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Empirical Study on General Purpose Cloud Manufacturing Platforms

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Abstract. Cloud manufacturing is a term that has been used in research since around 2011. In preparing this paper, the focus has shifted to approaches to link complex value-creating networks and a more efficient production utilization of service providers. The interim results of a study presented in this report highlight a section of publicly available industrial cloud manufacturing solutions within the production area of Germany in the fields of 3D printing, Computerized Numerical Control milling technology, and laser cutting in order to observe the industrial use of cloud manufacturing. For the presentation of the interim results, only platforms that offer the addressed manufacturing technologies as an all-in-one solution were considered to start at the highest abstraction of technical depth. For this purpose, reference components within the technology disciplines are defined based on the process characteristics which were evaluated on five cloud manufacturing platforms based on their performance. These platforms were selected through a broad keyword search of publicly available search engines and representative keywords, followed by filtering for a definition of cloud manufacturing and the manufacturing technologies supported. Finally, the results of the evaluation are discussed and the significant observations are highlighted.

Keywords: cloud manufacturing, manufacturing on-demand

1. Introduction

Cloud manufacturing (CM) represents a technical solution of digitalization that enables automated planning [1], commissioning [2], and partial orchestration as a digital platform [3]. As shown in Figure 1, customers and potential service providers register to a central platform. The products desired by customers as well as the production capabilities of service providers are abstracted via a neutral capability model. This capability model is used to find partners for incoming customer inquiries. Customer inquiries are supplemented with domain-specific assets (usually in the form of Computer-aided Design files). The CM platform determines the appropriate service provider for the inquiry and, with the help of the customer assets, determines a concrete offer from the respective service provider. Assets are usually exchanged with the respective service provider for this purpose. Finally, suitable services can be ordered and partially orchestrated via the CM platform.

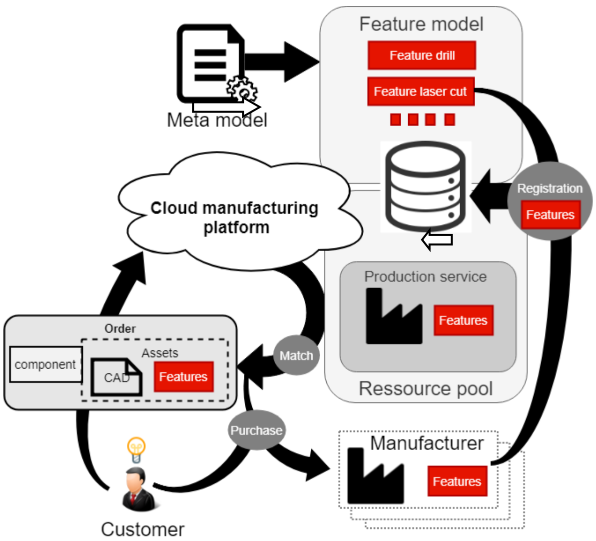

Fig. 1. Cloud manufacturing abstract representation

A well-defined CM model is represented here, for example, by the ManuService ontology of Lu et al. [4], which realizes a central platform in which nested production processes can be centrally planned via multiple service providers. For this, various variations with individual focuses exist, such as the approaches of the authors regarding a more symbiotic collective formation in the area of collective cloud manufacturing by Strljic et al. [5, 6] or the distributed production planning with a decentralized model as well as interface definition by Ellwein et al. [7, 8]. However, due to the complexity of the production processes to be planned and the orchestration of multi-stage value chains, only industrial CM platforms for commissioning manufacturing service providers from the fields of 3D printing, Computerized Numerical Control (CNC) milling technology, or water-steel/laser cutting are offered at the present time. For an improved overview of this research area, this study on existing solutions is conducted. In this publication, a broad overview of platforms is presented, which offer their customers the mentioned platforms as a complete solution. In the following publications, the advantages of platforms specialized in individual processes will be examined in comparison.

1.1. Structuring for Content and Procedure of the Study

The fundamental concept of cloud manufacturing is to encapsulate manufacturing resources and manufacturing capabilities as well as capacities in networks and make them available as services, according to the requirements and at the request of consumers. There is already a wide range of cloud manufacturing platforms, which offer capabilities for 3D printing, sheet metal cutting, and milling processes. However, they always vary in the way how an order is processed or how a wide range of production capabilities can be mapped. In the following sections, research on current cloud manufacturing platforms and the most commonly applied technologies will be presented, and a set of them is later on chosen based on defined criteria. An application scenario for this study is, as well, defined for further testing and comparison. Moreover, design specifications and restrictions for each technology and technique are shortly discussed. Finally, technologies and methods available on these platforms are compared, and accordingly, a final result will be delivered with the best platform’s performance.

