Fraunhofer IAPT

Analysis of measurement methods for density determination in additive manufacturing

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1 Aim of the study

In additive manufacturing (AM), various methods exist to determine the density or porosity of a part or component. A new method for automated density determination by Dimensionics Density — based on the Archimedes method — will be investigated in this study. A comparison of the different methods in terms of technical suitability, accuracy, time required and cost will be drawn. This comparison is considered from the perspective of three different use cases.

1.1 Importance density determination for additive manufacturing

In this study, different methods for determining the density of a specimen are investigated and compared. In particular, the special characteristics of AM are taken into account.

Compared to other manufacturing processes, AM is a comparatively young production method. Laser Powder Bed Fusion, the AM process used in this study, is based on a layer-by-layer exposure of powder to one or more lasers. These melt the powder locally, and the subsequent solidification bonds the individual layers together. In the next step, a new thin layer of powder is applied, which is again exposed locally. This is how components are built up layer by layer in the powder bed

In material development for AM processes, a large number of samples are generated for the development of practicable parameter sets. An initial assessment of the quality of the parameters is possible by determining the density. Due to porosities within the material, the measured density deviates from the theoretically possible density. For new materials, the aim is to find a process window for the process parameters in which the density generated is as close as possible to the theoretically possible density.

In series production, density determination can be used as statistical process control. At the same time, this technology can be used for machine release to quickly determine the process variations of the machine. In such scenarios, it is possible to use density determination as a useful supplement to established methods, such as tensile tests. Continuous monitoring of the manufacturing process is particularly desirable in AM, as the manufacturing process is subject to strong fluctuations. These fluctuations can be caused, for example, by variations in the powder material, changes in the optics of the laser, or degradation of the coater. The density of the component can serve as an indicator of the quality of the process.

1.2 Structure of the study

There are different ways to determine density, and a new method for automated density determination based on the Archimedes principle has been developed by Dimensionics Density. This new method will be compared with established methods and procedures.

First, the individual test methods are presented and their operating principle is explained. Subsequently, all test methods are considered in an experimental comparison, and the results of the comparison are analyzed, and the suitability of the different measurement methods is assessed. The comparison is carried out with test specimens made of AlSi10Mg, a material commonly used in AM.

Finally, the results of the methods are evaluated and put in context in terms of time, space, and cost. Three different use cases are considered, which differ mainly in the number of pieces to be analyzed. In conclusion, the optimal density determination method for each application is presented and possible combinations of the methods are explained.

2 Basics of density determination methods

In this chapter, the special characteristics of AM compared to conventional manufacturing processes are first highlighted. Subsequently, the functional principles of the density determination processes investigated will be presented.

2.1 Special characteristics of additive manufacturing

AM has some special features compared to conventional manufacturing processes. The additively manufactured component usually has a lower density than a conventionally manufactured component with the same shape. This negative deviation from the theoretical density is referred to as „porosity“ and is expressed as a percentage. Closed pores exist within the component, which can have different shapes. These pores can significantly affect the mechanical properties and jeopardize the functionality of the component. In a series production process with process parameters optimized for the selected material, the density of an additively manufactured component is >99.5% of the theoretically possible density, meaning <0.5% of the component are pores.

The surface of additively manufactured components is rougher than machined surfaces without post-treatment. This surface roughness can have an influence on density determination since complete wetting of the surface is more difficult. However, fluids with very low surface tensions and so low contact angles can be used here, which reduce or eliminate the problem.

In AM, many process and manufacturing parameters exist, some of which have a significant influence on the quality of the manufactured component. These parameters are subject to fluctuations, so continuous quality assurance is necessary to ensure the suitability of the component and the machine.

AM processes are more time-consuming and therefore more expensive than conventional manufacturing processes, so as many components as possible should be qualified for function. Destructive testing of components to be used is not practical. The suitability of parts is therefore determined by accompanying samples, or by non-destructive testing. To determine the effects of variations in the manufacturing process, tensile specimens are made as companion samples, which are then subjected to destructive testing. Non-destructive testing methods can be applied directly to the part to be qualified, and no correlation between the part and companion sample needs to be performed.

The determination of density is the most commonly used metric for the initial qualification of the component, as well as the process. Density can be determined in a variety of ways, both destructive and non-destructive. Density qualification is an essential part of quality assurance in AM. It is therefore important to test new methods and procedures in the market and evaluate their performance in terms of test durations, accuracy, as well as reproducibility.

In this study, four measurement methods are compared; two of these measurement methods determine an absolute density, i.e. a unit-based measured value. The other two measurement methods determine a relative, unitless density. In order to be able to compare all measurement methods, the absolute densities are converted into relative densities with the aid of a reference density. A more detailed explanation of this conversion is given in section 4. The choice of the reference density results in error propagation, which must be taken into account when comparing the methods.

Additively manufactured components are currently used in areas where high demands are placed on the quality of the component, for example in medical technology, aerospace, rail transport, or the defense industry. Therefore, quality assurance and its applied methods for component qualification are of great importance. Possibilities for optimizing quality assurance and the associated cost reductions enable AM to migrate into other areas. In the following paper, common methods that are used in quality assurance are presented.

2.2 Microscopic analysis of transverse sections

Micrographs are used in materials research and development. The sample to be examined is embedded in a matrix of epoxy resin and then processed in several steps with abrasive papers. Larger components must first be reduced to a smaller volume by a separation process. The dimensions of the specimen are limited by the grinding and embedding equipment. Grinding and polishing produce a smooth, planar cut surface that provides insight into the material condition. Detection and classification of defects are possible. Cracks, inclusions, and other defects can also be observed.
The considered section of a specimen and the material to be removed is shown schematically in Figure 1. After the ground specimen has been prepared, a two-dimensional section of the specimen is examined microscopically. This section is measured and the area where material is present is compared with the total area. Any reduction in this area due to pores thus corresponds to a reduction in the density of the component.

Grinding equipment from the Struers company is used at the Fraunhofer IAPT. For the embedding of the grinding tools, a hot

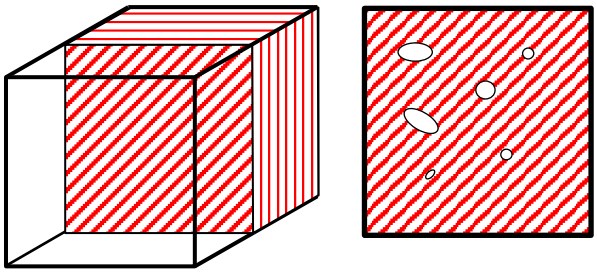

Figure 1. Schematic representation of a cross-section and the resulting micrograph with defects.

embedding device is used to embed the specimens as described in section 3. This produces cylinders with a diameter of 30mm, in which 5-6 specimens can be embedded. By simultaneously grinding the specimens in a single cylinder, the time required can be reduced. For larger parts, this advantage can only be used to a limited extent. Parts larger than the described diameter of 30mm must be prepared in the cold embedding process. The process is time-consuming and odor-intensive, so the size of the parts tends to be reduced to the minimum required level.

After grinding, the specimens are examined microscopically. Often this is an iterative process, as the final result of grinding and polishing does not meet the requirements. An optical microscope from the company Keyence is used at the Fraunhofer IAPT. This creates images of the ground surfaces, often creating one image per grind. This image is then binarized via an algorithm and the detected pores in the ground surface are analyzed. The result of the entire analysis is a porosity value, as well as a classification of the pores according to size and shape.

The advantages of the observation of transverse sections lie in the possibility to view the actual condition of the material. Pores can be detected and measured with a high resolution. Cracks and other defects in the component can also be detected. The shape of the pores — which provides information about defects in the process — can be determined. It is also possible to create a pore size distribution, which can be applied to untested components and their influence determined.

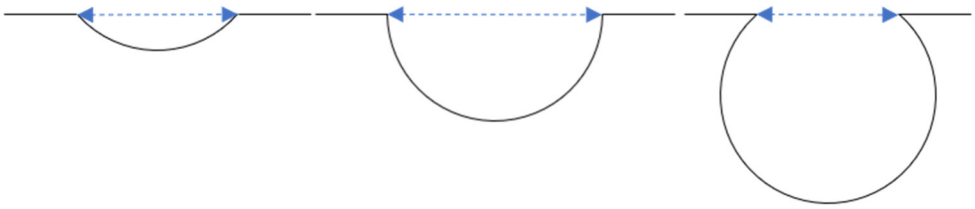

Figure 2: Determination of the pore size via the visible diameter on the ground surface.

The exclusively two-dimensional view has a disadvantage. It is not possible to determine a density over the entire component; only the three-dimensional state is inferred from the micrograph. If defects are localized at one position in the component, the detection probability is low. The pore size depends on the position of the microsection, therefore the true size of the pore is under or overestimated. This leads to deviations between the determined density and the actual density. The problem with this kind of determination is shown schematically in Figure 2.

Furthermore, the quality of the microsections (and thus also of the density determination) depends on the user and the material. The creation of micrographs is time-consuming and the grinding papers have to be changed regularly. Especially in AM, the other problems arise. In a powder-based manufacturing process, pores can be filled with powder. If this is exposed during grinding, it gets onto the sandpaper and can leave scratches and scores in the material. These scratches must then be ground away, which significantly increases the process time.

In addition, the analysis of micrographs is the only method listed here that destroys the test specimen. Especially in AM with comparatively high unit costs of components in series production, destruction of these is a problem. Therefore, accompanying samples are usually manufactured, which are produced in the same construction process, and from which the condition in the actual component is then inferred. However, additional material costs are also incurred here for the production of the accompanying samples.

Despite the machines used, this method is still characterized by manual work, be it cutting and sawing the specimens to size, embedding them in epoxy resin, or changing the abrasive paper and suspension solutions. Care must be taken to ensure a clean working method; the ground or polished surface is particularly sensitive to contamination and scratches. Often good results can only be obtained through experience, and the results are strongly dependent on the competence of an individual user.

The grinding of materials is time-consuming due to the low material removal rate and frequent change of grinding papers. Advantageous is the possibility to process several samples simultaneously, so that at higher quantities a scaling effect occurs and a lower total time is possible. It is also possible to purchase machines with a higher degree of automation to reduce manual labor time, but the effect on processing time is small. The creation of micrographs is still highly manual despite the higher level of automation.

