TUM.Additive

Memorandum on Additive Manufacturing
at the Technical University of Munich
as Part of the TUM AGENDA 2030

Contents

Preface

In the age of “Industry 4.0” the ability to create complex workpieces and shapes layer by layer spawns completely novel paths to geometrically complex systems whose functional properties were impossible to achieve with the classical manufacturing methods of the past. The spectrum of methodologies, still inadequately explored, invites interdisciplinary and cross-faculty research in practically every area of technology, science and medicine. These challenges call for the comprehensive research capacities of a technical university with a broad and differentiated portfolio of subjects and the ability to unify the various research cultures with one another on an interdisciplinary basis.

A SWOT analysis has shown that, with coordinated consolidation of the expertise already present today, the Technical University of Munich (TUM) can take the lead in additive manufacturing by bringing current developments to the relevant industries through a coherent research strategy. TUM can thus take on a decisive role in the fertilization of key technologies of the future and can make disruptive improvements in the economic viability of industrial manufacturing processes. Additive manufacturing processes exhibit methodological similarities of previously isolated subdisciplines that can be aligned across scales of several orders of magnitude. Here, cyber-physical systems are central to integration. Precision and reproducibility are among the particular strengths of additive manufacturing technologies.

The area of expertise “Industry 4.0 · Additive Manufacturing”* has been defined for the **Industry on Campus** alliance “*Additive Manufacturing Campus Bavaria*” as part of its future-oriented strategy adopted on December 6, 2018, **TUM.THE ENTREPRENEURIAL UNIVERSITY. Innovation by Talents, Excellence, and Responsibility**.

As part of the TUM AGENDA 2030, this memorandum exemplifies and simultaneously highlights the enormous interdisciplinary potential that TUM – 150 years after its founding – is only beginning to exploit.

Munich · Garching · Freising-Weihenstephan,
March 1, 2019

Wolfgang A. Herrmann
President

* Cf. TUM White Paper “Additive Manufacturing / Industry of the Future – Made in Bavaria” (December 2018).

1. Executive Summary

Additive manufacturing is fundamentally revolutionizing the manufacturing industry sectors:

- Digital transformation of the industrial manufacturing of functionally optimized components with complex geometries based on 3D designs in the core sectors Automotive · Aerospace & Aeronautics · Construction & Design · Medical & Health Technologies · Biofabrication & Regenerative Medicine · Industrial Catalysis;
- Sustainable production by conservation of energy and resources with important contributions toward achieving climate objectives;
- Securing Bavaria’s future as an economic stronghold and creating new commercial jobs, also outside of metropolitan regions.

The State of Bavaria has all the prerequisites necessary to implement the entire additive manufacturing process and value chain with its unique strengths and as an economic region to take the lead internationally in manufacturing technologies by pursuing an interdisciplinary and cross-sector approach.

With its strategic agenda TUM.Additive, the Technical University of Munich (TUM) is utilizing the historic opportunity to bring together existing expertise in research and teaching as well as infrastructures in the following core areas of additive manufacturing:

- Materials · Interfaces · Thermodynamics
- Design · Functional Geometries
- Production Techniques
- Sensor Technologies
- Numerical Mechanics and Simulation for Process Optimization
- Cyber-Physical Systems · Machine Intelligence · IT Security
- Verification · Quality Assurance (Materials Testing)
- Business Models for Additive Manufacturing.

In partnership with leading commercial enterprises, the Bavarian Additive Manufacturing Cluster is to develop integrated solution strategies in the core areas Materials, End-to-End Additive Manufacturing Processes and Digitalization in the Industry-on-Campus research alliance in order to accelerate the industrial use of additive manufacturing and the future-oriented transformation of manufacturing sectors. The Additive Manufacturing Research Institute is being established as a scientific core area of the cluster in order to specifically reinforce interdisciplinary fundamental research in the development of materials, processes and post-processing and its translation to industrial applications.

The TUM.Additive plan of action will be augmented by international partnerships, in particular with the German-French Academy for the Industry of the Future, The Imperial College London, and the Skolkovo Institute of Science and Technology (Moscow).

TUM is educating a new generation of specialists for the future-oriented field of additive manufacturing through innovative study and advanced training offers. By doing so, it will achieve the sustainable wide-scale implementation of additive manufacturing technologies in the manufacturing industries, anchored primarily in the medium-sized private economic sector.

2. Motivation and Opportunities

Among the various emerging technologies, additive manufacturing has the greatest potential for fundamentally revolutionizing the manufacturing industry sectors in upcoming years:

- Automotive
- Aerospace & Aeronautics
- Construction & Design
- Medical & Health Technologies
- Biofabrication & Regenerative Medicine
- Industrial Catalysis

New process technologies can use innovative raw materials as well as intelligent material combinations to create the widest possible variety of load-optimized and functional components with maximally complex geometries layer by layer (in an additive process) based on digital 3D designs. Unlike subtractive manufacturing processes (e.g., milling, turning) and without shaping tools (e.g., die-casting, injection molding), additive methods make primary shaping of metals, ceramics and plastics possible to form complex parts with a high degree of functional integration and maximum freedom of design. This considerably expands solution spaces in the production environment.

Additive manufacturing (powder bed fusion, vat photopolymerization, binder jetting, material extrusion, directed energy deposition, material jetting, sheet lamination) open up an enormous variety of possibilities in multi-layered 3D printing with variations in material state (powder, liquid, filament), heat or light sources (laser, thermal radiation, electron beam, plasma arc), number of print axes, feed systems and build chamber properties. Here, powder and beam-based methods are particularly well suited to industrial applications, as they make it possible to manufacture parts from technical materials with comparatively complex mechanical properties. Technical limitations, such as undercuts, cavities and large overhangs that restrict designers in classical manufacturing processes, are completely eliminated.

Additive manufacturing (AM) offers tremendous advantages in comparison to traditional production technologies:

- AM individualizes products and decentralizes production;
- AM drastically shortens the current development and production chain from the digital model to the finished product;
- AM allows tremendous freedom in design with significantly increased functional density ("form follows function") in the created workpieces, which are lighter and more resilient than the products of conventional manufacturing methods;
- AM does not require large production volumes in order to achieve cost efficiency; it is well-suited to "custom-tailored" individual manufacturing;
- AM implements bionic concepts for lightweight construction and enables the use of material combinations that would otherwise not be possible, such as graded materials for increasing material efficiency ("design of materials").

In combination with digital design and networking (cyber-physical systems), AM is expected to trigger a revolution with tremendous value creation benefits in manufacturing technologies and logistics, characterizing the age of Industry 4.0.

A key factor in the success of additive manufacturing in industrial value creation is a holistic, integrative and networked approach incorporating all fundamental business segments of the supply and value chains (design, development, procurement, inventory management, production, manufacturing design, quality control, logistics). This comprehensive view is necessary in order to efficiently utilize the enormous potential of additive manufacturing. In the medium term, these potentials have to be elevated from production areas with low unit quantities (rapid prototyping) – in spite of complex geometries and a high degree of individualization – to the potential of serial production (mass customization). The desired short production and delivery times must be reconciled with a constantly high level of product quality when implementing permanently defined manufacturing processes, when dealing with innovative materials, in the standardization of manufacturing processes and when considering compliance with valid standards. This requires the training of new specialist staff in order to guarantee the competitiveness of companies in the course of the transformation to Industry 4.0.

