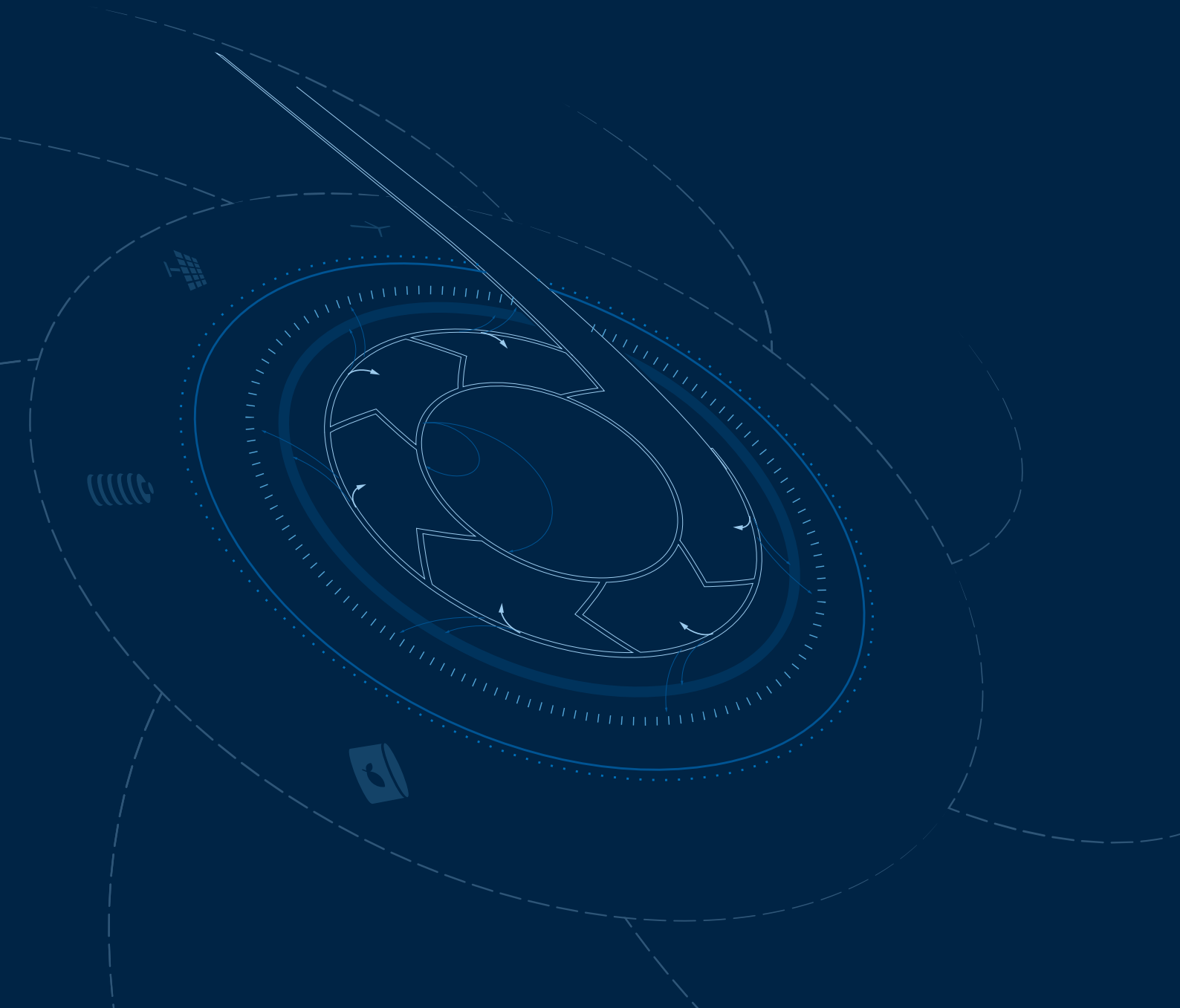
CirculaTUM

TUM Mission Network Circular Economy
at the Technical University of Munich
as Part of the TUM AGENDA 2030



CirculaTUM

Foreword

Our home planet, illuminated by the sun, floats through the endless expanse of space: the photo “Earthrise” was taken by astronaut William Anders in 1968 during the Apollo 8 mission. Symbolically, it can also be seen as representing the work “Economics of the Coming Spaceship Earth,” published by economist Kenneth E. Boulding two years earlier. In this work, Boulding postulates that a closed system without material exchange with the environment, like Earth in space, can reach its developmental limits.

Similarly, the study “The Limits to Growth” by the Club of Rome (1972) and the report “Our Common Future” by the Brundtland Commission (1987) reaffirm the fatal dependency of our growth on limited resources. Nevertheless, the global consumption of raw materials and fossil fuels, greenhouse gas emissions, and the amount of waste continue to increase.

How can we avoid extracting resources from the ground repeatedly to produce new goods? How can we utilize the potential of an economy based on circular principles to fulfill our ecological and social responsibilities while simultaneously enhancing economic success? The Circular Economy aims to reduce resource consumption, use resources more intelligently and efficiently, and, at the end of a product’s lifecycle, recycle, recover, and reintegrate materials as valuable resources for future products. Closing this loop requires a transdisciplinary innovation approach that combines the expertise of natural, engineering, life, economic, and social sciences with those of business partners along entire value chains and accelerates industrial implementation.

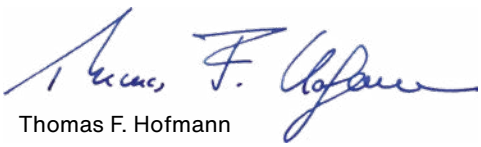
With foresight and the ambitious TUM Sustainable Futures Strategy 2030, TUM has focused on shaping a sustainable future. Exemplary of this is the TUM Campus Straubing for Biotechnology and Sustainability, with its integrative research and teaching approaches around renewable resources, biotechnology, and bioeconomy. Our TUM School of Life Sciences at the Weihenstephan campus conducts cross-scale research and teaching from molecular and cellular systems of plant and animal organisms to intelligent bioprocessing and natural ecosystem cycles, to human nutrition and health, in collaboration with the TUM School of Medicine and Health. The TUM School of Engineering and Design and the TUM School of Computation, Information and Technology make crucial contributions by using digitalization, technology, and process innovations to close industrial material cycles and product lifecycles, and to design our built environment as well as mobility, energy, and communication systems in a smarter and more sustainable manner. For developing new business models and their implementation in the economy, society, and politics, the TUM School of Management, the TUM School of Social Sciences and Technology, and the TUM Think Tank provide essential impulses. With the TUM Mission Network Circular Economy (CirculaTUM), we connect these institutions within TUM to consolidate research, teaching, education, and transfer in the field of Circular Economy.