2.3 Computed tomography

In computed tomography (CT), the specimen is exposed to X-rays. The density influences the brightness of the exposed imaging sensor. X-rays are absorbed during transmission through the material; this absorption is greater at higher densities of the material. If an X-ray beam hits a pore during transmission through the material, the energy is absorbed less due to the lower density within the pore. Therefore, the radiation hits the detector with higher energy and produces a darker image. By using a three-dimensional exposure strategy, it is possible to determine the shape and position of the pores.

A V|tome|x M from GE was used for the investigations. The resolution of the CT depends significantly on the size of the irradiated volume. For specimens used with an edge length of 10mm, a resolution of 10µm is possible, which corresponds to a voxel size of 10 μm^3 . Voxels are three-dimensional volume bodies, and they correspond to the smallest possible volume that can be represented by CT. The observation is equivalent to pixels of a screen or a camera but in three-dimensional space. At a resolution of 10µm in all spatial directions, the voxel has a volume of 10x10x10µm = 10μm^3 . In addition to its coordinates, the voxel has a gray value that correlates with the local density at that position. In order to reliably detect pores, at least 3 voxels per spatial direction are required. The smallest detectable pore thus has a diameter of 30µm.

The specimens considered in this study (cf. Sect. 3.2) were CT scanned for a period of approximately 1-2 hours; the time required to reconstruct the image data and analyze the results varied greatly, depending on the number and size of the pores. For this analysis, about another hour was needed.

The resolution of a CT scan is limited by the sensor used and the size of the component. The minimum resolution for conventional CTs is about 1µm. Lower resolutions are possible, but only small components can be analyzed, and the duration of the inspection increases. A trade-off is made here between a fine resolution, which also detects small pores, and the time required to inspect the component.

The advantages of CT lie in the ability to detect defects within the component non-destructively. These can be displayed three-dimensionally with suitable computer programs, and the effect of the defects can be determined without having to load the component.

A clear disadvantage lies in the high acquisition costs for the CT machine and the need for qualified personnel. This process must be certified according to ISO 9712 to be able to make reliable statements about the density of the component. Image processing and analysis require a combination of powerful software, computing capacity, and an experienced and qualified operator. The software and hardware, as well as the necessary IT infrastructure for transferring large amounts of data, are associated with corresponding costs. Transfer to external partners via cloud applications, for example, is difficult due to the size of the data.

Especially for more complex geometries, automated software tools cannot be used exclusively. Here, suitable filters and algorithms must be used to minimize artifacts and noise without removing existing pore data from the images. Furthermore, pores below the minimum resolution cannot be reliably detected.

CT determines the density without destroying the specimen, therefore the preparation effort for this test method is low. The time required is largely dependent on the required resolution, as well as the component size; no scaling effects occur with higher quantities.

In the CT analyses performed in this study, density was determined based on a 2D evaluation. It is possible to reconstruct and analyze the morphology of the pores to represent defects in three dimensions, but this application was not relevant to this study. The error between 2D and 3D evaluations is small because the database is identical. For the 3D evaluations, additional assumptions are made regarding the morphology to generate a pore-like representation from a cube-shaped voxel representation.

2.4 Archimedes method

Density determination according to the Archimedes principle is based on measuring the mass of a specimen in two different fluids. First, the weight is determined in air, then in a liquid, for example, water. Due to the different buoyancy forces of the specimen in both media, the density can be determined.

The effort required to carry out this density determination method is very low; all that is needed is a balance, as well as a basin with liquid and an apparatus for holding it. However, the results obtained depend on the accuracy of the balance, as well as on the precision of the experimental procedure. It is difficult to reproduce the results, which are strongly influenced by human factors. Test specimens are never placed in the exact same spot on the balance, and the manual operation of the balances leads to measurement deviations.

For specimens the density of which is lower than that of the fluid medium, the method is difficult to perform. Incomplete wetting influences the determination of the density. Air pockets between the body and the fluid increase buoyancy and falsify the result. Care must therefore be taken to ensure a suitable material pairing between fluid and solid. In contrast to the previous methods, only the density can be determined; no conclusion can be drawn about pore geometry or position. Archimedes density determination is also a non-destructive test method.

The environment can influence the density determination in this procedure. Changes in temperature and air humidity, as well as the fluid medium, can affect the results of weighing operations. Laboratory conditions and trained personnel are required to produce reliable measurement results.

The Archimedes method requires little time since only two measurements of the weight have to be made and the specimen does not have to be processed. In order to prevent the influence of immersion or turbulence in the fluid, the measurement is only carried out when the fluid is at rest again. Therefore, the measurement time in the fluid is extended. Here too, no positive scaling effects occur with higher quantities.

A Shimadzu AUW220D analytical balance with the associated density determination kit was used for the measurements. The balance was operated with a reading accuracy of 0.1mg.

For AM, the porosity of the component is important, which is specified as a percentage deviation from the density. For the Archimedes process, as well as for the automated density determination process, a reference density is useful. This can be determined, for example, via a good part, or via the theoretical material density.

2.5 Automated density determination

Automated density determination uses the Archimedes method described above in combination with modern automation technology. For this purpose, the samples to be measured are placed in a special component carrier, which is provided with openings on the underside. These component carriers are transported through the system by an axis robot and thus lowered centrally and precisely onto the scales. On the scales, themselves, a lift-out rack with pins is placed, which lifts the component over the openings in the component carrier and thus lifts the component out of the carrier. The automated handling eliminates human influence on the measurement, as the parts are always consumed identically onto the scales.

The scales are designed to be insulated from vibration to ensure maximum accuracy even in the production environment. In addition, all ambient conditions such as temperature, air pressure, and water temperature, are recorded via climate sensors, and their influence on the measurement result is taken into account directly in the evaluation algorithm when determining the density.

The measurement in both media takes place automatically, the user only has to load the machine. No scaling effects occur during the measurement, however, the one-time loading and automated density determination can reduce the required personnel effort.

The advantage of automation lies on the one hand in the faster processing of the density determination, and on the other hand in the higher reproducibility of the results. The fluid used is "STL-liquid", a specially developed surfactant solution that has a low surface tension and therefore also produces a lower contact angle between fluid and solid, hence the wetting is significantly higher. The specimen can be pre-wetted via a spray or by an additional immersion run, whereby cavities, rough surfaces as well as complex geometries are wetted significantly better.

The results of the measurements are automatically transferred to higher-level systems; no further evaluation or assessment steps are necessary. Therefore, fast data transfer to quality systems is possible.

3 Experimental comparison of the methods

3.1 Definition of boundary conditions

A total of 3 x 15 test specimens were made of AlSi10Mg. These were divided into three series as shown in Table 1. The test specimens were additively manufactured using laser powder bed fusion. Different process parameters were chosen for the test specimens, which create defects in the form of pores. Specimen set A was measured using only automated density determination. Specimen set B was ground and analyzed before the other measurements to confirm the expected porosities. Specimen set C was used to compare the different measurement methods. The density of the test specimens was determined using different methods, first the non-destructive testing methods, then destructively using a micrograph.

Table 1: Representation of the specimen series and their function

Specimen series	Measurement method	Comment
A	Automated density determination	To determine the repeatability and reproducibility
B	Micrograph	To investigate whether process parameters produce the desired pores
C	Automated density determination, computed tomography, Archimedes manual, Micrograph	Comparison test to analyze the differences between various measurement methods

3.2 Specimen geometry

Cubes were used as the sample geometry. These were developed at Fraunhofer IAPT as a standard for the development of parameters and have the advantage that a larger number can be processed simultaneously in the grinding machine. The cubes have a tapered surface so that they can be easily separated from each other, as well as from the build platform. The selected size of the cubes allows optimal utilization of the grinding machines, and the shape of the cubes is optimized for the grinding process. Figure 3 shows the test specimens.

Different defects are generated due to the selected process parameters. These can also occur in series production and are therefore of industrial relevance. The defects can be divided into three categories:

Gas pores are pores which are formed when the powder is heated locally to too high a temperature. The pores are relatively small and approximately spherical. If several gas pores occur in close proximity, they can combine and deviate from the spherical shape. Due to the small size of the pores, there is a risk that they cannot be reliably detected by a low-resolution CT scan.

Figure 3: Examined test specimens after fabrication

Spattering pores (or paint-of-fusion pores) occur when the energy density is locally too low. The powder is not completely melted and remains in the component. Spatter pores are significantly larger than gas pores, and have an almost lenticular contour and sharp edges. Among other things, they are formed by splashes of liquid metal that are released from the molten bath during exposure and distributed in the powder bed. Paint-of-fusion pores are notches within the component due to their size and shape. They also act as nucleation points for cracks in dynamically loaded components and are therefore particularly relevant for component suitability.

Edge porosities occur at the transition between contour exposure and hatching. The pores are characterized more by their location in the component than by their shape. They occur in areas close to the surface and have a negative influence on the fatigue strength of the component. Figure 4 shows an example of the various defects.

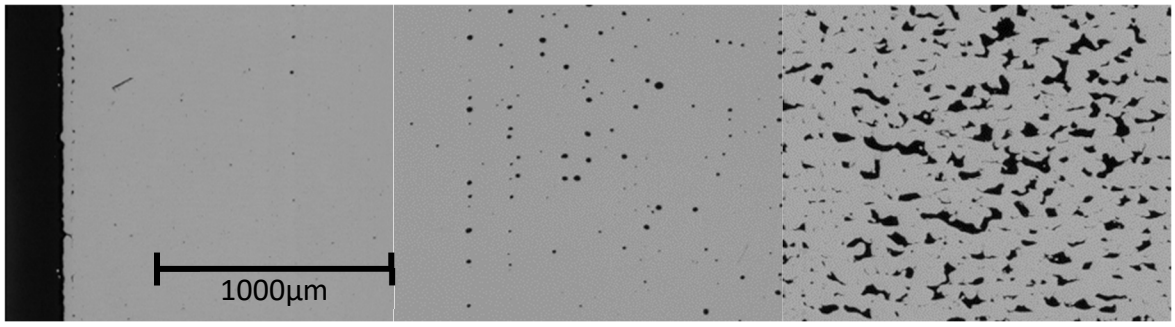

Figure 4. Detailed micrographs of specimens with a) edge porosity, b) gas pores and c) brittle pores.

4 Specimen analysis

The data described in Sect. 3.1 were analyzed. The density of all specimens in measurement series C was determined using each measurement method. Different process parameters were chosen to produce different defects. Furthermore, reference specimens were produced to represent the closest possible production run with very low porosity. The target relative densities are shown in Table 2. Micrographs were produced last, as these destroy the specimen.