3. Perspectives for the Science and Technology Ecosystem Bavaria

The sustainable industrial use of AM technologies requires research, development and optimization of the elementary process steps and of the process chain as a whole. Consequently, leading industrialized nations around the world have deployed AM Lighthouse Initiatives. For example, the United Kingdom has made a considerable investment in advanced manufacturing research facilities in Nottingham (80 million GBP[1]) and Sheffield (47 million GBP[2]). The research activities of these facilities are being supported with an additional 22 million GBP from the industry sector.[3] In the USA, the National Additive Manufacturing Innovation Institute was founded (50 million USD) as part of the "America Makes" initiative for the purpose of coordinating the national AM activities of universities and industrial sectors. Activities in the USA are strengthened by partnerships between national laboratories (Lawrence Livermore, Los Alamos) and leading universities and supported by strategic research funding (e.g., PSAAP). The "Made in China 2025" plan also provides for a national "Additive Manufacturing Technology Research Program", launched in 2016 with a volume of more than 50 million euros over a period of five years.[4]

Germany does not yet have any structured AM activities that allow research to be carried out seamlessly across the entire value chain and incorporate newly gained findings into the industrial value-added chain of additive production.

The State of Bavaria can develop into an international spearhead in the future-oriented industrial field of additive manufacturing; the conditions for this are uniquely favorable:

1 https://www.nottingham.ac.uk/news/pressreleases/2018/december/24m-nottingham-research-facility-opens-to-transform-uk-manufacturing-in-the-digital-age.aspx.

2 https://3dprintingindustry.com/news/47-million-facilities-established-in-the-university-of-sheffield-for-advanced-industrial-technologies-141507/.

3 Additive manufacturing in FP7 and Horizon 2020: Report from the EC Workshop on Additive Manufacturing, June 18, 2014.

4 https://www.merics.org/sites/default/files/2017-09/MPOC_No.2_MadeinChina2025.pdf.

- The Technical University of Munich (TUM) is Bavaria's internationally highly-respected top university with leading-edge expertise in additive manufacturing. Throughout its 150-year history, TUM has repeatedly demonstrated its crucial role in the transformation of the State of Bavaria from an agricultural state to a high-tech science and economy hub by forming strong alliances with the business and political sectors, and with society;
- Bavaria is home to world-class companies in the application sectors relevant to additive manufacturing: Automotive (BMW, Audi, Brose etc.) · Aerospace & Aeronautics (MTU, Airbus, GE Aviation, Aircraft Philipp etc.) · Energy (Siemens, MAN, Turbo SE etc.);
- Market leaders with complementary expertise along the additive manufacturing chain are located in Bavaria: GE Additive – leading expertise in materials and additive manufacturing technologies; Linde AG – market leader for industrial, process and specialty gases and the associated application technologies as key components in each step of the manufacturing chain (from metal powder production to surface finishing); Oerlikon AM – market leader in modern materials and surface technologies, comprehensive engineering expertise in key components of additive manufacturing;
- The world's leading system manufacturers for additive manufacturing are headquartered in Bavaria: Concept Laser GmbH (laser melting systems) · DMG Mori (laser melting and laser powder deposition machines) · EOS Group (laser melting and laser sintering systems) · ExOne (binder jetting system) · Kumovis (extrusion systems for medical technologies) · ProBeam (electron beam melting systems) · Voxeljet (binder jetting systems). Bavarian manufacturers of laser melting systems determine the development of the sector, with a worldwide market share of approximately 50%;
- The market's leading software system companies, such as Siemens and SAP, are working intensively on the data and simulation chain and the development of integrative platforms in additive manufacturing; they are headquartered in Bavaria or have close connections with Bavarian universities and research facilities;
- Leading certification service providers such as TÜV Süd and IABG offer a comprehensive service portfolio in the area of additive manufacturing. They also inspect and certify processes concerning 3D printing;
- The Munich Technology Conference on Additive Manufacturing (MTC2) has already highlighted Bavaria's capital Munich to the international scientific and economic communities as a player in the world of AM and effectively demonstrated its expertise.[5]

In national comparisons (e.g., Aachen, Dresden), Bavaria can implement the comprehensive end-to-end process and value chain with unique levels of strength at its competence hub Munich, where it can continue to develop its future-oriented expertise at the highest international level. The initial conditions open up unique development perspectives for Bavaria:

- An end-to-end approach to the value creation chain enables rapid industrialization and industry penetration by additive manufacturing, increases the innovative strength and international competitive ability of Bavarian companies (especially in the component supplier sector, characterized by SMEs) and secures the future viability of Bavaria as a scientific and economic location;
- The transfer of classical, locally concentrated manufacturing capacities to a new, decentralized and digitalized form of manufacturing will create new jobs, both inside and outside the metropolitan regions;

5 https://www.munichtechconference.com.

- The implementation of entirely new business models relating to the value chain of additive manufacturing represents enormous potential for the bustling start-up scene in Bavaria today;
- Secondary effects resulting from additive manufacturing (e.g., energy and resource efficiency) support Germany's objectives in terms of the sustainability and social compatibility of new technologies with weight savings and increased product functionality;
- In the medium term, the highly digitizable additive manufacturing processes will also simplify the repatriation of production back to Germany. This is because in the new value chains wage cost differences are much less important than the high quality of training, cutting-edge research, economic stability, excellent infrastructure and the proximity to the customer as decisive primary location criteria.

The transfer from classical manufacturing capacities to new, delocalized and digitalized manufacturing will generate new jobs throughout the state of Bavaria and will sustainably secure the long-term innovative power, agility and thus the competitive position of the Bavarian economy.

4. The "TUM.Additive" Agenda

Based on successful research alliance projects[6] in the topic area of additive manufacturing / Industry 4.0, the development strategy TUM.Additive is now emerging from mechanical engineering; it integrates the expertise of a total of 12 departments in a comprehensive plan of action. The strategy will be supported by the Industry-on-Campus research alliance Bavarian Additive Manufacturing Cluster currently taking shape in Garching (founding partners: TUM · Oerlikon · GE Additive · Linde) and by the collaboration of the Fraunhofer Additive Manufacturing Alliance with the Fraunhofer Research Institution for Casting, Composite and Processing Technology IGCV in Augsburg.[7]

An integral part of the cluster, the Additive Manufacturing Research Institute, will be founded with a focus on interdisciplinary research; the institute brings together new fundamental research with the relevant TUM faculties along the entire additive manufacturing value chain. In this configuration, the development of technology covers all technological levels of maturity along an unbroken development and process chain: Materials · Manufacturing techniques · Plant engineering and process control · Sensor technologies and analysis · Cyber-physical systems and machine intelligence · Verification/qualification of products · Development of new additive manufacturing business models

6 Collaborative projects: CRC 768: Managing Cycles in Innovation Processes – Integrated Development of Product-Service Systems Based on Technical Products (Coordinator: Prof. Vogel-Heuser); TRR 40: Fundamental Technologies for the Development of Future Space-Transport-System Components under High Thermal and Mechanical Loads (Coordinator: Prof. Adams); Industry Projects (Machine Tools and Production Technology, Professors Zäh/Reinhart); Bavarian Research Foundation: ShapeAM (capability of additive manufacturing technologies for the production of functional components with high quality requirements for industrial use), FORobotics (mobile, ad-hoc cooperating robot teams).

7 Fraunhofer Research Institution for Casting, Composite and Processing Technology IGCV: Focus on automated production in the fields of lightweight casting technologies and fiber-reinforced composites; led by TUM Profs. Reinhart, Drechsler and Volk; https://www.tum.de/die-tum/aktuelles/pressemitteilungen/detail/article/33441/.