We also need expressways for the accelerated transfer of new knowledge and developments into market-oriented innovations and economic practice. For this purpose, TUM has significantly expanded its innovation ecosystem with the TUM Venture Labs, the affiliated institute UnternehmerTUM, and top-tier industry partners. Through CirculaTUM and the innovation network “Circular Republic,” we connect actors across all disciplines and locations with start-ups and established companies along entire value chains. In doing so, we make significant contributions to industrial and societal transformation on the path to a circular economy.

The fundamental ideas for a Circular Economy have been around for a while—the necessity to implement them is more urgent than ever. Victor Hugo once said that nothing is more powerful than an idea whose time has come. We present some of our thoughts in this brochure. I invite you to support us in contributing to more sustainable economic practices with new scientific approaches. Enjoy the reading and find inspiration.

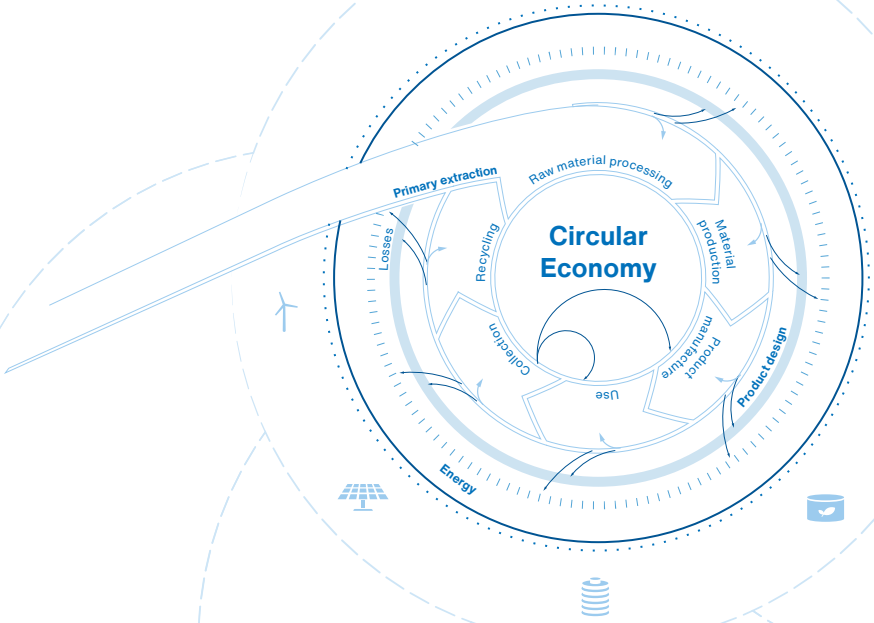
Munich ▪ Garching ▪ Freising-Weihenstephan ▪ Straubing ▪ Heilbronn ▪ Ottobrunn/Taufkirchen ▪ Singapore

Yours,



Thomas F. Hofmann
President

CirculaTUM



Annotation:

Our understanding of the Circular Economy is closely aligned with the definition by Kirchherr et al. (2017):

“The Circular Economy describes an economic system based on business models that replace the concept of an end-of-life for materials, products, and services in production/ distribution and consumption processes through avoidance, reuse, refurbishment, and recycling. This occurs at the micro level (products, companies, consumers), the meso level (eco-industrial parks), and the macro level (city, region, nation with the corresponding political environment), thereby achieving sustainable development with respect to environmental quality, economic prosperity, and social equity, for the benefit of current and future generations.”

Source: Kirchherr, J.; Reike, D. and Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127:221–232

Summary

How can we make value creation more sustainable and resilient, utilize resources more intelligently, and preserve them for future generations? Through the TUM Mission Network Circular Economy (CirculaTUM), the Technical University of Munich contributes to reinventing our economic system and decoupling prosperity from resource consumption.

The grand promise and primary ambition of the transformation towards a circular economy is to achieve climate protection and sustainability goals harmoniously while ensuring industrial competitiveness and supply security. It aims for an economy operating in as closed loops as possible, powered by renewable energy sources, where value is created and maintained sustainably.

To harness the significant potential of the Circular Economy, fundamental research on the concept, its possibilities, and its limitations is necessary. This includes developing new, sustainable solutions in technology, materials, and business models that need to be implemented directly and immediately due to the urgency of the challenges. Additionally, it involves understanding how to transform the economy and society.

Such a fundamental transformation requires a holistic, systemic, and circular approach. The Technical University of Munich, with its research profile and study programs, possesses unique capabilities. With its researchers' and students' insatiable curiosity, motivation, and entrepreneurial spirit, TUM can actively shape this epochal change.

The Mission Network CirculaTUM brings together TUM's diverse competencies across all disciplines and locations. This promotes the emergence of new research projects, supports the teaching of sustainable and systemic thinking in complex systems, and contributes to the activation of student engagement and entrepreneurial potential. As a driver of the paradigm shift towards a circular economy, CirculaTUM actively fosters exchanges with industry and society and makes a scientific contribution to industrial and societal transformation. This enables society, established companies, and start-ups to benefit from research findings and the expertise of well-trained specialists and leaders.

