SUMMARY

The Additive Manufacturing (AM) Powder Bed Fusion (PBF) [1] processes are enabler of new concepts and approaches for product design, production and even business modelling. Thus, new demands are created on the building cycles and the production run itself. Due to the characteristics of the layered build process, it is possible to manufacture parts with functional integration, having complex geometries and at the same time with a high degree of personalization. However, can AM technologies really find their way into industrial environments? Can highly customized unique parts be additively produced as efficiently as conventional mass-produced parts?

Large manufacturers of additive manufacturing systems deliver nowadays only the equipment, and do not support the needs of the users, mostly SMEs, as far as Quality Assurance (QA) is concerned.

Beginning to view AM in an industrial environment, reliable statements about product quality are indispensable. Statements regarding compliance with geometric tolerances and exact quantifiable physical parameters, in terms of product certification are therefore imperative. The sooner the identification, acquisition and in-process influence of these parameters became reality, the higher the efficiency of the AM processes are. Therefore, the quality of the AM parts must not only be sustainably secured, but also reproducible at any time.

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are the two most important AM PBF techniques, being the genuine hopes for the industrial contenders, ranging from automotive and even aerospace applications to the medical field. The quality of the SLS and SLM parts and their designed functionality can be very easily impaired, taking into consideration the following items:

- Nowadays the Quality Management (QM) and QA is not ensured.
- Neither Quality Standards nor a generally accepted QM Standard or System are available.
- A larger variety of parameters are influencing the manufacturing processes based on these techniques and so the quality of the build parts.

Regarding the QA chain for the SLS and SLM processes, with respect to inline Quality Control (QC) and in-process optimisation, the scientific needs are given by the fact that part quality problems, appearing during the production process and being caused by different factors, are leading to vulnerabilities, fractures, or product failures.

A reliable inline part and process monitoring as well as a real-time optimisation of the AM PBF processes are crucially, not only for the service providers in this field but also for all end users of the AM parts, so that the products meet the required quality and safety standards in the different fields of applications.

In this context, the concrete aim of the present thesis was the realisation of an AM PBF machine-independent, modular inline Quality Control (QC) system based on Industrial Image Processing (IIP), using the example of the SLS. Briefly, a user-friendly machine-independent and modular system using machine vision technology have arise in order to ensure and log, through an inline layer-by-layer inspection, the quality of the SLS produced parts.

Starting with outlining the background of AM, a critical analysis of the AM technologies, highlighting their suitability for a future batch production has been conducted. The result was that the SLS technology, despite limitations in terms of accuracy, cleaning efforts and surface finishing, is above the average in all areas of importance for a possible batch production.

In the same time IIP, known also as Machine Vision, is one of the most important computer vision field aside e.g. Medical Image Processing. IIP systems are extremely versatile: they can identify objects, verify the quality of a product, and even control different processes and machines. In this context, the question without a comprehensive scientific answer was: can 2D IIP ensure an inline quality control for an AM PBF process? Can 2D IIP be the enabler of the SLS batch production, by ensuring the quality and reliability of the manufacturing parts? Will it be possible to identify the inline defects having such a low scene contrast ratio (see Figure 1)?

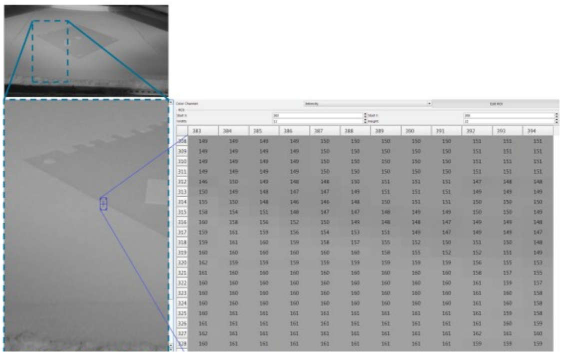

Figure 1. SLS layer: low scene contrast ratio.