1.2. Methodology of the Study and Platform Search Results

As a first step, research over existing national and global communities and corporations that offer cloud manufacturing platforms should be conducted. For this purpose, a broad search was first initiated. Previously defined search terms were applied via the search engines Google and Microsoft's Bing as well as the video platform YouTube to collect possible cloud manufacturing platforms. In the time span 09/2020 until 10/2020 following search terms were used:

- "Custom 3d prints online"
- "Cloud manufacturing service"
- "On-demand manufacturing"
- "Automated additive manufacturing services"

The findings were analysed with a depth search to obtain possible references to a digital manufacturing service. These were then compared with the definition of Liu et al. [9], according to which a digital platform with a process-abstracting model must bring together the parties: customer and producer. Through this, 41 digital platforms were researched as businesses on-demand products in the sense of cloud manufacturing in the three technology areas of additive manufacturing, CNC milling technology, and laser technology. Figure 2 illustrates the technological distribution of the resulting platforms, which highlights that most platforms focus on one technology area. The offered products are online manufacturing platforms that offer businesses on-demand and manufacturing services with access to a global network of manufacturing partners. In order to get access to these platforms, a user has to make first a registration, usually with an employee account. Then, with a few steps, including upload the designed part file, choosing the required process, online calculations with given parameters, and finally, product confirmation with the available manufacturers, an order can be placed.

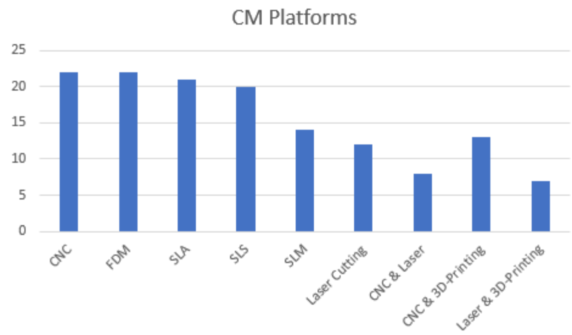

Fig. 2. Available cloud manufacturing platforms

Due to the wide variety of platforms been found, a predefined factor is established and states that a CM platform must have the ability to create parts and components throw the three main technologies (CNC-machining, additive manufacturing and laser-cutting) within each method and techniques. The number of platforms that support a combination of technologies is steadily decreasing as the number of technologies increases. For example, only 13 platforms are still able to represent the combination of 3D printing and CNC milling technology. The combination in the domain of laser cutting proves to be the most unusual, as it itself was represented with only 12 platforms, reducing the combination with CNC technology as well as 3D printing to eight and seven respectively. As a result, the platform's number has been reduced to five platforms which support all technologies, see Table I below. This table lists the abbreviation used, with the company name and headquarters of the filtered five platforms.

Table 1. Final cloud manufacturing platforms for testing

Platform's name	**Headquarter**
Xometry [1]	USA
Facturee [2]	Germany
3Dhubs [3]	Netherlands
3dExperiance [4]	France
Facfox [5]	China

1. https://xometry.de (visited 19/09/2020)
2. https://www.facturee.de (visited 28/09/2020)
3. https://laserhub.com (visited 25/09/2020)
4. https://make.3dexperience.3ds.com/welcome (visited 28/09/2020)
5. https://facfox.com, (visited 01/10/2020)

2. Use Case and Criteria Definition

For this study, the evaluation of these platforms is based on five main criteria, including: the material groups, features and parameters, leading time, end-cost, and user-friendliness of each individual platform. Starting with the material group as two materials for each process is chosen. One is a standard material that must be available on the evaluated platforms. Meanwhile, the second is a critical material, which adds additional complexity to the executed manufacturing process in terms of used tools and process parameterization; in other words, it is not most common. Another factor that is kept in mind is that the more material variety types available on the platform, the more credits this platform has in the evaluation. Moreover, each selected technology has different features that distinguish it from others. Therefore, these features play an essential role as criteria. As a result, Table II is created, with the main features and parameters that these techniques should be expected to have while executing the test process. In addition, if there are extra features mentioned in the table available on the platform, they are as well considered. Last but not least, many platforms offer their end product at various costs and different time windows, such as standard or express delivery. For that reason, end-cost and lead time will be addressed individually in the evaluation process. Finally, factors such as a good interface, available file formats, and successfully uploading files will be taken into consideration under user-friendliness criteria.

Table 2. Features and Parameters for Evaluations (+) Available / (-) Not Available

	CNC machining	FDM	SLA	SLS	SLM	Laser cutting
Quantity	+	+	+	+	+	+
Build	+	+	+	+	+	+
Surface quality	+	-	-	-	-	-
Tolerances	+	-	-	-	-	+
Infill percent	-	+	-	-	-	-
Layer thickness	-	+	+	+	+	-
Material color	-	+	+	+	-	-
Extra features:						
Dimensional control	+	+	+	+	+	+
Print orientation	-	-	+	+	-	-
Post-processing	+	+	+	+	+	+
Scaling/ M. units	-	+	+	+	+	-
Supporting documents	+	-	-	-	-	+
Additional notes	+	+	+	+	+	+

As aforementioned, customers of a CM platform submit a request onto the CM platform and set their desired product requirements through the platform's provided capability model, which is based on the supported CAD file formats and maps information containing the product definition and characterization. In that sense, parts for earlier mentioned technologies have been designed throw CAD design software with certain features and parameters that play to the method's strengths and fit within its capabilities. Therefore, some design restrictions and limitations must be considered by designing a part. These factors are discussed shortly for each technology and technique in following sections.

