Deliverable 4.2

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A STRATEGIC APPROACH TO INCREASING EUROPE'S VALUE PROPOSITION FOR ADDITIVE MANUFACTURING TECHNOLOGIES AND CAPABILITIES

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Report on new paradigm and ICT tools for AM integration

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Glossary

Acronym	Meaning
AM	Additive Manufacturing
CAD	Computer Aided Design
CAx	Computer Aided Technologies
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DIC	Digital Image Correlation
FEA	Finite Element Analysis
GUI	Graphical User Interface
HPC	High Performance Computing
I4.0	Industry 4.0
ICT	Information and Communications Technology
IoT	Internet of Things
LMD	Laser Metal Deposition
MOM	Manufacturing Operations Management
OEM	Original Equipment Manufacturer
NDT	Non Destructive Testing
PLM	Product Lifecycle Management
QA	Quality Assurance
SLM	Selective Laser Melting
VC	Value chain

1. Overview

This document constitutes *Deliverable D4.2 Report on new paradigms and ICT tools for AM integration* in the framework of the AM-Motion project "*A strategic approach to increasing Europe's value proposition for Additive Manufacturing technologies and capabilities*" (Project Acronym: AM-motion; Contract No.: 723560).

The related Task 4.1 and this report is devoted to identifying methodologies and ICT tools, which could assist rapid integration of Additive Manufacturing (AM). ICT tools and design methodologies are well established for traditional manufacturing processes such as casting and forging. However, due to fundamental differences between AM processes and traditional manufacturing methods, the traditional ICT-tools and design methodologies are not optimal for an effective and efficient use of AM. This study covers current ICT tools and technology surveillance on emergent tendencies for highly connected industries within AM. The analysed tools relate to each step of the AM value chain (VC) and cloud manufacturing under the umbrella of Industry 4.0.

2. Introduction: Differential aspects of Additive Manufacturing

AM technologies are already quite mature, however, there is still a need in ICT-based solutions for the improved use and integration of AM processes across the industrial manufacturing chain in order to open up their full potential for future use. In order to develop and critically evaluate methodologies and ICT tools which can assist rapid integration of AM technologies, an appreciation of the fundamental differences between AM and traditional manufacturing methods is required:

2.1. Design freedom

One of the challenges that had to be met in order to integrate AM into industrial production processes is the completely different way products can be designed. Unlike conventional manufacturing techniques, AM enables the manufacture of complex geometries and internal structures, imposes few limitations on product design, and allows the production of individualized products. Moreover, AM uses different design techniques compared to conventional manufacturing and generates different data formats. In this sense, the need for design rules that related to AM processes, capabilities and materials has been emphasised (Mani et al.; 2017).

Figure 1 ***Schematic illustrating product manufacturing using traditional techniques (top) vs using AM (bottom).***

(top) is a schematic view of how a traditionally manufactured product is established. Here, numerous external factors lead to an overall design. For manufacturability, this overall design is split up into smaller parts and in-turn individually designed to be manufactured and later assembled into the final product. All the external factors lead to a set of specifications, according to which the (overall) design is achieved. The overall design that has been divided into multiple subcomponents is mainly to facilitate manufacture of each part. Therefore, the end-responsibility is typically kept central at the overall design stage where the total specifications meet the design. Hence, designing the individual parts becomes (relatively) straightforward.

However, when using AM, there is less need to divide the overall design to facilitate manufacture (Figure 1 bottom): almost any part can be 3D-printed. Here, the overall complexity of the product does not decrease it actually increases considerably, to the extent that important engineering is involved in order to meet the specifications of each individual part. Much of the work that used to be centralised in the overall design and specifications has now shifted towards the individual part design. The impact of this on AM on the standard manufacturing workflow is therefore most substantial, where almost every aspect of the complete AM workflow needs to be considered.

