Functional, Technical and Economical Requirements Integration for Additive Manufacturing Design Education

Alain Bernard, Mary Kathryn Thompson, Giovanni Moroni, Tom Vaneker, Eujin Pei and Claude Barlier

1 Introduction

During the past decade, the use of Additive Manufacturing (AM) technology has undergone a transformation. Early AM applications were focused on producing static models and prototypes. Today, it is also used for the production of end use parts and products. Leveraging the geometric and material freedoms of AM for end use parts creates greater opportunities for designers, manufacturers and end users. However, not all parts are possible or cost-effective to produce using AM. This necessitates a better understanding of when, why and how to (re)design for the opportunities and constraints associated with these technologies. Design for Additive Manufacturing (DfAM) aims to develop the practice of designing and optimizing a product together with its production process. It aims to reduce development time and cost and increase performance, quality and profitability. This can include a collection of concrete tools,

---

A. Bernard (✉)
Laboratory for Digital Sciences in Nantes (LS2N UMR CNRS 6004),
Ecole centrale de Nantes, Engineering of Industrial Products and Systems,
IS3P Team for Systems Engineering: Products, Processes & Performances, Nantes, France
e-mail: alain.bernard@ec-nantes.fr

M. K. Thompson
Department of Mechanical Engineering, Technical University of Denmark Kgs,
Lyngby 2800, Denmark

G. Moroni
Department of Mechanical Engineering, Politecnico di Milano, Milan, Italy

T. Vaneker
Faculty of Engineering Technology, University of Twente, Enschede, Netherlands

E. Pei
Institute of Materials and Manufacturing, Brunel University London, London, UK

C. Barlier
CIRTES, R&D Centre for Additive Manufacturing, Pôle VirtuReaL, Saint-Dié-des-Vosges, France

E. Pei et al. (eds.), *Additive Manufacturing—Developments in Training and Education*, https://doi.org/10.1007/978-3-319-76084-1_12

techniques and guidelines to adapt a design to a given set of downstream constraints, and guidelines to help understand and quantify the effect of the design process on manufacturing (and vice versa). This may also help in understanding the relationship between design and manufacturing and its impact on the designer, the design process and design practice. DfAM can also account for these new opportunities, rules and constraints within the scope of AM (Thompson et al. 2016b).

With the use of AM, the final characteristics of the produced part, especially the material properties, as well as its functional capabilities and geometrical limits, are known only at the end of the production phase. Therefore, it is important to consider the AM production methods and to determine if the printed parts have to be post-treated. AM can be integrated or combined with other processes to form longer multistage process chains (Thompson et al. 2016a). Kim et al. (2015) proposed a systems approach for data flow structuring and decomposition in several steps, clarifying the need for data generation and transformation along the AM digital chain. AM technologies produce physical objects from digital information. This requires a digital dataflow to generate the instructions for the AM machines, followed by a physical workflow to transform the raw material into the final part. As described by Bernard et al. (2003), the process usually begins with a product idea, a set of 2D images or a physical 3D object which is then developed as a digital model using solid modelling, metrology or image reconstruction software. Next, the data is prepared and adapted to define the manufacturing constraints and limits of the part in the AM machine. Finally, the model is sliced or discretized to create instructions for the machine. New software formats have been developed and standardized to support AM data preparation and digital workflow. For example, the AMF format, which has native support for colour, materials, lattices and constellations, has been standardized and is intended to replace the purely geometrical and surface STL format. Education must also be adapted to integrate new design practices based on AM criteria, and to include more robust knowledge about material science and quality control for Design for Additive Manufacturing (DfAM).

2 Design for Additive Manufacturing

Design for Additive Manufacturing (DfAM) is more than theory—it includes concepts, practices and rules that are specific to each family of AM technology. The term ‘Design for Additive Manufacturing’ has been used extensively in literature (Doubrovski et al. 2012; Seepersad 2014; Vayre et al. 2012). DfAM is valid for all processes and process chains that involve AM. However, in practice, the design knowledge, tools, rules, processes and methodologies are different. AM processes enable the manufacture of different types of features and impose different types of constraints than other manufacturing processes. Therefore, AM requires different process-specific design rules and tools than conventional fabrication techniques (Gibson et al. 2010; Huang et al. 2015). AM provides opportunities, benefits and freedoms at three levels, namely, the product level with multi-scale complexity, the