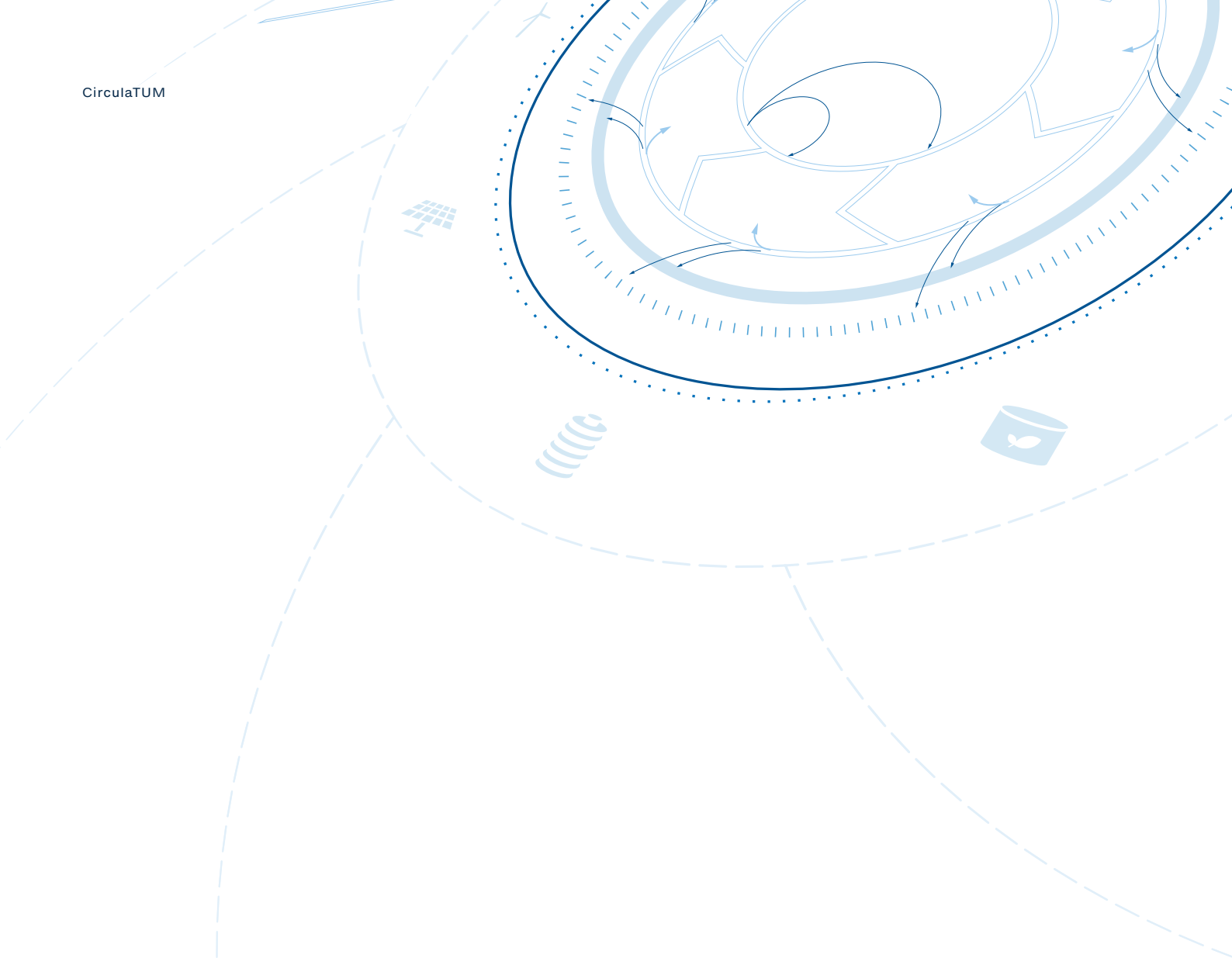
CirculaTUM focuses on industrial value creation, the built environment, and natural cycles. In all these contexts, cross-cutting themes such as business models and entrepreneurship, processes, and procedures, digital enablers, materials science and technology, accounting and evaluation or Circular Finance, consumer behavior, and social change, as well as governance and participation, are relevant in various ways and are addressed transdisciplinary.

→ **We look forward to exchanging ideas, welcoming new ideas, and engaging with partners who join the circular transformation and work with us to shape a sustainable future.**

Pol luted Korle
Lagoon in the center
of Accra (Ghana)

Motivation: Circular Economy as a Central Sustainability Strategy

Climate crisis, loss of biodiversity, threatened ecological balances: The planetary boundaries starkly illustrate the urgent need for a comprehensive transformation of human activities. While the global population has doubled since 1970 to 8 billion and is expected to reach 10 billion by 2050, the consumption of natural resources has more than tripled with a rising trend. The global concentration of greenhouse gases has reached levels not seen in at least 800,000 years. Currently, the global surface temperature is already about 1.1°C above the average of 1850–1900. Continuing with business as usual would trigger more and more tipping points—irreversible, self-reinforcing changes in ecosystems. Humanity has caused these potentially catastrophic changes, many of which are already happening today. Therefore, it must also find ways to solve them.



A promising solution is the realization of a sustainable Circular Economy. This aims at reducing, slowing, and closing material cycles—on the micro-level of products, materials, and people, the meso-level of eco-industrial parks and neighborhoods, and the macro-level of cities, regions, and countries. The Circular Economy also requires sustainable value creation and business models, supportive legal and economic frameworks, as well as changes in attitudes and behaviors. The goal behind this is to ensure that the valuable resources, on which prosperity and economic development depend, can still be used in the future, but no longer consumed. This can reduce emissions, protect biodiversity, and avoid the environmental impacts of raw material extraction, processing, and disposal after use.

Major economies worldwide are increasingly adopting the Circular Economy to achieve a challenging triple objective: improved environmental conditions, ensured economic development, and enhanced social justice. The Circular Economy plays a central role in the European Green Deal, China's 14th Five-Year Plan, and the sustainability programs of the USA and Japan. In this sense—and especially considering critical raw materials and vulnerable supply chains in times of geopolitical tensions—a Circular Economy will also significantly influence the competitiveness, security of supply, and technological sovereignty of economic systems.

However, numerous questions remain unresolved regarding the definition, measurement, and particularly the comprehensive implementation of the Circular Economy. Improved and new technologies, new business models, regulatory and governance adaptations, and changes in consumer and business behavior are needed. Reliable data is also necessary to determine the extent of the Circular Economy's contribution to achieving climate protection and sustainability goals and to identify potential conflicts between goals. Speed is crucial, as the measures taken by 2030 are decisive for meeting the targets of the Paris Agreement and the Sustainable Development Goals.

With its interdisciplinary research and study programs, TUM is uniquely positioned to actively and significantly contribute to this epochal challenge.

2.

Agenda Circular Economy

In the long term, TUM aims to make significant contributions to the development and implementation of the Circular Economy concept and thereby address industrial and societal sustainability challenges. TUM seeks to establish new approaches for integrated research, teaching, and knowledge transfer, and to help shape the emerging scientific discipline. Central to this effort is CirculaTUM, which consolidates the diverse competencies relevant to the Circular Economy across all disciplines and locations within TUM.

In this new, flexible, and learning structure, pioneering disciplinary approaches are combined with holistic approaches across all schools and locations (see the image below) and addressed transdisciplinarily in cooperation with industry and societal partners. In close collaboration with the TUM Venture Lab Sustainability and Circular as well as UnternehmerTUM and embedded in the excellent national and international cooperation network, an ecosystem for sustainable entrepreneurship is to be created, in which business and society can find support for their transformation and thus new "Circular Champions" can emerge.

Given the urgency of global challenges, activities will focus on two time horizons: On the one hand, the rapid introduction of the Circular Economy into existing material cycles to achieve immediate changes. On the other hand, comprehensive basic research is needed to lay conceptual, methodological, and technological foundations for medium- to long-term transformations and to fundamentally replace the currently prevailing linear economic logic based on fossil materials with a comprehensive and sustainable Circular Economy.