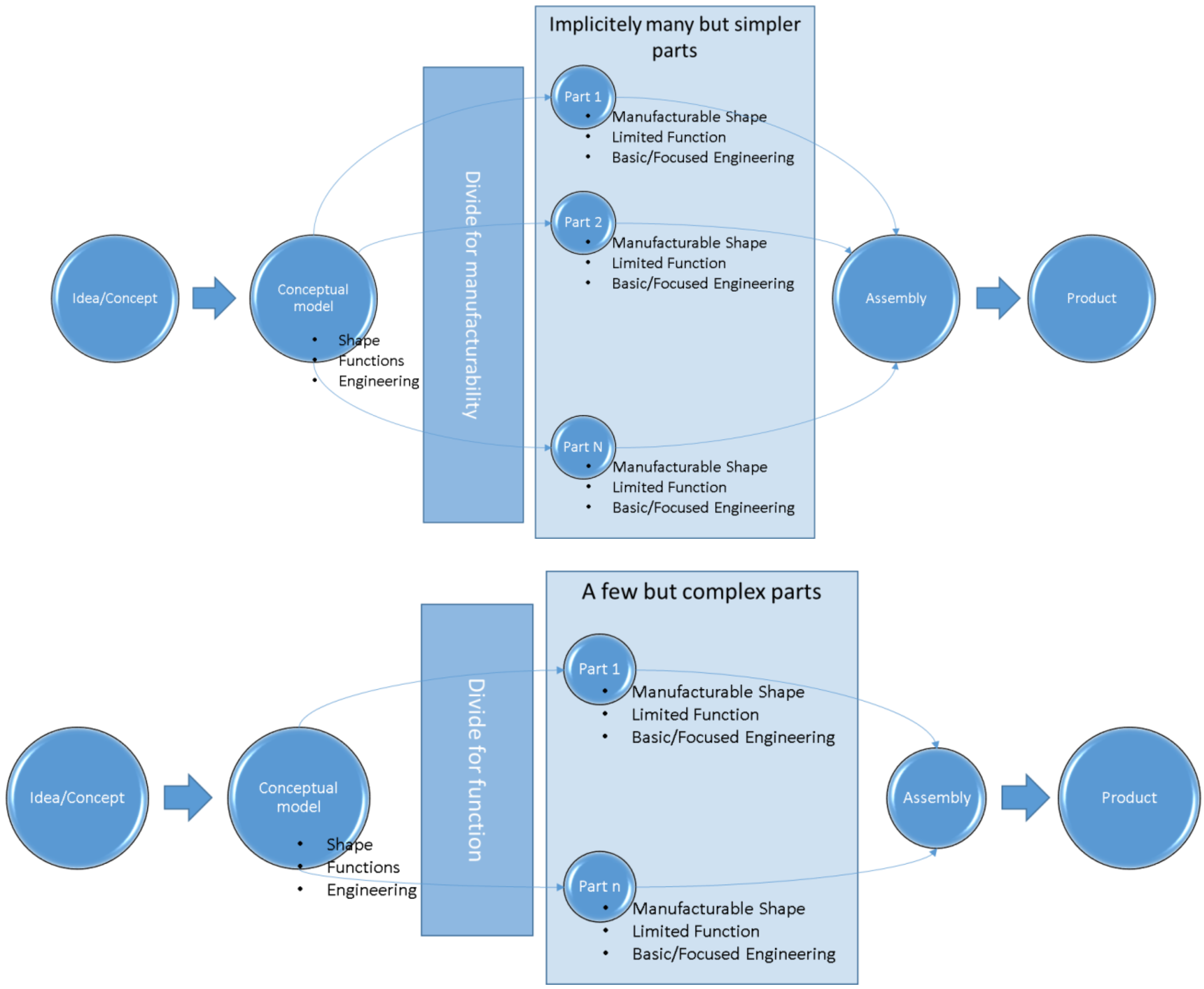

Figure 1 *Schematic illustrating product manufacturing using traditional techniques (top) vs using AM (bottom).*

Where traditionally, there are separate ICT tools for the different aspects of the life cycle of a product, all of these tools now need to be considered at the design stage to leverage the full benefits of the AM technology. Therefore, AM is pushing the classical computer aided market toward integration. What used to be different markets with their own products and even different providers is now undergoing consolidation, and many of these different providers are partnering and even merging to develop better integrated products to meet the demand of AM technology growth.

One of the drawbacks of the traditional 3D design programs is that they are unable to present and/or transpose important information for the AM process such as, the assignment of material properties or finite element method (FEM) simulations. Therefore, additional software solutions are required to interpret the 3D data and adjust AM objects, limiting the automation of the AM process chains.

The evolution toward integration of computer-aided products will lead to more efficient and generic solutions in the long-run. This integration has already started, with automation of dedicated chains for specific AM applications. This could be accelerated considerably by adopting a more modular approach in the ICT tools development and related research. Two examples of these automated chains are the Yuniku system for eyewear, a partnership between Hoya and Materialise (Hoya, 2018) and the VC for surgical knee guides, a partnership between Zimmer-Biomet and Materialise (Biomet, 2018).

2.2 Process integration

As AM has its origins in prototype and small-series manufacturing, it has been conceived as a very flexible process with a low degree of automation (Ritchter et al., 2016). Thus, current ICT-systems are not always suitable to make optimal use of this gained flexibility. Moreover, the AM process still requires a high level of manual intervention, where difficulties arise in the integration into other production chains. Therefore, specific ICT tools are required for the automation of AM processes (for instance, adjustment of planning and execution systems, continuous data supply, feeding of printers with print material, removal of printed objects) and a smooth arrangement with other processes.

Another important factor for successful process integration is the application and further development of customary quality assurance processes, such as non-destructive testing or 3D monitoring. The drive towards using AM in large-scale industrial environments is already underway. For example, Materialise have agreed a deal with Siemens PLM to integrate Materialise’s industry proven AM software technologies with Siemens' digital solutions. The objective is to accelerate the adoption of 3D printing for industrial production and to create a seamless process for designing and manufacturing parts using AM technology.

2.3. Increased data and connectivity

Inherent within AM processes is information creation and communication. While the output of an AM build is a physical object, the manufacturing process inevitably begins with information: a design is created via a drawing, design software, or the scanning of a physical object, creating data. This data is then communicated to machines that execute the build process. Ideally, data from the build process is then captured and exploited to improve the quality of the build process in some way, creating an in-situ process loop. This data based nature of AM offers a host of options for the best possible adaptation of this technology to the smart factories of the future where machines, equipment and logistical systems will exchange information as globally interconnected cyber-physical systems. It is here that the relationship between AM and the cutting edge concepts of Industry 4.0 and the Internet of things (IoT) becomes apparent.

Ideally, AM could be vertically integrated with commercial systems and horizontally with distributed process chains with realtime control capability, but this requires the development of new real time production control tools for the automated adjustment of virtually planned and real production processes, as well as the development of communication standards and tools for integrating AM into further production processes and smart factories.

2.4. On-line services

Additive manufacturing enables on-demand production of parts. Therefore, a number of printing companies offer on-line services for end-users that use AM resources over the internet instead of acquiring their own 3D printer.

Shapeways (Shapeways, 2018), one of the first movers in this market, is a 3D model marketplace and production service. Shapeways connects designers with consumers, thereby collecting a certain service and production fee. Customers design their own products by sending a CAD file to the Shapeways website, which is then built using AM. Designers can also sell their own designs to be 3D printed on demand for customers. Shapeways handles the financial transaction, manufacture, distribution and customer service; profits go to the designer. i.materialise (i.materialise, 2018) is a similar online 3D printing service – the user uploads their 3D file, the desired material, colour and finish is selected, a quote is generated and i.materialise then takes care of the production.