Fig. 1 Original seat 'OT'Arts' made of wood by Stratoconception (*source* Cirtes—Fabrication Additive Dunod 2015)

part level with macro-scale complexity and the material level with micro-scale complexity. Production and cost issues also need to be taken into account when designing the product. The use of AM can provide design freedoms and opportunities at the product level, including part consolidation, embedded parts and the direct production of assemblies. For example, AM allows designers to consolidate the parts of an existing assembly into a single printable object. This eliminates the joining time and cost and can also reduce inventory costs. It can also increase functionality and improve performance. Most often, this also reduces the overall mass, increases the durability and improves efficiency. AM allows objects such as small metal parts (bolts, nuts and bushings), tubes for cooling channels and shape memory alloys for actuated hinges to be embedded in printed parts. In addition, electrical components, conductive tracks, motors, batteries and sensors can be embedded or created in situ to print complete products and mechatronic devices. AM can also directly produce assemblies with moving or movable parts, such as crank and slider mechanisms, gears or joints. It can also produce discontinuous interlinked structures such as textiles. Incorporating the material and geometric freedoms of AM into macro-scale parts can provide a variety of aesthetic, functional, economic, emotional and ergonomic benefits. AM technologies utilize a large range of materials including polymers, metals and ceramics. Sheet lamination processes are compatible with paper, wood, cork, foam, metal and rubber (Barlier and Bernard 2015) (Figs. 1 and 2).

Investment casting moulds and cores have been printed in sand and large structures have been printed in clay and concrete (Fig. 3).

Material characteristics have to be closely linked to design rules and manufacturing capabilities. Simulation-based approaches will need to be considered to provide

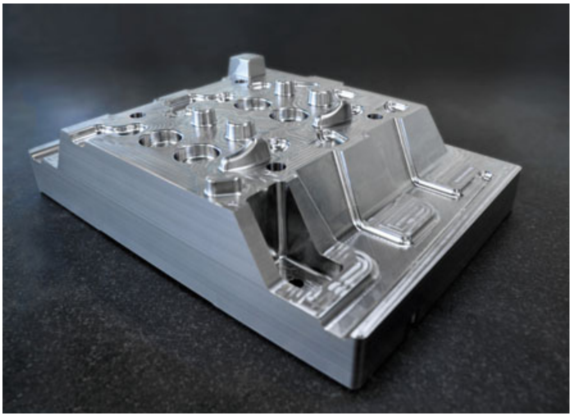


Fig. 2 Steel tooling for gravity casting with advanced conforming cooling made by Stratoconception (*source* Cirtes—Fabrication Additive Dunod 2015)

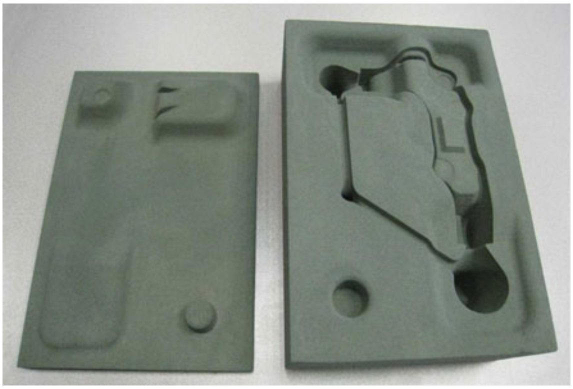


Fig. 3 Mould for casting made by sand sintering (*source* CTIF—Fabrication Additive Dunod 2015)

information with decision-making when choosing the AM build parameters and configuration (Fig. 4).

The use of AM enables the creation of complex internal features to increase functionality and improve performance. For example, AM has been used to create integrated air ducts and wiring conduits for industrial robots; 3D flexures for integrated actuators and universal grippers; complex internal pathways for acoustic damping devices; optimized fluid channels and internal micro vanes for ocular surgical devices. However, one of the most widely studied applications is conformal cooling. Conformal cooling channels follow the external geometry to provide more effective and consistent heat transfer (Fig. 5).

Pelaingre et al. (2002) have proposed a new concept of thermal regulation based on conformable thermal regulation surfaces instead of conformable cooling channels. In particular, these conformable cooling surfaces have been implemented in plastic injection tools and in aluminium diecasting tools (Pelaingre et al. 2004). Recent studies have focused on new applications of conformal cooling such as hot sheet metal forming (Mueller et al. 2013), strategies for increased performance such as

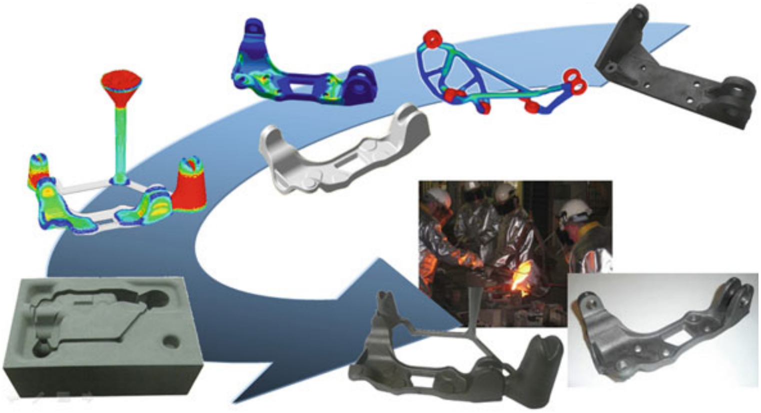
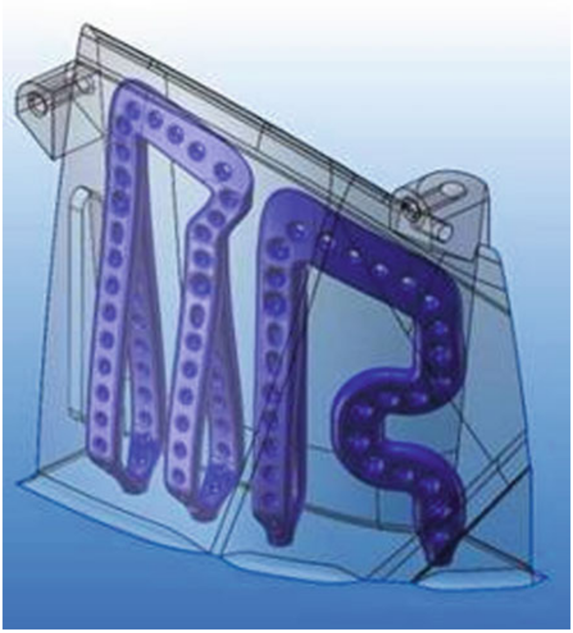