Table 2. Target relative densities and defect shapes of the specimens

Specimen	Target relative density	Comment
C1-C3	>99,5%	Density as high as possible as reference values, or in order to map a process close to series production
C4-C9	94-99%	Lacquer-of-fusion defects, probably filled with powder
C10-C15	~98-99,5%	Gas pores, pores not filled with powder

Correlation of measured densities and relative densities

Micrographs, as well as CT measurement, determine a relative density in percent, while the other measurement methods are based on the Archimedean principle and determine a density in units. To be able to compare all measuring methods in one representation, knowledge of the absolute density is necessary. This can be determined via the powder, or by reference measurements. Standard densities can also be used. In this study, no absolute density was determined. Therefore, a correlation of the measurement methods is used to conclude an absolute density. The derivation of this correlation is shown below. This is only necessary if there is no knowledge of the absolute, theoretically achievable density. The correlation was used to determine the most accurate density possible after AM. Due to variations in the chemical composition of the powder, or due to evaporation effects and different laser parameters, the densities can deviate from standard or reference densities. Since this study compares measurement methods, it makes sense to avoid deviations due to different powder compositions or standard densities.

Different quantities were determined in the series of measurements. In the measurements with CT (abbr. CT) and micrograph (abbr. MS) the porosity Φ was determined. This is defined as:

$$\Phi = 1 - \frac{\rho}{\rho_0}$$

With the relative density ρ and the absolute density ρ_0. In the Archimedean measurements (abbr. D) the relative density ρ was determined. These quantities are to be related to each other. All unknown quantities are shown with a cross bar above the quantity:

$$\Phi_{\mathrm{CT}} = 1 - \frac{\overline{\rho}}{\overline{\rho}_0}, \qquad \Phi_{\mathrm{MS}} = 1 - \frac{\overline{\rho}}{\overline{\rho}_0}, \qquad \overline{\Phi}_{\mathrm{D}} = 1 - \frac{\rho}{\overline{\rho}_0};$$

The absolute density is the same in all measurements and thus the connecting link of the measurements. The determination of the absolute density is possible as follows:

$$\overline{\rho}_0 = \frac{\overline{\rho}}{1 - \Phi_{\mathrm{CT,MS}}} = \frac{\rho}{1 - \overline{\Phi}_{\mathrm{D}}}$$

The density of the powder was not determined before the tests. If this density is known, the following conversion can be omitted. Since evaporation effects are neglected, the porosity must be > 0 and the measured density ρ must be smaller than the absolute density ρ_0. The maximum measured average density from 18 measurements is $\rho = 2{,}6606\,\frac{\mathrm{g}}{\mathrm{cm}^3}$which allows the lower limit of the absolute density to be determined. This density was measured in the sample cube C1, this cube has in the other measurement methods a relative percentage density of

$$1 - \Phi_{\mathrm{CT}} = 99{,}79\%,$$
$$1 - \Phi_{\mathrm{MS}} = 99{,}89\%.$$

Combining these porosity values with the measured density gives an absolute density of

$$\rho_{0_{\mathrm{CT}}} = \frac{\rho_{\mathrm{D}}}{1 - \Phi_{\mathrm{CT}}} = 2{,}6662\,\frac{\mathrm{g}}{\mathrm{cm}^3}, \quad \rho_{0_{\mathrm{MS}}} = \frac{\rho_{\mathrm{D}}}{1 - \Phi_{\mathrm{MS}}} = 2{,}6636\,\frac{\mathrm{g}}{\mathrm{cm}^3}, \quad \Delta_{\rho_{0_{\mathrm{CT,MS}}}} = 0{,}0026\,\frac{\mathrm{g}}{\mathrm{cm}^3}.$$

The use of cube C1 as a reference for the determination of the absolute density makes sense since the porosity is particularly low here, and thus measurement errors caused by pores are least pronounced. Based on this absolute density, the porosity values of the other cubes can be determined. As will be shown below, the scatter of the relative density in micrographs is strong, therefore the porosity value determined by this measurement method is not trustworthy and is therefore neglected for the determination of the absolute density. The absolute density is thus determined by correlating CT measurements and automated density determination and is $\rho_0 = 2{,}6662\,\frac{\mathrm{g}}{\mathrm{cm}^3}$.

Statistical scattering of porosity within the specimen

Both CT and micrographs are subject to systematic error in porosity determination. CT has a resolution limit below which small pores can no longer be reliably detected. At a resolution of 10µm, the smallest pore that can be reliably detected is 30µm in diameter. This corresponds to an area of 9 pixels, or a volume of 27 voxels. The influence of a single, non-detected pore on the total porosity is small. However, the number of these very small pores increases strongly, resulting in an influence when considered in total. This will be discussed in Sect. 4.2.3.

The micrograph can be considered as a section through the component. Assuming a random pore distribution, the porosity of a micrograph is defined by a probability distribution. To determine this distribution, the porosity determination of the CT can be used. The CT allows virtual sections through the component, with a minimum distance corresponding to the resolution.

In Figure 5 histograms of the specimens are shown. The data from the CT examinations are used; these consist of thousands of two-dimensional sections through the component, equivalent to a micrograph. The porosity is now determined in each of these sections. The histograms thus correspond to the sum of all sections through the specimen and represent the local scattering of the porosity. Only sections whose cut surface is above 2mm² are considered to exclude porosity outliers due to very small cut surfaces. In this approach, there is a difference in the three-dimensional volume evaluation. The pores are analyzed as voxels and not reconstructed, therefore an overestimation of porosity may occur. Since in both analysis methods, the geometry is determined based on the detected voxels, the difference is comparatively small.

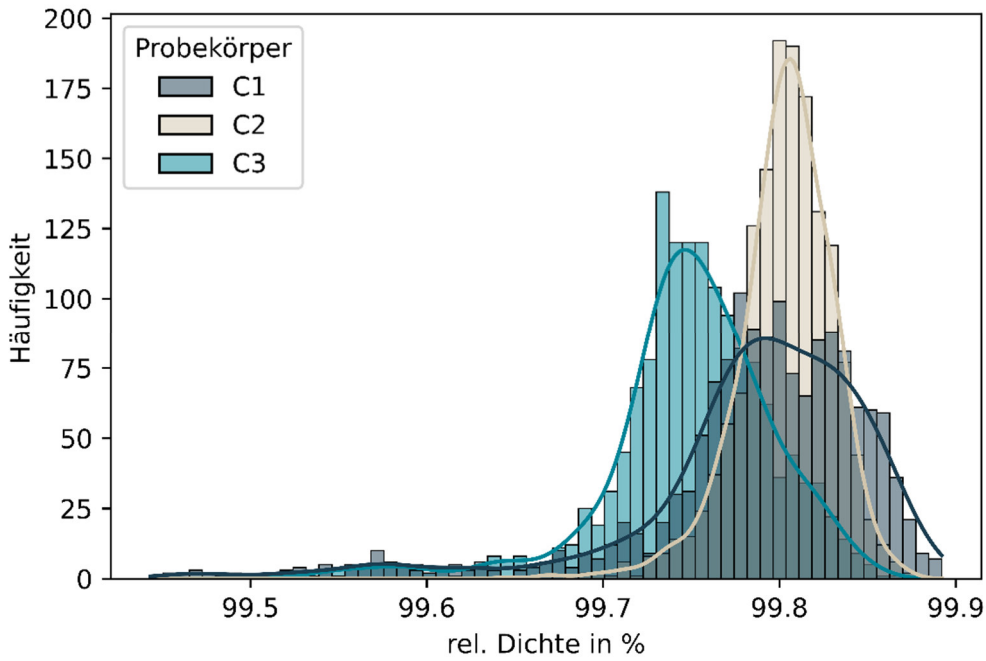

Figure 5Histogram of the relative density of the CT scans for specimen C1-C3.

For example, in specimen C1 there are about 100 cut surfaces the porosity of which is 99.80%. However, there are also outliers from 99.50% to 99.70%. For the CT investigations, these outliers are negligible, since the component is considered in the whole. This means that the sections are averaged, with a weighting corresponding to the section area of one section to the total area of all sections. However, the observation via histograms allows conclusions to be drawn about the informative value of micrographs. Here, the component is only considered locally, which is why the global density cannot be determined accurately. When extrapolating from a micrograph to the entire component, there is a risk of incorrectly determining the density. For a minimum statistical certainty, at least 3 micrographs of a component must be carried out, which significantly increases the time and financial expenditure.

Figure 6 shows the histograms of the relative density for the specimens with paint-of-fusion defects. The relative density scatters significantly more than for specimens C1-C3. While the average density of specimen C9 is about $94{,}1\ \%$, significant deviations downwards or even to higher densities are visible. Here, the danger of predicting false densities is even higher than for the previously considered specimens in Figure 5. Accordingly, the informative value of the micrographs is lower for higher porosity. The micrograph is also unsuitable for local porosity phenomena; the assumption of a homogeneous pore distribution in the component is incorrect.

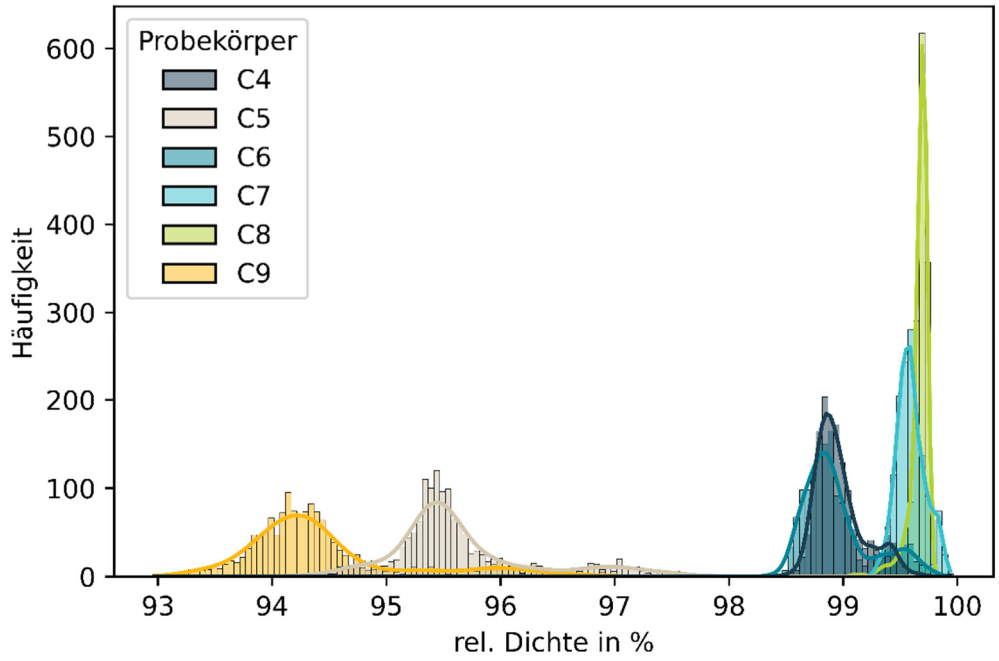

Figure 6Histogram of the relative density of the CT scans for specimen C4-C9.