3DHubs (3DHubs, 2018) is a platform to find nearby 3D printers. The basic idea behind 3DHubs is to share existing capacity of locally available printers, thus using the advantage of 3D printing as a local production facility. Services such as MakeXYZ (makexyz.com, 2018) also provide a market place for 3D printers, where users can locate providers and get a quote from the owner of the printer for the particular object they want to print. Online platforms, such as Kraftwürx (Kraftwürx, 2018), enable crowdsourcing of both design and manufacturing. Businesses and consumers alike can use these platforms. Kraftwürz and MakeXYZ both enable businesses to crowdsource the manufacturing of their products using various materials and finish qualities.

2.5. Innovative materials

AM technologies cover a wide range of materials, including plastic and metal powders, fillaments and pellets, as well as photopolymers and waxes. Composite, ceramics and biomaterials can be also processed by AM technologies. Moreover, new materials are an important driver for AM to become an established process in the future. Therefore, for helping decision making through the tremendous amount of existing information, specific material databases and related software tools that correlates materials and processes/machines are especially useful (Ritchter et al., 2016).

3. List of identified ICT tools and methodologies

In this section, a list of ICT tools which could assist integration and use of AM technologies is provided. This is not an exhaustive list and aims to provide a good overview summary of the different types of tools currently being used, along with a review of their functionality. The functionality of each tool is evaluated against eight different categories as presented below. The first seven of these categories reflect the set of AM VC steps:

1. Modelling and Simulation

Modelling and simulation can be used at different stages of the AM value chain. For example, process simulation is used to simulate the actual AM process, to allow for improved part and process parameter selection, or to assess how changes in parameters influence part behaviour. The build can be simulated layer by layer by multiphysics modelling, creating a holistic model from the microstructure right up to the assembly level. This provides an analysis of how the build process will impact performance (for example, distortion, and residual stress), creating better estimates of part quality and models of part life cycles. More importantly, these models can be used to influence the build process. This is iterative until a design which is fully optimized (with respect to thermal or mechanical performance for example) is obtained. Once the process of the design-analysis feedback loop is completed, a revised CAD file is generated and passed onto the next phase of build planning and simulation. Such simulation stages are often very data-intensive and high-performance computing (HPC) facilities may be required. Commercial analysis packages and custom packages exist and require in-depth expertise in computational mechanics to adapt and apply.

2. Design

Design modelling software is required to create new designs, or to modify existing designs. This is often achieved by the creation of new digital parts through CAD or through 3D scanning of existing physical parts. Specific considerations for the design step include: design and slicing software, interoperability between the different AM steps, use rights, and maintaining traceability from physical object to scan data to CAD model.

Design optimisation software can be used to leverage benefits such as reducing component mass and increasing component stiffness. This includes: topology optimisation, shape optimisation, topography optimisation of the part to be built through static or dynamic analysis, FEA (Finite element analysis), CFD (computational fluid dynamics). The design is analysed to better understand the structural, thermal, material, and fluid flow properties of the part, and modified to optimize, for example, the stiffness to weight ratio. Light weighting by replacing bulk solid regions with lattice structures is also frequently used – see for example (Primo, et al., 2017).

3. Materials

A key component of the AM value chain is materials. This category includes material databases and software tools which are able to identify relationships between material properties and AM build process parameters.

4. Build Process

Build preparation is fundamental to AM, and includes: STL-file repair, automated support structure generation (size, position, number, etc.), build orientation, nesting algorithms to utilise space on the build plate, interlocking and collision detection, slicing, scan patterns and job file generation, direct loading, log retrieval.

This category includes optimization of the number, position and size of the build support structures. The more support structures that are used, the more material necessary and the higher the post-processing costs – as well as a lower surface quality. Support structures are absolutely necessary to anchor the part to the build platform (they prevent curling and reduce the risk of the part getting dislodged by the re-coater), conduct heat (process stability) and prevent molten metal from sinking through the powder bed (for downfacing areas and avoiding dross formation). Therefore, optimization of the number, position and location of these supports is crucial part in the build process.

Build process monitoring that refers to the in-situ monitoring of temperatures, distortion, material levels, feedback loops to control process parameters during the build process, etc. is also included in this category. On the other hand, resource management is required for organising print queues, print scheduling and general workflow automation software, also for printability checks and part sorting.

5. Post Processing

Post processing is the final stage in the AM of a component, where the part receives finishing touches such as removal of support structures to separate parts from the build platform, smoothing and painting. Post-processing generally improves the quality of the part and ensures that the parts meet the design specifications. Post processing can enhance a part's surface characteristics, geometry accuracy, aesthetics and mechanical properties. Parts can be milled, drilled or polished. Heat treatment is often included as well as shot peening to improve the mechanical and tactile properties of the surface. Hot isostatic pressing (HIP) is a process in which the products are kept at high temperature and high pressure in an inert atmosphere for a certain period. Through the high temperature the materials become 'plastic' and through the high pressure voids collapse while the surfaces of the voids are fused together thus eliminating defects in the materials and improving mechanical properties especially fatigue properties. Electro polishing is often used to minimise roughness, deburring, brightening and passivating, particularly for surfaces exposed to abrasive media.

6. Product

This category includes: general product management; Product Lifecycle Management (PLM), Life Cycle Assessment (LCA); track/trace of customer data; supplier components, product and manufacturing costs; customer and relations management (CRM); Quality Assurance and "Testing" of samples. Non Destructive Testing (NDT) might include computed tomography, white light interferometry and surface profilometry. To validate the performance of the product, and ensure they are fit for purpose, mechanical testing, fatigue, DIC and corrosion analyses may be performed.