Fig. 4 Complete development phase of a part produced from the mould made by sand sintering (*source* CTIF—Fabrication Additive Dunod 2015)

Fig. 5 Insert of mould with thermal regulation (*source* PEP—Fabrication Additive Dunod 2015)



profiled conformal cooling channels (Altaf et al. 2013) and indirect and hybrid AM for more efficient and cost-effective production such as using AM to produce wax patterns for indirect tooling (Bernard et al. 2003). AM technologies can be used to produce macrostructure topology optimized objects. Topology optimization is a numerical approach that identifies where certain materials should be placed within the three-dimensional part to achieve a desired functionality (e.g. stiffness) for a given

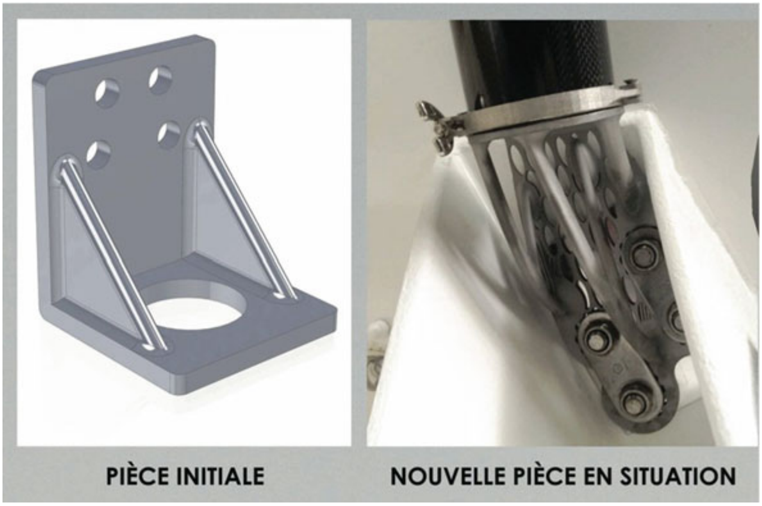


Fig. 6 On the left: initial part; on the right: optimized part (*source* Volume—Fabrication Additive Dunod 2015)

set of loads and constraints while optimizing qualities such as minimal material usage/weight or uniform stress distribution. Macrostructure topology optimization assumes that the structure is composed of a single homogeneous material and that material is either present or absent in each part of the design domain. Although the optimization is often only in the structural domain, examples of multi-physics topology optimization (e.g. with thermal and structural degrees of freedom) can be found in the literature (Gao and Zhang 2010). Macrostructure topology optimization is especially useful in aerospace and automotive industries where weight reduction can lead to substantial energy savings over the usable life of the product (Fig. 6).

In addition, AM also allows designers to consider modifying and combining materials for micro- and mesostructures to create new properties, forms and functionality. AM can create three-dimensional lattices and trusses with specific mechanical, thermal, optical and biological properties (Yan et al. 2012). In structural engineering, the orientation and diameter of the individual struts within a truss or lattice can be optimized to improve the stress distribution, strength and manufacturability (Teufelhart and Reinhart 2012). Various optimization methods exist for the design of periodic mesoscale cellular structures. Topology optimization is often used, but the designer has to consider issues of homogenization (the individual cell must be much smaller than the design space in all directions) and periodicity (the material inside the cell must be such that it corresponds to the material in the adjoining cell). Manufacturing constraints, such as minimum wall thickness and minimum feature size, must also be considered. Although uniform lattices are common, there is no limit to the number of cell types and volume fractions that can be used. For example, structures can be topology optimized using different cell types and volume fractions

(Brackett et al. 2011). Cellular lattices can also have spatial variations (Rumpf et al. 2013). Because AM simultaneously creates an object's material and geometry, it can be used to create custom alloys and composite materials. For example, it is possible to create custom mixes of powders and/or binders, to alternate feedstock materials and to embed fibres in order to create in situ composites, increase mechanical strength, modify the thermal expansion coefficient and obtain electrically tuneable stiffness. Similarly, it is possible to control the porosity, microstructure and material properties of metal, polymer and ceramic parts through the choice of materials, process parameters and build orientation. AM processes with micro- or nanoscale resolution can also create custom surfaces, textures and porosities. Multi-material AM can be used to produce multi-material topology optimized structures, custom laminates and composites. Some AM processes can vary the material percentage composition in different parts of the model to create functionally graded objects (Bobbio et al. 2017).