This close alliance of fundamental research and industrial application research is a national uniquely qualifying feature of the Bavarian Additive Manufacturing Cluster, which in this configuration will make decisive contributions to the accelerated industrialization of additive manufacturing technologies.

Strategic Objectives

The TUM.Additive agenda has the following objectives:

- To accelerate the transformation of the entire engineering process in key sectors (Automotive · Aerospace & Aeronautics · Construction & Design · Medical Technology & Health Technologies · Biofabrication & Regenerative Medicine · Industrial Catalysis) ranging all the way to design and manufacturing methods using new integrative research and development strategies;
- To make a significant contribution to the industrialization of additive manufacturing by forming alliances with leading commercial enterprises[8] and international academic-sector partners[9] as well as by spinning off innovative high-tech startups[10];
- To produce a new generation of specialists for the future-oriented field of additive manufacturing through innovative educational and continuing education concepts.

Transdisciplinary, Integrated Research Approach

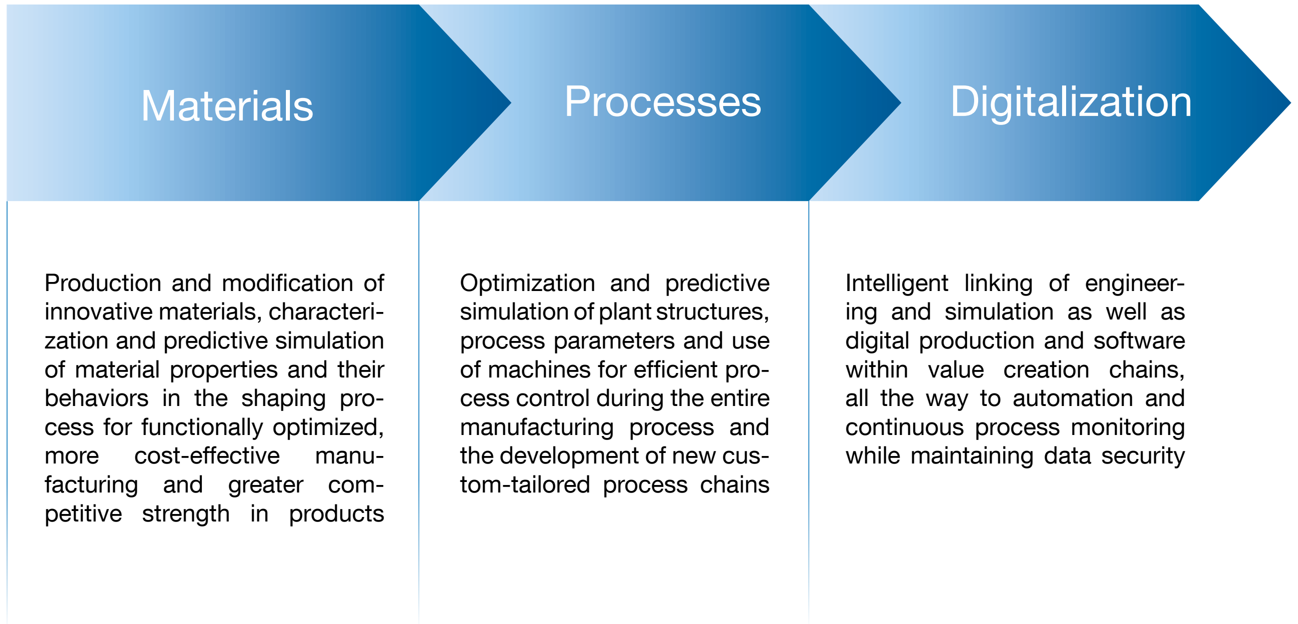
TUM.Additive has three main focus areas in a cross-domain (materials technology, process technology, mechanical engineering and simulation technology) and material-integrative research approach (metals, plastics, ceramics, concrete, composite materials, filler materials, biomaterials):

1. AM Materials (Advanced Materials): Manufacture and functionally-oriented modification of innovative materials such as high-performance metals (such as nickel-based alloys, copper or steels that are impossible or difficult to weld), high-performance plastics (such as anisotropic reinforcement, flame protection) and ceramic materials; characterization, predictive simulation and validation of micro, meso and macroscopic material properties and of their behavior in the shaping process for functionally optimized, more cost-effective manufacturing and increased product competitiveness;
2. End-to-End Additive Manufacturing Processes: Optimization and predictive simulation of plant construction and machine design (e.g., ability to automate supply and distribution of powder as well as powder removal), process parameters and machine utilization for efficient process control (e.g., ability to calibrate, minimum use of materials) during the entire manufacturing process; development of new functionally optimized process chains;

8 Airbus/Ariane Group, GE Additive, Linde AG, Oerlikon, SAP, Siemens, TÜV Süd, Clariant.

9 Collaboration with the Skolkovo Institute of Science and Technology (Moscow) and the Skoltech Center for Design, Manufacturing and Materials; https://www.skoltech.ru/en/.

10 TUM is the leader among German universities with an impressively successful rate of development: 29 → 76 start-ups (2011 vs. 2017) • > 800 companies founded by TUM members since 1998 (currently > 15,000 jobs) • As yet 8 TUM spinoffs are publicly traded, e.g., Celonis AG (founded 2011) > 1 billion US$ enterprise value ("Unicorn"). Examples of companies founded in the field of additive manufacturing: Voxeljet (industrial 3D printing systems for plastics and sand), Vectoflow GmbH (flow probes for 3D printing), Kumovis (3D printing for medical applications; skull plates and spinal column implants).



TUM.Additive: Integrative research and teaching along the entire process and value-creation chain.

3. Digitalization: Intelligent linking of engineering and simulation, digital production and software within value chains for automation and continuous process monitoring while ensuring data security (virtualization of the entire process chain).

Research Partnerships

TUM uses established and successful industrial partnerships with Airbus/Ariane Group, GE Additive, Linde AG, Oerlikon, SAP, Siemens and TÜV Süd to strategically consolidate expertise along the entire additive manufacturing chain and to orient expertise to the future for the generation of synergies:

- Airbus/Ariane Group: Market leader in the fields of aerospace & aeronautics as well as propulsion technologies;
- GE Additive: Leading expertise in materials technologies and additive manufacturing technologies (e.g., Acram EBM, Concept Laser GmbH);
- Linde AG: Market leader in industrial, process and specialty gases as key components in each step of the manufacturing chain (from metal powder production all the way to surface finishing);
- Oerlikon: Market leader in modern materials and surface technologies, comprehensive engineering expertise with key components of additive manufacturing;
- SAP: Market leader in enterprise software for digital manufacturing and networking of manufacturing companies with 3D printing vendors and service providers as well as materials suppliers and OEMs;
- Siemens: Market leader for integrated software and automation solutions for additive manufacturing in industrial use;
- TÜV Süd: Inspection and certification for additive series manufacturing in the areas Hardware & Software, Feedstock & Material Properties, Process Chain Certification, Product Testing, Certification & Approval, Company Certification and Training & Standards;

- Clariant: Innovative 3D printing technologies have been developed in the field of heterogeneous catalysis at the TUM Catalysis Research Center since late 2014 as a part of Munich Catalysis (MuniCat or Munich Catalysis Alliance of Clariant and Technical University of Munich), a topically and strategically oriented catalysis research alliance. This avantgarde approach is unparalleled worldwide and provides access to catalyst shape geometries that would not be accessible using any other method that is currently technically applicable. The basic findings gave rise to the Bavarian Research Foundation research cluster 3DKat.