7. End of Life

The End of Life category is used here with respect to AM products supplied to customers that have reached the end of their useful life (from the vendor's point of view). AM technology can offer extended product life, achieved through technical approaches such as repair, remanufacture and refurbishment, and more sustainable socio-economic patterns such as stronger person-product affinities and closer relationships between producers and consumers.

8. Cloud Enabled

Cloud manufacturing is the concept of using manufacturing resources in a service-oriented way over the Internet. The cloud offers the potential to integrate different ICT tools across the AM Value Chain. For ICT tools and AM hardware which are cloud enabled, the cloud provides a concept to embed, connect and utilise existing manufacturing resources. The cloud also facilitates the use of 3D printing resources over the internet, instead of end users acquiring their own 3D printer. Furthermore, cloud enabled software may accelerate product and design development, something with which many companies can struggle, particularly if the time taken to involve the right people in a decision, or feedback from people is delayed due to globally distrusted teams. Cloud enabled products can mitigate these delays, since information is exchanged and stored on servers which can be accessed 24/7 from any location equipped with internet access (Holmes, 2014).

The (non-exhaustive) list of ICT tools is provided in Table 1. The products in this table are not listed in any particular order.

Table 1 – List of ICT tools currently used throughout the AM value chain.

Tool			Modelling & Simulation	Design	Materials	Build Process	Post Processing	Product	End of Life	Cloud Enabled
1	SolidWorks 2018	DASSAULT SYSTEMES SOLIDWORKS	✓	✓		✓				✓
2	3D Experience	DASSAULT SYSTEMES	✓	✓		✓		✓		✓
3	Autodesk Fusion 360			✓						✓
4	Ansys SpaceClaim	ANSYS SpaceClaim		✓				✓		
5	Ansys 3DSYM	3DSYM	✓							
6	Altair OptiStruct	OptiStruct®		✓						
7	Autodesk Inventor, AutoCAD, Maya			✓						
8	Autodesk Meshmixer	AUTODESK® MESHMIXER®		✓						
9	Autodesk Netfabb					✓				
10	Autodesk Pan Computing		✓							
11	Autodesk Within Medical			✓		✓				
12	Simpleware	SYNOPSYS® Silicon to Software simpleware		✓						
13	Geomagic Design X	3D SYSTEMS		✓						

14	Geomagic for SolidWorks			✓						
15	Geomagic Wrap			✓						
16	Geomagic Sculpt			✓						
17	Geomagic Freeform			✓						
18	3DSprint			✓		✓				
19	3DXpert			✓		✓				
20			✓	✓		✓				✓
21	Exasim		✓							✓
22	Insight					✓				
23	Simufact		✓	✓			✓			
24	Digimat-AM		✓	✓	✓					
25	3-matic			✓						
26	Magics			✓		✓				
27	Build Processor					✓				

28	Streamics							✓		
29	Magics Reporting							✓		
30	Robot							✓		
31	Control Platform					✓		✓		
32	Inspector							✓		
33	Cloud									✓
34	OrthoView							✓		
35	MimicsinPrint			✓						
36	Surgicase							✓		
37	ProPlan CMF							✓		
38	Mimics			✓						
39	Frustum		✓	✓						
40	MeshLab			✓						
41	Creo 4.0			✓		✓				

42	RP Platform	RP PLATFORM						✓		
43	GRABCAD Print	stratasys	✓			✓				✓
44	NX 12	SIEMENS		✓		✓				
45	Simcenter™		✓	✓				✓		
46	Teamcenter™							✓	✓	
47	SIMATIC IT							✓	✓	
48	SIMATIC WinCC							✓	✓	
49	MindSphere									✓
50	GRANTA MI: Additive Manufacturing Package	GRANTA MI MATERIAL INTELLIGENCE			✓	✓		✓		
51	Senvol Database	SENVOL			✓					
52	Ultimaker	Cura Software				✓				
53	Thingiverse		✓			✓				✓
54	Shapeways		✓			✓				✓
55	Virfac Additive manufcaturing - Geonx	VIRFAC	✓			✓				

56	Amphyon de Additive Works		✓			✓				
TOTALS			**15**	**28**	**2**	**20**	**1**	**16**	**3**	**10**

4. Analysis of ICT tools

Whilst the list of ICT tools presented in Section 3 is not exhaustive, it does reveal some interesting trends. Firstly, of the 56 tools listed in Table 1 (which do not appear in any particular order), there is not a single software product with capabilities spanning all eight categories. That said, the Digital Enterprise Suite from Siemens purports to address the entire AM value-chain. This suite is based on a range of Siemens' software, including Siemens' NX™, an integrated computer-aided design, manufacturing and engineering (CAD/CAM/CAE) solution, the Simcenter™ portfolio, a robust suite of simulation software and test solutions, Teamcenter® software, the world's most widely used digital lifecycle management system, and SIMATIC IT and SIMATIC WinCC, two elements of Siemens' recognized Manufacturing Operations Management (MOM) portfolio for production execution, and MindSphere, the cloud-based open IoT operating system and Siemens' scalable automation components. This holistic approach covering the entire AM value chain is highlighted in Figure 2. This integrated solution for AM covers:

- Siemens AM Consulting services
- Part Manufacturing Platform – Siemens' global gateway to on-demand design and manufacturing
- Engineering and printing services - from Design for AM to finished parts using AM technology through Material Solutions and Mobility Services
- Tailored financial solutions for investment in Additive Manufacturing technologies