When teaching design with respect to the main benefits of AM, one has to consider that AM's direct digital workflow and freeform geometry can be combined to fabricate objects with almost any kind of complexity and any degree of customization. This includes products that can be custom-fit to an existing person or object; products that can be personalized based on individual or group preferences and mass-customized products that can be produced with infinite variations. This is the case when designing medical devices based on individual data. In the medical and dental industries, AM is being used to produce a wide variety of personalized and bespoke products including hearing aids; dental crowns, implants and dentures; biomedical implants for hard and soft tissues; customized casts, splints and orthotics and prostheses. AM is also used to produce patient-specific models to facilitate surgical planning and surgical guides to improve accuracy and efficiency. When considering product design, and especially when using AM, mass customization can be one important differentiating factor when providing products dedicated to individuals. For example, AM has been used to produce custom-fit consumer products such as running shoes and earbuds, personalized products such as—eyeglasses and bespoke objects such as 3D portraits created from photographs or 3D scans. Designers and artists have also used AM to customize furniture and lighting fixtures to produce unique artefacts.

3 Constraints and Quality Considerations in Design for Additive Manufacturing

While AM seems to have unlimited potential, it does not have unlimited capabilities. Designers must take into account many types of constraints, including those associated with CAD and the digitization of their ideas; the digital and physical discretization of the parts to be produced; the characteristics of AM processes and the current capabilities of AM machines; the impact of AM processing on material properties and the requirements for processing materials using various AM techniques; new challenges and requirements associated with metrology and quality control;

through-life requirements and considerations such as maintenance, repair and recycling; and external factors including the regulatory environment. While many of these constraints also apply to other types of manufacturing technologies, the bottom-up nature of AM means they can have very different implications for designs, the design process and the intermediate artefacts that are created to support production. When considering the AM value chain, producing digital models for AM is challenging because most commercially available CAD programs are parametric NURBS systems. These are well suited to modelling geometries associated with traditional manufacturing processes (extrusions, revolves, lofts, etc.) but are often inadequate for the more organic shapes and complex, multi-scale geometries associated with AM. In addition, traditional CAD systems cannot generate multi-scale cellular and lattice structures, model or denote colour, specify the material to use, indicate material variation within an object, or specify tolerances. To overcome these limitations, AM CAD systems require a new interface that can develop complex shapes and structures and a data structure that can store their properties. Researchers are working to overcome CAD and digitalization constraints by developing new data formats that can handle material related information. Multi-material capability has also been built into the AMF format. However, there remain many challenges when designing for heterogeneity taking into account the shape and material distribution to meet the functionality, requirements, or constraints of the artefact. Issues include what granularity to consider during the design phase, how to handle material variation analytically, and whether the resulting design can be satisfactorily manufactured using a given AM process. The coupling between the design, representation, analysis, optimization and manufacture still needs to be resolved. This coupling effort is necessary because manufacturing parameters have a substantial influence on the final result with respect to all characteristics of the final object, in particular, the layer thickness, the manufacturing direction and the support structures. Post-treatments are also influenced by these AM process parameters and the global economic performance depends on the value chain effectiveness and robustness (Thompson et al. 2016a). For example, even if supports are needed for some processes, they can be minimized, and consequently, manufacturing time, material consumption and finishing operations can be optimized. These considerations should be taken into account when defining the design and production strategy, otherwise, they may result in costly redesign later in the product development process. The process-specific characteristics, machine specific constraints, choice of material(s) and in some cases the support strategy, place limitations on the parts that can be built and define the qualities and characteristics of the parts. These build parameters determine the warpage, shrinkage, accuracy and precision of the part; the dimensional stability; the surface roughness; the minimum feature size; the minimum spacing between features; the maximum aspect ratio of a feature; and the unsupported and supported feature shapes and sizes that can be produced. Given these constraints, designers must choose an AM process that can produce the specified part in the specified material with the required quality, choose a non-AM process or combination of AM and traditional processes that have the required capabilities, or modify the design and its production strategy to compensate for the constraints that are imposed by AM.

