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INDUSTRIALIZATION AND CURRENT FIELD EXPERIENCE OF ADDITIVELY MANUFACTURED GAS TURBINE COMPONENTS

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ABSTRACT

During the last years, a new revolutionary way of manufacturing - Additive Manufacturing (AM) has emerged the industry and is considered as a game-changer. This technology enables OEMs to manufacture and repair gas turbine components faster and at the same time with enhanced functionality and performance. Currently Siemens Power Generation is using this technology for prototyping, manufacturing, repair of gas turbine components, and spare part manufacturing [1-3]. Industrialization of the AM technology at Siemens Power Generation and current accumulated field experience of AM manufactured components will be discussed in this article.

Siemens applied AM technology for the repair of gas turbine components in particular for burners of the SGT-700 and SGT-800 industrial gas turbines. It was shown that the replacement of conventional repair with AM resulted in significant reduction of repair time. Moreover, modifications and upgrades opportunities can be incorporated in the repairs.

Another successful application of AM technology at Siemens is the manufacturing of advanced burner swirl for SGT-750 industrial gas turbine. In this case AM was the only technology which enabled manufacturing of this design of the swirl.

An excellent example of the effective application of AM technology for re-manufacturing of obsolete components was demonstrated by AM manufacturing of a water pump impeller, part of the fire protection system at one of the nuclear power station in Slovenia. In this case the 3D model of the impeller was obtained by X-ray tomography followed by digital ‘repair’ of the scanned model to original geometry and subsequent 3D-printing including qualification.

At Siemens the concept of ‘Spare parts on demands’ was launched by 3D-printed SGT-1000F burners tips for a district heating power station in Czech Republic.

INTRODUCTION

AM enables improved product development possibilities, mainly through reduced time to component testing and more time for iterative design development. Low volume manufacturing is possible due to the ability to avoid costs related to tooling manufacturing and minimized need for machining operations. In particular industry segments AM has gained trust and is in use. The production method is considered to be immature with scepticism to material performance and limited knowledge about process variations still. Process monitoring is not well-established yet as well. Therefore, large efforts have to be put into qualification and validation of AM components today. With an increased knowledge and understanding of the process and materials the competitiveness of AM processes will dramatically change.

Already today Aerospace and Automotive industry has identified the benefit of generating weight-optimized geometries with adequate strength. Oil and Gas industry can utilize the process in applications similar to aerospace and automotive, but the focus here can be found in lead time reduction for new manufacture and instant spare part availability for secure production without long equipment outage periods.

As already mentioned, AM is a revolutionary technology enabling component performance enhancement and delivery time reduction at the same time. AM is a new dimension in the integrated design and manufacturing converting our dreams into reality, with practically no limitation and at extremely short delivery time.

With this technology complex components with a high degree of functional integration can be produced as one integral part with higher performance and in majority of the cases practically at the same cost (e.g. gas turbine burners with lower emissions and higher lifetime, gas turbine vanes with better cooling efficiency and longer life time).

At Siemens AM technology is used (in this article we will discuss mainly SLM ─ Selective Laser Melting AM technology) for the following main applications:

- Rapid prototyping,
- Rapid manufacturing for new apparatus and spare parts, and
- Rapid repair.

APPLICATIONS

Rapid Prototyping Integration of AM into the product development process enables significant speed up of design and validation of new components and system and ensures high reliability and performance of newly designed components prior to final engine test and product release.

In the past, due to long delivery of new components manufactured by conventional methods (e.g. casting), component validation testing was accomplished almost at the end of the development process during the final engine test. This is why a conventional development procedure incorporates some disadvantages and consequences:

- Sequential development process,
- Conservative development approach,
- Moderate development targets/results,
- Long development cycles.

With the new approach, AM is an integral part of the development process and can be used for rapid component design and manufacturing. Hence, following advantages could be realized:

- Parallel and integrated development processes,
- Radical development approaches,
- Ambitious development targets/results,
- Fast development cycles.

Some facts: utilization of AM technology at Siemens for turbine blade design enables the evaluation of a few blade cooling concepts and their tests in real engine environment in a few months instead of a few years.

Rapid Manufacturing For Siemens Power Generation, industrialization of AM technology also enabling new opportunities for spare part and supply chain enhancement:

- Quick re-manufacturing of the obsolete components, that are not in production any more,
- Manufacturing of spare parts on demand,
- Regionalization of rapid manufacturing, and
- Simplification of logistics as well as investment reduction on stocks (valid for both Customers and OEM).