International Alliances

Partnerships with commercial enterprises are reinforced by the German-French Academy for the Industry of the Future, a German-French research alliance with approximately 20 industry partners founded in 2015 by TUM and Institute Mines Télécom (IMT) that promotes research and educational programs regarding all aspects of Industry 4.0. In collaboration with the Skolkovo Institute of Science and Technology (Moscow) and the Skoltech Center for Design, Manufacturing and Materials, a Collaborative Research Center/Transregio (Coordinator: Prof. Adams) is currently being formed at TUM.

5. Core Competences of the Technical University of Munich (TUM) in the Area of Additive Manufacturing

5.1 Materials · Interfaces · Thermodynamics

Additive manufacturing processes are based on an intimate understanding of materials, ranging from their properties and modeling, all the way to the development of manufacturing processes from the atomic level to the finished product. This includes the areas of tribology, surface structuring, ceramic layers, polymer processing, nanometallurgy, biomaterials and live-cell systems, among others.

TUM has interdisciplinary expertise in six departments (CH, PH, MW, BGU, WZW, ME), two central institutes (Catalysis Research Center[11], Walter Schottky Institute[12]) and two integrative research centers (TUM Campus Straubing[13], Munich School of BioEngineering[14]) in the field of materials research on solids, fluids and biomaterials and their physical-chemical properties and functionalities, all the way to their application in mechanical engineering, automotive, aerospace & aeronautics, construction & design, medical technology and foodstuffs. TUM.Additive generates new findings in support of the future use of the enormous application potentials for construction materials, metals, non-structured (fluid) and vitreous materials, polymers and material combinations (e.g., inorganic-organic hybrids) for realization of the best possible product functionalities. Working on the foundation of TUM's material science expertise, a "Material Genome" database is to be created, which classifies material families according to their properties and interactions as well as their possible application areas. The database will also consider the material changes that occur during the course of manufacturing procedures in the final product.

Professorship/Expertise	Name	Faculty
Biochemical Engineering	Dirk Weuster-Botz	MW
Biomechanics	Oliver Lieleg	MW
Medical Materials and Medical Implant Design	Petra Mela	MW
Micro Technology and Medical Device Technology	Tim Lüth	MW
Materials Engineering of Metals	Peter Mayr	MW
Materials Science and Mechanics of Materials	Ewald Werner	MW
Aerodynamics and Fluid Mechanics	Nikolaus A. Adams	MW/LRG
Computational Thermo-Fluid Dynamics	Wolfgang Polifke	MW
Interface Materials Engineering	TBA	MW
Multi-Scale Modeling of Fluid Materials	TBA	MW
Plasma Material Interaction	Rudolf Neu	MW
Thermodynamics	Thomas Sattelmayer	MW
Metal Forming and Casting	Wolfram Volk	MW
Carbon Composites	Klaus Drechsler	MW/LRG
Concrete Structures	Oliver Fischer	BGU
Materials Science and Testing	Christoph Gehlen	BGU
Metal Structures	Martin Mensinger	BGU
Mineral Engineering	Detlef Heinz	BGU
Synthesis of Innovative Materials	Tom Nilges	CH
Macromolecular Chemistry	Bernhard Rieger	CH
Functional Materials	Peter Müller-Buschbaum	PH
Biopolymer Chemistry	Dieter Langosch	WZW
Biothermodynamics	Mirjana Minceva	WZW
Fluid Dynamics of Complex Biosystems	Nathalie Germann	WZW
Chemistry of Biogenic Resources	Volker Sieber	TUMCS
Biogenic Polymers	Cordt Zollfrank	TUMCS

Additional professorships (planned):
Additive Materials (MW) · Composite Materials (TUMCS) · Unconventional Materials (CH) · Biogenic Functional Materials (TUMCS) · Food Material Science (WZW).

11 Catalysis Research Center (CRC): New reaction and synthesis paths for the production of functional materials; http://www.crc.tum.de.

12 Walter Schottky Institute – Center for Nanotechnology and Nanomaterials (WSI): Creation and structural modification of nanomaterials; https://www.wsi.tum.de/.

13 TUM Campus Straubing: Biomaterials from renewable resources; https://www.cs.tum.de/de/.

14 Munich School of BioEngineering (MSB): Synthetic biology and biomaterials; https://www.bioengineering.tum.de.

In addition to metals, ceramics and polymers there is a particular focus on functional biomaterials, since renewable raw materials and functionally optimized biopolymers open up innovative application areas in medical technologies (e.g., personalized implants, porous 3D scaffolds, controlled dissolving stents), in food design & engineering as well as for a wide variety of bio-compatible material structures and (composite) material structures. 3D printing of live-cell complexes ("tissue engineering") and nanoscale biostructures presents manufacturing technologies with considerable multi-physical challenges and requires a special understanding of the behavior of fluids and gases in the smallest of spaces (microfluidics). For example, the issue of exact and ultra-precise delivery of nutrients for vascular formation in cells and cell tissues has not yet been resolved.

5.2 Design · Functional Geometries

Whereas design aspects in classical engineering were by and large limited to accommodating manufacturing requirements, in additive manufacturing design is an integral part of the overall development and production process. Additive manufacturing technologies highlight a wide variety of design limitations in existing manufacturing procedures and allow the production of highly complex components. In the future, the functionality of the product will be central; in a second step, the physical properties and structures can be derived, which then indicate the appropriate material. Additive manufacturing allows flexible and quick design changes, since it requires only geometric data, and the geometries of existing products can be captured quickly by means of 3D scanning processes such as computer tomography (reverse engineering). The combination of various scales and materials, more than anything, as well as the use of simulation models introduces an unimaginable range of design freedoms and functional geometries (microscale engineering) for integrating the desired functions of the end product into the manufacturing process. In addition to the pure creation of adapted geometries, the wide variety of system technologies and materials used also allows the modified realization of material structures, such as structures with cavities and lightweight structures with varying material densities and porosities across the component cross-section, and special structural properties specified by design.

In a step towards rethinking the conventional design and prototype workflow, TUM is creating a new potential dimension for Design Thinking with the guiding vision of "Human-Centered Engineering and Future Design" (TUM Institutional Strategy 2018/19). A new Integrative Research Center, the TUM Institute for Technology Design[15] consolidates leading expertise from natural sciences, engineering, computer and economic sciences, architecture and industrial design. It opens up completely new, value-creating effects on the entire spectrum of process and product design by additive manufacturing design rooted in science. Throughout the TUM. Additive agenda, suitable components are analyzed, identifying those for which additive manufacturing and functionally-oriented redesign promises technological or economic benefits. The corresponding design possibilities at TUM range from the simulation of biological models (Leonardo da Vinci Center for Bionics[16]), all the way to the adapted realization of specifically conceived structural approaches. The potential of these structures is investigated in terms of specific materials and processes; appropriate processes are formulated, simulated, and then tested based on realistic requirements.

15 Partners: Dyson School of Design Engineering (IC London); Design Academy Eindhoven; Singapore University of Technology and Design; Stanford Institute of Design.

16 Leonardo da Vinci Center for Bionics: Transfer to revolutionary technical systems of evolutionary solutions from nature and the configurational principles and organizational aspects behind biological systems; http://www.bionik.tum.de.