Because of all of these influential factors, teaching design in the field of AM requires new design rules. A number of AM design guides have been published to outline process and machine specific constraints and considerations. Materialize published 19 design guides for a variety of materials (Materialise 2015). Each guide provides a set of ‘design specifications’ that include minimum wall thickness, minimum detail size, expected accuracy, maximum part size, clearance and if interlocking or enclosed parts are possible. These are followed by a set of ‘basic rules, tips and tricks’ that are material and process-specific. Stratasys published three guides that address DMLS (Stratasys 2015a), FDM (Stratasys 2015b) and laser sintering (Stratasys 2015c). These are also process-specific with little overlap in content. Shapeways published design guidelines for 16 materials (Shapeways 2016). Each guide includes the minimum and maximum bounding box, minimum supported and unsupported wall thickness and wire size, minimum embossed and engraved detail, minimum escape holes for entrapped material, if enclosed and interlocking parts are possible, if multiple parts per file is possible, the expected accuracy and the expected look and feel of material. Additional material specific information such as design tips and information about handling and care of the final parts is also included. 3D systems published two design guides that focus on application-specific considerations for brass (3D Systems 2015a) and plastic (3D Systems 2015b) SLS components that include features such as internal channels, cages, assemblies, interlocking/woven parts, springs, hinges, snap fits and threads. In the academic literature, Adam and Zimmer (2014) presented a catalogue of design rules for laser sintering, laser melting and FDM that address geometric constraints such as sharp edges, element transitions, unsupported features and feature spacing. Additional process-specific design rules have been proposed for Fused Deposition Modelling (FDM) (Teitelbaum 2009), Selective Laser Melting (SLM) (Thomas 2009), Electron Beam Melting (EBM) (Vayre et al. 2013) and Wire Arc Additive Manufacturing (WAAM) (Mehnen et al. 2014). While design rules and guidelines can provide a useful starting point, they do not provide information about individual machines and local capabilities.

4 Cost Considerations in Design for Additive Manufacturing

When designing, it is important to be aware of the impact of design decisions and choices with respect to different Key Performance Indicators (KPIs). The use of functional analysis helps to define those KPIs and the corresponding expected level of performance. Cost is one of these KPIs and when using AM, it is not always easy to anticipate the direct cost and potential cost savings in the early stages of design. Very often, key factors such as part complexity and quality are chosen to explore basic models that could give some close approximations of the final cost. It is very important to be very careful when approximating the cost of AM production because it is often viewed as one of the biggest barriers to adoption in industry. AM costs are usually divided into well-structured direct production costs (e.g. labour, material and machine costs) and ill-structured costs (related to build failures, transportation, inventory, etc.) (Thomas and Gilbert 2014). Early cost models focused on the well-structured costs and were intended to compare AM processes to each other or traditional manufacturing processes and to identify strategies for process and product cost optimization.

Hopkinson and Dickens (2003) proposed one of the earliest generic AM cost models. This model assumes that one product will be produced on the same machine for the entire economic lifespan of the machine. It includes machine costs (purchase, depreciation and maintenance), labour costs (operator, setup and post-processing) and material costs (direct material costs and material cost for support structures). Ruffo et al. (2006) expanded upon that work to create a more flexible and realistic cost model that included different parts in a single build; indirect costs such as administrative costs, part design and production overhead; and the cost of powder material reuse and waste. More recently, Atzeni and Salmi (2012) developed a model to estimate the cost of Direct Metal Laser Sintering (DMLS) metal parts. It included machine costs (including interest and maintenance over a 5-year usable life), material costs (volume multiplied by 1.1 to compensate for support and waste) and pre- and post-processing costs such as labour. Many variations of these cost models exist in the literature. Li (2006) included labour costs for pre- and post-processing, material costs (part volume/0.7 to account for support and material waste), machine cost per hour (purchase cost over annual utilization and years until return) and overhead (rent, electricity, etc.). More recently, Grimm (2010) considered pre-printing and post-processing time; capital costs (machines, facilities, etc.); annual operating costs (service, maintenance, consumables, material disposal, etc.); and hourly costs (assuming a 60% utilization rate). Baumers (2012) considered total indirect cost per machine hour (machine costs, overhead, labour, utilization rates and usable equipment lives), material cost and electricity costs. Gibson et al. (2010) included labour costs (including setting up the build, post-processing and cleaning and resetting the machine), machine purchase cost (allocated based on the part build time and machine usable life), machine operation costs (including maintenance, utilities, floor space, overhead, etc.) and material costs (based on part volume, multiplied by up to 1.5 to account for support and multiplied by up to 7 to account for material waste). Lindeman et al. (2012) built on the work of Gibson et al. with an extensive model to define machine costs. They introduced a part complexity factor to allow for the increased time needed to design support structures and place complex parts in the build environment. Rickenbacher et al. (2013) developed one of the most comprehensive models to date. Their model includes detailed cost estimates based on the full SLM process chain and is suitable for jobs with different parts sizes, complexities and quantities. One of the most critical issues is to determine the machine working time (build time) with respect to the specific characteristics of a given machine (Zhang and Bernard 2013). The build time dictates how machine costs are allocated to a given part. It is therefore essential for accurate AM cost estimations (di Angelo and di Stefano 2011). Existing build time models (Zhang et al. 2015) can be grouped into 3 categories: models dedicated to one process using a limit set of parameters;

generic build time models that use many parameters to estimate build times; and parametric models that use neural networks to predict production times based on historic data. Although the energy consumption of the AM processes is important from life cycle and sustainability perspectives (Kellens et al. 2011), it plays a minor role in cost comparisons today.