2.1. 3D-Printing Technologies

Three-dimensional printing or rapid prototyping are [10] processes in which components are fabricated straight from computer models by selectively curing, depositing, or consolidating materials in successive layers. Over the past decade, these technologies have rapidly developed into a new paradigm called additive manufacturing. Additive manufacturing (AM) was first developed in the 1980s and according to the American Society of Testing and Materials (ASTM) [11] is defined as “The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies; Synonyms: 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and free-form fabrication.” The range of AM technologies is classified, according to the ASTM, into several categories: material extrusion, powder bed fusion and vat photo-polymerization, binder jetting, material jetting, direct energy deposition, and sheet lamination. Each category includes several distinct processes with the same selective modelling of the layer’s principle. Due to the evolution of rapid prototyping technologies, it has become possible to fetch mass production parts within a short time, explaining the increasingly growing demand for AM machines. While there are a wide variety of technologies, most of these operate on the same underlying principle. The following section summarizes some of the key processes for these technologies.

2.2. Fused deposition modeling and fused filament fabrication

The most extensive installed base of AM techniques [12] is based on material extrusion. A technology that was developed relatively early on is the deposition of thermoplastics by extrusion. Fused Deposition Modelling (FDM), or Fused Filament Fabrication (FFF), is an additive manufacturing process that belongs to the material extrusion family. FDM [13] is the most widely used 3D Printing technology. It represents the vastest installed base of 3D printers globally and is usually the most common technology known among 3d printing manufacturing communities. FDM method shapes three-dimensional objects from CAD-generated solid, wireframe, or surface model data. A layer of material is deposited in a predetermined way, layer-by-layer from the bottom up, by a nozzle onto a plate. The build plate either moves down, or the nozzle moves up, and then a new layer of material is deposited. Furthermore, the extrusion speed, temperature and nozzle travel rate are controlled to deposit the material onto a build platform selectively or previous layers, fusing one layer onto the next. The designed object emerges as a substantial three-dimensional part without the need for tooling. Finally, thermoplastic polymers are a type of used material and come in a so-called filament form [14].

Like other manufacturing techniques, FDM has some limitations and constraints concerning what can be printed. These limitations and discussed methods can be implemented at the design phase to specify their impact on print quality [15]. Some features, such as wall thickness, are restricted by the filament size and applied features. Commonly features that are thinner than twice the filament's thickness usually do not get printed successfully. Another important feature is a hole diameter and orientation. FDM will often print vertical axis holes undersized. The decrease in diameter occurs [15] for many reasons, but most importantly, this can be an issue, especially when printing small diameter holes because of the ratio of hole diameter to nozzle diameter. For that, the minimum average diameter must be kept in mind. The orientation of holes is fundamental, and resolution tends to be best when printed parallel to the XY-axis. Moreover, changing the print orientation can eliminate the need for support structure as it might be challenging to remove support in the horizontal axis holes. Anisotropic property plays an essential role in designing 3d parts, as its role strength is triggered when parts have physical properties that vary in other orientations. It is a matter with additively manufactured parts due to the layer-by-layer material deposition to construct the part. Build orientation, part geometry, and pre-processing techniques can all be employed for these process-specific strength characteristics [16]. Finally, according to these design rules and specifications, a designed part (see Figure 3) has been chosen for this technique, as the applied features can be as well suitable. In addition, the offered and possible values for the most common features engaged in FDM parts have been summarized in Table III.

Table 3. Design Rules and Specifications for FDM Technology

Features	**Design specifications**
Un-/Supported walls	0.8mm thick
Overhangs	45°
Hole diameter	Ø2mm
Embossed/engraved details	0.6mm wide, 2mm high
Horizontal bridges	10mm
Moving parts	0.5mm
Minimum features	2mm
Pin diameter	3mm
Tolerance	±0.5 percent

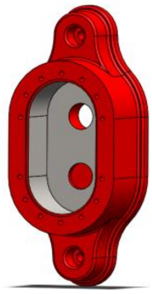

Fig. 3.Gear pump housing for FDM printing machine.

2.3. Vat polymerization

Another major 3D printing technique frequently used is photopolymerization, which generally refers to curing photo-reactive polymers using a laser, light, or ultraviolet (UV). Vat photopolymerization (VP) is described as “an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization” [11] and to be considered as the current state of the art owing to its unique outstanding print resolution, more remarkable efficiency, surface finish and printing accuracy. The most common VP process is Stereolithography (SLA). SLA was the first commercial AM system, developed in 1884 by Charles Hull, who then founded 3D System Corporation in 1986. The SLA process's main advantage is its ability to fabricate parts with smooth surfaces, making them ideal for visual prototypes and a high accuracy level with intricate details. The basic principle of the SLA process is the polymerization of a photosensitive resin [17]. The materials used in SLA are photosensitive thermoset polymers that come in a liquid form. In case of very high accuracy or smooth surface finish parts are required, SLA [10] is the most cost-effective 3D printing technology available. Moreover, SLA has many shared characteristics and features with Direct Light Processing (DLP), another VP 3D printing technology, which will be be treated as equivalents.