4.1 Accuracy

The relative percentage density determined with all measurement methods is now compared. A breakdown is made between the different defect categories. It can be assumed that in the case of paint-of-fusion defects, powder remains in the pores, which influences the density determination according to the Archimedes method. The porosity should therefore be lower in these measurements, or the relative percent density higher. Similarly, the entrapment of gas in gas pores will affect the measured density. Since the gas has a significantly lower density than the powder, the relative percent density will be lower.

Measurement method	Abbreviation	Color
Computed tomography	CT	
Micrograph	MS	
Automated density determination	D	
Manual Archimedes method	A	

In Figure 7 the density of the reference specimens is shown. For specimen C1, the density is identical for the measurement methods with CT and the density balance. The density balance allows multiple, fast measurements. Therefore, three measurements were performed for higher statistical accuracy. The micrograph differs for specimens C1 and C2 from the other measurement methods; this can be explained by the scattering of the porosity in the component. In the manual Archimedes method, a total of three measurements were carried out for specimen C1, the scatter of the relative density is significantly higher compared to the automated density determination, and this can be traced back to manual influences.

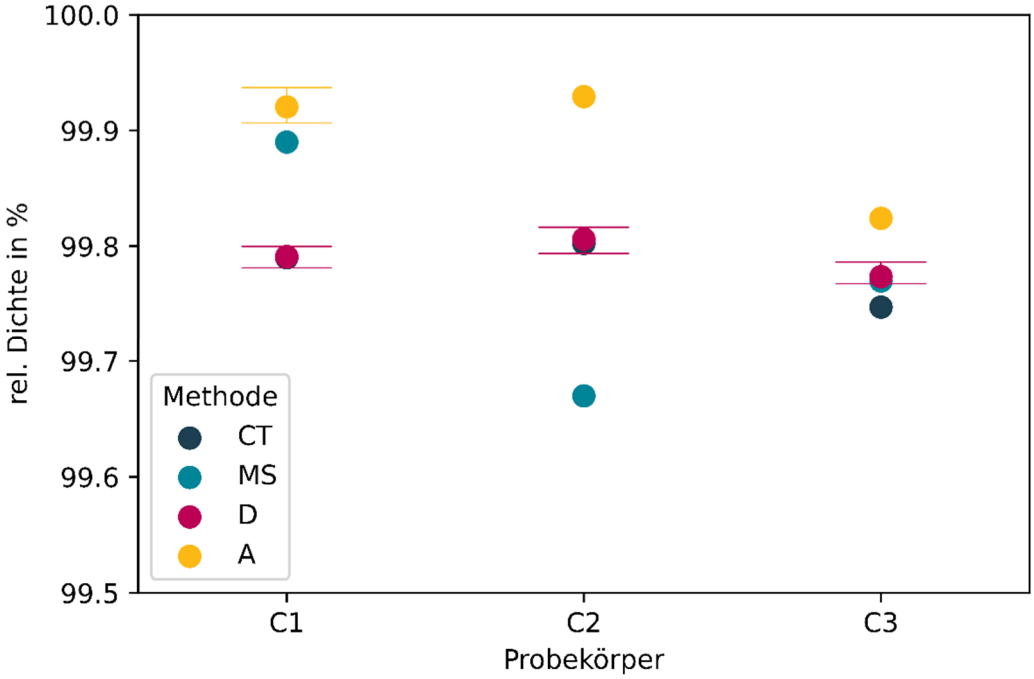

Figure 7: Relative density in percent for the reference specimens C1-C3.

Figure 8 also shows the relative percent densities, in particular for the specimens with induced paint-of-fusion defects. The density here differs significantly over the entire measurement series. This trend is reflected by all measurement methods. Measurement with CT determines the highest respective relative percent density for all specimens. The results of the micrographs differ clearly in specimens C5 and C9 from the results of the other measuring methods. In the other specimens, there is an approximate agreement on the determined relative density, with the results of the density balance placed between the other measurement methods.

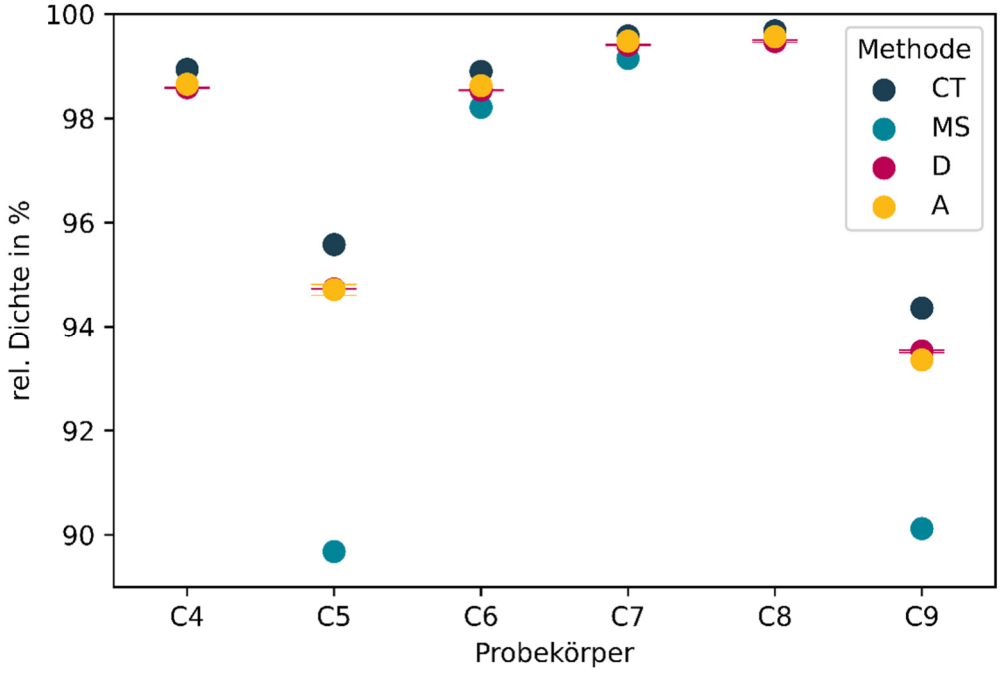

Figure 8: Relative percent density for specimens C4-C9 with paint-of-fusion defects.

The uncertainty of all measuring methods increases with higher porosity. For the Archimedean measurement methods, this is due to the aforementioned influence of gas or powder. In CT, the smaller density difference between the component and the powder makes it more difficult to determine the size of the pore. As a result, the density is estimated to be higher. In the micrograph, scratches can occur due to powder inclusion, which makes automated density determination more difficult; furthermore, the relative densities scatter much more widely, as shown in Figure 6.

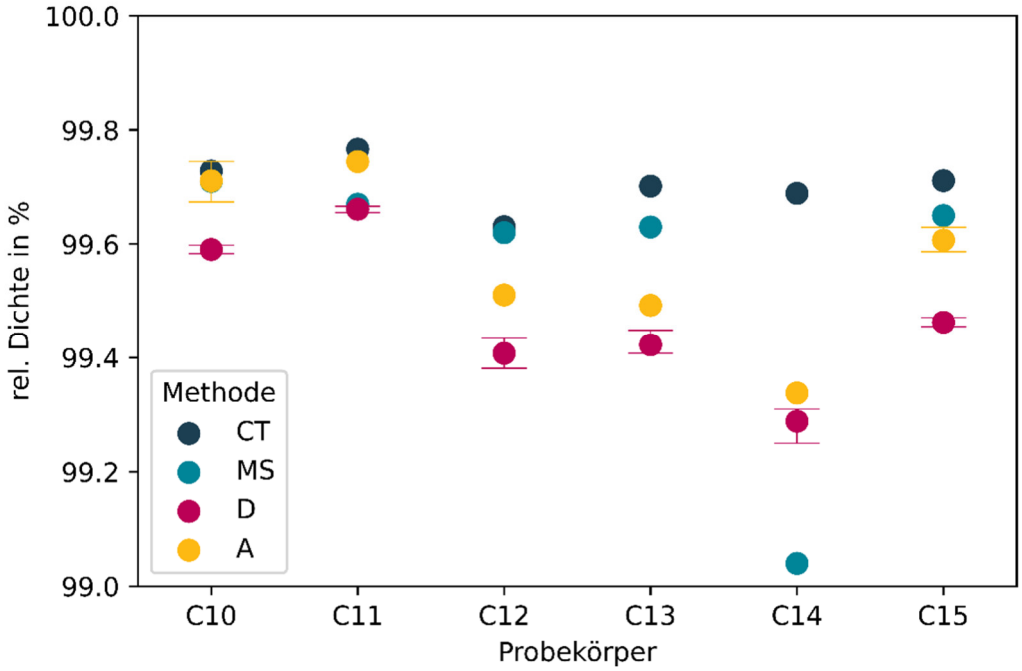

Figure 9: Relative density in percent for the test specimens C10-C15 with gas pores.

Figure 9 shows the results of the measurements for the specimens with gas pores. The density differences between the specimens are significantly lower than for the specimens with varnish-of-fusion defects. Gas pores are significantly smaller than paint-of-fusion defects, so the detection of these pores with a CT scan is difficult. This deviation is particularly pronounced in specimen C14, where the relative density is between $1 - \Phi_{\mathrm{CT}} = 99{,}69\%$ and $1 - \Phi_{\mathrm{MS}} = 99{,}04\%$. The measurements with the automated density balance lie between the results of the other measurement methods. In Table 3 the relative densities of the specimens determined with the different measurement methods are shown. The CT data were additionally analyzed with a theoretical resolution of 50µm, the relative densities increase due to the lower resolution.

Table 3: The relative densities and standard deviations in % determined with the measurement methods considered. For the CT and the micrographs, no standard deviations can be determined due to the measurement procedure.