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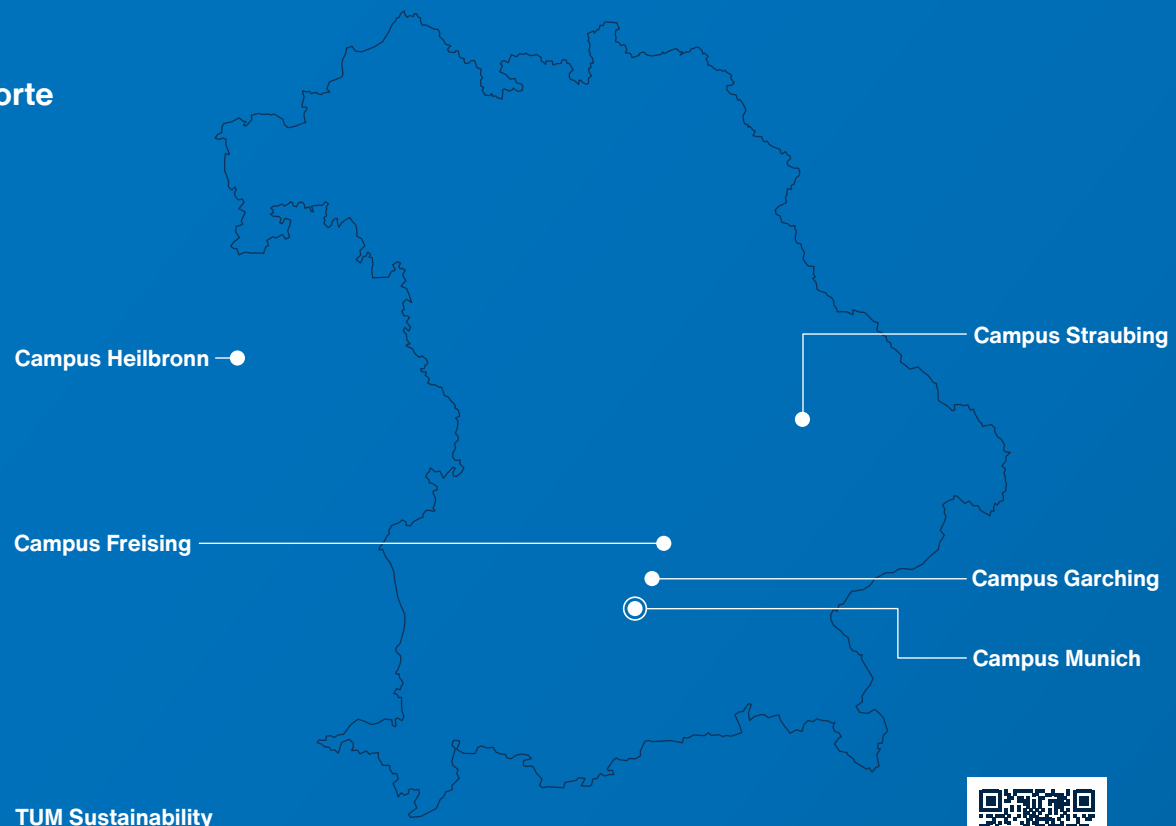

TUM Sustainability

TUM Asia

Circular Republic x UnternehmerTUM

TUM Venture Labs

Link to CirculaTUM Member Overview

For the success of such a transformation, science bears a special responsibility. This is especially true for TUM, with its unique and excellent research profile and study programs, as well as its self-conception as an entrepreneurial university and servant of society. To make significant contributions to industrial and societal transformation, CirculaTUM aims to create a substantive and organizational foundation. By doing so, TUM intends to meet its aspirations and take a leading role in the sustainable transformation of the economy and society, as illustrated in the figure below.

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Vision und Mission

3

Key Focus Areas at TUM

The work on Circular Economy at TUM focuses on three key thematic areas. However, these areas are not isolated from each other; rather, they exhibit numerous overlaps and interactions that are addressed holistically within CirculaTUM.

3.1 Industrial Value Creation

The manufacturing industry significantly contributes to economic development in Germany and globally. However, the substantial prosperity created in many countries since the industrial revolution has largely relied on the extraction of natural resources as the foundation for all subsequent steps in the value chain over the past two centuries. This reliance is critical not only in current times of resource scarcity and vulnerable supply chains but especially because extraction and processing of raw materials are associated with over half of CO_2 emissions and an estimated 80% of biodiversity loss.

If today's level of prosperity is to be maintained at least and is to spread to other regions worldwide, economic development must be decoupled from the consumption of natural resources. This applies to practically all areas of industrial value creation, including technology and process solutions, the closing of material and product cycles, and the consideration of sustainability and circularity principles in product design, production, and logistics. Additionally, more efficient forms of utilization and operation (such as through sharing approaches), maximizing product lifespan (through maintenance, repair, and reuse), as well as recovery, reprocessing, refurbishment, separation, sorting, and recycling are crucial aspects. All of these efforts must be embedded in holistic business models and new forms of entrepreneurial cooperation within value creation networks. Success critically depends on societal frameworks and the maturity of users.

With its specialized expertise in classical engineering, robotics, materials science, the full spectrum of natural sciences, as well as in sustainability assessment and business model development, TUM can support industry on the path towards the Circular Economy. In two projects with the automotive industry and with companies in the industrial middle market.

They are working on processes to intelligently network and automate the disassembly of vehicles or technical devices at the end of their product life cycle. The goal is to preserve the components used at the highest possible value level and reuse them in new products, rather than disposing of them and destroying the value created previously.

In another project, research is focused on the direct utilization of secondary steel granulate in additive manufacturing processes. This approach could enable the creation of a new product with a completely different geometry directly from an old product, without requiring melting or transportation processes. Production technology and logistics collaborate in such projects, integrating image recognition techniques and mechatronic tasks, alongside process and conveying solutions that facilitate new product designs.

At the same time, it is important to overcome established ways of thinking and enable new solutions at the interfaces of disciplines. In the context of industrial value creation, product development and design take precedence, as they significantly influence the product's lifecycle. The development and implementation of fully circular production and logistics systems, including solutions and technologies for use, recovery, and closing the loop, along with potential business models, represent another crucial area of action. This involves establishing an entirely new industrial system overall.

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3.2 Built Environment

To accommodate the globally increasing population, approximately 230 billion square meters of ground area will need to be sealed with new buildings by 2060. This represents a doubling compared to the 2018 figures. Without corresponding countermeasures, the environmental impacts that are already significant today, particularly CO_2 emissions, will continue to rise. Building construction and usage account for 30% to 60% of energy consumption, raw material consumption, waste generation, greenhouse gas emissions, and water consumption in Europe.

Therefore, we need a fundamental shift in construction: Sociological, ecological, and economic incentives must be created for a circular economy in the building sector. The circular economy offers solutions to use materials from non-renewable resources and other resources such as water, soil, and energy as efficiently as possible, while avoiding waste and pollution into the environment.

The use of biogenic building materials also plays a crucial role in this context. In particular, the reuse of existing structures and the recycling of materials bound within buildings offer significant potential.

This approach allows for the substitution and conservation of primary resources, as well as the minimization of waste and residual material streams. It substantially contributes to improving resource efficiency and reducing CO_2 emissions in the construction sector.