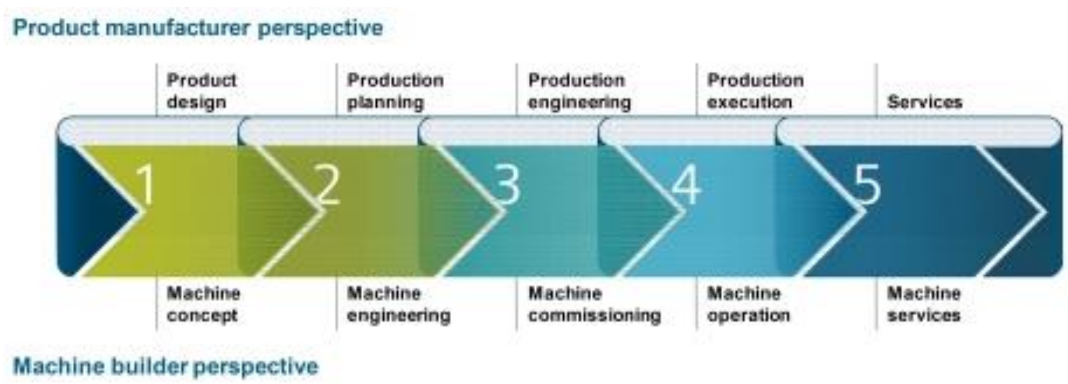

Figure 2 – *The Siemens holistic approach to optimise the enture additive manufactuing value chain (Siemens, 2017)*

To follow is an outline of the reviewed ICT tools per VC category, highlighting some of the key features:

<u>Process simulation</u>

Fifteen tools are capable of simulating the AM build process, from detailed layer-by-layer multiphysics modelling of the microstructure right up to the assembly level. These simulations provide an analysis of how the build process will impact part performance, quantified in terms of distortion and residual stress. It should also be noted that other commercially available software, such as Abaqus can be used to simulate AM build processes, however as yet, such software packages do not have AM-specific modules, and so do not feature in Table 1.

The simulation and design phases are closely linked: modelling and simulation can be used to refine AM designs and optimize the process parameters before fabrication begins. The driver is to optimize the design and fabrication of the part, to ensure that it is manufactured in as efficient and effective way as possible. Products such as SolidWorks 2018 (#1) and Autodesk Netfabb (#9) are also able to incorporate metallurgical models into process simulations, to enable the prediction of phase concentrations and tensile anisotropy caused by part built orientation and process parameter selection. Such simulations require significant technical expertise, from the preparation stage to the analysis stage, and currently, "blackbox" ICT tools for this kind of complex analysis do not exist. These simulations are also demanding in terms of central processing unit (CPU) and file storage requirements.

Design

Twenty-eight of the tools studied offer design capabilities ranging from basic CAD, to advanced topology optimization, design and optimization of AM lattice structures and generation of material porosity for medical applications. This does not come as a surprise, since CAD tools are ubiquitous throughout all manufacturing industries, not just AM, and many software vendors are marketing their design products as tools for AM. Indeed, there has been a flurry of activity for integration of AM in "standard" CAD systems.

Ideally, AM design software should facilitate easy adherence to design rules (such as design for minimum support material or minimum post-processing) for specific AM processes. Altair OptiStruct (#6) for example, is equipped to perform design optimisation of additively manufactured lattice structures, and this optimisation can be performed with various constraints (such as minimum structural member size that can be 3D printed, or maximum overhang angle). Magics (#29) by Materialise contains an advanced STL editor tailored for AM design. It offers the potential to design and include metal and plastic build support structures, tree supports, and contains extensive build validation tools – which are guided by AM design rules.

Materials

One of the key challenges for AM technology, which affects the entire AM VC, is that of materials. In particular, the properties of AM materials (especially metal powder) is one of the greatest sources of uncertainty (Berman, 2012, Gibson, et al., 2010), although note that standards such as ASTM F3049-14 (Standard Guide for Characterizing Properties of Metal Powders Used for AM Processes) have been developed. Whilst many of the modelling and simulation tools (such as SolidWorkds 2018, AutoDesk NetFabb) contain multiple advanced material laws, including temperature and strain rate dependent elastic and plastic constituitve laws and damage mechanisms, these software products do not contain material databases. There were only two tools reviewed that contain material properties databases. The Senvol Database (#51) by Granta Design acts as a reference resource with details of over 550 AM machines and over 700 compatible materials. The Senvol Database allows the user to browse and search based on material type, property, or compatible machines. Machines can be compared based on supported processes, manufacturer, part size, cost, or materials. The Senvol Database integrates with The Granta MI:Additive Manufacturing (#50) tool, which provides industry best practice data structures and tools to capture the complete history of the AM process data. The software can for example plot properties and process parameters against one another and identify trends, manage and compare data from experiment and simulation. Logfiles can be imported directly from AM machines (including Renishaw, EOS, Arcam, and SLM Solution). Granta also markets a tool named Granta CES Selector, which is able to compare different materials, gaining insigh into different material properties through a convenient user interface. The second ICT tool with a materials database is Digimat-AM (#18), which contains a database of material grades for reinforcing and unfilled polymer plastic materials and a collection of material models from the Digimat MX database. Free databases (not from Original Equipment Manufacturers (OMEs) also exist, for example, Campus Plastics, which is free online database for resins for participating material producers (CAMPUS, 2018) .

Build processing

Of these 20 tools, 14 offer build process capabilities in some capacity, such as STL preparation and manipulation, slicing and job file generation. It should be noted that whilst tools such as Ansys SpaceClaim (#4) can prepare 3D CAD models for printing, allowing the user to analyze and repair dirty or corrupt faceted data, or quickly create, edit and prepare optimized models for 3-D printing, it is not build processing software – e.g. it does not slice the STL file or prepare jobs for submission to the 3D printer.