Today Siemens has several combustor components of Siemens gas turbines across all power classes in commercial operation. One of the first successful applications of AM serial manufacturing at Siemens was the manufacturing of advanced burner swirlers for the SGT-750 industrial gas turbine as shown in Figure 1.

Figure 1: Advanced burner swirl manufactured by AM for SGT-750 industrial gas turbine

In this case, AM was the only technology enabling the manufacturing of the highly complex swirl design. Since the introduction of the SGT-750 industrial gas turbine to market in 2013, AM manufactured swirlers are in continuous commercial operation. In 2017 the fleet leader accumulated 30,000 hours of operation.

Rapid Repair Repair of components has also been identified as an application with big potential [2,3]. Damaged areas of material can be removed and rebuilt. Just as for new manufacturing, the lead time reduction is expected to be significant, especially for complex compound structures or raw materials with long lead time from order to supply.

The recently developed SGT-700 and SGT-800 burner tip repair procedure by SLM technology is ten times quicker than previously used conventional repair procedure, as it allows avoiding quite a few manufacturing and inspection processes.

Replacement of conventional repair processes with SLM provided not only a significant reduction of repair time, but also an opportunity to upgrade repaired components to the latest design.

AM FOR GAS TURBINE COMPONENTS REPAIR

By the introduction of SLM technology within gas turbine repair back in 2013, Siemens took the first step to bring the new technology out from the laboratory into an industrial production environment. Burner tip repair has for a very long time been done by conventional methods – i.e. cutting off the tip and replacing it with a pre-manufactured one. However, in 2013 Siemens launched the first burner repaired by SLM technology [1].

By doing so it involved a far wider group of people and it was also subject to a more production adopted process thinking involving quality assurance and logistic handling. Special processes were developed to support the SLM repair procedure.

Typical damage to be repaired The burner tip face is directed into the combustion chamber and exposed to the hot gas and heat radiation from the flame (see Figure 2), causing thermomechanical fatigue and oxidation damages to the tip. The rest of the burner is protected by the combustion chamber and, in general, exposed to low thermal and mechanical loads.

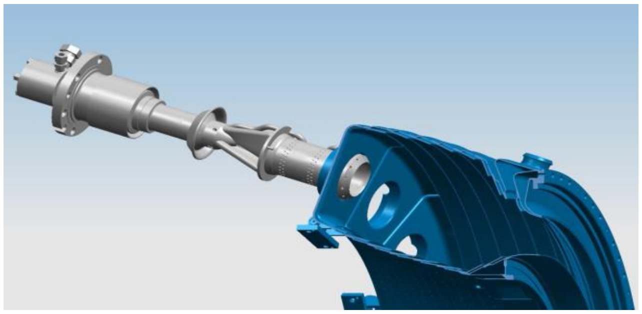


Figure 2: Typical burner and combustor configuration of burner (left) and combustion chamber.

During the repair process the tip is replaced. Earlier, conventional cutting and welding operations were utilized, processes in which Siemens has vast experience after repairing more than 5,000 burners during the last 15 years.

AM repair process description and industrialization challenges The traditional repair method was replaced with an innovative AM repair process based on SLM in a customized AM machine.

Even if fatigue and oxidation are only affecting the outmost 10 mm of the burner tip, the internal design of the burner makes it more favorable to cut the tip further upstream.

At the original conventional repair process with a traditional TIG welding the burner was cut 120 mm upstream as Figure 3 illustrates (red line). This involved removing the complete burner head including the external fuel pipes and instrumentation.

At SLM repair the cut is made 20 mm upstream indicated by the purple line. This location is chosen so that it will give a proper surface to start on, without too thin edges, and still a reasonable small amount of material to rebuild.

Figure 3: Gas turbine burner repairs in the traditional fashion (red line) and the described novel repair process (purple line).

The new SLM repair process (see purple line) consists of the following major steps:

a) Remove the damaged tip by machining,
b) Position the burner in a special fixture,
c) Position the CAD model on the substrate burner face with the help of a position- finding camera system,
d) “3D-print” a new tip in place,
e) Remove powder particles from cavities, and
f) Disassemble the fixture.