To develop the building stock more sustainably, it is essential to emphasize durability, the use of secondary raw materials, and the establishment of closed material loops. This requires sustainable, reliable, and secure data availability. It forms the basis for establishing an effective value chain network involving all stakeholders (investors, construction industry, waste management, capital markets).

To be able to specifically manage and control material and energy flows, it requires comprehensive design, construction, analysis, and evaluation methods that allow for considering and mapping the environmental impacts of a building throughout its entire lifecycle. Scenarios for the future use and lifespan of components and buildings can support both the handling of existing structures and the conception of new buildings. Circular deconstruction concepts must already be considered during the initial creation of constructions.

Solar power and rainwater: the “Nexus Haus” utilizes almost exclusively natural resources

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Digital tools are needed to manage raw and construction material flows, to locate, quantify, and assess the reusability and further usability of materials embedded in the building stock. Building Information Modeling (BIM) and the concept of the "digital twin" provide a digital basis for strategic material flow and resource management in the construction industry. There is a very high need for research in this area. Moreover, procedures must be intensified to ensure the safe use of circular or cascaded materials and products, thus achieving the necessary resource efficiency in the construction industry.

3.3 Natural Cycles and Bioeconomy

Natural cycles serve as a model for a circular bioeconomy in terms of well-balanced systems of material cycles. Thus, the design principles of nature can lead to effective solutions in product and process design. Additionally, renewable raw materials can be replaced with biomass. Biotechnological production processes have the potential to convert substances more energy-efficiently and environmentally friendly than traditional methods.

A biological transformation, however, depends on the availability of corresponding raw materials regionally, nationally, and internationally, and whether possible competitive uses, especially in the food and feed sector as well as the energy sector, can be resolved. Additionally, resilient infrastructures must be established for their harvesting, transport, and processing. It should be noted that bioeconomic solutions often cannot represent a 1:1 replacement for existing products and value chains. However, they offer the opportunity to develop new and innovative functionalities and thus application possibilities that go beyond what is currently known.

Additionally, these raw materials and production processes also initiate new business and usage models in the sense of a circular bioeconomy. For example, integrating waste streams from conventional agriculture with scalable biotechnological processes, such as the fermentative production of value- adding fungal, yeast, algae, and bacterial biomass, can yield efficiency gains.

This approach can significantly reduce the pressure on the steadily shrinking agricultural land and promote raw material and product independence from third countries. Thus, the bioeconomy acts as an important enabler for the Circular Economy, with the potential to make significant positive contributions to sustainability and climate protection, provided the mentioned challenges are overcome and mass- and energy-efficient utilization cascades are developed.

Besides the clear need for research to develop innovative biotechnological processes upon which bio-based value chains can be built, there is a fundamental need for action: starting with the question of how the large-scale transition to the use of renewable biomass from agriculture, forestry, and aquaculture will alter material flows. It is necessary to examine how the significantly increasing demand for primary biological resources expected in a circular economy can continue to be sustainably met, without exceeding planetary boundaries or becoming uneconomical, for example, by turning former waste products into sought-after raw materials. Furthermore, primary production should be linked to ecological enhancements, such as regeneration of the biosphere, reduced water, air, and soil pollution, and promotion of biodiversity. These challenges have clear political and economic dimensions and are crucial for analyzing the role that bioeconomy and biotechnology can play in sustainable development. To promote these processes, it is also important to identify existing obstacles and demonstrate how they can be overcome through suitable regulations.

Professor Dr. Brück in the Algae Technology Center: Research on Sustainable Production of Carbon Fibers

TUM possesses synergistic expertise in the field of bioeconomy, particularly at the TUM School of Engineering and Design, the TUM School of Natural Sciences, the TUM School of Life Sciences, and the TUM Campus Straubing for Biotechnology and Sustainability. These range from synthetic biology and the development of biotechnological conversion processes in various organisms and systems (bacterial, fungal, and algae-based cell factories as well as cell-free systems), to comprehensive chemical-technical analytics, research on biogenic (composite) materials, to primary production systems in forestry and agriculture and the resulting value creation systems. Additionally, learning from nature in the form of bionics or biomimetics plays a role in redesigning products, materials, and processes. Moreover, there are numerous research groups addressing associated economic and socio- scientific questions. This enables us to achieve a holistic systemic perspective.

Key future research fields include questions about available raw material potentials from agriculture and forestry, how these will specifically change within the context of climate change, and how evidence-based climate adaptation should be structured. In developing materials and processes based on renewable resources, it is crucial to use raw materials as efficiently as possible—considering their entirety—and to design products in a way that allows for recycling within a sustainable circular economy. The (re-)use of biogenic by-products, co-products, and residues, for example from the wood or food industries, through innovative upcycling concepts should be increasingly prioritized over immediate energetic use, aiming to keep the carbon contained in these materials bound for as long as possible. In collaboration with external industrial partners, the large-scale deployment of developed materials and processes should also be accompanied and managed, ensuring the sustainability of the overall system is not compromised.

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TUM's Areas of Expertise for the Circular Economy

4.1 Business Models and Entrepreneurship

Sustainable business models are a crucial component in implementing a circular economy. They are built on a sustainable understanding of value and encompass the entire lifecycle of products or services. They also necessitate a shift in consumer behavior. Examples include concepts like the sharing economy, packaging-free approaches, sustainable packaging solutions, and second-life approaches for specific products such as batteries for electric vehicles and energy storage.
These sustainable business models can be formulated and implemented by both new and established companies, ranging from small and medium-sized enterprises (SMEs) to international corporations.

However, these necessary approaches must not remain in the realm of ideas; they need to be implemented in practice, ideally in the form of a scalable business model that can have a globally relevant impact. TUM, as an Entrepreneurial University, has set the goal, together with its affiliated institute UnternehmerTUM GmbH, to lead Europe in translating important research findings into innovative business models. In doing so, TUM addresses a critical weakness of today's innovation landscape in Germany: too little of the research funding translates into entrepreneurial ventures.

Therefore, UnternehmerTUM and TUM have actively engaged in the Circular Economy Initiative Germany and hold positions on the board of the multi-year BDI (Federation of German Industries) Circular Economy Initiative, particularly within the Technology and Regulation working groups. Their aim is to collaborate with industrial companies from all sectors to introduce new solutions for the circular economy into economic and regulatory practice.
Additionally, the new Munich Urban CoLab, a collaboration involving TUM laboratories, UnternehmerTUM, entrepreneurship activities, public authorities, and innovation centers of several major corporations, provides an environment where stakeholders can rapidly prototype and implement new systemic and sustainable business models in an "Open Innovation" approach. This is a significant advantage for advancing the Circular Economy.

From this unique entrepreneurial ecosystem, CIRCULAR REPUBLIC drives the comprehensive industrial and societal transformation as an implementation-focused industry alliance in close collaboration with business partners. Founding partners include BMW, alongside Aurubis, Palfinger, PreZero, SAP, the Tengelmann Group, Webasto, and many others.