5 Conclusions

This chapter has presented the major design opportunities, constraints and costs associated with DfAM. To achieve the full benefits of AM, designers must learn to think differently while focusing on creating robust industrial solutions with added value. Design theories, processes, methods, tools and techniques must be combined or developed to address the inherent coupling between material, geometry and quality in these systems. Specialized and application-specific tools must be developed to support the design of cellular structures, metamaterials, heterogeneous artefacts and biological scaffolds. It must be acknowledged that each build is a design artefact with its own requirements and constraints and its own features (e.g. support structures, part layout, etc.) to be designed and optimized. Thus, DfAM must extend beyond the product to the production system and consider the entire value chain (Zhang et al. 2016).

With respect to this last remark, teaching should be practiced with a real systemic vision of AM by considering the different influence factors that relate to the lifecycle requirements of the parts. Indeed, in particular, AM will continue to redefine the roles and relationships of the designer and the manufacturer for truly global rapid product development (Bernard and Fischer 2002). In fact, with AM, teaching design becomes teaching knowledge-based lifecycle design of the product based on the powerfulness of additive manufacturing. To face such a goal, the developments of methods and tools must be compiled and made available to support design activities and training in educational institutions and in industry.

References

3D Systems Inc. (2015a). Design Guide—Brass inserts for SLS parts. Retrieved from January 10, 2018, from http://www.3dsystems.com/sites/www.3dsystems.com/files/brass_inserts_guide_for_sls_parts_0.pdf.

3D Systems Inc. (2015b). SLS® plastics design guide. Retrieved January 10, 2018, from http://www.3dsystems.com/resources/sls-plastics-design-guide.

Adam, G. A. O., & Zimmer, D. (2014). Design for additive manufacturing: Element transitions and aggregated structures. *CIRP Journal of Manufacturing Science and Technology, 7,* 20–28.

Altaf, K., Rani, A. M. A., & Raghavan, V. R. (2013). Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools. *Rapid Prototyping Journal, 19*(4), 220–229.

Atzeni, E., & Salmi, A. (2012). Economics of additive manufacturing for end-usable metal parts. *The International Journal of Advanced Manufacturing Technology, 62*(9–12), 1147–1155.

Barlier, C., & Bernard, A. (2015). Fabrication additive: Du Prototypage Rapide à l'impression 3D. Dunod.

Baumers, M. (2012). Economic aspects of additive manufacturing: Benefits, costs and energy consumption. Doctoral dissertation.

Bernard, A., & Fischer, A. (2002). New trends on rapid product development. *CIRP Annals—Manufacturing Technology, 51*(2), 635–652.

Bernard, A., Delplace, J. C., Perry, N., & Gabriel, S. (2003). Integration of CAD and rapid manufacturing for sand casting optimisation. *Rapid Prototyping Journal, 9*(5), 327–333.

Bobbio, L. D., Otis, R. A., Borgonia, J. P., Dillon, R. P., Shapiro, A. A., Liu, Z.-K., et al. (2017). Additive manufacturing of a functionally graded material from Ti-6Al-4 V to Invar: Experimental characterization and thermodynamic calculations. *Acta Materalia, 127,* 133–142.

Brackett, D., Ashcroft, I., & Hague, R. (2011). Topology optimization for additive manufacturing, In *22nd Proceedings of the SFF Symposium*, Austin, TX.

di Angelo, L., & di Stefano, P. (2011). A neural network-based build time estimator for layer manufactured objects. *The International Journal of Advanced Manufacturing Technology, 57*(1–4), 215–224.

Doubrovski, E. L., Verlinden, J. C., & Horvath, I. (2012). First steps towards collaboratively edited design for additive manufacturing knowledge. In *Solid Freeform Fabrication Symposium* (pp. 891–901).

Gao, T., & Zhang, W. (2010). Topology optimization involving thermo-elastic stress loads. *Structural and Multidisciplinary Optimization, 42*(5), 725–738.

Gibson, I., Rosen, D. W., & Stucker, B. (2010). *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. New York: Springer.

Grimm, T. A. (2010) 3D printer benchmark: North American Edition. TA Grimm & Associates Inc. Retrieved January 10, 2015, from www.tagrimm.com.

Hopkinson, N., & Dickens, P. (2003). Analysis of rapid manufacturing—Using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217*(1), 31–39.

Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive manufacturing: current state, future potential, gaps and needs, and recommendations. *Journal of Manufacturing Science and Engineering, 137*(1), 014001.

Kellens, K., Yasa, E., Renaldi, R., Dewulf, W., Kruth, J. P., & Duflou, J. (2011). Energy and resource efficiency of SLS/SLM processes (Keynote Paper). In *SFF Symposium 2011* (pp. 1–16).

Kim, D. B., Witherell, P., Lipman, R., & Feng, S. C. (2015). Streamlining the additive manufacturing digital spectrum: A systems approach. *Additive Manufacturing, 5,* 20–30.