Professorship/Expertise	Name	Faculty
Architectural Design and Participation	Francis Kéré	AR
Architectural Design and Building Envelope	Tina Wolf	AR
Architectural Design and Conception	Uta Graff	AR
Architectural Design, Rebuilding and Conservation	Andreas Hild	AR
Digital Fabrication	TBA	AR/BGU
Spatial Art and Lighting Design	Hannelore Deubzer	AR
Structural Design	Rainer Barthel	AR
Urban Architecture	Dietrich Fink	AR
Urban Design	Benedikt Boucsein	AR
Architectural Design and Timber Construction	Hermann Kaufmann	AR
Building Technology and Climate Responsive Design	Thomas Auer	AR
Industrial Design	Fritz Frenkler	AR
Product Development and Light-Weight Design	Markus Zimmermann	MW/LRG

Additional professorships (planned):
Bio-Nanoprinting (PH/ME) · Design for Additive Manufacturing · Building Product Design (AR/BGU).

5.3 Fabrication Technologies

In order to realize an extensive range of design features and functionalities, as part of TUM.Additive TUM is building a broad spectrum of processes for various applications using metal and intermetallic materials, plastics, multi-material systems and biosystems from 3D printing processes:

- 3D printing processes (for the generation of complex electronic structures, for example);
- jet-based processes (such as the time and material-efficient manufacture of microstructures, all the way to large-volume components);
- powder bed procedures (e.g., for manufacturing components with a high degree of geometrical freedom as well as very fine structure and surfaces).

Professorship/Expertise	Name	Faculty
Micro Technology and Medical Device Technology	Tim Lüth	MW
Metal Forming and Casting	Wolfram Volk	MW
Carbon Composites	Klaus Drechsler	MW/LRG
Automatic Control	Boris Lohmann	MW
Bioseparation Engineering	Sonja Berensmeier	MW
Vibroacoustics of Vehicles and Machines	Steffen Marburg	MW
Industrial Management and Assembly Technologies	Gunther Reinhart	MW
Automation and Information Systems	Birgit Vogel-Heuser	MW
Machine Tools and Industrial Management	Michael Zäh	MW
Materials Handling, Material Flow, Logistics	Johannes Fottner	MW
Machine Elements	Karsten Stahl	MW
Laser-Based Additive Manufacturing	TBA	MW

Additional professorships (planned):
Metal-Based Additive Manufacturing (MW) · Hybrid Additive Manufacturing (MW) · Additive Machine Digital Twins (MW) · Manufacturing Systems and Assembly Solutions (MW) · Tissue Engineering (WZW/ME).

The TUM Institute for Machine Tools and Industrial Management (iwb) is one of Germany's largest production technology research facilities, with core expertise in the areas of additive manufacturing, machine tools, assembly technologies and robotics, joining and separation technologies, and in the field of production management and logistics.

5.4 Sensor Technologies

Because of their complex interaction, even minimal changes in individual process parameters as well as environmental influences (like heat accumulation, heating, contamination) can lead to a significant change in product quality. TUM.Additive therefore focuses on the development of custom-tailored process monitoring sensors combined with intelligent image processing systems for additive processes. This makes it possible to acquire new information on key processes, to understand the effects of incorrect parameterization, and to develop quality assurance methods and active process regulation to achieve defect-free and precise structures, especially with complex components. Modern sensor systems are also the electronic interfaces of new cyber-physical systems. Electrochemical sensor fields can also record the chemical signals of cells in real time. New professorial appointments at the Department of Electrical and Computer Engineering are oriented toward research on innovative sensor technologies.

Professorship/Expertise	Name	Faculty
Circuit Design	Ralf Brederlow	EI
Electronic Design Automation	Ulf Schlichtmann	EI
Hybrid Electronic Systems	Franz Kreupl	EI
Micro- and Nanosystems Technology	TBA	EI
Neuroelectronics	Bernhard Wolfrum	EI
Nano- and Quantum Sensors	TBA	EI
Sensor Systems	TBA	EI

5.5 Numerical Mechanics and Simulation for Process Optimization

As part of TUM.Additive, TUM is intensifying its efforts to link mathematical expertise with modern manufacturing technologies and is opening up new possibilities for profiling and application in the joint focus area of the Departments of Mechanical Engineering and Mathematics.

Professorship/Expertise	Name	Faculty
Aerodynamics and Fluid Mechanics	Nikolaus A. Adams	MW/LRG
Applied Mechanics	Daniel J. Rixen	MW
Continuum Mechanics	Phaedon Koutsourelakis	MW
Mechanics and High Performance Computing	Michael W. Gee	MW
Numerical Mechanics	Wolfgang A. Wall	MW
Applied Numerical Analysis	Felix Krahmer	MA
Applied Numerical Analysis	Massimo Fornasier	MA
Numerical Mathematics	Barbara Wohlmuth	MA
Numerical Mathematics / Scientific Computing	Folkmar Bornemann	MA
Numerics of Complex Systems	Oliver Junge	MA
Optimal Control	Boris Vexler	MA
Scientific Computing	Elisabeth Ullmann	MA
Structural Mechanics	Gerhard Müller	BGU

Simulations generate findings on temperature fields, phase states, tensions, strains and distortion in order to improve process understanding in additive series manufacturing and to counteract material and structural defects in the process depending on the material and geometry of the product to be created.

5.6 Cyber-Physical Systems · Machine Intelligence · IT Security

Digital Twins are generated with the objective of creating functional end products that do not require manual post-processing; working as a kind of "data blueprint", the Digital Twins are a digital representation of the entire production process resulting in a given product. Digital Twins are highly precise and almost exact virtual simulation models of the end products. Cyber-physical systems use high-performance data infrastructures to combine software solutions and Digital Twins with electronic and mechanical components in order to achieve networked control of all systems and machines throughout the phases of the lifecycle, from the product idea to development, all the way to production. The entire value chain is optimized, rather than just individual production steps; production resources and materials can be sorted and prioritized exactly, the products can be individually adapted. Rises in the level of networking and digitalization promote the interaction between humans and robots as well as the focused use of their respective individual strengths. New methods of machine learning and artificial intelligence round out the portfolio for product-focused and information-based key issues.

The Munich School of Robotics and Machine Intelligence (MSRM, 2017; Director: S. Haddadin) leverages the international reputation of TUM in AI research (#6int/#1DE: THE-Review 2018) and connects it with robotics and perception sciences to develop innovative and sustainable technological solutions for future manufacturing. Fortiss GmbH is the associated application platform. TUM realizes the potential of automation using cyber-physical measurement robots for 3D digitalization and utilizes mobile autonomous robots as adaptable production resources (worker assistance systems). Digital manufacturing processes also pose completely new data security requirements. Preventing unauthorized access and manipulation calls for new technical solutions based on digital encryption technologies. TUM.Additive is meeting these challenges in a cross-faculty constellation. With the support of the TUM Data Science Institute (currently in formation) and the Leibniz Supercomputing Centre (LRZ)[17] on the Garching campus, interactive visualization software, Big Data platforms and methods for managing large amounts of process data (logs from robots, lasers, CAM, sensor bus signals) and digital image data (e.g., from temperature measurement, diagnosis) are being formulated in order to properly interpret process data, simplify error analysis and enable verification documentation.

17 Leibniz Supercomputing Centre (LRZ): SuperMUC: 26.7 petaflops/sec, #8 in the worldwide ranking; high-performance computing will produce faster and, above all, more reliable responses to Big Data questions, visualizations and virtual reality. This will give a previously impossible precision to the computing-intensive simulations and modeling of Digital Twins.