Specimen	CT (10µm)	CT (50µm)	Micro-graph	Dimensionics[1]	Archimedes manual[2]
C1	99,79	99,92	99,89	$99{,}79 \pm 0{,}022$	$99{,}92 \pm 0{,}029$
C2	99,80	99,94	99,67	$99{,}81 \pm 0{,}011$	99,93
C3	99,75	99,92	99,77	$99{,}77 \pm 0{,}011$	99,82
C4	98,94	99,19	98,63	$98{,}59 \pm 0{,}013$	98,65

[1] The values are given with a standard deviation in both directions as a tolerance. For specimens C1, C5, C10, C15 the number of measurements is n=18, for the other specimens n=3.

[2] The values are given with a standard deviation in both directions as a tolerance. For specimens C1, C5, C10, C15 the number of measurements is n=3, for the other specimens n=1. Therefore the determination of the standard deviation is not possible.

Specimen	CT (10µm)	CT (50µm)	Micro-graph	Dimensionics[1]	Archimedes manual[2]
C5	95,58	96,07	89,68	94,73 ± 0,020	94,72 ± 0,186
C6	98,90	99,02	98,21	98,54 ± 0,009	98,63
C7	99,58	99,63	99,16	99,40 ± 0,011	99,48
C8	99,68	99,88	99,48	99,47 ± 0,025	99,57
C9	94,36	94,79	90,13	93,52 ± 0,024	93,35
C10	99,73	99,92	99,71	99,59 ± 0,017	99,71 ± 0,057
C11	99,77	99,93	99,68	99,66 ± 0,006	99,74
C12	99,63	99,90	99,62	99,41 ± 0,026	99,51
C13	99,70	99,90	99,64	99,42 ± 0,023	99,49
C14	99,69	99,91	99,04	99,29 ± 0,034	99,34
C15	99,71	99,90	99,65	99,46 ± 0,019	99,61 ± 0,036

4.2 Reproducibility

In addition to the accuracy of the measurement, the reproducibility of the testing process is of great importance for series production. In Figure 5 and Figure 6, the scattering of micrographs was shown on the basis of virtual micrographs with CT data. In order to obtain statistical certainty about the relative density, several micrographs in the specimen are therefore necessary. This significantly increases the time and cost involved.

In CT scans, density is determined by volume — the larger ratio of pores to material and the averaging over the entire volume make this method less susceptible to the scatter that occurs in micrographs. The quality of the CT reconstruction increases with an increasing number of images, however, the acquisition of these images is time-consuming and thus significantly increases the overall cost of the measurement method.

The general suitability of a measuring or testing system for the determination of a characteristic value, in particular, the capability indices c_g and $c_{gk}$is described, among other things, by VDA 5. This is divided into the proof of the measurement system suitability, the measurement process suitability, the conformity assessment, and the ongoing verification. The complete consideration of test process suitability is not considered in this study. However, some assessments are given on partial factors of the suitability of the different systems.

4.2.1 Measuring equipment resolution

The resolution of the measuring equipment must be sufficiently high for the measurement. As a rule, a resolution of $< 5\%$ is required. The percentage value here refers to the tolerance. For example, the resolution required for the measurement of a dimensional $10 \pm 0{,}1\mathrm{mm}$ is equal to $0{,}01\mathrm{mm}$ (5% of 0.2 mm tolerance).

Porosity is determined optically in both micrographs and CT scans. For CT scans, the resolution depends on the component geometry and size. For micrographs, the resolution depends on the magnification of the microscope and the camera's resolution. There is the possibility of stitching, where several detailed images are merged into one large image. This allows a larger area to be analyzed at high resolution. The resolution of a camera is given in pixels; pixels are the smallest square areas in which a color or brightness value is constant. In the experiments carried out, 218 pixels correspond to 1000 µm, so one pixel has an edge length of 4.59 µm. A higher resolution is possible by using a camera with more pixels or by using a higher optical magnification.

A tolerance range is defined for the density determination. $TOL = 0.2\%$ is defined. An exemplary determination of the relative density can be shown via $1 - \Phi = 99{,}5\% \pm 0{,}1\%$ is shown. In the following, it is checked whether the measuring methods have the required resolution for this tolerance range.

In the case considered, the specimens have a cube-like contour with an edge length of 10mm. In cross-section, this leads to an area of $10\mathrm{mm} \cdot 10\mathrm{mm} = 100\mathrm{mm}^2$. With the expected relative density of $99{,}5\%$, the pore area is therefore $0{,}5\mathrm{mm}^2 \pm 0{,}1\mathrm{mm}^2$. A resolution of $< 5\%$ is required, so the tolerance area is $0{,}2\mathrm{mm}^2 \cdot 5\% = 0.01\mathrm{mm}^2$. The resolution of micrographs is $4{,}59\mu\mathrm{m} \cdot 4{,}59\mu\mathrm{m} = 21{,}07\mu\mathrm{m}^2$ and is thus significantly smaller than the required resolution.

For larger components, it is possible to create multiple high-resolution images via stitching. Therefore, in theory, the minimum resolution is independent of the component size. In practice, the resolution is adapted to the component size, since the data to be processed increases sharply, just as the time required and the benefit of a very high resolution is relatively low.

In the CT images, the volume is considered. The specimens have a volume of $100\mathrm{mm}^3$, for the same assumed tolerance of $\pm 0{,}1\%$ the pore volume corresponds to $0{,}5\mathrm{mm}^3 \pm 0{,}1\mathrm{mm}^3$, therefore a minimum volume resolution of $0{,}2\mathrm{mm}^3 * 5\% = 0{,}01\mathrm{mm}^3$ is necessary. The resolution used in the experiments is $10\mu\mathrm{m}$ where a pore can only be detected from 3 pixels, so the minimum length resolution increases to $30\mu\mathrm{m}$ correspondingly the voxel size is $(30\mu\mathrm{m})^3 = 27000\mu\mathrm{m}^3$ and thus significantly smaller than the required volume resolution.

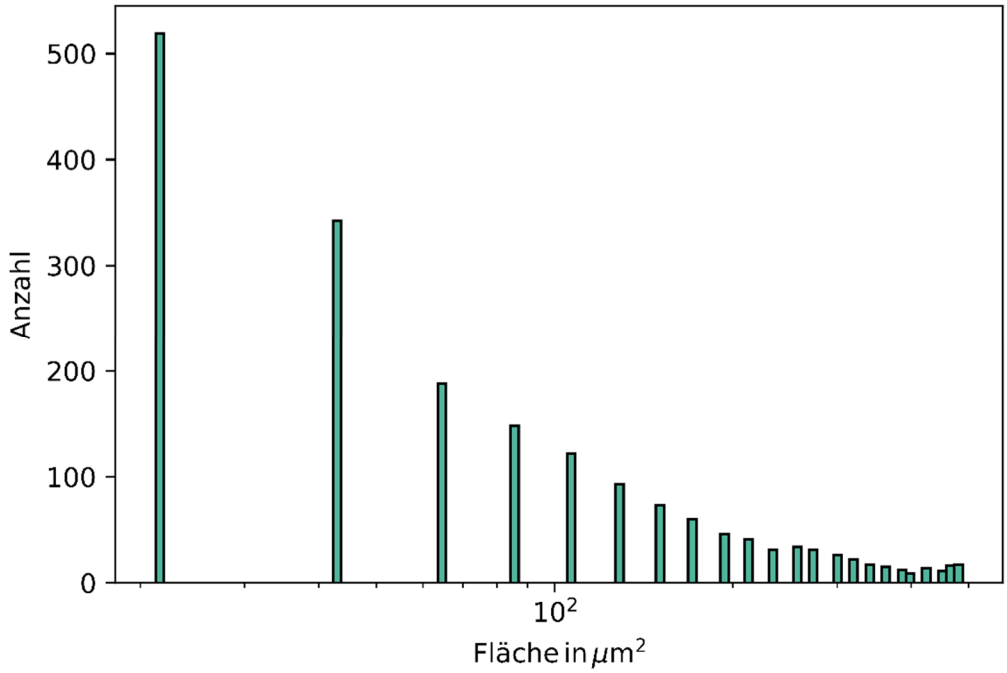

Figure 10: Section of a histogram of the pore area distribution in the micrograph in semi-logarithmic representation from 0 to 500 µm² . Due to the discrete number of pixels, the pore size and area cannot be represented continuously.

For larger components, the resolution of the CT scan decreases. For a cube-shaped specimen with an edge length of $100\mathrm{mm}$ the edge length of the voxels increases to $100\mu\mathrm{m}$ increases. With the same tolerance values, a volume resolution of $2\mathrm{mm}^3 \cdot 5\% = 0{,}1\mathrm{mm}^3$ is necessary. The voxel volume corresponds to $(300\mu\mathrm{m})^3 = 0.027\mathrm{mm}^3$, and is now significantly higher than in the previous case.

These calculations are not useful because they assume that the porosity is a large area or volume. In reality, however, the density corresponds to a sum of many pores of different sizes. The smallest detectable pores thus correspond to the resolution limit of the measuring instrument. For the micrograph, this limit in the case under consideration is the area of one pixel, i.e. $(4{,}59\mu\mathrm{m})^2 = 21{,}07\mu\mathrm{m}^2$. The next largest pore has an extension of 2 pixels in one direction and one pixel in the other, the area corresponding to $21{,}07\mu\mathrm{m}^2 \cdot 2 = 42{,}14\mu\mathrm{m}^2$. Small pores can therefore only be described in discrete steps, depending on the size of the pixels.

This is shown in Figure 10. In the area of small pores, strong jumps of the pore areas occur due to the discrete resolution of the image. The first column corresponds to a pore area of one pixel, and the second column to a pore area of two pixels. Smaller pores cannot be detected, here the micrograph has a resolution limit. For CT scans, this is shown similarly in Figure 10, but due to the three-dimensional resolution, it is related to the pore volume instead of the area. In the case under

consideration, pores with a volume of $V \geq (3 \cdot 10\mu\text{m})^3 = 27000\mu\text{m}^3 = 27$ Voxel can be captured. Accordingly, smaller pores cannot be detected.

The effect of the pores at the dissolution limit on the relative density depends on several factors. If the total porosity is high, such as in the specimens shown with paint-of-fusion defects, the proportion of small pores in the total pore area is low. As the relative density increases, the pore area decreases, so if the number of small pores remains the same, their proportion of the pore area increases. For series production with high relative densities, the resolution limit can therefore certainly have a relevant influence on the capability of the measuring device.