Additional supporting processes were developed for:

a) Quality assurance and inspection methods,
b) Powder handling and reconditioning of powder batches,
c) Process and material qualification, and
d) Development of methods for mechanical integrity calculation.

To accurately position the CAD-model that is to be printed onto the burner substrate, an optical system was incorporated in the SLM machine. From the camera image the substrate edges are identified and the software adjusts the position of the CAD-model in X, Y and tangential direction.

The DLE (Dry Low Emission) burners to be repaired have a height of about 720 mm. To accommodate an entire burner, the AM machine was re-designed in critical areas such as the z-axis responsible for the precise downward movement of the powder bed and the burner substrate during the layer-by-layer manufacturing. A unique holder-lifter device had to be designed in order to guarantee an ergonomically acceptable work position for the operator when loading and unloading the burner from the machine as Figure 4**Error! Reference source not found.** reveals. This re-design also impacts the powder handling and gas flow characteristics in the process chamber of AM machine.

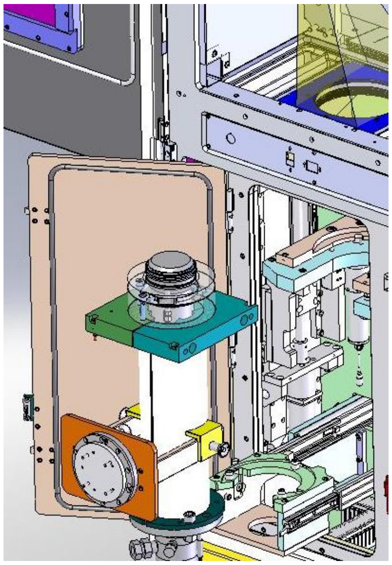


Figure 4: New machine design with novel z-axis configuration and process chamber design (curtesy of EOS GmbH).

Quality assurance By introducing this new technology there was also a need to review and develop additional supporting quality assurance steps to ensure a reliable process chain. In particular, the correct component geometry and parameter setting need to be loaded into the machine equipment. Here, this means that a large number of different unified job files in the .jz-format must be handled.

It must also be possible to, from each repaired burner, trace back the used powder batch and its recycled properties.

To keep track of this data Siemens decided to use a digital solution and introduced a manufacturing execution system (MES) based on the latest standard of the Siemens Simatic IT "Unified Architecture (UA)" as outlined in Figure 5.

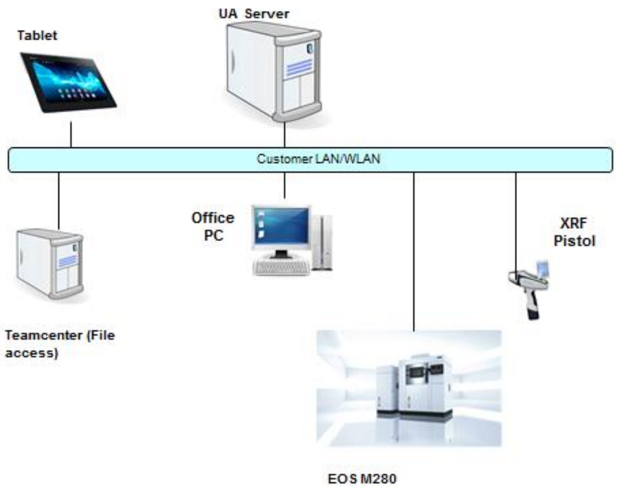


Figure 5: Manufacturing execution system (MES) architecture.

Field validation and burners examination Since the introduction in 2013, a number of burner sets have been put in operation and there has not been reported any faults related to any burner repair male function so far.

There has also been made detailed examinations of burners at Siemens' material laboratory both by non-destructive testing (NDT) and destructive examination [4-6]. NDT has been carried out via ultrasonic (immersion technique) and penetrant (fluorescent dye) testing prior to destructive examination of the burner tips. The burner tip areas subject to examination are shown in Figure 6.

Figure 6: Burner tip area subject to destructive examination.

Examination results The non-destructive and destructive examinations showed that all burners subjected to these tests were in serviceable condition with the following examination details:

- The penetrant testing did not reveal any defects on the surface.
- Oxidation could be seen up to 50 µm into the material. Some areas revealed grain boundary attack as well as light surface oxidation.
- The bond coat appeared to be in good condition with aluminum-rich phases still present.
- The hardness of the printed material between the pilot holes and the burner tips exhibited little change.

