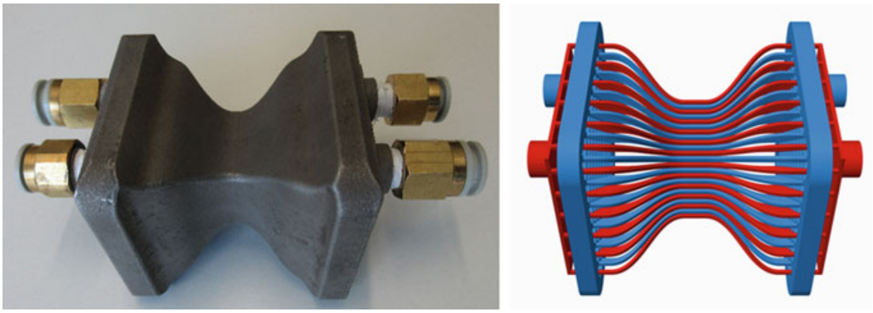

Fig. 7 Case studies. Optimization of geometry for mass and heat transfer applications. Heat exchanger application

plexity advantage. Ignoring the limitations of conventional manufacturing methods, the new geometry consists of 144 very narrow pipes that are placed next to each other, alternating between hot and cold pipes. The convergence of the many channels into four main flow ports was done via a lattice and chamber method, in which the cold pipes flow into the lattice and the hot pipes continue through the gaps of the lattice and reach the chamber. This type of design makes it possible to reach heat exchange efficiencies more than ten times higher than with traditional counterflow heat exchangers. The manufacturing process of the new design is also more streamlined in comparison with traditional heat exchangers, which require extensive assembly. The heat exchanger presented here requires no post-processing other than the removal from the build plate, heat treatment to get rid of residual stresses left over from the AM process, and threading the flow ports for connectors. In fact, machining the part to achieve better surface quality would be detrimental to the performance of the heat exchanger because the inherent surface roughness of the selective laser melting process is beneficial due to the increased surface area and improved flow characteristics.

2.3 How to Justify Technology Implementation? Steps Towards Technology Transfer

Currently, many of the industry-driven technology evaluation programs on AM technology transfer are interlinked with the replacement, redesign or repair of components for legacy systems. For example, in spare-part applications or retrofitting existing obsolete machine components. However, the traditional approach for design and manufacture are based on conventional manufacturing constrains. In this regard, the materials are highly standardized (e.g. ASTM steel, aluminium, casted iron, etc.), and manufacturing processes (e.g. subtractive and forming methods) of the legacy systems are well known and mature. When trying to justify the implementation of

AM materials to replace component or parts in a similar legacy system, the logical top-down engineering process is to compare the functional requirement of the original design. Thus, engineers evaluate the material properties (e.g. tensile strength, elongation at break, impact strength, etc.) and Geometrical and Dimensional Tolerances (e.g. GD&T) obtained by a conventional process with those obtained by AM. However, the outcome of this approach is that parts manufactured additively are of inferior quality and more expensive in comparison and will limit AM to prototyping applications. The cases presented in Figs. 1 and 2 demonstrate that AM manufacturing implementation based on manufacturing cost reduction will not become a viable option for medium or high volume production. The justification of AM technology transfer based on cost parameters will only be possible in the production of one-of-a-kind, very small production lots or the 'manufacturing of few'.

A different approach and potentially more beneficial for the design engineering process is to consider the full product life cycle involved in traditional manufacturing methods. For example, the reduction of delivery time can boost AM applications (i.e. availability for low volume production, bridge manufacturing and production on demand). In many occasions, technology transfer can be justified exclusively focusing on AM as a faster solution to produce a few parts, for example, when tooling or parts are not readily available for short volume production, as in the case presented in Fig. 3. AM can reduce the lead time in new product introductions or in the provision of spare parts for the manufacturing of low volumes. Another factor is the possibility of 'mass-customization' of industrial components or complete systems. The case presented in Fig. 4 shows how the impact of design modification shifts the economical breakeven point to the right in a linear manner. To this end, during the design engineering process of new mechanical systems, the engineering team should have a holistic perspective to evaluate the impact of product variation, thus being able to simplify the manufacturing process as well as the design by the implementation of highly customizable AM key mechanical components. A similar approach can be used when using functional optimization. The cases presented in the previous section show how an improved performance can be achieved in terms of simplified mechanical constructions. The cases in Fig. 5 show how two consolidated solutions have become viable since AM allowed the simplification of the overall system. In addition, the topology optimization cases in Fig. 6a and the functional optimization case in Fig. 6b demonstrates how traditional geometrical limitations of subtractive methods of production can be overcome, thus, allowing the production of key components with an increased value in terms of performance.