For the part's quality monitoring, during the build cycles, another question, still without a comprehensive scientific answer, was: which are the overall tasks for an inline QC system? Which are the overall effects of the influencing parameters on AM processes having an appearance during the manufacturing process itself? In this context, embedded in the state of the art, a comprehensive approach was developed in order to identify all defects and failures having an appearance during the build cycles of the AM PBF processes. For all AM PBF techniques, the approach's starting point are the four categories of the QM aspects: *Equipment*, *Feedstock*, *Production* including Batch, and *Part* including Finish [2]. The overall inline defects and failures for the respective AM PBF process are given by the in-process appearance of the *Potential Quality Failure Effects* (Figure 2).

A prioritisation of the determined inline defects and failures was implemented in order to assure a firm foundation for the development of an inline QC system, respectively for future in-process control schemes. For the ranking of the probability and severity of the *Potential Quality Failure Causes* and of their corresponding effects, respectively of the inline defects and failures, two factors have been taken into account: their occurrence frequency and the sunk costs directly implicated. A Design of Experiments (DoE) has been implemented in order to generate clear-cut conclusions for the ranking of the frequency of the inline defects and failures.

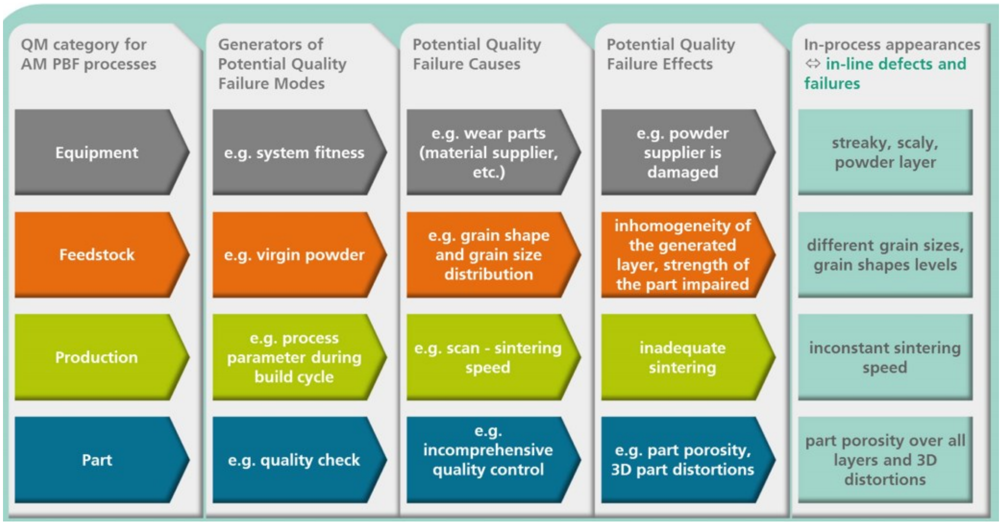

Figure 2. Schematic diagram of the approach for the identification of inline defects and failures during AM PBF processes.

For an inline QC system [3], in order to develop a concept as well for a hardware (HW), as for a software (SW) platform, the ranked tasks have been classified, taking into account the AM PBF production steps. Based on the classified tasks, an overall concept for an inline QC system in the AM PBF production was worked out as a *novelty*[1].

The HW platform is a modular one, in order to allow in the future:

- to add easily other sensors in order to solve new quality issues that will appear with the development of the AM PBF machines,
- to adapt easily the system to other AM PBF processes,
- to allow a data fusion of the sensors on the Software (SW) side of the future system.

Exemplarily for a SLS machine Formiga P100 (Fa. EOS), for an overall inline QC system, the appropriate technologies and sensors for a multi-sensor analysis and field monitoring have been grouped in necessary system modules in order to solve the classified tasks. Three Inline Quality Control System Modules (IQCSM), two Machine Vision Systems and one Thermography System, are necessary, in order to cover the overall tasks [3]. Further more, concerning the design of the hardware architecture, the overall hardware concept, and interfaces have been worked out.