Current status and accumulated operation experience Since the introduction in 2013, Siemens has successfully repaired and put in operation a great number of SLM repaired burners. During the repair older variants have been modified and updated to the latest standard. A number of these burners have been laboratory examined after operation and shown to be in excellent condition which was confirmed by metallurgical investigations.

The SLM repair method is now the first choice when repairing burners and is considered to be mature. In 2017 the fleet leader has been operated more than 30,000 EOH (equivalent operation hours) and the unit with most start/stop cycles has recorded more than 500 starts.

ADDITIVE MANUFACTURING FOR SPARE PARTS ON DEMAND

The on time availability of spare parts for maintenance and repair purposes is key in energy business and in particular for gas turbines as the core product of gas fired power plants. Hence, the plant operating companies are interested in reliable service concepts. Siemens as an OEM and experienced MRO company is therefore looking for concepts to improve the up-time of their gas turbines through innovative service concepts. Additive manufacturing is playing an important role for these service concepts.

Through AM parts can be manufactured on demand within short lead times. Usually the required time till delivery reduces from months to weeks. Typically, the technology is beneficial in replacing complex investment cast products by a tool-less production chain making expensive casting dies obsolete. This is beneficial in case the supply chain needs to be adapted but also if upgrades are required. Additionally, AM can be cost efficient in particular for smaller lot sizes where conventional machining suffers from the ability to stream line production.

Nonetheless, cost out potential in AM suffers also from small lot sizes since the conventional part of the manufacturing chain massively contributes to the overall costs. Moreover, the full potential of AM is only leveraged by appropriate design. However, a design change might be considered as commercially ineffective for a mature frame that is no longer in serial production.

The SGT-1000F is such a mature engine (Figure 7). It is made for power generation with highest efficiency for industrial applications and fossil power plants. With its 24 burners in an annular combustion chamber it is set-up similar to the well-known SGT5-4000F.

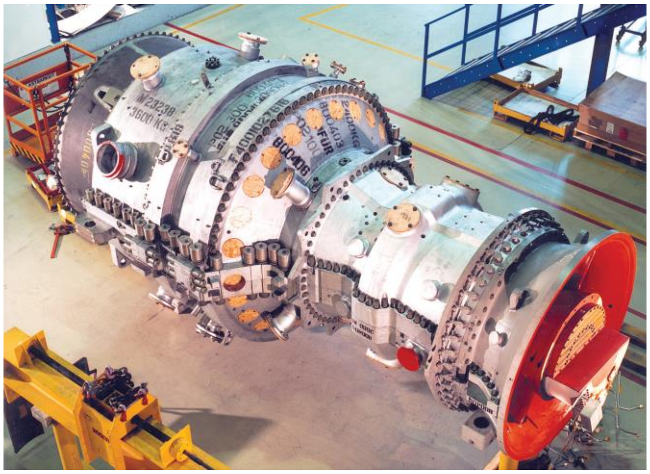


Figure 7: SGT-1000F is utilized for power generation in industrial applications and fossil power plants.

Components of the combustion systems are in particular attractive for additive manufacturing due to the still moderate temperature regime governed by the compressor cooling air and the high complexity of the parts.

Based on the burner head of the SGT-1000F, as shown in **Error! Reference source not found.**, the full industrialization and qualification process shall be illustrated. The head of the pilot burner is a fuel-air-mixer for the pilot flame and conventionally sourced as an investment cast part made from a Ni-based alloy.

Figure 8: Additively generated burner head of the SGT-1000F.

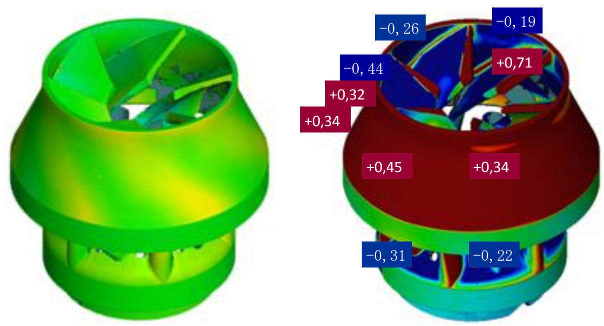
Industrialization and qualification process Even though there is a significant hype around additive manufacturing, industrialization and qualification needs to be carried out extremely thoroughly. For the component at hand the following procedure was ran through:

1) AM SLM process set-up and material data assessment,
2) Lifing and functional evaluation,
3) Pre-qualification,
4) Process and product qualification (PPQ),
5) Delivery and use.