A number of tools are available for to oversee the build process. For example, 3D Sprint (#18) by 3D Systems is a tool specifically for preparing and optimizing the CAD data and then managing the build process specifically for 3D plastics printers. The software uses intelligent tools to set orientation constrains and find the ideal print times, surface finish and optimization of support structures. The software nests and packs parts on the build platform to utilize space efficiently and has built-in quality checks which are executed before printing to identify any potentially risks associated with the build. Materialise Build Processor provides slicing, job file generation, direct loading, log file retrieval and real time monitoring for a number of platforms: Arcam, BP, EOS BP, Renishaw BP, SLM BP, HP BP and Concept Laser BP to name but a few.

Post processing

The review revealed one single tool which directly supports post processing – namely Simufact Additive (#23) my MSC Software. Simufact simulates metal-based AM powder bed fusion and laser metal deposition processes (covered by Simufact Welding). The software can compute deformation of the final part and the base plate and can predict the effect of having several components in the build space at the same time. It is also possible to minimize residual stress and optimise the support structures. With regards post processing capabilities, Simufact Additive is able to predict the condition of the part after heat treatment and stress relieving processing and can simulate base plate and support structure removal.

Product

Sixteen tools offer capabilities for general product management, track/trace of customer data, etc. Of these 16 tools, only five were found to also offer build process capabilities.

As noted in Section 2, the traditional manufacturing VC is usually perceived to be linear, focused on the production of physical objects. Information generated during the manufacturing VC for AM on the other hand, makes the structure of the VC far more dynamic, and can be seen to form a circular feedback loop. Throughout the entire I4.0 VC – from design and development to manufacture, sale and service – ways to improve a product or service, generated through analysis and feedback of information and data exchange may emerge. This requires dedicated management tools for the entire AM VC. Fifteen tools offer capabilities for general product management, track/trace of customer data, recording and monitoring of the AM machine utilisation and part inspection information. Materialise provide a number of different production management software solutions specifically tailored for AM. Streamics (#28) for example is a pre-configured AM-specific database system to help and manage 3D printing operations. The software acts as a centralized management system for day-to-day AM operations including managing request backlogs, tracking of AM process data, machine availability and build scheduling, and an interface with dedicated web portal to streamline communication with stakeholders.

Magics Reporting (#29) is another ICT tool developed by Materialise, which permits quotations to be quickly generated, based on part parameters and visual inspection and evaluating file quality. From this information, professional reports can be generated. The "Product" category also includes mechanical testing of as-built parts. Standards for evaluating mechanical properties of metal materials made via AM processes exist (such as ASTM F3122: 2014). This standard acts as a guide to existing standards or variations of existing ASTM standards that may be used to determine specific mechanical properties of materials made with AM processes. Standards such as ASTM F2971: 2013 (standard practice for reporting data for test specimens prepared by AM) also exist that outline procedures for reporting results by testing or evaluation of specimens produced by AM.

The Granta MI:Additive Manufacturing Package (#50) software can be used to capture data required for future qualification or certification of the part. Input data can be captured according to ASTM standards and automated qualification reports can be generated. The Granta MI:Additive Manufacturing Package also allows access to the Senvol Database to search and compare materials.

Product and End of life

Only three tools (from Siemens) were found to directly offer capabilities in the End of Life product category: TeamCentre, SIMATIC IT and SIMATIC WinCC.

Siemens PLM Software provides a number of different product lifecycle management (PLM) and manufacturing operations management (MOM) tools such as TeamCentre, SIMATIC IT and SIMATIC WinCC. These solutions can be integrated with AM work flows, and permit maximisation of knowledge and management value, creation of effective service plans (asset health etc.) and optimise service work with schedule visibility. Sciaky Inc., a metal AM solutions provider, is to adopt Siemens' product lifecycle management (PLM) software products to support its EBAM solution. With the integration of PLM, Sciaky is set to advance its technology's capabilities. The company believes it can now offer its current, and future, customers a solution that integrates with the same technology that they use every day. Together, EBAM and PLM will help users enhance the decision making behind product development, ultimately producing better results.

Cloud enabled

It is interesting to observe that all 10 cloud-enabled tools have either design and/or modelling and simulation capabilities, except for two – Materialise Cloud (#33) and Siemens MindSphere (#49) – which are dedicated cloud computing platforms, rather than standalone ICT tools. This suggests that, to-date, the areas of the AM VC which have benefitted most from cloud computing facilities have been the modelling and simulation and design steps, most likely because of the CPU gains that can be leveraged through pooling shared resources and due to the large data storage for complex CAD files available on cloud servers.

Modeling, simulation, design and build process

From the ICT tools that were reviewed, only three products, SolidWorks 2018 (#1), Autodesk Netfabb (#9) and 3Dexperience (#3) have capabilities spanning modelling and simulation, design, and the build process stage.

With SolidWorks 2018, the user can perform part design and basic topology optimization under linear static loads and restraints. The result from this optimization is a smoothed mesh file which can be sent directly to 3D printers for printing from the SolidWorks GUI. SolidWorks can output STL format, but also the 3MF and AMF formats, which provide more information about the model bring printed, such as build orientation, color and material. SolidWorks 2018 is cloud enabled, facilitating data storage, 3D instant messaging, update sessions and designer to extended team –or customer engagement. The CAD design capabilities of SolidWorks 2018 is certainly cloud enabled, however it is not clear from the SolidWorks website across which categories (i.e. modelling and simulation, or build process) this cloud capability extends.