Professorship/Expertise	Name	Faculty
Automatic Control Engineering	Martin Buss	EI
Embedded Systems and Internet of Things	Sebastian Steinhorst	EI
Human-Machine Communication	Gerhard Rigoll	EI
Robotics and System Intelligence	Sami Haddadin	EI/IN
Cyber-Physical Systems	Matthias Althoff	IN
Information Systems	Helmut Krcmar	IN
Data Mining and Analytics	Stephan Günnemann	IN
Large-Scale Data Analytics and Machine Learning	TBA	IN
Network Architectures and Services	Georg Carle	IN
Robotics and Embedded Systems	Alois Knoll	IN
Scientific Computing	Hans-Joachim Bungartz	IN
Software and Systems Engineering	Alexander Pretschner	IN
Hardware-Aware Algorithmics and Software for High Performance Computing	Michael Bader	IN
IT Security	Claudia Eckert	IN
Theoretical Foundations of Artificial Intelligence	TBA	IN
Cyber-Physical Systems in Production Engineering	Marco Caccamo	MW
Automation and Information Systems	Birgit Vogel-Heuser	MW
Safe Embedded Systems	Julien Provost	MW

Additional professorships (planned):
Digital Twins and Virtual Products (LRG).

5.7 Verification · Quality Assurance (Materials Testing)

Similarly to the methods employed in conventional manufacturing processes, strict compliance with quality standards in every sub-step of the process chain is the prerequisite for the additive manufacturing of cost-effective and high-quality products. Dimensional stability, freedom from cracks, homogeneity of grain structures and materials, density, strength, hardness, surface quality, and internal stress are among the particularly critical quality parameters in the additive manufacturing of components.

Taking advantage of synergies with physics, electrical engineering, information sciences, and the Research Neutron Source Heinz Maier-Leibnitz (FRM II)[18], the metal analysis

18 Research Neutron Source Heinz Maier-Leibnitz (FRM II): TUM central institute (joint federal and state-level financing). Scientific use as Heinz Maier-Leibnitz Zentrum (MLZ) in cooperation with Helmholtz Jülich/Geesthacht, participation of the Max Planck Society (MPG)/several universities; including the structural analysis of functional materials; https://www.frm2.tum.de.

laboratory[19] of the Department of Mechanical Engineering and the Chair of Non-Destructive Testing (NDT), TUM.Additive has access to non-destructive testing procedures for the examination of materials, components, systems and structures in the core disciplines of construction and mechanical engineering as well as in the fields of architecture, geophysics and medical technology. Aside from testing material properties, knowledge is gained on the geometrical dimensions as well as the material composition of the structures created using additive methods.

Professorship/Expertise	Name	Faculty
Non-Disruptive Testing	Christian Grosse	BGU/MW
Materials Science and Testing	Christoph Gehlen	BGU
Soil Mechanics and Foundation Engineering, Rock Mechanics and Tunneling	Roberto Cudmani	BGU
Traffic Route Construction	Stephan Freudenstein	BGU
Machine Tools and Industrial Management	Michael Zäh	MW

5.8 Business Models for Additive Manufacturing

TUM.Additive utilizes the expertise of the TUM School of Management in Munich and at the educational campus Heilbronn to develop new economic models for the areas of additive manufacturing and digitalization. For example, at the new TUM campus in Heilbronn, business models of the dynamic founder scene in the Munich metropolitan region are compared with medium-sized family companies in Baden-Württemberg (referred to as “Hidden Champions”). The practically-oriented research is specifically interested in determining which strategies are best suited with regard to the digital transformation and how innovative, flexible and reactive the various corporate structures are.

19 Metal analysis laboratory – Department of Mechanical Engineering: including the use of a computer tomography system for high-resolution structural investigations, focused ion beam microscopy for material testing.

Professorship/Expertise	Name	Faculty
Financial Controlling	Gunther Friedl	WI
Production and Supply Chain Management	Martin Grunow	WI
Operations Management	Rainer Kolisch	WI
Logistics and Supply Chain Management	Stefan Minner	WI
Operations Research	Andreas S. Schulz	WI
Corporate Management	Alwine Mohnen	WI
Science & Technology Policy	Ruth Müller	WI/WZW
Marketing and Consumer Research	Jutta Roosen	WI
Marketing	Christoph Ungemach	WI
Strategy and Organization	Isabell M. Welpe	WI
Technology and Innovation Management	Joachim Henkel	WI
Innovation Research	Sebastian Pfotenhauer	MCTS

Additional professorships (planned):
Additive Manufacturing for Companies (WI) · 3D Opportunity and Business Capability (WI).

6. High-Potential Growth Areas and Fields of Application

6.1 Construction & Design

Additive technologies are attributed an enormous economic potential in the construction sector and in the manufacture of complex architectonic structures; the dynamics of current developments are particularly impressive. Extensive expertise in the fields of construction and design are anchored in the TUM Department of Architecture, the TUM Department of Civil, Geo and Environmental Engineering, in Technical Construction Chemicals and at the Leonhard Obermeyer Center[20]. Various innovative materials and processes are investigated, modeled, and simulated. For example, the first facades from the 3D printer based on the principles of nature (bionics) were developed at TUM. The facades contain thin-walled tubes which enable improved air circulation for optimized internal building climates.[21]

TUM.Additive uses the research expertise developed in recent years at the Departments of Civil, Geo and Environmental Engineering and Architecture. TUM has the uniquely qualifying feature of being able to consider extrusion processes in parallel with and as compared to selectively binding (particle-bed based) processes. Activities at TUM on selective binding with Cement Paste Intrusion, a procedure with extremely high potential in terms of practical construction, are groundbreaking around the

20 Leonhard Obermeyer Center: The center, located on the TUM main campus, is dedicated to the design, creation and maintenance of the built environment. Digital methods and technologies are used to create ecologically and economically sustainable structures and operational concepts.

21 https://www.tum.de/die-tum/aktuelles/pressemitteilungen/detail/article/34984/.

world. The competitive strength of TUM is also internationally respected in the fields of Building Information Modelling, simulation of additive processes and in the area of topology optimization. An initiative for a Collaborative Research Center (SFB)/Transregio "Additive Manufacturing in Construction – The Challenge of Large Scale" together with the Technische Universität Braunschweig has succeeded in the draft phase; the full proposal has been submitted to the German Research Foundation (DFG) in May 2019.

TUM.Additive concentrates on expanding established leading-edge expertise, such as large-scale format particle-bed 3D printing. More specifically, future innovations will create and further develop materials, processes and digital tools in regard to their reproducibility and reliability in order to achieve the quality assurance and cost-efficiency necessary in construction practice.

Relevant professorships in addition to the experts listed in chapter 5	Name	Faculty
Architectural Informatics	Frank Petzold	AR
Energy-Efficient, Sustainable Building and Planning	Werner Lang	AR
Building Construction and Material Science	Florian Musso	AR
Building Realization and Robotics	Thomas Bock	AR
Building Technology and Climate Responsive Design	Thomas Auer	AR
Timber Structures and Building Construction	Stefan Winter	AR
Structural Mechanics	Gerhard Müller	BGU
Computation in Engineering	Ernst Rank	BGU
Computational Modeling and Simulation	André Borrmann	BGU
Construction Process Management	TBA	BGU
Material Science and Testing	Christoph Gehlen	BGU
Structural Design	Kai-Uwe Bletzinger	BGU
Materials Handling, Material Flow, Logistics	Johannes Fottner	MW
Machine Tools and Manufacturing Technology	Prof. Michael Zäh	MW
Construction Chemistry	TBA	CH

TUM.Additive accelerates the transfer of findings from fundamental research to the industrial scale through strategic alliances with leading industrial partners. One current example is a project for a translucent, three-story, 3D-printed facade for the temporary entry hall to the Deutsche Museum during several years of renovation work (Project: M. Mungenast, AR, beginning of construction planned for 2019).