A dedicated common software (SW) framework, the AM PBF Inline Quality Control Platform (AM-IQCP), was developed based on [4]. AM-IQCP, emphasising an automatic data evaluation platform, includes different modules for the different evaluation strategies. All suitable interfaces, algorithms (the ones specifically for each technology as well as the ones corresponding to the data fusions), together with their complex functionality, can be then modular implemented under the AM-IQCP framework. The AM-IQCP application is developed under Microsoft Visual Studio (Visual C++) with Qt (32-bit and 64-bit). Designed as a modular software

[1] *"forming a distinct contribution to the knowledge of the subject and/or evidence of originality by the discovery of new facts and/or by the exercise of independent critical power"* [14]

framework, AM-IQCP allows the integration of different plug-ins and libraries at any time and the separation of the functionality of the platform into independent, interchangeable modules.

Starting from the HW concept, respectively from the appropriate technologies and sensors for the data and signal acquisition necessary to cover all the ranked tasks, the HW implementation concentrated on one inline QC system module, the IQCSM 2, as its' successful implementation cover the most ranked tasks determined. The development of the IQCSM 2, which is an AM PBF specific Machine Vision System, was conducted on a SLS machine, namely the EOS Formiga P100. The basis of the construction is an aluminum modular profile system. The modularity is ensured at any time in any place. For each component (e.g. machine vision camera, lighting sources) special connectors have been developed, so that comprehensive adjustment possibilities for every sensor added are given (e.g. position in (x,y,z), angle).

Another component of the machine vision system, as critical as the imagine acquisition hardware component, is the inline image acquisition and processing engine itself, that renders and communicates the final result.

Novelty[1]. The implemented SW engine of the inline QC system for reliable AM PBF processes, using the example of SLS, consist of two main IIP routines: the *Inline Image Acquisition* and the *Quality Control* one. The modularity of the platform easily allows the integration of new algorithms at any time. In this way, the HW modularity is strongly supported by the SW. All algorithms have been implemented in C++, in form of plugins. A modular framework, the EyeVision3 framework, was integrated in order to assure a basic development environment (e.g. image memories are directly managed by the framework). The Open CV "imgproc" and "calib3D" modules have been integrated.

For the development, implementation and validation of the modular inline QC system components the US National Institute of Standards and Technology (NIST) test artefact has been used [5].

Novelty[1]. The developed system is an AM PBF machine-independent one: the data acquisition is triggered directly by a dedicated SW subroutine over a data analysis, the data being delivered by the machine vision HW components. The overall advanced IIP SW routine, not only ensures an inline layer-by-layer inspection of the additive manufacture parts, but generates at the same time a quality protocol for each produced part. The standalone SW application, with a friendly GUI, is thanks to the Qt library implementation, operating system (OS) independent. In this way, the software application can run not only on Intel or on AMD, but also on ARM and MIPS architecture based systems. Through the SW and HW integration a modular system has been achieved that can continuously inspect the quality delivered by the AM PBF production and give an inline feedback to the machine operator.

The two main developed software routines, the *IIP for Inline Image Acquisition* and the *IIP for Quality Control*, and their subroutines have been integrated, connected with each other, in a final advanced IIP SW routine, which ensures an inline QC of the AM PBF SLS process.

IIP for Inline Image Acquisition. The developed Machine Vision System is a machine-independent one. This means that the data acquisition process cannot be triggered by a machine signal. The scientific challenge was, based on the live image information, to develop an IIP routine which acquires the significant images at the right time. The image acquisition corresponding to a sintered or a powder layer will be triggered by the position of the material supplier (Figure 3). After the image is captured, the image distortion correction takes place as well as the layer type identification.

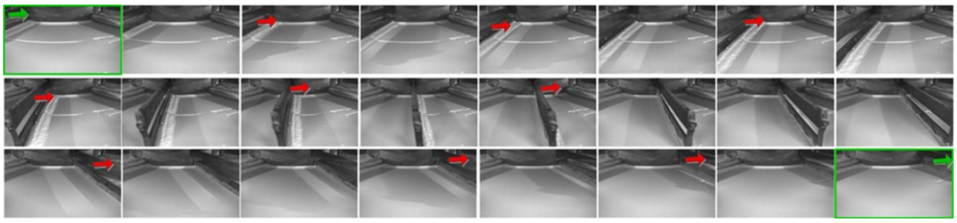

Figure 3. Exemplarily wiper movement (left-to-right) – first and last image of this sequence will be acquired for the quality control.