In VP-based AM systems such as SLA, manufacturing begins [18] as the build platform is first positioned in the liquid photopolymer tank at a distance of one-layer height for the liquid's surface. Then comes the deposition of a single layer of photopolymer on the build platform using a recoating mechanism. Meanwhile, a UV laser creates the required pattern on the resin surface with the next layer by selectively curing and solidifying the photopolymer resin. The laser beam is focused on the pre-established path using a group of mirrors. Thus, the whole cross-sectional area of the model is scanned, so the produced part is entirely solid. Finally, once a layer is finished, the platform moves at a safe distance and the sweeper blade recoats the surface with a fresh layer of photopolymer, and then patterning it with the UV laser. The process then repeats until the part is fully complete. It is important to mention that SLA can process only with a single material, and accordingly, support structures are made from the same material of the part [17].

As mentioned before, the model must be appropriately designed following the guidelines specified for deployed technology. Because SLA belongs to the AM family, it has the same features as FDM but with different specification values. One of the main design features for SLA is a support structure. The process takes place in a tank with liquid resin. Therefore, components need to be attached or fixed to the platform, preventing them from floating away. For that reason, a support structure, either external or internal, is mainly required for all parts built using the SLA method. Furthermore, the possible range of values for the most common features in SLA parts have been summarized in Table IV. Once again, according to the design rules and required specifications, a designed part, see Figure. 4, has been chosen for this technique [19].

Features	**Design specifications**
Supported walls	0.4mm thick
Unsupported walls	0.6mm thick
Overhangs	At least 19° from level
Support structure	Always required
Hole diameter	greater than Ø0.5mm
Embossed/engraved details	0.1mm in height, 0.4mm wide and thick
Moving parts	0.2mm or 0.1 snug fit
Minimum features	0.8mm
Pin diameter	Average of 0.7mm
Tolerance	Lower limit ±0.15mm

Table 4. Design Rules and Specifications for SLA Technology

2.4. Polymer power bed fusion

Powder bed fusion (PBF) [20] is an additive manufacturing technique that selectively fuses areas of powder using directed thermal energy [20]. This energy source has some implications for the monitoring and detection modalities adopted but achieves the same end result. These sources can be high-power lasers (most traditional thermal sources), electron beams (e-beams), and plasma. PBF techniques that employ lasers are known as laser sintering machines (LS). The word “sintering” [21] is a historical term and a misnomer, as the process generally involves partially or entirely melting materials, in contrast to traditional powdered metal sintering using a mold and heat pressure to give compaction. Selective laser sintering (SLS), Direct metal laser sintering (DMLS), and Selective laser melting (SLM) are few famous PBF based technologies.

Fig. 4.Turbine blade for SLA printing machine.

Selective laser sintering (SLS) is a thermoplastic polymer that comes in a granular form. Manufacturing begins with the powder bin and the build area being first heated just below the polymer's melting temperature;

then, a recoating blade spreads a thin layer of powder over the build platform. Meanwhile, a CO2 laser scans the next layer's contour and selectively sinters (fuses together) the polymer powder particles. Nevertheless, what keeps sintering apart from melting, is that the powder does not fully melt but rather heat it to the point that the powder can fuse together on a molecular level [21]. Furthermore, once a layer is completed, the build platform moves downwards, and the blade recoats the surface. The process then repeats until the whole part is complete. Eventually, the parts are entirely encapsulated and covered with unsintered powder. In addition to that, the remaining unsintered powder is gathered and can be reused for another print, in contrast to SLA powder, which is only 50 percent recyclable.

Features	Design specifications
Wall thickness	0.7mm - 2.0mm depending on material types
Hole diameter	greater than Ø1.5mm
Escape hole	Min. of Ø3.5mm
Embossed/engraved details	Min. of 1mm in depth/height
Moving parts	0.2mm or 0.1 snug fit
Minimum features	0.8mm
Pin diameter	Average of 0.8mm
Tolerance	Lower limit ±0.3mm

Table 5. Design Rules and Specifications for SLS Technology

One of the main advantages is that [20] SLS can be used for both prototyping of functional polymer components and small production runs, as it offers very high design freedom and high accuracy. No need for support structures is one of the most practical features of designing and printing parts using SLS as the unsintered powder covering the part removes the requirement for support [21]. SLS can be used to deliver many functional components, including axles, threads, tanks, and hinges. More specifically, SLS is one of the only 3D printing methods that can produce functional living hinges. In consequence, a living hinge box has been designed, as shown in Figure 5. The hinge geometry that has been designed has typical dimensions, as it might also be used for an injection moulded part. Besides, the thickness at the center of the hinge is 0.4 mm, and this would mean that the hinge's thinnest part of three layers would be used when printing at 140-micron layer height. Finally, while SLS parts are less susceptible to delamination of layers when compared to FDM [22], the build direction is still an essential factor when designing living hinges; to ensure the performance of a living hinge, parts should be orientated so that the hinge's width, rather than the length, is built up one layer at a time. That will often mean printing the part in the vertical build direction. To summarize the most common design features and specifications, the Table V has been created.