Major parts of the process were derived from existing experience within Siemens in industrialization and qualification of advanced technologies.

As a starting point a process designed for the particular Ni-based material by Materials Solutions a Siemens Business was utilized. Based on the design requirements physical and mechanical properties were generated covering the expected temperature range during service. The comparison to cast material properties revealed a substantial gain in materials performance for the static, but also for the respective fatigue properties.

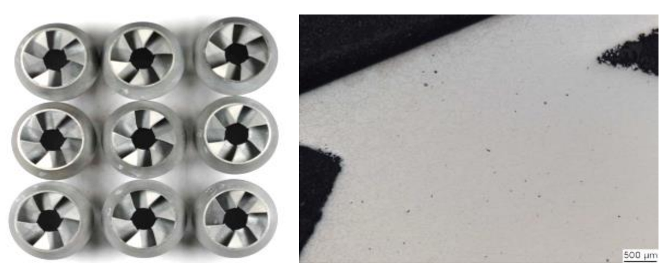
The subsequent step involved geometry related investigations such as the comparison of the printed and the original cast part with the design intend (Figure 9 (a) and (b)). As it turns out, the printed part showed with a maximum of 0.2 mm deviation far better accuracy compared to the cast part. However, it was decided to resemble the printed part to the machine proven geometry which caused little effort due to the tool-less manufacturing method.



(a) (b)

Figure 9: Comparison between 3D-model and (a) SLM component as well as (b) investment cast component; red – positive deviation / blue – negative deviation.

Within the pre-qualification phase, manufacturing trials were conducted to iterate on the optimum nesting of the parts including the according support structure required as depicted in Figure 10 (a). Both are heavily related to the final print time and therewith major cost contributors. Moreover, microstructural investigation on the components was performed, in particular in areas with potential stress concentrations which can cause cracking in SLM components. As the micrograph in Figure 10 (b) reveals the part is dense and free of crack indications.



(a) (b)

Figure 10: Pre-qualification: (a) determination of manufacturing set-up on the SLM machine and (b) microstructural investigation.

Within the PPQ the entire manufacturing set-up was investigated including all required post processing steps such as heat treatment, separation of the parts from the build plate, and non-destructive testing. It is noteworthy that the geometrical accuracy of a key feature was met precisely regardless of the position of the component across the build plate (compare to Figure **Error! Not a valid bookmark self-reference.**10 (a)). The scatter of the key diameter measured less than 0.02 mm.

Field validation and fleet leader Prior to delivery and installation, an implementation and inspection schedule was decided so that on a frequent basis, according to the inspection plan of the engine, field feedback can be gathered to support maturing the new manufacturing technology. It is of the utmost importance to circumvent any potential field issues which could have a negative impact on the engine performance and availability.

Hence, a well maintained engine was picked to install the first burner heads after the formal approval of the customer. This particular machine does not only act as a validation site, but is at the same time the fleet leader for this particular component which can only be ordered as an additive part from Siemens. Meanwhile, the engine has reached its first minor hot gas path inspection after the installation of the AM-made components. In numbers this is greater than 8000 EOH. Based on the feedback by the fact finders, no indications were found as Figure **Error! Reference source not found.**11 indicates.

Figure 11: Additively manufactured burner head after the first minor hot gas path inspection.

SIEMENS SETS MILESTONE WITH FIRST 3D-PRINTED PART OPERATING IN NUCLEAR POWER PLANT (NPP)

Following the integration of 3D-printing as part of its digital services portfolio, Siemens has achieved an industrial breakthrough with the first successful commercial installation and continuing safe operation of a 3D-printed part in a nuclear power plant. Because of the stringent safety and reliability requirements in the nuclear sector, achieving this qualification is a significant accomplishment**.**

The replacement part produced for the Krško nuclear power plant in Slovenia is a metallic impeller for a fire protection pump, as shown in Figure 12, that is in constant rotating operation.

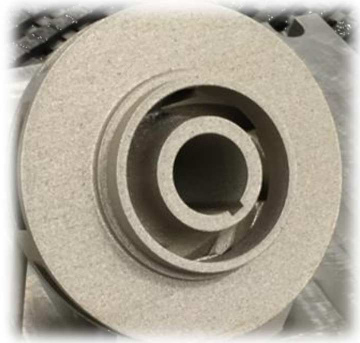


Figure 12: First 3D- printed impeller for a fire protection pump for the Krško nuclear power plant.