IIP for Quality Control. In case of powder layers (see Figure 4): if no serious failures are found then a subtle failure inspection takes place. If no further failures are found, the layer will be classified as i.O., else it will be classified as n.i.O. If one wide or subtle failure is found during the automatic inspection of the powder layer then the failure will be logged in the part quality protocol.

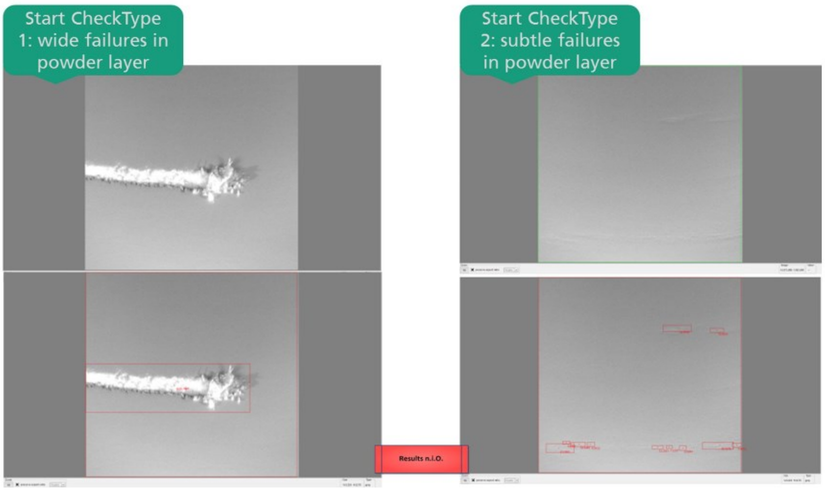

Figure 4. Pulver layer inspection: exemplarily results of the *IIP for Quality Control* SW routine.

In case of sintered layers (see Figure 5): if no serious, wide, or subtle failures are found, a nominal/actual comparison of the sintered features number takes place. If the numbers are different, the layer is classified as n.i.O.; a quality problem appeared, as in the sintered layer the number of features differ to the one in the nominal layer. If the number of the features is the same, the measuring operations for different features are executed and the results are compared with nominal values, taking into consideration the tolerances. Every detected defect will be logged in the part quality protocol.