The 3DExperience (#3) software portfolio offered by Dassault Systems includes products such Additive Manufacturing Engineer, Programmer and Researcher. These products can facilitate preparation and validation of the AM process, and provide process simulation capabilities for AM that captures distortion and residual stress for AM and plastic components. Within the 3Dexperience Portfolio, bill of materials software such as ENOVIA can provide a connected, global and site-specific view of bill of materials and a common automated development and change provides to maintain materials tracking and usage. Products also exist for product planning and program management, quality and compliance, sales and operations planning and product life cycle management. The majority of these 3Dexperience products are cloud enabled, however it is not clear from the 3DS website how connected/integrated these individual products are. Dassault Systems have also developed a specific tool called MyShape for Airbus (Clapaud, 2016). Airbus actively use MyShape, integrated within the 3Dexperience software to design both structural and non-structural components. The software integrates both functions of design and simulation. Design criteria, such as fatigue performance, the mass and stiffness response, are taken into account in the design stage for AM.

Autodesk Netfabb, which is cloud enabled, has also capabilities on spanning modelling and simulation, design, and the build process stage. Netfabb has advanced CAD design capabilities, including geometry edit, and repair tools. It can be integrated with AutoDesk Nastran to conduct engineering simulation, and perform topology optimization and lattice optimization based on design loading and weight. Multiscale modelling simulations can be performed for thermal and mechanical part response and to predict the distortion of the build plate. In terms of the build process category, Netfabb is able to configure optimal build supports, which is a semi-automated process, and has packing algorithms to optimize parts position within the build volume. Build strategies (scanning and raster patterns) can be optimized for specific builds, and during the build process, the software is able to detect re-coater interference and can monitor for potential support failure.

Apart from the general categories considered in Table 1, it should be noted that some of the reviewed software are conceived for specific AM:

Specific AM applications

There are a number of custom software products for very specific applications and even specific customers, such as the Materialise medical software (see tools #34 - #38 for example). These products serve the

Medical industry through, for example, 3D model reconstruction from medical image data (MimicsinPrint) and planning and ordering of surgical implants (Surgicase).

5. Conclusions and Recommendations

Currently, a single ICT tool which covers the complete AM value chain does not exist. Major software vendors such as Siemens and Materialise do however offer individual software products which cover the entire AM VC (although note that Materialise does not offer modelling and simulation software).

Major software giants in the field of CAD like Dassault (Catia, SolidWorks), Siemens (NX), Autodesk (AutoCAD, Inventor) that originally were not involved in AM now rapidly started developing AM features in their software either by new developments or by acquisition of companies with a history in AM.

The main conclusions and recommendations drawn from this study are as follows:

*** Post Processing should be considered in AM software at the design and build processing stages:** This review revealed only one known ICT tool, Simufact, which directly addresses post-processing of AM parts, and Simufact is modelling and simulation software. A part will be printed with many different surface finishes, depending on its orientation with relation to the build plate, the position in the build envelope and its own geometry. To determine the optimal surface finish for the intended application, the printing method (e.g. SLM or LMD) and critical surfaces in orienting the part should be considered, as should the speed of the build. Therefore, part post-processing needs to be considered during the design and build processing stages of the AM VC. It is recommended therefore that effort be devoted to formulating guidance or rules at the design and build process stages which consider AM part post-processing. These rules should be built into the software and checks carried out on the design to warn against potential risks during the later post-processing stages (much like the preliminary checks performed by build processing software to protect against re-coater interference etc.).

*** Current ICT tools have limited scope for addressing End Of Life:** It is also not clear how current state-of-the-art software addresses end-of-life considerations for AM parts. This may be due in part to the relative infancy of AM technology compared to traditional manufacturing techniques, such as machining. In particular, there is a lack of knowledge and understanding of the environmental performance of AM systems (Huang, et al., 2013) as well as the performance of products made through AM. As a result, it might be that, to date, there has not been sufficient drive to develop software to analyze and interpret end of life data for AM components. The Granta MI:Additive Manufacturing Package (#43) software can be used to capture data required for future qualification or certification of the part, and data and information colleted using this software would be useful for developing new ICT tools which cater for end of life considerations.

Currently, no software exists which enables engineers to verify the compliance of the designs with the different quality inspection techniques. For example, if the geometry of a certain part exceeds a certain thinkcness, then it wil not be possible to gain inspection information via X-ray, and so an alternative inspection technique should be used. It would be useful to have AM ICT tools which are able to make these assessments at the design stage of the AM workflow.

***Validated AM-Specific Materials databases should be integrated with modelling and simulation software:** It can be time-consuming for engineers to find the right materials data. Materials testing and subsequent analysis is complex, difficult, and expensive and the results are often lost or not shared effectively, leading to repeated work and use of inaccurate information. Materials data has its own lifecycle: it constantly changes with inputs from new tests, suppliers, or the field. This review has revealed that there is limited AM-specific materials databases available. For example, the majority of modelling and simulation software used for AM does not leverage AM-specific material databases. It would be beneficial to, for example, integrate AM-specific material databases such as Senvol with simulation software such as Netfabb and SolidWorks. The properties of AM materials require validation and standardization to enable wider adoption and consistent performance.

*** Software to monitor and adjust build process parameters in-situ needs further development:** None of the current, commercially available ICT tools that have been reviewed are directly capable of providing in-situ feedback to adjust the process parameters during a build, to mitigate unwanted effects, such as distortion. More effort should be dedicated to developing intelligent in-situ feedback software, which is not just capable of logging build process progress, but is capable of making complex decisions, such as adjusting laser power or scan speed, to prevent build failure or excessive distortion. Steps are being taken in this direction – for example, Fraunhofer IPA are developing software called InsideOut. The software will be capable of interfacing with 3D printing machines, and makes the control data available to the application via cloud computing. The InsideOut software links this control data to a CAD model. The result is that the viewer will be able to see an animated machine models that moves almost in real time. In contrast to normal live-streams the user will be able to interact with the application to gather additional information about the build process. For example, an interface will allow the user to click on a part of the live CAD model to display the temperature at that location, or to display the fill level or print nozzle coordinates. This software is currently under development, and Fraunhofer IPA are looking for interested companies to partners in the development of InsideOut.