The water pump provides pressure for the fire protection system at the plant. The original impeller was in operation since the plant was commissioned in 1981; its original manufacturer is no longer in business. Obsolete, non-OEM parts are particularly well-suited for this new technology as they and their designs are virtually impossible to obtain. This technology thus allows mature operating plants to continue operating and achieving or, as in the Krško case, even extending, their full life expectancy.

Siemens' team of experts in Slovenia reverse-engineered and created a "digital twin" of the part. The company's additive manufacturing facility in Finspång, Sweden, then applied its advanced AM process using a 3D-printer to produce the part.

Meeting the Krško NPP's stringent quality and safety assurance requirements required extensive testing that was performed jointly with the Krško operations team over several months, ensuring that the new 3D-printed part would perform safely and reliably. Further material testing at an independent institute as well as a CT scan showed that the material properties of the 3D-printed part were superior to those of the original part.

A Siemens designed and manufactured water pump impeller using Additive Manufacturing and 3D-printing is operating in Slovenia's Krško nuclear power plant.

AM CHALLENGES AND OPPORTUNITIES CAN BE MANAGED BY DIGITALIZATION

Present situation: immature process. The situation today (see Fig. 13, A.1) is governed by the perception that although additive manufacturing has such a great potential, the performance and understanding of the process is far from perfect. If the technology shall lift off and really become 'industrial', great steps must be taken in order to overcome the hurdles.

Make 3D-printing in metal as easy, safe, and economically viable as paper printing Our goal (see Fig. 13, A.2) is to simplify the processes around AM so much that users will experience the same natural ease that one is used to when printing on paper. This is the mission statement of Digitalization of AM. We have a long way to go, but eventually this goal will be reached. Then we will have attained a mature industrial process.

Process understanding, monitoring and quality assurance Process understanding and monitoring (see Fig. 13, B.1) are the typical domains of AM equipment suppliers today. As a normal user of the technology you are not able to penetrate all the implications and barriers of IP-protected systems. Many AM-machine OEMs treat the market still as if no requirements or standards for commercial manufacturing and repair existed.

Especially the inability or unwillingness to publish and standardize SLM-documentation like the welding procedures specifications (WPS) that are commonplace in the traditional welding market must be seen as critical.

Thus, for the owner of the machine openly accessible sensors for e.g. optical, infra-red, electrical, torque or acoustic - probably combined - in equally openly accessible data collection platforms will be developed (see Fig. 13, B.2). The use of standardized industrial interfaces for communication, e.g. Open Platform Communication (OPC), is preferred. Data traffic must be protected against integrity attacks.

The sheer amount of the collected data and the needed reaction speed makes automation necessary. Storage of the data, maybe after compression, should take place in a secured cloud application. By doing so, a simple roll out to a global 3D-Printer Network is enabled. Only in this fashion the large scale certified AM-production can be realized in an economical way, e.g. according to aerospace regulations.

Reduced cost for the qualification and certification of material properties In the present way of working, huge amounts of (offline) test bars and (in-batch) witness coupons must be produced. This alone is a costly endeavor, but the greatest cost contribution is surely the destructive and non-destructive testing activities that are needed today (see Fig. 13, B.3). The goal is to be able to predict the material property of a print job in all necessary detail by only looking on the collected in-process monitoring sensor data sets.

The user of the AM technology who can determine the quality status of the process by simply using the sensor data produced by the machine process more or less ”free of charge” will have a fantastic cost and time advantage compared to competitors who need to do the checking by traditional means afterwards or in parallel.

The dream of having a ”digital material twin” is soon within our grasp by means of digitalization: we need big data mining strategies in cloud applications, visualization tools, and smart algorithms that simulate even the most extreme human expert knowledge.

Speeding up and avoiding silos A functioning end-to-end software solution (see Fig. 13, B.4) will help increase the speed of the development work.

Looking from above onto the different offerings that AM-machine OEMs present to the market, compatibility between the solutions seems to be more or less non-existent – and by the vendors not even desired (see Fig. 13, B.5).