Circular Hackfest at Makerspace in the Munich Urban CoLab during Circular Republic Festivals 2023

In addition to "Enablement" formats for both established and young companies, support for startup-corporate collaborations, and broad awareness-building efforts such as the CIRCULAR REPUBLIC FESTIVAL, a central European event for the Circular Economy, CIRCULAR REPUBLIC's main activities focus on initiating and orchestrating crucial cross-company collaboration. Through sector- or value-chain-specific multi- stakeholder projects, CIRCULAR REPUBLIC pilots and scales the closure of material loops, for instance in areas like battery materials, textiles, and electronic products.

TUM ranks number 1 in spin-offs across all German rankings. In the field of Circular Economy, for instance, TUM has fostered companies like TWAICE, which plays a crucial role in battery lifecycle management, and Beworm, specializing in biotic recycling of polymers. Overall, within the TUM/UnternehmerTUM ecosystem, more than one startup is founded weekly, and these startups attract over two billion US dollars in venture capital annually.

Building on this, TUM and UnternehmerTUM have launched a new joint initiative with the TUM Venture Labs, aimed at increasing spin-offs from scientific research in key future fields by a factor of ten. The TUM Venture Lab Sustainability and Circular Economy focuses on establishing benchmarks and methods for the circular economy across all TUM Venture Labs.

Additionally, it fosters its own startups in circular economy, bioeconomy, and other crucial areas for a sustainable world of tomorrow.

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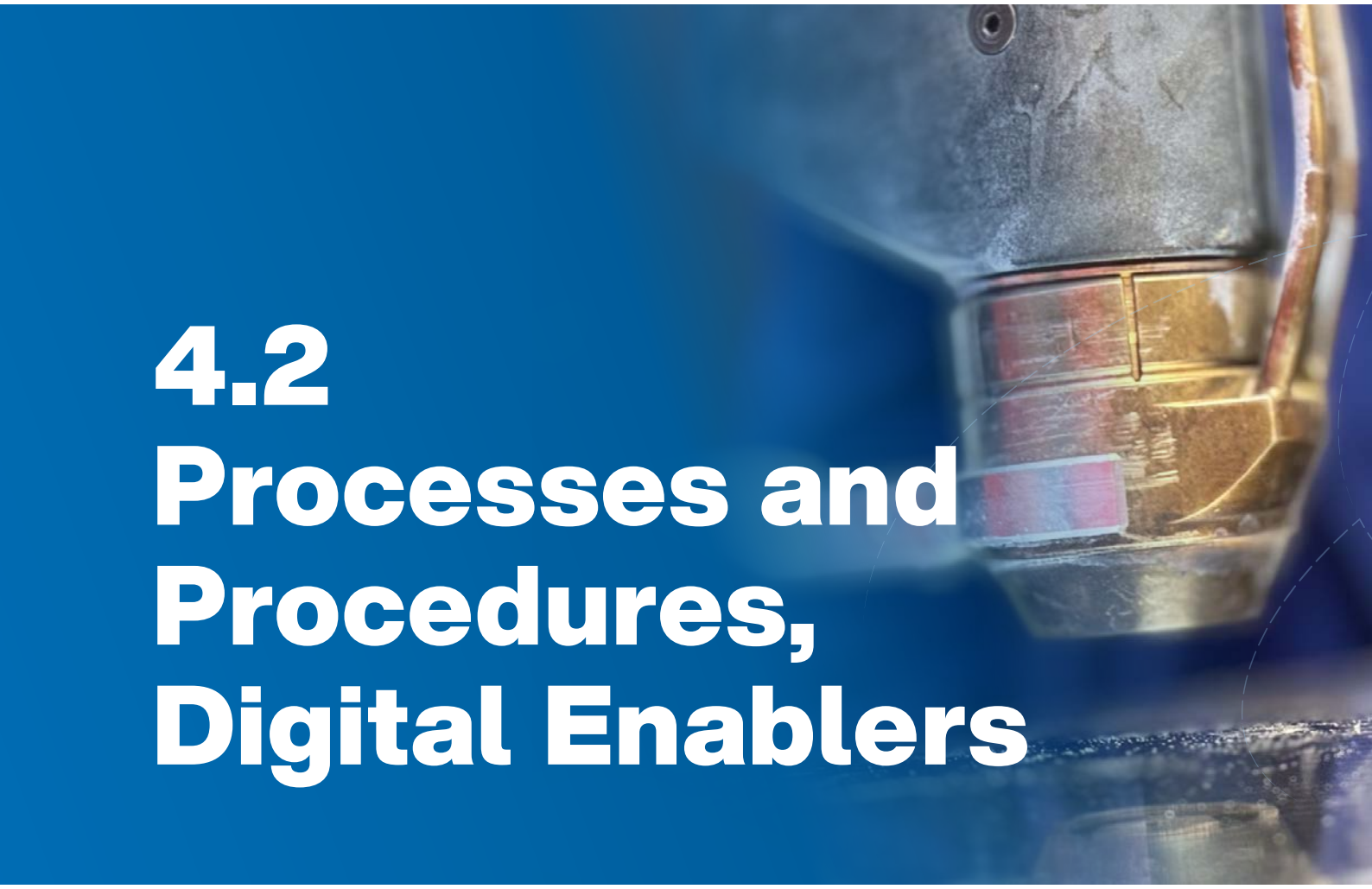

4.2 Processes and Procedures, Digital Enablers

Global supply chains that can fail, excessive exploitation of limited environmental and climate-damaging resources, and overconsumption in the Western world leading to waste problems in poorer regions: We urgently need to rethink to preserve our planet for future generations. The slow but steady increase in this shift is evident in the growing number of people prioritizing sustainable and fair consumption. Politics are also responding with initial steps towards stricter regulations, such as mitigating climate change or ensuring social standards in supply chains. For businesses, these changes mean they must produce more sustainably and robustly and adjust their supply chains accordingly to remain competitive. Linear economic and production systems must evolve into circular systems to meet sustainability goals.

Digitalization can support these efforts and is the next logical step towards making processes and procedures sustainable. It facilitates the exchange of information between end- customers, suppliers, and manufacturers, enabling the discovery of synergies. This can help in returning products to factories at the end of their lifecycle for refurbishment.

By involving global partners, these processes can also occur locally, adding more value on-site and contributing to sustainable economic development. Digitalization has the potential to accelerate the shift towards sustainable, circular production.

For TUM, this transformation represents both opportunity and challenge. Existing methodological research paradigms must be questioned to expand the solution space for circular processes. Manufacturing technical products from locally sourced materials, the return or disassembly process, and a development process focused on End-of-Life (EOL) are just a few of the numerous process steps that need to be rethought in research as well. However, the resulting degrees of freedom for innovation outweigh the risks. The opportunity to provide a proof of concept for industry motivates us at TUM.