6.2 Aerospace & Aeronautics

As a key industry, the German aeronautics industry will have to implement innovative manufacturing processes in order to secure its long-term competitive strength. The aerospace & aeronautics industry has been one of the central driver industries of additive manufacturing for approximately 20 years. The main reason for this is that the materials frequently used in design, such as titanium alloys or nickel-based alloys, are extraordinarily expensive to machine. The German finance daily "Handelsblatt" (November 18, 2018) forecast growth in the additive manufacturing industry in aerospace & aeronautics at a factor of 24, from 0.4 billion euros in 2015 to 9.6 billion euros in 2030. Such strong growth will only be possible by leveraging the potential of the "Design for Additive" approach in the design of new component assemblies for future aircraft generations. Thus, it will be possible to realize complex, top-quality lightweight components with new properties and functions on a cost-efficient basis. These procedures can be applied most importantly to those components that result in fuel savings because of weight reductions or lead to lower noise emissions due to improved designs. Additive manufacturing will be one of the most significant growth segments in this field, provided it is possible to master the associated new technological challenges. With the new Department of Aerospace, Aeronautics and Geodesy (LGR, founded in 2018) and the TUM.Additive agenda, TUM is taking advantage of the opportunity to synergistically consolidate core competencies that were previously distributed among several facilities and to develop them into a new profile area of "German Engineering" at TUM in connection with the internationally outstanding German Aerospace Center (DLR, Helmholtz).[22]

The focus initiative TUM.Additive is the TUM response to the challenges of additive manufacturing in aerospace & aeronautics: At present, the selection of materials available for additive manufacturing processes is limited. Not all the materials necessary for applications in the high-temperature range both for space vehicles and for aircraft engines are available today. These include, for example, the need for high-temperature-proof nickel-based alloys for aeronautics and platinum alloys for combustion chambers used to steer satellites. The development of more efficient aircraft engines with lighter engine parts is a prerequisite for reducing the negative impact on the environment associated with the worldwide increase in air traffic as well as the operating costs for flight systems. TUM is researching the use of beam melting technologies to build complex structures using additive layer manufacturing to facilitate reducing the mass of these components while at the same time guaranteeing the desired properties. One special challenge for additive manufacturing in aerospace & aeronautics is the fulfillment of the highest possible quality requirements. It will only be possible to fulfill these requirements if the process chain is mastered from the production of the raw materials, all the way to the thermal post-treatment of components. Challenges exist, in particular, in terms of reliable and at the same time economical post-treatment of surfaces. Furthermore, there are still no robust process chains today for the manufacture of metallic components with dimensions up to several meters. The high quality requirements are to be assured by certification procedures in line with the industry standard. The challenge here is that process-related errors can only be detected on a limited basis once the construction process has been completed. Challenges result in terms of the economical combination of in-process and post-process checks as well as in the continuing development of non-destructive

22 https://www.tum.de/die-tum/aktuelles/pressemitteilungen/detail/article/34955/.

testing procedures. The integration of simulation tools is an important prerequisite for the economical application of additive manufacturing processes.

It is not yet possible to meet the prevalent current aviation and astronautics standards in the area of simulation-supported component configuration with lightweight bionic structures that can only be produced using additive manufacturing methods. New simulation tools are being developed that make it possible to manufacture the engine components with a minimal rejection rate and without complicated prior test series. These tools can be used to represent those process steps of a real manufacturing process which are relevant to distortion as well as the temperature fields occurring on the parts. They can thus be used to calculate the resulting deformations and internal stresses with adequate precision and make it possible to optimize engine components on a component-specific basis. Based on manufacturing data, simulation-supported optimization is to be used to compensate for manufacturing-related deviations in dimensional stability.

Relevant professorships in addition to the experts listed in chapter 5	Person	Faculty
Aircraft Design	Mirko Hornung	MW/LRG
Aerodynamics and Fluid Mechanics	Nikolaus A. Adams	MW/LRG
Carbon Composites	Klaus Drechsler	MW/LRG
Helicopter Technology	Manfred Hajek	MW/LRG
Product Development and Light Construction	Markus Zimmermann	MW/LRG
Flight Systems Dynamics	Florian Holzapfel	MW/LRG
Astronautics	Ulrich Walter	MW/LRG
Rocket Propulsion	Oskar J. Haidn	MW/LRG
Space Transportation Systems	TBA	LRG
Turbomachinery and Flight Propulsion	Volker Gümmer	MW/LRG

6.3 Automotive

The automotive industry is one of Germany's most important industry sectors. The application areas of additive manufacturing procedures in the automotive sector today are primarily in the field of rapid prototyping. In some cases, parts are also manufactured in series production.

Building on many years of experience and expertise in the field of vehicles and mobility, the TUM.Additive agenda is now focusing on the automotive sector's major technical challenges in terms of the cost-competitive manufacture of component parts with additive methods. Until now, parts made by using additive manufacturing are only rarely competitive, since the materials used (e.g., aluminum alloys) can be manufactured on a cost-efficient basis using conventional die casting or machining processes. Accordingly, the growth forecast of the Handelsblatt (November 18, 2018) for the use of additive manufacturing technologies in

the automotive industry was significantly lower than the growth predicted for the aerospace & aeronautics sector. Starting with 0.3 billion euros in 2015, growth by a factor of 9 to 2.6 billion euros in 2030 is expected. There is an urgent need to increase the setup rates, which can only be achieved with innovative machine concepts such as multiple laser melting machines, for example. The production of cost-effective starter materials such as metal powder and the formulation of quality-assuring recycling routines for reuse of the powder are also central challenges in this context. To reduce manufacturing costs, automated process chains are to be conceived that fulfill the established requirements for process stability and Overall Equipment Effectiveness (OEE). In the area of product development, new potentials of "Design for Additive" are to be leveraged, in particular with respect to functional integration, and used to the best possible benefit of the customer.

Relevant professorships in addition to the experts listed in chapter 5	Person	Faculty
Automotive Technology	Markus Lienkamp	MW
Ergonomics	Klaus Bengler	MW
Control Technology	Boris Lohmann	MW
Industrial Management and Assembly Technologies	Gunther Reinhart	MW
Machine Elements	Karsten Stahl	MW
Metal Forming and Casting	Wolfram Volk	MW
Internal Combustion Engines	Georg Wachtmeister	MW
Machine Tools and Manufacturing Technology	Michael F. Zäh	MW
Applied Mechanics	Daniel Rixen	MW
Vibroacoustics of Vehicles and Machines	Steffen Marburg	MW

6.4 Medical & Health Technologies

Rapid technologies are already indispensable in the medical sector today, for example in dental applications. Individual products such as dental implants and dentures can be produced faster and more cost-effectively using generative procedures than is the case with conventional methods. And enormous development perspectives are still expected for additive manufacturing in the medical technology sector: Additive manufacturing can be used to create individually adapted medical appliances optimized in terms of weight and strength properties on a very cost-effective basis and within very short periods of time. For example, medical appliances can be modified anatomically and biomechanically to suit individual patient requirements, and highly functionally integrated systems for minimally invasive surgical procedures can be implemented. Great progress has already been made in the areas of orthopedic technology and materials for synthetic bone substitutes, e.g., the additive manufacture of porous titanium or titanium alloy structures for patient-specific implants using selective laser melting, implants and scaffolds that dissolve inside the body, and the integration of ceramic nanoparticles in binder systems to improve the mechanical stability of 3D-printed bone substitutes. In the next generation of artificial bones, resorbable implants will be produced using Selective Laser Melting and will be pervaded by fine pore channels which create a lattice structure that the adjacent bone can grow into. The development of protheses promises enormous future potential for generative manufacturing. This will eliminate the painstaking process of having the patient try the prosthesis on; instead the necessary data and individual dimensions will be generated directly on the computer and then integrated in the construction of the prosthesis.