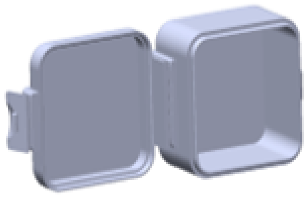

Fig. 5. Living hinge box for SLS printing machine.

2.5. Metal powder power bed fusion

The selective laser melting technology (SLM) belongs as well to the family of additive manufacturing processes, more specifically to the powder bed fusion 3D printing group. SLM is considered one of the most promising AM processes known for its freedom of manufacturing constraints that allow complex geometries and high material efficiency. It was developed [23] by Fockele and Schwarze (F&S) in cooperation with the Fraunhofer institute of laser technology in 1999 to produce metal components from metallic powders. SLM part consists of a cluster of individual single layers and tracks, and from the sequence of layers, a 3D object is sintered. A laser completely melts metallic powder particles and selectively fuses and bonds them together, building a part layer-by-layer, forming a 3D component. SLM delivers parts from a single metal with a single melting temperature. During the process, successive metal powder layers are fully melted and consolidated on top of each other. At the end, the entire area of the model is scanned, and the process is repeated until the whole part is complete. Today, 3D printer manufacturers [13] offer machines with powerful double or multi-laser techniques to ensure the full benefits of SLM technology. On the other hand, compared to polymers PBF [21], the high thermal conductivity, propensity to oxidize, high surface tension, and high laser reflectivity of metal powders make them significantly more difficult to process than polymers. Moreover, the cost of metal printing is significantly high; that is why simulation usually comes into action to predict the part's behaviour during processing to avoid extra expenses [24].

Features	Design specifications
Wall thickness	Min. of 0.4mm
Hole diameter	Between Ø0.5mm and 6mm without support
Escape hole	Min. of Ø2mm-Ø5mm
Moving parts	0.2mm or 0.1 snug fit
Minimum features	0.6mm
Aspect ratio	8:1 build height to section width
Tolerance	Lower limit ±0.127mm

Table 6. Design Rules and Specifications for SLM Technology

Fig. 6. Compressor wheel for SLM printing machine.

When designing parts for metal printing, several design suggestions help to reach better part's quality and dimensional accuracy. CNC machining is a perfect fit when delivering the tightest tolerances, a wide variety of available materials, and fast turn-around globally [25]. However, if a design has complex geometries, AM might be the most satisfactory solution. A compressor wheel has been selected accordingly, as shown in Figure 6, and the properties are summarized in Table VI. With a 0.5 mm minimum wall thickness, this designed part cannot be processed with a CNC machine due to vibration and tool geometry. On the other hand, the SLM technique suits it perfectly with a minimum of 0.4 mm in wall width (complex geometry).

2.6. CNC Milling

Computer numerical control (CNC) is [26] the automated control of machining tools such as drills and mills. CNC machining is the most broadly used subtractive manufacturing technology. Due to its high repeatability, it is suitable for both one-off jobs and low-to-medium volume production, as it creates pieces with tight tolerances and higher material characteristics. There are different types of CNC machines when it comes to the way it cuts the workpieces. Most CNC milling systems have three simple linear degrees of freedom: the X, Y, and Z-axis. 5-axis CNC systems are fitted for producing parts with high geometric complexity and may eliminate the necessity for duplicated machine setups as it utilizes two of these rotation axes. In the CNC process, the material (metal, plastic, wood, ceramic, or composite) is removed from a solid block applying various cutting tools to deliver a part based on a CAD model of the required part. Every cutting step and parameters [27] are fed in the form of G-code programming into the computer, in contrast to conventional machining. If the component has complex features that cannot be reached by the cutting tool in a single setup (or so-called Done-in-One) [26], then the block must be turned over and refixed one more time.

With CNC machining [27], not every design can be manufactured easily. Therefore, a focus on the term “Design for Manufacturing and Assembly” (DFMA) might be needed to cut the manufacturing cost or speed up the production. The design restrictions in CNC machining are a natural result of the cutting process mechanics that includes tool access, tool geometry, workpiece and tool stiffness. Internal edges [15] are one of the essential features CNC part design, as using the recommended value for internal or vertical corner radius ensures that a suitable diameter tool can be used and aligns with the recommended cavity depth guidelines. Furthermore, the walls of the CNC-machined part should ideally be at least 0.8 mm thick for metals or 1.5 mm thick for plastics, as thinner unsupported walls raise the vibrations that appear during machining and decrease the degree of the achievable accuracy. Finally, Tolerances determine the boundaries for a sufficient dimension (typically ± 0.125 mm). According to these design rules and specifications, three designed parts (see Figures 3, 7, 8) have been created for different types of CNC machining to take part further in study cases. They vary from low to high complexity, starting with 3-axis, 4-axis machines, and eventually 5-axis machines, in order to determine if a platform can manufacture the designed parts using these machine types. Finally, the suggested and achievable values for CNC machined parts have been summarized in Table VII.