In the histogram in Figure 10, 519 pores have an area of one pixel, which corresponds to a total pore area of 519 pixels, i.e. $10934{,}34\mu\text{m}^2$. This value is above the required tolerance area of $0{,}01\text{mm}^2 = 10000\mu\text{m}^2$. So while these small pores have a small effect on the total area, the limited resolution of the micrographs limits the tolerance possibility. It can be assumed that pores also exist beyond the detection limit of one pixel. Based on the increasing number of smaller and smaller pores, these are likely to be represented in greater numbers than the detected pores. It is possible to detect smaller pores by a finer resolution, but this increases associated cost and time.

The problem of limited resolution is also relevant for CTs. Here, the maximum possible resolution is also strongly dependent on the material used, as well as the thickness of the component. For larger components, only low resolutions are possible. There is, therefore, a risk that the component is certified as having a higher relative density, or as being free of pores, although in reality, it has porosity. This problem is illustrated in Figure 11, which considers the relative density in specimen C14 for different CT resolutions. The relative density approaches a value of 100% with increasing voxel size since small pores can no longer be detected.

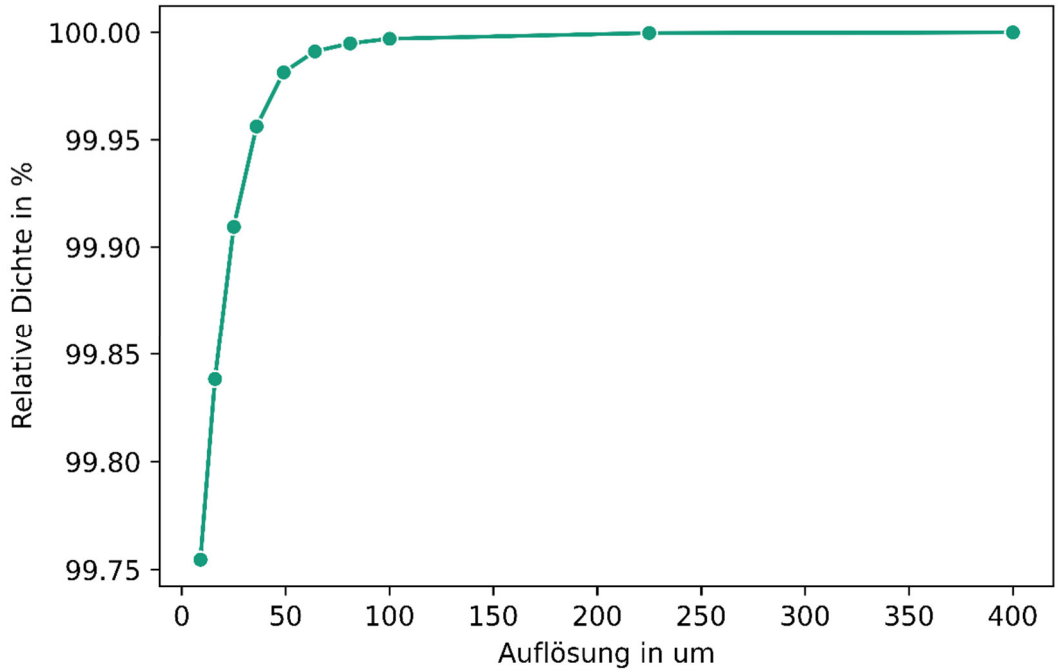

Figure 11: Calculated relative density of specimen C14 for different resolutions of the CT.

The resolution of the measurements according to the Archimedean principle depends on the accuracy of the balance used. With the used absolute density of $\rho_{0_{CT}} = 2{,}6662\,\frac{\text{g}}{\text{cm}^3}$ the tolerance of $\pm 0{,}1\%$ corresponds to a density change of $\Delta\rho = 0{,}002662\,\frac{\text{g}}{\text{cm}^3}$. The automated density determination gives an accuracy of $0{,}001\,\frac{\text{g}}{\text{cm}^3}$ and is thus within the necessary tolerance. The resolution of the manual density determination is the same as the resolution of the automated density determination. A discretization of the results takes place only by the balance, so the possible tolerance range is therefore directly dependent on the resolution of the balances used.

4.2.2 Determination of repeatability

Repeatability is determined via repeated measurements on a part. For micrographs and CT scans, the result of the repeated measurement is the same as for a single measurement, since both methods use a deterministic algorithm to determine the relative density. Any deviations can therefore only be attributed to the data acquisition. Due to the high cost, no repeated CT scans were performed, so repeatability cannot be determined here.

Since the porosity of micrographs varies considerably within the component, as described in Sect. 4, the expected repeatability of the measurement is low. Destructive testing does not allow repeatability to be investigated for this measurement tool.

The repeatability of CT images depends on the placement of the specimen on the scan platform. Small pores could be detected as smaller or larger if placed differently. The real size and shape of the pores can be inadequately detected at the resolution limit. Therefore, a slight variation of the porosity values can be assumed for the same resolution and the same specimen.

In the automated density determination, 15 measurements were performed on each of 11 different specimens, and the maximum standard deviation determined was $\sigma = 0{,}0008 \frac{\mathrm{g}}{\mathrm{cm}^3} = 0{,}03\%$. All measured values for each specimen are within 6σ.

4.2.3 Reproducibility

The reproducibility represents the influence of different testers on the measurement result. Under the same conditions, several inspectors measure the same part several times. The micrograph is unsuitable for this test because specimen preparation destroys the part. CT scans are automated apart from specimen placement, so there is little influence from users. However, in the image processing and filtering of the scans, operator influence may again occur, depending on the experience of the users. For the automated density determination, only the placement in the sample carrier is manual, the rest of the measurement is automated. Therefore, a low manual influence on the measurements can be assumed, corresponding to high reproducibility. Based on experience at Fraunhofer IAPT, the manual Archimedes method is strongly dependent on the respective user's experience, as well as the care taken during the process.

4.3 Defect detection

The measurements according to Archimedes' principle do not allow direct determination of the defect type. Here, the micrograph, as well as the CT scan, have an advantage. With these methods, a two- or three-dimensional reconstruction of the pores is possible, which simplifies a subsequent evaluation concerning effects on static or dynamic material properties. CT scans are limited in resolution by the thickness (or volume) of the material. For the density cubes used with a volume of 10x10x10mm, a resolution of 10µm could be achieved. For larger components only a lower resolution can be achieved, therefore the detection of defects is more difficult. For reliable detection and spatial imaging, the defect must have three times the size of the minimum resolution, which in the case considered is 30µm in each spatial direction. Gas pores in particular have a smaller size than this, and detection of these pores is therefore not possible with a CT scan. This is also shown in Figure 9. Specimens C10-C15, in which gas pores were specifically created, are evaluated with a higher density in the CT scan than in the other methods. In the case of the Archimedean methods, the gas contained in the pores can have an influence, lowering the relative density to lower values.

For the specimens with paint-of-fusion defects, deviations also occur between all measurement methods. CT scans estimate the relative density highest here. There is a possibility that paint-of-fusion defects are difficult to represent by these methods. CT data are binarized for density determination. The classic algorithm for binarization is the Otsu algorithm, which divides the grayscale image into two classes and attempts to minimize the variance within those classes. Here, the gray levels correspond to relative density, with material labeled as dark and pores as light. For paint-of-fusion defects, the density difference between material and pore is smaller than for gas pores. Therefore, the division into two classes is also much more difficult. The algorithm still considers parts of the paint-of-fusion defect as solid material. Therefore, the defects are estimated to be smaller than they are in reality, and, accordingly, the relative density is higher.

The micrograph is unsuitable as a local snapshot to make a qualified statement about the relative density. Especially in the case of varnish-of-fusion defects, the local porosity varies strongly, as also shown in Figure 6. A statement here is only possible with considerable statistical uncertainty. For the Archimedean methods, a deviation can also be assumed, since the powder within the pores influences the relative density. A quantitative evaluation of this deviation is difficult, since the amount of powder still present in the defects, as well as the relative density within the defect, cannot be determined. However, the measurement results follow the trend of the CT measurements, which is why it can be assumed that the measuring system has a basic capability for density determination even for paint-of-fusion defects.

5 Evaluation of the procedures

5.1 Suitability for additive manufacturing

All methods are basically capable of determining the relative density of AM parts and components. However, there are differences in accuracy, resolution, repeatability, and the possibility of defect detection.

At Fraunhofer IAPT, micrographs are usually created for parameter development. These allow a view into the specimen, whereby defects can be classified according to their type. In section 4 it was shown that these micrographs only allow local conclusions to be drawn and that the relative density within the specimen can deviate considerably. For reliable conclusions about the relative density, the specimen must be ground and analyzed at several positions, which increases the amount of work and time required. The results have sufficient accuracy for the institute, even if limitations occur with regard to the minimum pore size.

CT scans allow a three-dimensional view through the component. This is equivalent to performing hundreds to thousands of slices through the material. It is thus possible to make a global statement about the porosity, but layers can also be analyzed for anomalies or strong deviations. The images taken with a CT are limited by the resolution, which is lower than that of a micrograph. Thus, fewer small pores can be detected. The CT works based on the density differences of the material. While there is a large difference between solid material and pore for gas pores, this is smaller for lack-of-fusion defects, which is why the size of these defects is underestimated.

The Archimedes method can determine the global relative density of the component. The main problem of this method is the lack of repeatability and variation due to manual measurement. The resolution here is largely determined by the balance used. As long as this measures sufficiently accurately, clear statements about the relative density are possible.

The automated density determination removes the user from the Archimedean measurement and therefore has significantly higher repeatability and lower fluctuations. This method is the only one that is traceable, so it can be referenced to a recognized standard via a measurement chain. Compared to micrographs and CT scans, the measurement is also much shorter, making it easier to take multiple measurements for greater statistical confidence, and this makes this method suitable for evaluating the process capability of machines. Establishing the process capability of machines is an essential step for the production of series components via AM. It is continuously determined by external influencing factors, such as temperature. These influencing factors are included and compensated for in the density calculation, which means that operation in environments without laboratory conditions is also possible.

5.2 Effort

The effort for the determination of the density of AM parts differs between the procedures used and also depends on the number of pieces examined. Below, the time required, the dimensions of the machines, and the degree of qualification required for employees are considered.

5.2.1 Microscopic analysis of transverse sections

The working time required for the microscopic analysis of transverse sections is shown in Table 4 It is possible to process several specimens simultaneously, which reduces the time required per specimen. This scaling effect is taken into account in terms of associated costs. The space required for the operation of the machines is small but depends on the degree of automation of the grinding machine. Simple machines can be placed on a standard table, and larger machines with an automatic changing unit have a space requirement of approximately 3.5 m^3 . In addition to the grinding machines, an embedding device is necessary; if cold embedding is used, working under a fume hood must be ensured. If the component is too large for embedding, or processing in the grinding machine, it must be reduced to an acceptable size. This is done by a cutting machine, a saw with strong water cooling. This can be placed on a table in the same way as an embedding machine.