*** Software interoperability should be ensured across the AM value chain:** One of the key issues to address for the AM ICT industry is software interoperability. There is a need for standardisation of input/output of different steps within the entire AM VC. All the software reviewed in this study is proprietary. Proprietary software is designed for the specific needs of an organization and works only within a given operating environment. By contrary, non-proprietary software is developed by a community of volunteers often paid by other organizations and can be free or relatively low cost. Proprietary software may be advantageous when moving data from one step in the process to the next because it can be designed with the organization's specific security requirements and organizational needs in mind – the bespoke tools produced by Materialise for the Medical industry are examples of this. This may however limit the organisation to invest in proprietary software across the entire AM VC, which may be seen as a restriction.

While use of standards, such as ISO STEP AP 242 for managing model-based 3D engineering, can help improve interoperability between the stages of the AM VC, they only apply when all stakeholders adhere to the same approach. Tests of file interoperability between tools used within an AM process step should be conducted to ensure the successful migration of data. Additionally, CAD tool interoperability presents a notable consideration for designers and engineers. Exchanging files across design platforms used in the design step or between multiple CAD tools has historically been at the root of many design challenges. Issues can range from the loss of dimensional data within the CAD file to "broken" design model representations, which is evidenced in many of the "design equipped" software tools of Section 3, which have driven software vendors to introduce geometry edit and repair functionality to correct faulty CAD files.

***The approach to data management should be carefully considered:** The outputs of advanced modeling and simulation, in terms of data quantity, can be on the order of petabytes or more. To properly integrate the modelling and simulation stages into the entire AM VC, this data need to be incorporated (at some level) into a manufacturer's PLM solution. Simulation data has considerations similar to scan and design data, including compliance, storage, and integrity.

In combination with improved 3D-scanning and reverse-engineering capabilities, AM poses risks to the intellectual property rights of product designs (Kurfess & Cass, 2014). As AM technology advances, copying a 3D design and converting it into shareable 3D design data may become as easy as photocopying or scanning a document. This is the issue of digital property rights which is perceived by some as one of the most severe economic consequences of AM (Piller, et al., 2015). The security of ICT tools and methodologies that are employed at all stages of the AM VC therefore need careful consideration to ensure that data protection policy is adhered to (Brody & Pureswaran, 2013). For example, Kubler, et al., (2016) the authors conclude that cloud-based manufacturing is currently not widely adopted due to security concerns.

*** Foster Talent & Expertise:** Firms need to recruit and retain talent and expertise in order to best make use of AM digital technology. The AM VC involves a wide range of different software tools, which, in turn, requires a wide breadth of expertise. Multi physics modelling packages are a prime example: these codes require in-depth expertise in computational mechanics, thermal analysis and material microstructure to adapt and apply. Efforts are underway to operationalize these codes for widespread use, but if modelling and simulation is to be integrated fully into the AM VC, fostering and retaining talent and expertise in this area will be critical.

*** Compliance with design rules from the early design stages is important:** In order to utilize AM to its full potential and to consider the restrictions from the start, a design guideline is necessary to support the whole design process. CAx tools which have integrated AM design capabilities should include functionality to adhere to AM design guidelines, with the ability to distinguish between process characteristics, design principles and design rules; each supporting the designer during different stages of the design process. For example, Leutenecker-Twelsiek, et al., (2016) have hilighted that part orientation in the build space has a strong influence on many quality characteristics, and therefore the influence of part orientation in design rules should be considered. Ideally, a process for determining the part orientation in the early stage of the design process should be available in the software.

***AM software should be cloud enabled:** The use of cloud-based applications is going to increase, as the financial and business benefits are compelling for organizations, particularly for SMEs. The cloud can serve as an integration backbone for inter-enterprise collaboration, enabling data to be exchanged any time and from anywhere between enterprises across the world through virtualized IT infrastructure. The cloud offers the potential to integrate different ICT tools across the AM VC. For ICT tools and AM hardware which are cloud enabled, the cloud provides a concept to embed, connect and utilise existing manufacturing resources. The cloud also facilitates the use of 3D printing resources over the internet, instead of end users acquiring their own 3D printer. Furthermore, cloud enabled software may accelerate product and design development, something with which many companies can struggle, particularly if the time taken to involve the right people in a decision, or feedback from people is delayed due to globally distrusted teams

Finally, it is interesting to see that the need for integration of software functions is acknowledged by several parties starting up strategic collaborations or even strategic acquisition. For example software giants in the field of CAD like Dassault (Catia, SolidWorks), Siemens (NX), Autodesk (AutoCAD, Inventor) that originally were not involved in AM now rapidly started developing AM features in their software either by new developments or by recent acquisition of companies with a history in AM. For example, the acquisitions of Netfabb by Autodesk.

Siemens and Materialise have integrated AM technology from Materialise into Siemens' NX™ software, streamlining the design-to-manufacturing process for the rapidly growing universe of products being produced using AM. The new solution leverages proven Materialise technology to enable NX computer-aided design, manufacturing and engineering (CAD/CAM/CAE) software to accurately and completely prepare CAD models for powder bed fusion and material jetting 3D printing processes (Materialise, 2017).

Also major machine tool builders acknowledge the need for integrating their equipment in the digital environment seeking connection and collaboration to software vendors addressing mutual interests. In this scope strategic collaborations between for example Materialise and machine tool builder EOS could be mentioned.

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