Table 7. Design Rules and Specifications for CNC Technology

Features	Design specifications
Cavities/Pockets	Max Depths: 4x cavity width
Vertical corner radius	1/3X cavity depth or larger
Unsupported wall	0.8mm (metals), 1.5mm (plastics)
Hole diameter	Ø2.5mm
Hole Maximum Depth	10x nominal diameter (Typical)
Tapping	L ¡ 3x Diameter
Minimum features	0.6mm
Threads	Size: min. M2
Floor fillets	Not recommended
Tolerance	±0.125mm

2.7. Laser Cutting and Post Processing

Laser cutting is a high preciseness CNC thermal technology that employs a high-power laser beam to cut, melt, or burn a material sheet. It can be conducted by melting or vaporizing the material through a focused beam of light to cut and engrave sheet material to the required design specification. It is capable of producing complex parts without using a custom-designed tool. Most laser cutting machines are conducted using CO2 or Nd:YAG lasers, as they are the two most widely used industrial lasers [28]. The general principles of cutting are equivalent for both types of laser; however, CO2 lasers leverage the market for good reasons. CO2 laser light wavelength is ten times that of the Nd:YAG machines. The Nd:YAG laser is, on the other hand, a crystal that is utilized as a lasing medium for solid-state lasers.

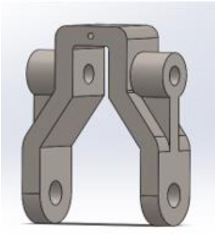

Fig. 7.Cardan joint design for 4-axis CNC machine

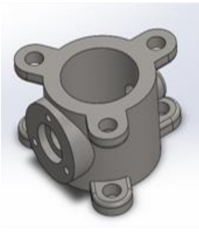

Fig. 8. Butterfly valve housing desing for 5-axis CNC machine

As a first step [29], a sheet of material is cut to size, positioned on the machine's bed, and the workpiece is hooked onto the platform. Power is modified and adjusted based on a few aspects, such as the type of material being cut and the sheet's thickness. A laser beam focused then onto the workpiece's surface through a lens. Moreover, the mechanism for specifying a combination of material, assist gas, and laser type can be divided into different classifications: fusion cutting, vaporization cutting, chemical degradation, and oxidation cutting. Finally, many factors affect the end-product quality, which include the lens focusing and the workpiece thickness. Laser cutting [30] can perform with tolerances from ± 0.127mm of precision. It is necessary for laser cutting and bending processes to keep common standards in mind for different design features. The sheet thickness determines the part's strength and weight, minimum bend relief, hole sizes, hems, and other important design features. Likewise, a sheet metal design has been created accordingly (see Figure 9 and Table VIII).

Table 8. Design Rules and Specifications for Laser Cuttring Technology

Features	**Design specifications**
Tolerance	ranges between ± 0.127 mm and ±0.381 mm depending on selected features.
Bend relief parameters	D = material thickness plus the radius of a bend, W = of a bend relief should be equal to 1.5 times the material thickness.
Vertical corner radius	1/3X cavity depth or larger
Unsupported wall	0.8mm (metals), 1.5mm (plastics)
Hole diameter	equal to the materials thickness or 1.00 mm, whichever is greater.
Spacing Between Holes	equal to 1.2 times the material thickness.
Hole to Bend Distance	from the edge to a bend should be 3 times the material thickness.
Hems	min. diameter of an open-/tear-hem is equal to the material thickness.
Flanges	min. width of a bend relief is one material thickness or 1.50 mm, whichever is greater

Fig. 9. Sheet metal design for laser cutting process

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	ABS	☑ (2 types)	☑ (1 types)	☑ (3 types)	☑ (1 types)	☑ (2 types)
	Nylon (PA 6)	☒	☑	☑	☑	☑
	Available	8	8	8	8	8
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Infill percent	☑	☒	☑	☒	☒
	Layer thickness	☒	☒	☑	☒	☒
	Material color	☑	☑	☑	☑	☑
	Geometry optimization	☒	☒	☑	☑	☒
	Print orientation	☒	☒	☑	☒	☒
	Post processing	☒	☒	☒	☑	☒
	Scaling / Measurement unit	☒	☒	☒	☒	☒
	Additional notes	☑	☑	☑	☒	☑
End-Cost		240.85	☒	382.42	269.74	☒
Lead Time		15 days	20+ days	9 Days	15+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 10. FDM cloud manufacturing platform evaluation results

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	Clear resin	☑	☑	☑	☑	☑
	PP-Like resin	☒	☒	☑	☑	☑
	Available	5	3	11	14	9
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Layer thickness	☒	☒	☑	☒	☒
	Material color	☑	☑	☑	☑	☑
	Geometry optimization	☒	☒	☑	☑	☒
	Print orientation	☒	☒	☑	☒	☑
	Post processing	☒	☒	☒	☑	☒
	Scaling / Measurement unit	☒	☒	☑	☑	☑
	Additional notes	☑	☑	☑	☒	☑
End-Cost		145.06 €	☒	169.79 €	☒	74.30 $
Lead Time		13 days	20+ days	9 Days	15+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 11. SLA cloud manufacturing platform evaluation results