Figure 8 shows a summary of the key enablers for AM technology transfer. To justify AM implementation in production activities, the design engineering process should look at these three interlinked parameters in a holistic manner (i.e. cost, time and functionality). If we only look at the cost, AM will only allow the 'manufacturing of few', ramp-up manufacturing or the production of one-of-a-kind components. To this end, AM-enabled tool-less production will have a positive impact on the upfront of manufacturing ramp-up. Second, the time parameter can become an enabler for AM implementation due to the increased availability to produce parts on demand. Many times AM can become a faster solution when tooling and parts are not read-

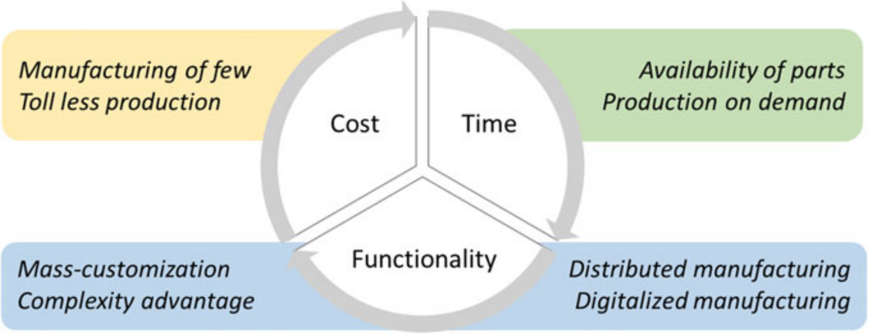

Fig. 8 Summary of the key enablers in the integration of AM in industrial manufacturing operations

ily available when they are needed. In this regard, AM can enable the reduction of lead time in low and medium production and new product introductions. In addition, parts can be manufactured only when needed, thus reducing cost and simplifying logistics utilizing digital inventories as well as the reduction of Stock Keeping Units (SKUs). Finally, improved functionality becomes the key parameter that makes AM truly competitive versus other conventional manufacturing methods. For example, industrial 'mass-customization' combines the low unitary costs of mass-production processes with the flexibility of individual customization. On the other hand, the 'complexity advantage' allows improved product performance by topology optimization to decrease weight, maximize stiffness and mass/heat transfer efficiency. In addition, part consolidation can simplify designs into primary key elements. Another advantage in the future of AM technology transfer is its role in the digitalization of manufacturing. In this context, AM inherently supports digital manufacturing. AM benefits are the increased control of the manufacturing process (i.e. digitalized information flow and material flow) and the possibility to develop distributed models of production on demand. However, to allow future distributed manufacturing models to be implemented, there is a need to develop a network of AM services with the ability to post-process the parts to meet engineering requirements and a network of trustworthy material suppliers.