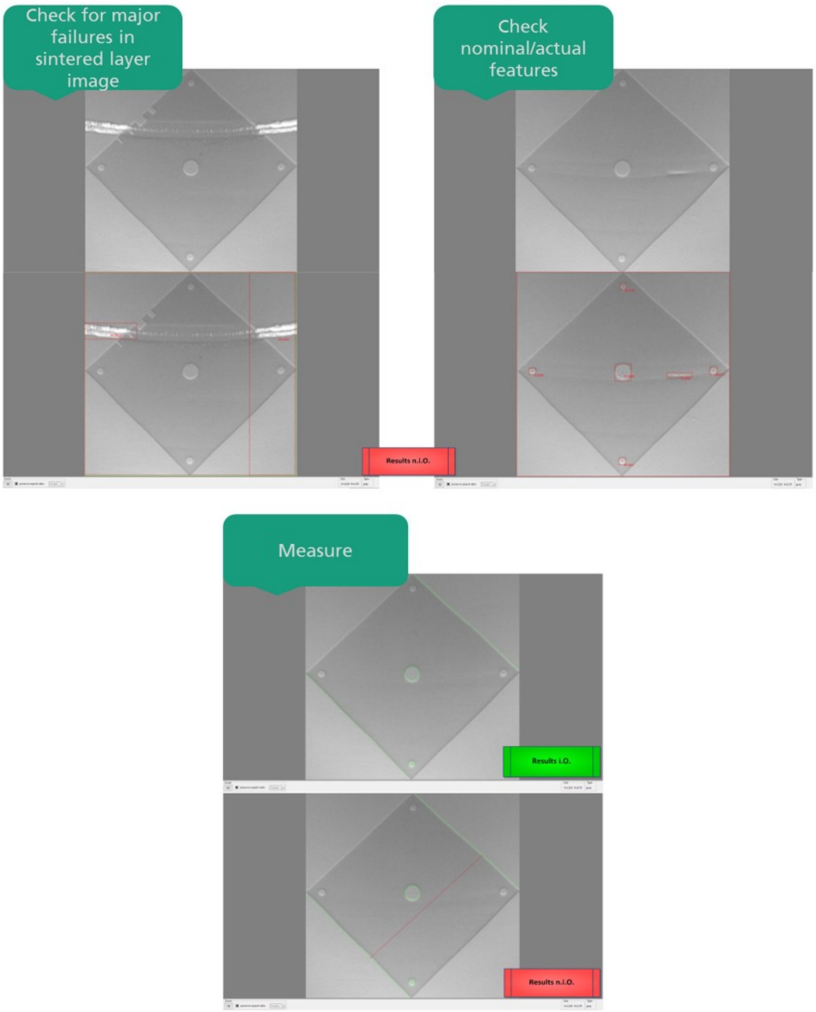

Figure 5. Sintered layer inspection: exemplarily results of the *IIP for Quality Control* SW routine.

In both cases, after the evaluation procedures, the user is informed about the layer inspection results and the system will wait for the trigger signal, given by the SW routine *IIP for Inline Image Acquisition*, in order to acquire the next image.

The developed graphical user interface (GUI) is a very friendly one. Two layouts have been implemented: the *Inspection Program Setup* and the *Inline Inspection* one (see Figure 6). The first one is for an advanced user that can parametrise the SW for a specific build job; the other, independent from the user qualification degree, where the user is just loading a build specific inspection program and just runs it.

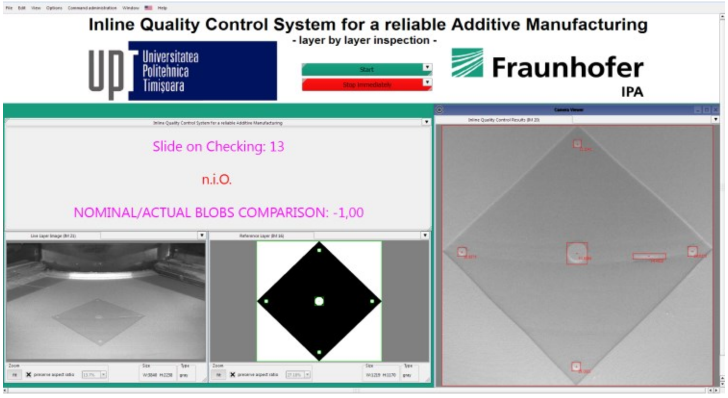

Figure 6. GUI layout: *Inline Inspection*.

In order to bring together the HW and SW components of the system, only an Ethernet cable is necessary, which ensures the data transfer from the Machine Vision Camera over the GigE Network Board to the system running the application. The overall implemented system is presented in Figure 7. The system has been installed on the EOS Formiga P100 at Fraunhofer Institute for Manufacturing Engineering and Automation IPA (Fraunhofer IPA), where in-process, the quality of the manufactured parts was inspected. The user has the possibility to stop the process in case of serious failures and has for each manufactured part a quality protocol.

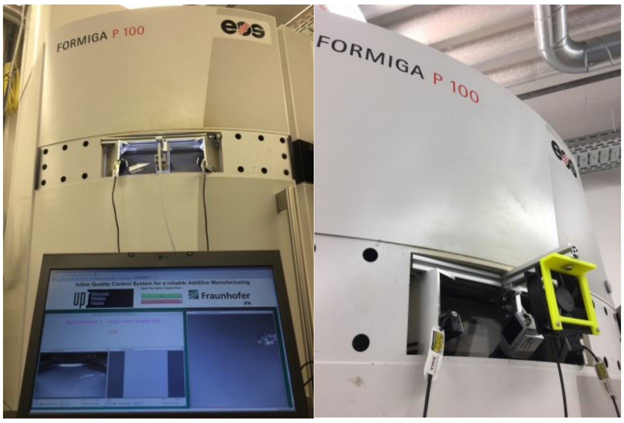

Figure 7. Hardware and software integration in final system (left); system HW with integrated fan (right).

The verification stage was very important in order to further improve the system and to verify the results achieved. As up to date, no inline system ensures the quality control of AM PBF produced parts, it was necessary to use, as reference for the verification of the results, an offline technology; therefore, the advantages of industrial computed tomography (CT) have been used [6]. The CT results are confirming the results obtained by the inline QC system.