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	PA 12	☑	☑	☑	☑	☑
	PA 12 (Alumide)	☑	☒	☒	☒	☒
	Availability	5	1	2	2	3
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Layer thickness	☒	☒	☑	☒	☒
	Material color	☑	☑	☑	☑	☑
	Geometry optimization	☒	☒	☑	☑	☒
	Print orientation	☒	☒	☑	☒	☑
	Post processing	☒	☒	☒	☑	☒
	Scaling / Measurement unit	☒	☒	☑	☑	☑
	Additional notes	☑	☑	☑	☒	☑
End-Cost		57.86 €	☒	98.60 €	100.41 €	39.24 $
Lead Time		11 days	20+ days	9 Days	17+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 12. SLS cloud manufacturing platform evaluation results

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	Aluminum super-alloys	☑	☑	☑	☑	☑
	Cobalt-chrome super-alloys	☒	☒	☒	☒	☒
	Available	4	2	2	5	7
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Layer thickness	☒	☒	☑	☒	☒
	Material color	☑	☑	☑	☑	☑
	Geometry optimization	☒	☒	☑	☑	☒
	Post processing	☒	☒	☒	☑	☒
	Scaling / Measurement unit	☒	☒	☑	☑	☑
	Additional notes	☑	☑	☑	☒	☑
End-Cost		148.19 €	☒	555.32 €	☒	☒
Lead Time		18 days	25+ days	13 Days	18+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 13. SLM cloud manufacturing platform evaluation results

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	Stainless Steel	☑ (3 types)	☑ (20+ type)	☑ (11 types)	☑ (20+ types)	☑ (2 types)
	Titanium	☑	☑	☑	☑	☒
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Surface quality	☑	☒	☑	☒	☒
	Tolerances	☑	☒	☑	☑	☒
	Geometry optimization	☒	☒	☑	☑	☒
	Finishes	☑	☒	☑	☑	☑
	Supporting documents	☑	☑	☑	☑	☒
	Additional notes	☑	☑	☑	☒	☑
End-Cost		704.08/ 330.31/ 2,949.29	☒	1,305.73 / 590.52/ 7,125,94	☒	☒
Lead Time		40 days	20+ days	18 days	25+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 14. CNC cloud manufacturing platform evaluation results

		CMP_1	CMP_2	CMP_3	CMP_4	CMP_5
Material Group	Aluminum	☑ (2 types)	☑ (10+ type)	☑ (2 types)	☑ (5 types)	☑ (2 types)
	Copper	☒	☑	☑	☒	☒
Features and Parameters	Quantity	☑	☑	☑	☑	☑
	Build size	☑	☑	☑	☑	☑
	Surface quality	☑	☒	☑	☒	☒
	Tolerances	☑	☒	☑	☑	☒
	Geometry optimization	☒	☒	☑	☑	☒
	Finishes	☑	☒	☑	☑	☑
	Supporting documents	☑	☑	☑	☑	☒
	Additional notes	☑	☑	☑	☒	☑
End-Cost		367.26	☒	938.22	☒	☒
Lead Time		35 days	25+ days	14 days	20+ days	☒
User friendly	File Formats	18	4	9	11	13
	Successfully Uploaded?	☑	☑	☑	☑	☑
	Good Interface?	☑	☒	☑	☑	☒

Fig. 15. Laser cutting cloud manufacturing platform evaluation results

3. Validation results and interpretation

As aforementioned, each selected technology has different features that distinguish it from others. In this chapter, several tests (which represent one technique or method) are executed individually based on previously mentioned technologies with every test table created. Moreover, sub-factors, such as material types and parameters, are selected from Table II regarding their belonging to manufacturing technology. Finally, every factor is given a weight based on its importance to ensure the best results.

3.1. Validation Result 3D-Printing Technologies

Test tables (see Figures 10 – 13) are created with different variations for testing these platforms' reliabilities against the four different techniques employed in this study. CMP_3 proves to be the best through these different methods. In addition to CMP_1, CMP_4 has presented a satisfactory service; they lack, however, the layer thickness feature, which is considered to be an essential factor in 3d printing technology. Furthermore, based on the given materials and parameters in most test cases, CMP_2 and CMP_5 have been given by the criteria end-cost the lowest ranking since both have not automatically offered the manufacturing costs. In addition, CMP_5 has not provided any lead time, which indicates the lowest performance and capabilities.

3.2. Validation Result CNC Milling

Since the three CNC machining processes are identical in all criteria, they are evaluated in the same table. The price, however, varies, and this has been presented in Figure 14. In general, all five CM platforms are relatively acceptable. CMP_3 has submitted the best performance. On the other hand, CMP_1 has offered an excellent service, but it lacks the geometry optimization feature, which is one of the required factors for CNC machining. CMP_2, CMP_4, and CMP_5 have been given in this test case by the criteria end-cost lowest ranking, as all three have not automatically provided the manufacturing costs. Finally, for CMP_5, many important aspects have been absent, such as material shortage and tolerance variation. Moreover, it has not proposed any lead time, hence the lowest capabilities.