This is why a strong and potent user of AM-technology with deep insight and a broad spectrum of knowledge must step in to drive the market into the direction of a global and universal technical and legally binding standardization.

This role as a bridge and translator can be filled by Siemens with its wide range of expertise and offerings.

Moreover, a global player like Siemens wishes to come close to its customers around the globe in order to increase customer value. What would suit this purpose better than offering a complete digitally-driven market approach with a printer network, component or process consulting and correspondingly decentralized, secured and cloud-based digital frameworks?

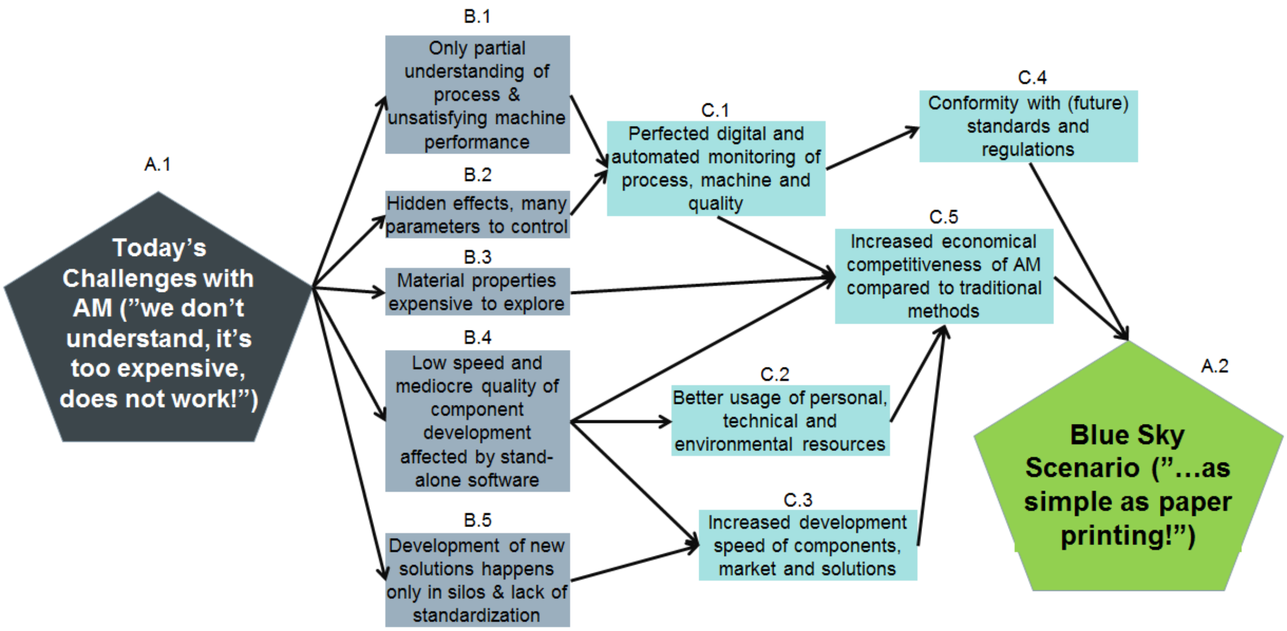


Figure 13: Why the market needs digitalization of additive manufacturing

CONCLUSION

- Siemens Power Generation is using AM technology for prototyping, manufacturing and repair of gas turbine components
- Siemens applied AM technology for the repair of the SGT-700 and SGT-800 burners. Replacement of conventional repair with AM resulted in significant reduction of repair time, life cycle extension and the opportunity to modify burners to latest version. By 2017 the fleet leader has exceeded more than 30,000 EOH.
- Siemens successfully applied AM technology for manufacturing of advanced burner swirlers of SGT-750 industrial gas turbine. In this case, AM was the only technology to manufacture the complex swirl design. In 2017 the fleet leader accumulated 30,000 EOH.
- The concept of 'Spare parts on demand' was launched by 3D-printed SGT-1000F burners heads for a district heat power station in Czech Republic. In 2017 the fleet leader accumulated more than 8,000 EOH.
- Siemens has achieved an industry breakthrough with the first successful reverse engineered, commercial installation and continuing safe operation of a 3D-printed part in a nuclear power plant. Because of the stringent safety and reliability requirements in the nuclear sector, achieving this qualification is a significant accomplishment**.**
- In 2017 Siemens accumulated more than 100,000 hours of operation for the components that are in serial production.

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