The system accuracy is first given by the hardware components. The machine vision camera has a resolution of 10 MP (3856 x 2764 pixels). Taking into consideration the Modulation Transfer Function (MTF) of the used lens and the working distance of 350mm, the resulted field of view is 320x240 mm. Based on this, the system optical resolution is 82 microns. This accuracy is the same for the 200x250mm inspected area, corresponding to the build platform. However, because the necessity of an image distortion correction, given by the fact that the camera system is not parallel with the build platform to be inspected, the pixel size in real world units lowered to 116 microns. Therefore, in order to evaluate the inspection and measure accuracy, we will refer to pixel units.

The developed system can identify failures having a size of at least three pixels even if the image contrast is extremely low (see Figure 8).

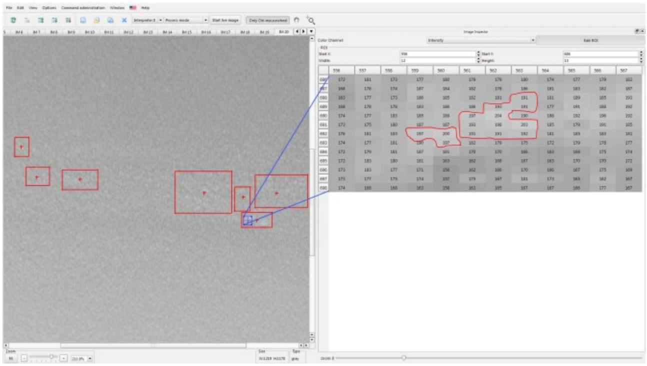

Figure 8. Powder layer image: one n.i.O. region with detailed pixel values.

For the measured features, as circle diameters and distances, the accuracy is given by the accuracy with which the features are automatically found in the image. For a sintered layer the Figure 9 demonstrate the system high capability to fit such geometries in such low contrast images.

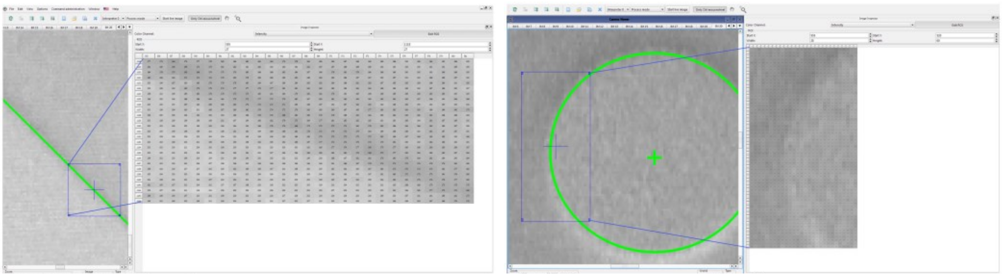

Figure 9. Sintered layer image: fitted line (left) and fitted circle (right).

The overall obtained results are, taking into consideration the given low image contrast, an achievement which reflects the distinct contribution to the field of inline QC for the AM PBF processes.

Conclusions

Starting from the critical analysis of the state of the art of the QC and QA of the AM PBF processes, the main goal of the present thesis was to bring distinct contributions in the field of inline QC, aiming to create a firm foundation for a reliable future additive batch production.

The thesis treats a series of theoretical issues concerning the parts' quality monitoring during the build cycles, which is influenced by a huge number of parameters. An approach for the determination of the overall effects of this influencing parameter, having an appearance during the AM PBF processes, have been carried out. The overall sistem tasks have been in this way determined and a comprehensive concept for an inline QC system in the AM PBF production was accomplished.

The applicative part of the thesis presents the development and implementation of an inline QC system for the AM PBF, based on IIP, using the example of one of the most promising technology, for a future batch and even serial AM production, namely the SLS manufacturing process. The development and implementation of the experimental research work took place at the Fraunhofer IPA.

Over the determination of the technologies, and sensors necessary for data acquisition and the design of the hardware architecture, an experimental hardware setup was worked out. During the development stage, important aspects have been considered as e.g. the price/performance ratio and the modularity of the HW platform. A very important aspect is here the achievement of a machine independent HW platform.