3.3. Validation Result Laser Cutting and Post Processing

In this test case, CMP_3 has submitted the best performance as well, see Figure 15. Although CMP_1 has not offered a sufficient number of materials, it has presented all main features and parameters that should be expected to have according to the defined study case. Furthermore, CMP_5 has proven to have a higher performance than CMP_2, as it has provided extra features, such as various surface finishes.

3.4. Complete Results and Interpretation

Based on the given results mentioned above, one can observe a clear difference between the performance of each CM platform. The final results are illustrated in figure 16. As it can be noticed here, CMP_3 proves to be the best through different technologies and methods. Throughout each study test case, it has the highest ranking by criteria features and parameters, as well as leading time. Another major advantage is DFM tool Algorithm. It gives the customer the chance to analyse the suitability of the part's geometry under consideration of the required technology. As a result, it has a significant impact on the whole process regarding manufacturability and design failures. When it comes to pricing, it has the most expensive manufacturing costs, and that is due to the low quantity number of required parts. However, starting with ten parts or more, the end cost of a single component will be reduced dramatically. CMP_1, on the other hand, does not have this problem, as it reveals to be the cheapest in most cases. Besides, it has the highest ranking for user-friendliness with more than 15 file formats available and a pleasing interface. For an average performance, CMP_4 comes at the 3rd place that covers many essential factors, such as material groups, in most test cases. Furthermore, CMP_2 has the poorest performance due to many reasons. For instance, an online calculation is not available on its platform. Hence, the end-cost factor was inaccessible during testing, and the leading time was not precisely estimated. Moreover, it has a deficient interface and accepts only four file formats.

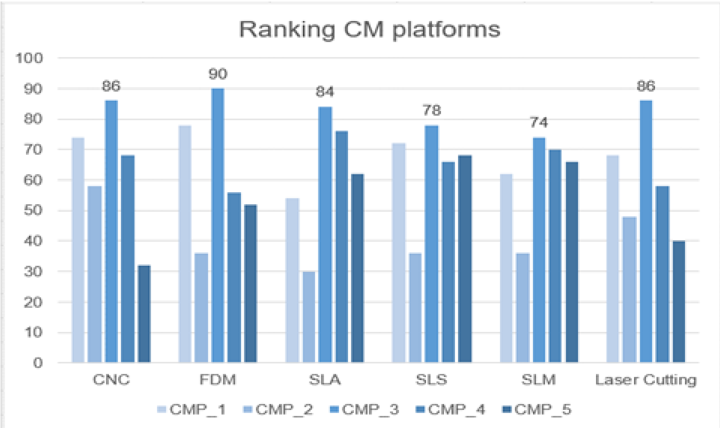

Fig. 16. CM platform ranking system

4. Conclusion

In this work, the design and implementation of a study on the technical characteristics of CM platforms were performed based on an application scenario. In the beginning, detailed literature research was conducted on the requirements and characteristics of cloud manufacturing and each manufacturing technology with its main benefits and limitations. Later on, parts for each technology have been designed using CAD design software with certain features and parameters that play to the method's strengths and fit within its capabilities. Furthermore, existing cloud manufacturing solutions were researched, and five CM platforms were tested based on five canonical criteria, which are popularly used in the manufacturing community to evaluate a platform. After simulating more than eight tests, an evaluation matrix was created. Based on these different criteria, CM platform CMP_3 was chosen for being relatively the best out of the five platforms.

For additional research, there are other CM platforms that can be further tested, as they are more specialized in specific technology with extra features and parameters that can be enhanced in detail. Finally, there is the detection algorithm employed by one of the platforms which examined the uploaded CAD file and check if the designed part specifications match the process requirements. In other words, if its eligible to be manufactured by the chosen methods from the customer. Therefore, the following publications of this study will focus on the technical depth of individual domain-specific CM platforms as well as the customer support with decision guidance tools in order to get a more detailed insight into the CM area and to highlight the individual unique selling points of process-specialized platforms.

5. Disclaimer

The enumeration of CMP_1 up to CMP5 has not to be directly related to the order of the mentioned platform list. The results are presented not to choose a winner or rate concrete platforms against each other. All content is only presented to give an overview of available platforms, possible achievable goals on the current market and technical gaps between platforms. To get a correct linking between the enumeration and the platforms contact the authors. When conducting the study validation, only the listed components were evaluated as test objects with the selected materials on the platforms. The special and individual platform functions were not included in the evaluation. Therefore, the results must be viewed critically in this context. In addition, only the results promised by the respective cloud manufacturing platform were considered, and these were not compared with the real production results for their quality characteristics. Finally, the results were produced in time period 10/2020 until 12/2020 and may be suffering from secondary effects of the COVID-19 pandemic. Thus, delivery dates and pricing must also be considered critically and can differ significantly according to the current order situation.

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