Li, F. (2006) Automated cost estimation for 3-Axis CNC milling and stereolithography rapid prototyping. Retrieved January 3, 2018, from http://mspace.lib.umanitoba.ca/jspui/handle/1993/8882.

Lindeman, C., Jahnke, U., Moi, M., Koch, R. (2012). Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In *Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference*, vol. 23.

Materialise, N. V. (2015). *Design guides homepage*. Retrieved January 2, 2018, from https://i.materialise.com/materials/design-guides.

Mehnen, J., Ding, J., Lockett, H., & Kazanas, P. (2014). Design study for wire and arc additive manufacture. *International Journal of Product Development 20*, *19*(1–3), 2–20.

Mueller, B., Gebauer, M., Polster, S., Neugebauer, R., Malek, R., Kotzian, M., & Hund, R. (2013). Resource-efficient hot sheet metal forming by innovative die cooling with laser beam melted tooling components. In *High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping*. CRC Press.

Pelaingre, C., Barlier, C., Levaillant, C., & Batoz, J. L. (2002). Rapid Tooling for Thermoplastic injection molding: A cooling channels innovating design method for molds; RPD and Moulds Event 2002 (Moldes); CENTIFE, Mariagrande, Portugal; 7–11 October 2002.

Pelaingre, C., Barlier, C., & Thabourey J. (2004). Innovating cooling channels system by the Stratoconception process; ProtoDesign, Feria Valencia; Valencia, Espagne; 6 mai 2004.

Rickenbacher, L., Spierings, A., & Wegener, K. (2013). An integrated cost-model for selective laser melting (SLM). *Rapid Prototyping Journal, 19*(3), 208–214.

Ruffo, M., Tuck, C., & Hague, R. (2006). Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220*(9), 1417–1427.

Rumpf, R. C., Pazos, J., Garcia, C. R., Ochoa, L., & Wicker, R. (2013). 3D printed lattices with spatially variant self-collimation. *Progress in Electromagnetics Research, 139,* 1–14.

Seepersad, C. C. (2014). Challenges and opportunities in design for additive manufacturing. *3D Printing and Additive Manufacturing*, *1*(1), 10–13.

Shapeways (2016) Materials homepage. Retrieved January 02, 2018, from http://www.shapeways.com/materials/.

Stratasys Ltd. (2015a) Direct metal laser sintering (DMLS) design guideline. Retrieved January 02, 2016, from https://www.stratasysdirect.com/resources/direct-metal-laser-sintering-dmls/.

Stratasys Ltd. (2015b). Fused deposition modeling design guideline. Retrieved January 02, 2018, from https://www.stratasysdirect.com/resources/fused-deposition-modeling/.

Stratasys Ltd. (2015c). Laser sintering design guideline. Retrieved January 02, 2018, from https://www.stratasysdirect.com/resources/laser-sintering/.

Teitelbaum, G. A. (2009). Proposed build guidelines for use in fused deposition modeling to reduce build time and material volume. ProQuest.

Teufelhart, S., & Reinhart, G. (2012). Optimization of strut diameters in lattice structures. In *Proceedings of the 23rd Solid Freeform Fabrication (SFF) Symposium*.

Thomas D.S., & Gilbert, S.W. (2014). Costs and Cost Effectiveness of Additive Manufacturing; A Literature Review and Discussion. NIST Special Publication 1176.

Thomas, D. (2009). The development of design rules for selective laser melting. Doctoral dissertation, University of Wales.

Thompson, M. K., Stolfi, A., & Mischkot, M. (2016a). Process chain modeling and selection in an additive manufacturing context. *CIRP Journal of Manufacturing Science and Technology, 12,* 25–34.

Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, I., Gibson, I., et al. (2016b). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals-Manufacturing Technology, 65*(2), 737–760.

Vayre, B., Vignat, F., & Villeneuve, F. (2013). Identification on some design key parameters for additive manufacturing: Application on electron beam melting. *Procedia CIRP, 7,* 264–269.

Vayre, B., Vignat, F., & Villeneuve, F. (2012). Designing for additive manufacturing. *Procedia CIRP, 3,* 632–637.

Yan, C., Hao, L., Hussein, A., & Raymont, D. (2012). Evaluations of cellular lattice structures manufactured using selective laser melting. *International Journal of Machine Tools and Manufacture, 62,* 32–38.

Zhang, Y., & Bernard, A. (2013). Generic build time estimation model for parts produced by SLS. In *High value manufacturing: Advanced research in virtual and rapid prototyping. Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping* (pp. 43–48).

Zhang, Y., Bernard, A., Munguia Valenzuel, J., & Karunakaran, K. P. (2015). Fast adaptive modeling method for build time estimation in Additive Manufacturing. *CIRP Journal of Manufacturing Science and Technology, 10,* 49–60.

Zhang, Y., Bernard, A., Gupta, R. K., & Harik R. (2016). Feature based orientation optimization for additive manufacturing. *Rapid Prototyping Journal*, *22*(2).