3 Conclusions and Future Perspectives

AM has evolved from a marginal technology to an important tool for resolving engineering challenges. If we look at the fundamentals of successful technology transfer, AM intrinsically demands new knowledge in organizations as well as a different attitude and set of rules in engineering design and manufacturing education. On one side, the new knowledge can be costly and difficult to assimilate in companies. On the other side, it also stresses management, leadership and decision-making roles, especially for small and medium-size OEMs that lack R and D capabilities and capital for long-term investments. AM technologies clearly benefit from strategies based on economies of scope and customer integration in the value chain. The industrialization of AM systems is an ongoing endeavour, as the transition from 'economies of scale to economies of one' is becoming a reality in many industrial domains. Design engineering education should transmit the idea that AM cannot be the universal replacement for traditional manufacturing methods; AM requires integration with conventional manufacturing plants and automation of processes. However, it has become an important value-adding manufacturing method for high-end design applications and manufacturing of complex mechanical key components. AM will replace conventional manufacturing in cases where the production volume of the intended product is small or unknown and where the ability to rapidly adapt the production needs become a fundamental variable. In addition, the key parameter for successful technology transfer is to find industrial applications that can be improved in performance (e.g. mass-customization, complexity advantage, part consolidation, topology optimizations, etc.). We anticipate the huge potential for growth of AM applications in traditional OEMs, especially in manufacturing applications from which completely new products and processes can be innovated. The education of a new engineering workforce should apply AM education and concepts to relatively small and highly complex plastic components and incrementally open up to applications for larger and metallic components. The engineering schools should present a clear picture of the economical side of new technology investment. AM materials and machine costs will still be a barrier for technology transfer. However, AM requires adopting a broad perspective on time. During the design engineering process, one should consider the full production lifecycle involved in traditional manufacturing methods, as the availability of AM-produced parts, reduction of SKUs, time-to-market as well as delivery lead times can become fundamental in the service operation of manufacturing companies. In summary, newly trained design engineers should evaluate AM in end-manufacturing applications by looking at the interlinks between AM cost structures, the availability and delivery time of AM, and the increased functionality of products enabled by AM methods in comparison with established methods of design and production.

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Iñigo Flores Ituarte (PhD) is an early stage scholar and Post-Doctoral researcher at Aalto University (Finland) and visiting researcher at Singapore University of Technology and Design (SUTD). His research activities focusses on digital design methods, process and design optimization, and integration of Additive Manufacturing technologies into industrial processes. He received his doctoral degree in 2017 at Aalto University. In his academic activity, starting 2014, he has published more than 15 scientific publications and contributed to several books. His research activities are mostly problem-based and industry-motivated from where he combines theory and practice to evaluate critically the future role of modern Additive Manufacturing technologies.

Niklas Kretzschmar, M.Sc. is a PhD candidate at Aalto University (Finland) in the Department of Production Engineering. His research focuses on technical and economic additive manufacturing applications. He is currently working on technology transfer and support methods to validate additive manufacturing applications, digital spare parts, bioprinting as well as design for additive manufacturing approaches using the TRIZ methodology and axiomatic design to optimize specific components. He has received an MSc in Mechanical Engineering and Management from the Technical University of Munich (TUM) in 2015 and has worked in the manufacturing industry before starting his PhD.

Sergei Chekurov, M.Sc. is working towards the degree of Doctor of Science in the field of Additive Manufacturing at the School of Engineering of Aalto University. His current focus is on hydraulic and heat transfer applications of AM and extension of Design for AM frameworks.

Jouni Partanen (PhD) is a Professor of Advanced Production Technologies and the Head of Mechanical Engineering Department in Aalto University. He is an academic scientist and an experienced high technology industry leader (15 years) in product development, advanced research, production and product management. Dr. Jouni Partanen has been a key equipment developer for 3D Systems in California, the leading Additive Manufacturing Technology company in the world. He is named as an inventor in more than 50 patents issued internationally in the most significant high technology markets. His academic career spans from university and research laboratory positions in Finland, England and California. He has more than 100 publications with over 2000 citations (Google Scholar, H-index of 29), including articles in leading scientific journals, like Nature and Physical Review Letters.

Jukka Tuomi, Lic.Sc. (Tech.) is research manager in Aalto University and he is President of Finnish 3D Printing network FIRPA (Finnish Rapid Prototyping Association). He has written over 50 scientific papers, book chapters and conference proceeding articles about 3D Printing, Additive Manufacturing (AM), 3D Modeling and Product and Production Development. He has been international scientific committee member in over 20 conferences and he has presented in over 50 international conferences and seminars in about 20 different countries worldwide. Jukka Tuomi is representing Aalto University in European Institute of Technology and Innovation (EIT) Digital Industry program project. EIT Digital is a leading European digital innovation and entrepreneurial education organizsation driving Europe's digital transformation.

External Resources: Aalto University is a Finnish multidisciplinary university founded in 2010 by merging The Helsinki School of Economics, The University of Art and Design Helsinki, and Helsinki University of Technology (which is the formerly independent Helsinki University of Technology, the second-oldest university in Finland and the leading Finnish university of technology). The research group in Advanced Production Technologies under the school of Engineering that works in externally funded research closely with diverse industrial partners in developing solutions for industrial and medical applications of Additive Manufacturing and laser based manufacturing systems. http://mecheng.aalto.fi/en.