Table 4: Working steps for the analysis of transverse sections

Work steps	**Time in min**
Preparation of the sample	5
Embedding in polymer matrix	15
Rough grinding	120
Fine grinding	120
Polishing	30
Microscopy / Density determination	2
Total	**292**

In addition to the grinding and embedding machines, a microscope is required. Here, a spatial separation of the work steps is necessary, as the optical devices of the microscope are sensitive to contamination. The microscope can also be placed on a table.

No special qualification is required to operate the machines. However, the quality and the time required for the grinding patterns can be influenced by the experience of the user. This includes, for example, the optical quality check after each grinding phase, or the choice of different grinding papers and durations. For the comparison of several specimens to each other, parallel grinding of the specimens is recommended.

5.2.2 Computed tomography

Table 5: Work steps for computed tomography

Work steps	**Time in min**
Placement of the sample	5
Tomography	90
3D reconstruction of the specimen	30
Density determination	25
Total	**150**

Computer tomographs are significantly larger than grinding machines. The machine size is also dependent on the size of the component being examined. The specimens considered in this study were analyzed by a GE brand V|tome|x M computer tomograph. This CT has a size of 2600x2060x1570 (WxHxD in mm) and a weight of about 8 tons. The working steps for the analysis of CT data for density determination is shown in Table 5.

A CT unit works with X-rays, so appropriate qualifications are required to protect the user and third parties. It is also necessary to designate a radiation protection officer, as well as a radiation protection responsible person, in the company. An experienced operator may be able to reduce the machine time required and improve the quality of the data produced. Operator certification will reduce misinterpretation and increase the robustness of the results. The time to commission the machine can take about a month, depending on the approving authorities.

In addition to formal approval from authorities, the operator of the CT must be well-trained and experienced to minimize errors in image acquisition and processing. These errors (for example artifacts or noise) can complicate the determination of density and have a striking effect on the accuracy of the measurement procedure.

5.2.3 Archimedes method

Table 6: Working steps in the manual Archimedes method

Work steps	Time in min
Measurement in air	1
Measurement in fluid	3
Density determination	1
Data collection and dissemination	2
Total	**7**

The space required for the measurement is small. Only a balance and suitable measuring equipment are required. However, measurements according to the Archimedes method are sensitive to environmental influences, therefore laboratory conditions are required for accurate measurements. The temperature of the air, the air pressure, as well as the fluid temperature should be kept as constant as possible; changes in these influencing factors have a strong effect on the measurement results. The working steps are shown in Table 6. The costs for the construction and operation of a laboratory room were not included in the financial consideration.

The user must exercise the necessary care and must know the influencing factors from the environment (temperatures, air pressure). The user can inadvertently influence the result by manual action, therefore experienced personnel are preferred.

5.2.4 Automated density determination

Table 7: Work steps in automated density determination

Work steps	Time in min
Measurement in air	0,5
Measurement in fluid	1
Density determination & internal sample handling	0,5
Total	**2**

The space required is larger than for the manual Archimedes process due to automation, but significantly smaller than a CT machine, or a complete grinding facility. A closed system as a large model has a space requirement of 3 m^2 , and smaller systems about 1 mm^2 . Due to the encapsulation of the machine and the continuous recording of the environmental conditions, no laboratory conditions are necessary. The automated work steps are shown in Table 7.

Since the measurement is automated and the user only takes over the assembly, no special qualification is necessary. Only a one-time training is required for handling the system.

5.2.5 Conclusion on effort estimation

A tabular presentation of the effort estimation is shown in Table 8. This evaluation represents a summary of the estimates made above, as well as the results of the analyses. The evaluation is deliberately fuzzy since the individual factors are weighted differently depending on the application.

Table 8: Effort estimation of the density determination methods

	Micrographs	CT	Archimedes	Automated density determination
Time expenditure	High	High	Low	Low
Spatial effort	Medium	High	Low	Medium
User qualification level	Medium	High	Medium	Low
Component size is limited by	Grinding machine	Resolution	Liquid bath	Liquid bath
		Machine	Scale	Scale
Accuracy	High	Medium	High	High
Reproducibility	Low	High	Low	High
Quality of the results	Low	High	Low	High
Comment		Resolution sensitivity	Reference density necessary	Reference density necessary

5.3 Financial consideration

5.3.1 Use cases

Different scenarios are considered for the analysis. These differ mainly in the quantities and degrees of automation of production. The financial cost of evaluating the test specimens is listed below. The quality of the data obtained is not included in the financial consideration. It can be assumed that processes with a low level of reproducibility require a higher number of necessary tests to be able to make a statistically valid statement.

The use cases differ financially mainly in the quantities and personnel costs. The investment costs are similar in all cases and are shown in Table 9 below. The prices listed serve as guidelines; individual combinations are possible based on the existing use case. For example, in the case of CT, expensive analysis software could be dispensed with if capable personnel perform the analysis. This is accompanied by higher personnel costs.

With higher quantities, further automation of the machines for creating the micrographs is conceivable, but the supply of completely automated grinding machines is very limited. The automated density determination can be carried out in several automation levels; for application case 1, version S is considered due to the lower number of pieces, and version M is for the other applications.

Table 9: Necessary investments for density determination

Micrograph		µCT		Archimedes		Disionic Density S		Disionic Density M	
Reflected light micro-scope incl. software	50 t€	µCT	210 t€						
Wet cutting machine	8 t€	Software	30 t€						
Embedding device	2 t€	Training	5 t€			Plant incl. soft-ware	100 t€	Plant incl. soft-ware	180 t€
Grinding and polishing machine	5 t€	Acceptance etc.	5 t€	Density scale	2,2 t€				
Total	65 t€		250 t€		2,2 t€		100 t€		180 t€

A useful life of 7 years is considered, with 230 working days per year and a 40-hour week. Table 10 shows the costs for the operation of the measuring methods. These include investment costs, electricity costs, and the costs for consumables. For the micrograph, the possible scaling effects are included. It is assumed that 30 specimens can be ground simultaneously. This optimization is only possible with small specimens as shown in Figure 3 For larger bodies or real components, therefore, the cost per measurement increases. Consumables are the used grinding papers, embedding material, as well as suspensions for polishing. The Archimedes method, as well as the automated density determination method, use a water-surfactant solution, which must be renewed regularly.

Use case 1: Research institute

A research institute such as the Fraunhofer IAPT is considered. The production here is characterized by the development of parameter sets with a high number of manufactured test specimens, as well as by the production of individual components in small quantities for research purposes. At Fraunhofer IAPT, about 1500 density cubes are analyzed annually. For work without specifically required expertise, student assistants can be used, therefore personnel costs are low. The µCT cannot be used by students due to lack of qualifications, the personnel cost rate is correspondingly higher. Table 10 shows the total costs of the different methods for use case 1. The lowest total costs per measurement are possible with the automated density determination, followed by the manual Archimedes method, the preparation of micrographs, and the µCT.

For automated density determination and CT, not 100% of the time required was calculated as personnel working time. The reason for this is that both processes have a higher degree of automation, which means that the personnel do not have to operate the machine continuously and can use the time productively elsewhere. In automated density determination, a throughput of 12 parts per hour is assumed. The personnel time required for loading and starting the measurements is 10 minutes per hour, which corresponds to a personnel time of 0.83 minutes per part. For the CT, a measurement time of 150 minutes is assumed, this corresponds to a part throughput of 0.4 parts per hour. A personnel expenditure of 30 minutes per component is assumed.

Table 10: Total costs of the density determination methods for application case 1

		Micrograph	µCT	Archimedes	Disionic Density
Measuring time in minutes		**292**	**150**	**5**	**2**
Investment costs	Per minute	0,08 €	0,32 €	0,003 €	0,13 €
	Per measurement	**24,56 €**	**48,52 €**	**0,014 €**	**0,26 €**
Electricity costs	Power consumption	1,06 kW	8 kW	0,1 kW	0,8 kW
	Per minute	0,006 €	0,06 €	0,0008 €	0,006 €
	Per measurement	**2,32€**	**9 €**	**0,004 €**	**0,012 €**
Consumables	Per measurement	**50,00 €**	**0,00 €**	**0,50 €**	**0,50 €**
Unit costs	Per measurement	**76,88 €**	**57,52 €**	**0,52 €**	**0,77 €**
Personnel costs	Per minute	0,22 €	0,83 €	0,22 €	0,22 €
	Per measurement	**63,27 €**	**25,00 €**	**1,08 €**	**0,36 €**
Total cost	Per measurement	140,15 €	82,52 €	1,60 €	1,13 €
	Scaling factor	30	-	-	-
	Per measurement	**4,67 €**	**82,52 €**	**1,60 €**	**1,13 €**
	Minimum required measurements for the stat. Safety	3	-	3	-
	Per component	**14,02 €**	**82,52 €**	**4,80 €**	**1,13 €**

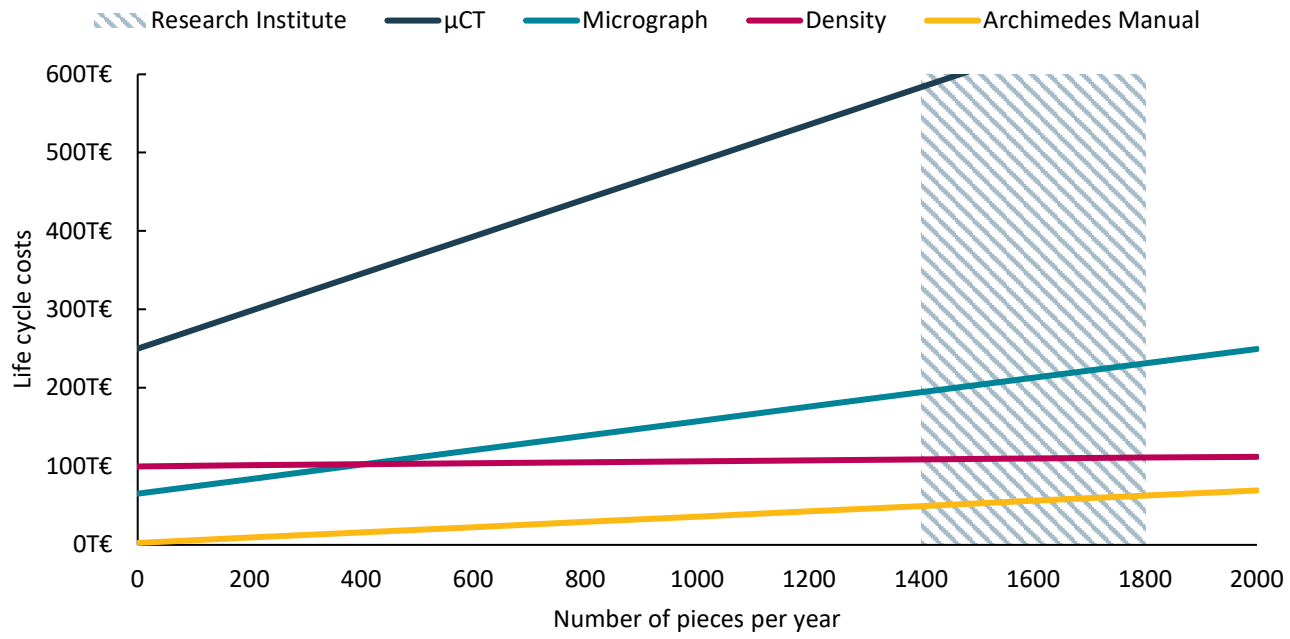

Figure 12. Costs incurred by the density determination methods as a function of the number of units analyzed per year for application case 1.