The agenda TUM.Additive consolidates the expertise present in the Departments of Mechanical Engineering and Chemistry, the Munich School of Bioengineering and School of Medicine in the area of plastic and biopolymer-based additive manufacturing procedures.

The selection of suitable plastics is limited because of the frequent direct contact of the medical products with parts of the human organism. It will only be possible to fully leverage the potential of additive manufacturing for medical technologies if high-performance polymers can be processed with a high degree of process reliability under medical-grade conditions. The focus is therefore on the compatibility of these polymers with the human body, resistance to the conditions of use in and outside of the body and on good mechanical properties as implant materials. In addition, TUM.Additive is concentrating on the growing problem of a shortage of donor organs in transplantational medicine.

Relevant professorships in addition to the experts listed in chapter 5	**Name**	**Faculty**
Biomedical Electronics	Oliver Hayden	EI
Biomedical Physics	Franz Pfeiffer	PH
Medical Materials and Medical Implant Design	TBA	MW
Micro Technology and Medical Device Technology	Tim Lueth	MW
Orthopedics	Rüdiger Eisenhart-Rothe	ME
Plant and Process Technology	Harald Klein	MW
Sport Equipment and Sport Materials	Veit Senner	MW
Vibroacoustics of Vehicles and Machines	Steffen Marburg	MW

6.5 Biofabrication & Regenerative Medicine

TUM.Additive also has an impact on regenerative medicine and the life sciences. It combines activities from the School of Medicine, Department of Sport and Health Sciences, the School of Life Sciences and the TUM Straubing campus. Building on the current focus on extrusion-based 3D printing and 3D plotting of renewable, organic materials and pasty biopolymer hydrogels, TUM.Additive is adding research activities relating to the 3D bioprinting of foodstuffs (plant-based analogs to meat) and "custom-tailored diets", based on genetic information, the bodily condition and the lifestyles of the respective population groups.

Experts estimate that the market for materials required in tissue engineering is growing at approximately 30 percent per year and will reach the three-billion-dollar mark by 2021. TUM is therefore concentrating on the additive biofabrication of cell tissues, building on a number of prior successes in this field. The most notable examples are the TUM-IAS focus group for regenerative medicine[23] and the Center for Applied Tissue Engineering and Regenerative Medicine (CANTER), a partnership between TUM, Ludwig-Maximilians-Universität Munich (LMU) and the Munich University of Applied Sciences (MUAS), in which experts from the fields of surgery/regenerative medicine, cell biology and microbiology, bioengineering, biophysics, and mechanical engineering/medical technology work together in the laboratory on the creation of tissue from the body's own cells.

Potentially the use of stem cells in the layer-by-layer creation of skin, myocardial and cartilage tissue and functional organs is possible, although research is still in the very early stages. In this context the research agenda at TUM is being expanded to include ethically, socially, politically and societally relevant issues; this also utilizes the expertise of the Munich Center for Technology in Society[24] and of the TUM School of Governance[25].

Relevant professorships in addition to the experts listed in chapter 5	**Name**	**Faculty**
Medical Materials and Medical Implant Design	Petra Mela	MW
Experimental Plastic Surgery	Arndt Schilling	ME
Biomechanics (MRI Orthopedics)	Rainer Burkart	ME
Synthetic Biosystems	Friedrich Simmel	PH
Experimental Biophysics	Henrick Dietz	PH
Biomechanics	Oliver Lieleg	MW
Biological Chemistry	Arne Skerra	WZW
Food Chemistry and Molecular Sensory Science	Thomas Hofmann	WZW
Lifestock Biotechnology	Angelika Schnieke	WZW
Process Systems Engineering	Heiko Briesen	WZW
Brewing and Beverage Technology	Thomas Becker	WZW
Food and Bioprocess Engineering	Ulrich Kulozik	WZW
Wood Bioprocesses	Phillipp Benz	WZW
Biogenic Polymers	Cordt Zollfrank	TUMCS
Microbial Biotechnology	Bastian Blombach	TUMCS

23 https://www.ias.tum.de/en/research-areas/medical-natural-sciences/alumni-focus-groups/regenerative-medicine/.

24 The Munich Center for Technology in Society (MCTS) is an integrative research center of the Technical University of Munich. As one of the most important centers for scientific and technological research in Europe, the MCTS works to understand and help shape the widely varied interactions of science, technology and society; https://www.mcts.tum.de.

25 The TUM School of Governance investigates the mutual interactions between politics, society, business and technology. It then works to establish an interdisciplinary and transdisciplinary social-scientific understanding of these interactions; https://www.gov.tum.de.

6.6 Industrial Catalysis

The chemical industry is a principal mainstay of the German national economy. Following an era of extensive restructuring and expansive internationalization, the industry has remained competitive in worldwide competition. Energy-saving and resource-efficient production processes, linked with the expansion of the sustainability strategy based on renewable (biogenic) resources, are regarded as the decisive competitive factors of the future. The German chemical industry, rooted in science, will be able to leverage competitive efficiency advantages in the field of catalytic transformation if it is successful in the manufacture of structurally-defined catalyst systems. The TUM Catalysis Research Center (CRC) is pursuing this objective together with Clariant in the strategic alliance Munich Catalysis. After recently receiving support from the Bavarian Research Foundation, the interdisciplinary research cluster 3DKat is developing innovative 3D printing technologies for custom-tailored catalyst shape geometries. These geometries make it possible to improve the previously low selectivity of heterogeneous catalysts by orders of magnitude, moving the application spectrum and the profitability of catalytic material conversion processes into a new era (cf. section 5.2.).

Relevant professorships in addition to the experts listed in chapter 5	Name	Faculty
Industrial Catalysis	Richard Fischer (Clariant/TUM)	CH/CRC
Inorganic and Metal-Organic Chemistry	Roland A. Fischer	CH/CRC
Synthetic Biotechnology	Thomas Brück	CH
Macromolecular Chemistry	Bernhard Rieger	CH/CRC
Inorganic Chemistry with Focus on New Materials	Thomas Fässler	CH
Molecular Catalysis	Fritz E. Kühn	CH/CRC
Synthesis and Characterisation of Innovative Materials	Tom Nilges	CH
Technical Electrochemistry	Hubert Gasteiger	CH/CRC
Chemical Physics	Katharina Krischer	PH/CRC
Chemical Technology I	Kai-Olaf Hinrichsen	CH/CRC
Chemical Technology II	Johannes Lercher	CH/CRC

Munich, March 1, 2019

Thomas F. Hofmann
Senior Vice President Research and Innovation

List of Abbreviations for Faculties and Centers

AR	Architecture
BGU	Department of Civil, Geo and Environmental Engineering
CRC	Catalysis Research Center
EDU	TUM School of Education
EI	Electrical and Computer Engineering
IN	Informatics
LRG	Aerospace, Aeronautics and Geodesy
MA	Mathematics
MCTS	Munich Center for Technology in Society
ME	Medicine
MW	Mechanical Engineering
PH	Physics
SG	Sport and Health Sciences
TUMCS	TUM Campus Straubing for Biotechnology and Sustainability
WI	School of Management
WZW	School of Life Sciences Weihenstephan

Editorial Notes

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