Plasma Powder Torch in 3DPMD Printing of Secondary Aluminum at the Chair of Materials Engineering of Additive Manufacturing

In the coming years, we will continue to pursue ongoing projects and initiate new ideas. Our primary focus will be on developing and implementing methods for sustainable production systems, transferring them across various industries and sectors. It is already foreseeable that this will lead to a significant "bottom-up" contribution towards evaluating sustainability in production processes. Instead of relying on external analyses, we empower companies to proactively drive internal change.

The goal of our network is to make sustainable production a foundational principle in manufacturing, akin to the Lean movement.

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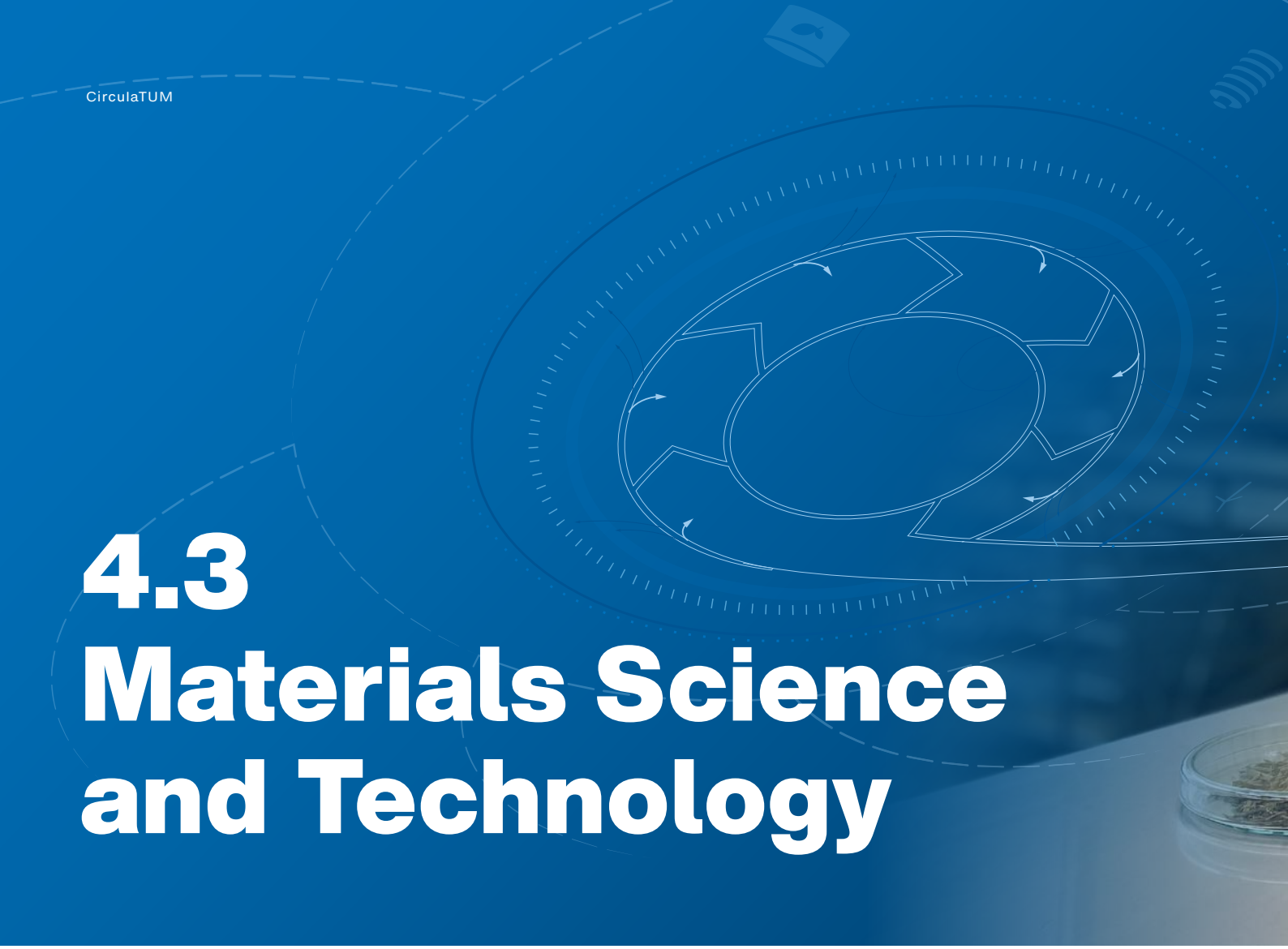

4.3 Materials Science and Technology

Materials and substances form the foundation for many technical innovations and the production of consumer goods. They play a crucial role in industrial applications such as energy and environmental technology, mechanical and plant engineering, architecture and construction, medical technology, and the mobility industry. Consequently, they are pivotal in the transformation towards a circular economy.

Producing primary metals requires significant resources with far-reaching consequences, especially in terms of climate-related emissions. In contrast, recycling rates are often low, and there are significant quality losses where recycling does occur. This is particularly true for many metals classified as critical, but it also applies to numerous other common material classes.

Given limited availability, volatile markets, and significant environmental and climate protection efforts, challenges and opportunities arise for the Circular Economy concerning materials science and new technologies such as Additive Manufacturing or Biotechnology. Addressing material science, process engineering, logistical, and industrial questions becomes crucial to close material loops or deploy new technologies within the circular economy framework.

Biogenic and biobased materials offer the potential to sustainably produce advanced structural and functional materials.

Recovering materials and reintroducing them into a cycle is challenging. From a materials science perspective, the influence of contaminants in the recycling and processing process significantly impacts the quality and properties of the recovered raw materials. From a production engineering perspective, the question is how to manufacture components that can be easily disassembled and separated in a largely pure form. Monomaterial composites would be highly desirable and forward-thinking in this regard, as they do not require complex separation processes. However, the development of material logistics is also essential.

Through its interdisciplinary expertise, excellent facilities, and a very strong network, TUM can make a significant contribution to enabling sustainable material cycles, increasing the use of renewable resources, and further developing new technologies like additive manufacturing for a sustainable Circular Economy that meets industrial needs.

Bioregional
Design Lab

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The Munich Institute of Integrated Materials, Energy and Process Engineering, the TUM Campus Straubing for Biotechnology and Sustainability, and the initiatives TUM. Additive and TUM.Wood are successful examples of collaborations among outstanding scientists from various disciplines who work together to address complex scientific questions.