Further, the software components for the layer-by layer inspection have been developed, in form of two main SW routines based on IIP: one for the machine independent data acquisition and the other one for dedicated algorithms for data evaluation during the AM PBF manufacturing processes. During the inline QC of the part being produced, all detected failures are logged in a dedicated part quality protocol, over the AM PBF production time. In this way, not only the quality of the parts, but also the prerequisite for using the AM PBF parts in industrial environments are ensured. The applicative part of the thesis concludes with the implementation and testing of an innovative and novel inline QC system, mounted on a SLS machine from the company EOS [7], namely the Formiga P100.

The fact that the conducted research work is closing a gap in the state of the art concerning the QC and QA of AM PBF processes, is also given by its high degree of applicability. In order to install the system no approval of the manufacturers of the AM PBF systems is needed, as there is no necessity to access the HW interfaces of the AM machines. Thus, no ISO standards certificates are necessary for the integration of the system on the machines. The system provides at the same time the possibility of being extended at any time, with further sensors and/or algorithms. Herewith a firm basis for a future in-situ AM PBF process optimisation was attained.

The doctoral thesis statements are proved to be true, as the achieved QC system ensures inline, tirelessly the quality of the parts build on a SLS machine at the company cirp GmbH [8]. Here continuously, during the AM PBF production, the inline QC system:

- detects quality failures during production process,
- offers a quality report of the produced parts,
- offers to the user the possibility to cancel the production process in extreme cases,

- needs no users with technical expert knowledge, since it requires a small number of input parameters.

A dissemination of the conducted research work, representing the content of this doctoral thesis, has been carried out in [9] [10] [11] [3] [12] [13] [14].

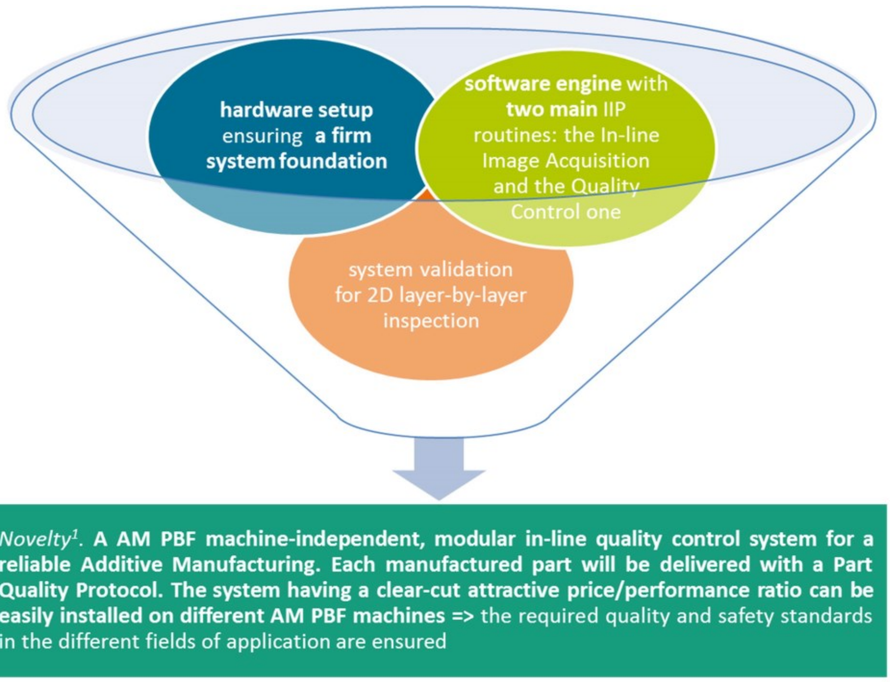

Figure 10. Inline QC system for the AM PBF processes: forming the main distinct contribution to the knowledge of the QC in the field of tomorrow's additive production.