Professor A. Bernard 58, graduated in 1982, Ph.D. in 1989, was associate-Professor, from 1990 to 1996 in Centrale Paris. From September 1996 to October 2001, he was Professor in CRAN, Nancy I, in the 'Integrated Design and Manufacturing' team. Since October 2001, he has been Professor at Centrale Nantes and Dean for Research from 2007 to 2012. He is a researcher in LS2 N laboratory (UMR CNRS 6004) leading the 'Systems Engineering –Products-Processes-Performances' team. His research topics are KM, PLM, information system modelling, interoperability, enterprise modelling, systems performance assessment, virtual engineering, additive manufacturing. He supervised more than 30 Ph.D. students. He published more than 150 papers in refereed international journals and books. He is vice-President of AFPR (French Association on Rapid prototyping and Additive Manufacturing), vice-chairman of WG5.1 of IFIP (Global Product Development for the whole product lifecycle) and member of CIRP Council. He co-coordinated and coauthored two books in French in the field of Additive manufacturing: Le prototypage rapide (Hermès 1998); Fabrication additive (Dunod 2015). Actually, he is leading an Industry 4.0 project at Centrale Nantes and is developing a learning factory with its digital twin.

Dr. Mary Kathryn Thompson is a professional author, independent scholar, freelance editor and staff engineer at GE Additive. She earned her SB, SM and Ph.D. in Mechanical Engineering from the Massachusetts Institute of Technology (MIT), and has held faculty positions at the Korea Advanced Institute of Science and Technology (KAIST) and the Technical University of Denmark (DTU). Her research takes an integrated, interdisciplinary, multi-scale and often exploratory approach to design, manufacturing and product development.

Giovanni Moroni is Full Professor in Manufacturing Technology and Systems since 2005 at Politecnico di Milano, Mechanical Engineering Department, where he coordinates the Manufacturing and Production Systems research line and he is a member of the Scientific Committee of the Department. At present he is Associate Member of CIRP—The International Academy for Production Engineering); member of AITeM—the Italian Association for Manufacturing—and of the Board of AFIL—Lombardy Region Intelligent Factory Association. Recently, he has been a National High-end Foreign Experts at School of Mechanical Engineering, Tongji University, Shanghai, P.R. of China (01/2015–12/2017). His main activities are related to geometrical product specification and verification, knowledge-based process planning and digital manufacturing.

Dr. T. Vaneker 49, is assistant professor at the University of Twente, the Netherlands and is the ad-interim head of the Manufacturing Systems research group. He co-founded TEAM, the Twente center of Excellence for Additive Manufacturing. Furthermore, he is the program director of the PDEng program on robotics. His research interest focuses on additive manufacturing and industrial automation and robotics. From an educational point of view, he is involved in the development and execution of the design programs within Mechanical Engineering and Industrial design Engineering.

Dr. Eujin Pei is the Director for the Product Design and Product Design Engineering programmes at Brunel University London. His research focuses on Design for Additive Manufacturing and Applications for Functionally Graded Additive Manufacturing. He is the Convenor for the International Standards Organisation Technical Committee ISO/TC261/WG4 and Chairs' meetings related to Data Transfer and Design for Additive Manufacture. He is Chair for the British Standards Institute BSI/AMT/8 for Additive Manufacturing. Eujin is also a Chartered Engineer (CEng) and a Chartered Technological Product Designer (CTPD). He is active in various industry and knowledge transfer projects in the UK and across EU. Eujin is also the Managing Editor for the *Progress in Additive Manufacturing Journal* published by SpringerNature.

Claude Barlier Pr HDR, graduated as agrégé from ENS Cachan and with a Doctoral degree from ENSAM Paris. Claude Barlier specializes in Additive Manufacturing and in the Digital Product Development field. He was Professor of the Mines-Telecom Institute, until 2016. In the 1980s, his research led to the patented additive manufacturing process Stratoconception® and the patented machining monitoring system Actarus®. In 1991, based on his patented work, he created, and since then heads CIRTES SA in Saint-Dié-des-Vosges, a Contractual Research Company, which is a leader in Additive Manufacturing (rapid prototyping and tooling) and in advanced machining. In 2000, he initiated with Mines Nancy and Mines Albi, the GIP-InSIC Engineering School, Higher Institute of Engineering Design of which he was the director from its creation until December 2015. In 2010, with 20 associated industrial and financial partners, he created a national level innovation platform INORI SAS, which he has since then chaired. He is the founder of VirtuReal® based in Saint-Dié-des-Vosges, an European centre of excellence for research to industrialization. C. Barlier is the author of numerous patents and publications, several reference works and software in mechanics at Editions Dunod, Casteilla and Foucher. He coordinated the collective work 'Conception en Mécanique Industrielle', from the collection 'Les Référentiels Dunod' published by DUNOD. He is also coauthor with Alain Bernard of the reference book on Additive Manufacturing, published by DUNOD in September 2015.

External Resources: École centrale de Nantes is a French engineering university established in 1919 and ranked within the top engineering schools in France. https://www.ec-nantes.fr.