In Figure 12 the costs incurred over the lifetime of the machines as a function of the number of pieces analyzed per year is shown. Due to the low personnel costs at the research institute and the low acquisition costs, the manual Archimedes method is the cheapest. The µCT is expensive to purchase as well as to operate since it cannot rely on auxiliary personnel. The cost of micrographs rises steeply due to the high amount and cost of labor required, and the high percentage of consumables. The automated density determination is cheaper than the preparation of micrographs for the number of pieces considered. At the Fraunhofer Institute, a micrograph is usually created for density determination. Especially in the creation of parameter windows, it is useful to know not only the density of the specimen but also the morphology of the defects, therefore the

micrograph is a suitable measurement method, even if this method has strong limitations in reproducibility, as described in section 4.2. The manual Archimedes method is usually not relied upon because of high measurement uncertainty due to human and environmental factors.

Use cases 2 & 3: Contract manufacturer and series production

Table 11: Total costs of density determination methods for use cases 2 & 3.

		Micrograph	µCT	Archimedes	Disionic Density
Measuring time in minutes		**292**	**150**	**5**	**2**
Investment costs	Per minute	0,08 €	0,32 €	0,003 €	0,36 €
	Per measurement	**24,56 €**	**9,70 €**	**0,014 €**	**0,725 €**
Electricity costs	Power consumption	1,06 kW	8 kW	0,1 kW	0,8 kW
	Per minute	0,006 €	0,06 €	0,0008 €	0,006 €
	Per measurement	**1,75€**	**1,8 €**	**0,004 €**	**0,012 €**
Consumables	Per measurement	**50 €**	**0 €**	**0,5 €**	**0,5 €**
Unit costs	Per measurement	**76,31 €**	**57,52 €**	**0,52 €**	**0,98 €**
Personnel costs	Per minute	0,83 €	0,83 €	0,83 €	0,83 €
	Per measurement	**243,33 €**	**25,00 €**	**4,17 €**	**0,69 €**
Total cost	Per measurement	320,21 €	82,52 €	4,17 €	1,67 €
	Scaling factor	30	-	-	-
	Per measurement	**10,67 €**	**82,52 €**	**4,17 €**	**1,67 €**
	Minimum required measurements for stat. Safety	3	-	3	-
	Per component	**32,02€**	**82,52 €**	**14,05 €**	**1,67 €**

The second use case involves a contract manufacturer who produces components to order and has to ensure their quality independently. The quantities here are significantly higher than in the first use case. In addition, it is assumed that proven parameters are used and the scatter of the density is less pronounced than at a research institute. Quality assurance is carried out either directly on the component or via accompanying samples, which are produced simultaneously with the components during the printing process and then examined.

A higher number of pieces is assumed in use case 2 than in use case 1. The density determination can be carried out here via accompanying samples, for example, density cubes, or directly on the manufactured component, as long as the test method is non-destructive. Compared to the research institute, the personnel costs are now identical for each method and are at the level of a technician. Testing from actual components is advantageous because there is no need to extrapolate data from companion samples to the component. Furthermore, the powder is saved and the limited space on the build platform can be better utilized. Again, for the automated density determination, as well as the CT, a proportional calculation of the labor costs is used. For Dimensionic Density, a part throughput of 24 parts per hour, as well as a personnel cost of 10 minutes per hour is assumed. In the application under consideration, the CT has a throughput of one part every 2.5 hours, i.e. 0.4 parts per hour. A labor input of 30 minutes per part is assumed.

In series production (the third use case considered) a higher number of identical components are produced. Their quality must be ensured either continuously or via random sampling. Possible cost savings during operation are much more decisive here than the initial investment costs. Since most conventional methods for density determination are only suitable for series production to a limited extent, 100% testing of the components may be dispensed with.

In Figure 13 similar to Figure 12, the costs incurred for the density determination methods are shown as a function of the number of pieces analyzed per year. Compared to use case 1, the personnel costs are significantly higher, therefore the costs for all manual procedures increase more strongly.

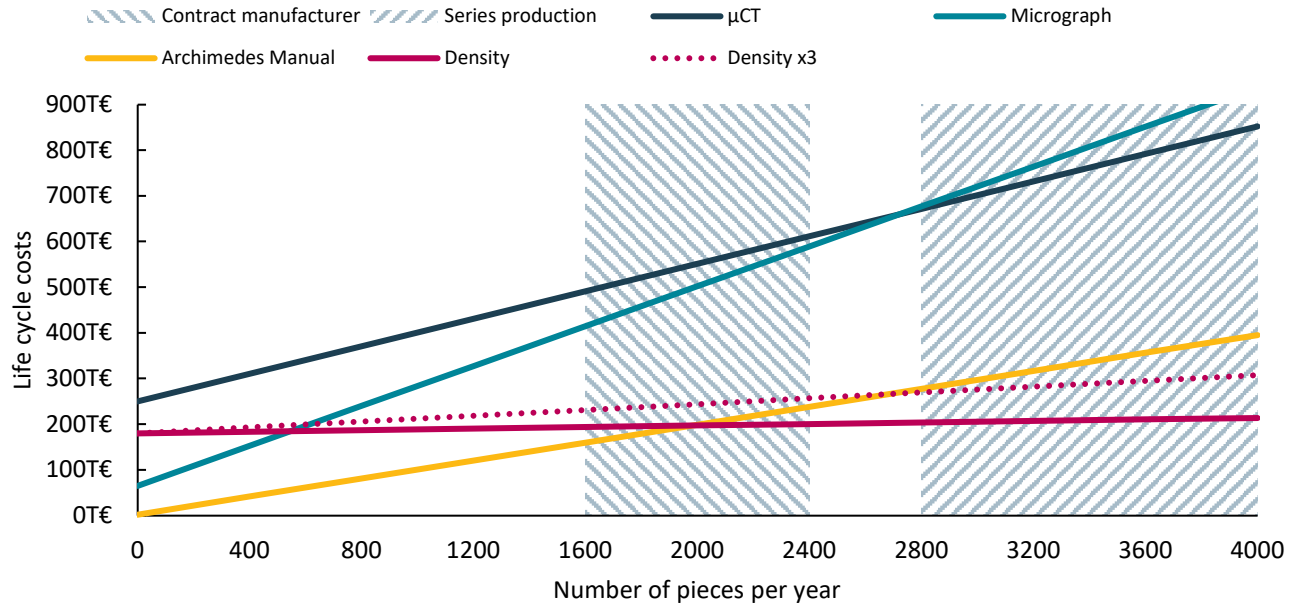

Figure 13Costs incurred by the density determination methods as a function of the number of units per year for use cases 2 and 3.

For use cases 2 & 3, automated density determination is the most favorable measurement method. Compared to the other application methods. The running costs due to personnel are significantly lower, as is the need for multiple measurements. Even when performing multiple measurements to increase statistical confidence (dashed red line in Figure 13), the method is still the most cost-effective.

5.4 Potentials in quality assurance

The examined methods differ in time taken and financial outlay, in the necessary qualification of the user, and in the quality of the achieved results.

Micrographs provide insight into the microstructure of a component and allow an evaluation of the pore shape. This is useful for parameter development since it is relatively easy to evaluate a parameter set. From the author's point of view, the micrograph is unsuitable for use in series production. The significant variation of the porosity within the component does not allow any statistically significant statements. Only with a high number of micrographs of the same specimen can a reliable statement be made. However, micrographs are relatively costly and time-consuming and are therefore not suitable for series production. In addition, since the method is destructive, only companion specimens can be examined.

CT investigations allow a three-dimensional reconstruction of a component. Due to the global consideration of porosity, this method is tolerant of porosity fluctuations within the component. The only obstacles to its use in series production are the comparatively high investment costs and the relatively long testing time. Furthermore, pores can only be imaged up to a certain resolution limit, which increases with larger component dimensions. This means that potentially critical pores cannot be detected on larger components. For more complex components, image processing and porosity determination are much more complex. This requires an experienced user, as well as powerful algorithms.

The manual Archimedes method is basically capable of determining the density of an AM-produced part or component. However, manual use can influence and affect the measurement result. This influence leads to high statistical uncertainty, which is why the method is often neglected.

Automated density determination addresses the weaknesses of the manual Archimedes method by automating most of the measurements. It also compensates for any environmental influence by recording the ambient parameters. In addition, the measurement is significantly faster than other methods considered. Therefore, this method is particularly recommended in areas where a statement on the density has to be made quickly or frequently. With this method, machine approvals can be simplified and thus the costs for quality assurance can be reduced.

A disadvantage of the Archimedean methods is that they cannot provide any (or only limited), information on the morphology of the defects. A combination of a standard automated density determination, as well as the performance of micrographs for a more detailed investigation of detected deviations in parts would be conceivable. Likewise, a combination of automated density determination and CT would also be useful, possibly with outsourcing of the CT scans to external service providers if the automated density determination has detected a deviation from the tolerated porosity. This would provide both a density determination that is suitable for series production and the possibility of precise examination when defective components are detected. Quality assurance would thus be faster and less expensive on the one hand, and potentially more accurate than a single procedure on the other.

6 Further reading

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