In conclusion, the main objective of the thesis was achieved. Through all distinct contributions, culminating in the inline QC system for the AM PBF production (see Figure 10), the first enabler of the large AM PBF batch production was realised, namely a system that:

- ensures a machine-independent approach;
- is able to work uninterruptedly, performing 100% inline inspection, hence improved AM product quality, higher yields and lower production costs;
- can detect quality failures during AM PBF production processes;
- creates a quality report of the produced part;
- can indirect cancel the production process in extreme cases;
- has a clear-cut attractive price/performance ratio.

Through these achivements, the results of this doctoral thesis open up further research work topics, as e.g.: part inspection on 3D level; conjunction with production accompanying methods for the operational quality assurance (e.g. Statistical Process Control); direct correlation between each detected failure and its associated production parameters for a future applicable in-situ process optimisation.

REFERENCES

[1] ASTM International, ISO/ASTM 52900-15, Standard Terminology for Additive Manufacturing – General Principles – Terminology, West Conshohocken: , 2015.

[2] M. Schmid and G. Levy, "Quality Management and Estimation of Quality Costs for Additive Manufacturing with SLS," in *Proc. of Direct Digital Manufacturing Conference 2012*, Berlin, 2012.

[3] S. Fulga, A. Davidescu and I. Effenberger, "Conceptual approach for an in-line quality control system in Additive Manufacturing Powder Bed Fusion processes," in *Paper will be presented at the 4th international conference on computing and solution in manufacturing engineering - CoSME'16*, Brasov, to be published, 2016.

[4] I. Effenberger, T. Felix, A. Frommknecht and S. Fulga, "Machine vision platform for non-destructive testing methods of fibre reinforced plastics," in *Proc. 19th World Conference on Non-Destructive Testing 2016*, Munich/Germany, 2016.

[5] S. Moylan, J. Slotwinski, A. Cooke, K. Jurrens and M. A. Donmez, "An Additive Manufacturing Test Artifact," *J. RES. NATL. INST. STAN. (Journal of Research of the National Institute of Standards and Technology),* vol. 119, p. 429, 2014.

[6] J. Kroll, S. Botta, J. Breuninger and A. Verl, "Adaptive quality assurance of the product development process of Additive Manufacturing with modern 3D data evaluation methods," in *IS&T/SPIE Electronic Imaging*, Burlingame, California, United States, 2013.

[7] EOS GmbH, http://www.eos.info/en.

[8] cirp GmbH, 2016. [Online]. Available: https://www.cirp.de/verfahren/lasersintern_EN.php5.

[9] S. Fulga, A. Davidescu, I. Effenberger and A. Verl, "In-line quality control system for a reliable Additive Manufacturing -layer by layer inspection-," in *Paper will be presented at the International Conference on Additive Technologies - iCAT 2016*, Nürnberg, to be published, 2016.

[10] S. Fulga, A. Davidescu, I. Effenberger and A. Verl, "Tasks for in-line quality control and in-situ optimisation of Additive Manufacturing Powder Bed Fusion Processes (Professional)," in *Paper will be presented at the International Conference on Additive Technologies - iCAT 2016*, Nürnberg, to be published, 2016.

[11] S. Fulga, A. Davidescu and I. Effenberger, "Identification of in-line defects and failures during Additive Manufacturing Powder Bed Fusion processes," in *Paper will be presented at the 4th international conference on computing and solution in manufacturing engineering - CoSME'16*, Brasov, to be published, 2016.

[12] S. Fulga, "Qualität 4.0 für die additive Fertigung der Zukunft : Intelligente Qualitätssicherung und Optimierung," in *Vortragsforum:Qualität 4.0 - Neue Herausforderungen an die Mess- und Prüftechnik*, Stuttgart, 2016.

[13] S. Fulga, "Qualität 4.0 für die additive Fertigung von Kunststoffbauteilen : Intelligente Qualitätssicherung und Optimierung," in *20. Anwenderforum Rapid Product Development*, Stuttgart, 2015.

[14] G. Kreiseler, J. Kroll, S. Fulga and I. Effenberger, "Quality assurance for the complete process chain of Additive Manufacturing with modern metrology techniques," *Proceedings of the 14th International Conference of the European Society for Precision Engineering and Nanotechnology,* vol. 1, pp. 121-124, 2014.

[15] D. Silverman, "Doing Qualitative Research," Sage Publications, London, 2009.