Alongside solving fundamental scientific questions, TUM promotes continuous technology transfer into industry. For instance, around 20 doctoral candidates at the TUM-Oerlikon Advanced Manufacturing Institute research across the entire value chain of modern production, focusing on topics such as materials and material cycles, advanced processing techniques, and digitalization. In large collaborative projects like the "Future Sustainable Car Materials," funded by the Federal Ministry for Economic Affairs and Climate Action, TUM collaborates with 16 partners from academia and industry to develop new materials for groundbreaking, sustainable vehicle components. The goal is to establish a material cycle for complex products like vehicles that minimizes losses and energy consumption.

In the field of biogenic polymers, research includes qualifying Cottonid, a cellulose-based structural material, for various applications, studying the biodegradability of plastics, and developing new bioplastics (films, fibers, nonwovens) from regional biomass. Additionally, research focuses on biogenic functional materials for energy-related technologies (such as lighting and photovoltaics). Particularly, protein hybrid materials like luminescent and structural proteins are investigated for sustainable electroactive materials used in high-performance thin-film lighting and photovoltaic devices, without relying on rare earths or toxic elements.

4.4 Accounting and Evaluation, Circular Finance

Circular Economy must not be an end in itself but must demonstrate its benefits in terms of ecological, economic, and social criteria. Only then can all stakeholders, including companies, investors, consumers, and society as a whole, be convinced that circular economy solutions are meaningful.

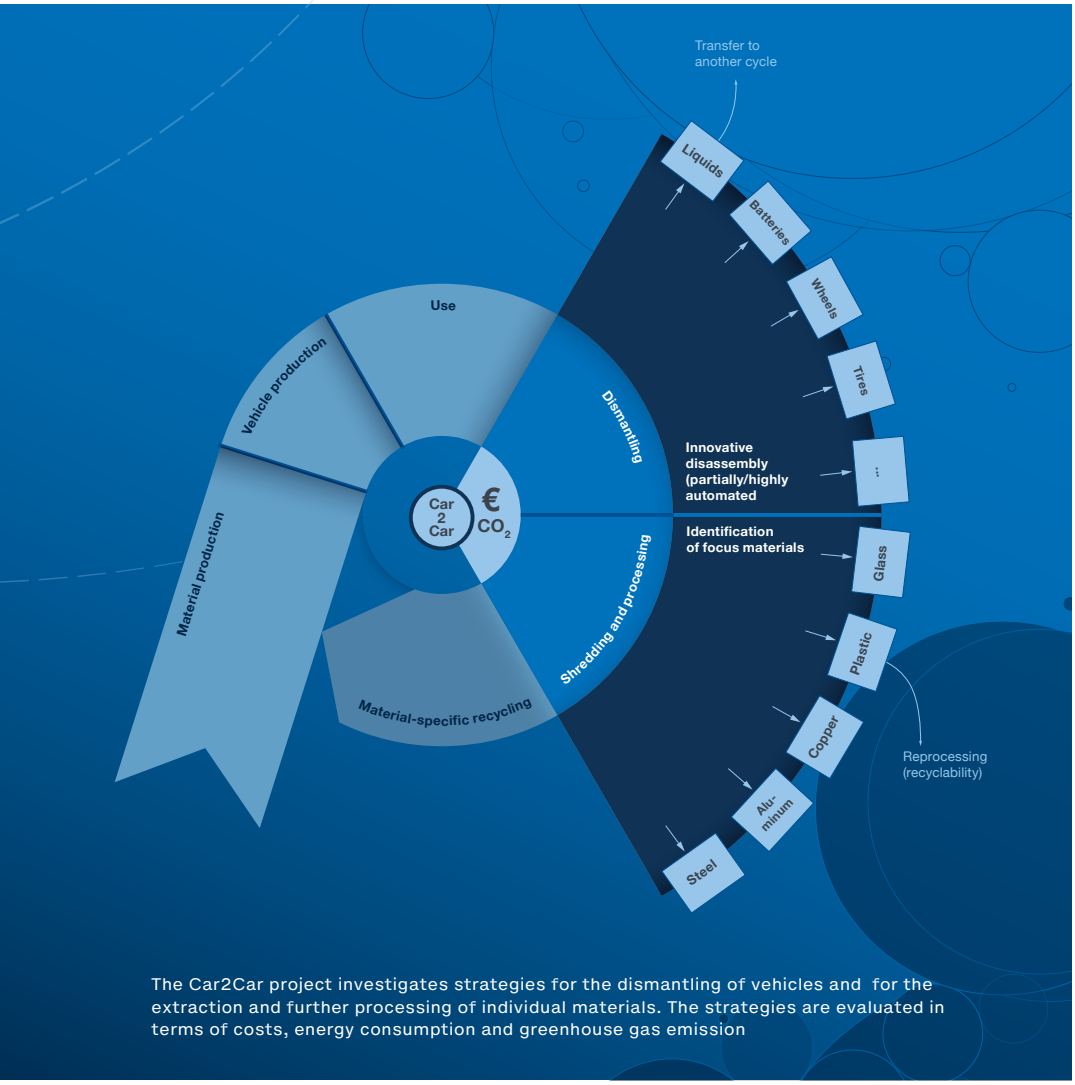
For entrepreneurs and investors, the question revolves around accounting methods and economic viability. Consumers need information about the sustainability of products and services. Only through this can long-term successful concepts of the Circular Economy be identified, developed, and implemented.

The scientific community finds numerous intriguing research fields in this context. Initial findings suggest, for example, that a Circular Economy is associated with lower risks for businesses and can lead to higher risk-adjusted returns.

Research projects at TUM focus on how to quantify sustainability-related risks and incorporate them into risk models. These results enable a more precise assessment of risks, thereby effectively financing companies and projects that utilize Circular Economy concepts.

To assess products, key technologies, and services, Life Cycle Sustainability Assessment methods are used to determine their environmental, economic, and social impacts. By integrating these assessments throughout development, optimal solutions can be achieved, conflicting objectives can be identified, and potential issues can be prevented from being shifted elsewhere.

Through simulation and optimization, it is possible to determine how political decisions impact individual solutions as well as aggregated economic sectors. This allows entrepreneurs, investors, and political decision-makers to assess the consequences effectively.



The Car2Car project investigates strategies for the dismantling of vehicles and for the extraction and further processing of individual materials. The strategies are evaluated in terms of costs, energy consumption and greenhouse gas emission

The goal of a research agenda must be to develop a set of evaluation models and metrics that allow companies, products, and technologies to be assessed in terms of their Circular Economy criteria. Additionally, companies themselves need a management toolkit that supports them in transforming their business activities.

In addition, consumers need information about products and services that transparently and reliably show their costs over the lifecycle, as well as their ecological and social impacts, in a way that is understandable yet comprehensive.

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4.5 Consumer Behavior and Social Change

Circular economy offerings, such as recycled or refurbished products, swap and resale platforms for second-hand goods, rental models, or sharing platforms, are becoming increasingly prevalent in consumers' daily lives. Conversely, consumers are crucial in establishing new circular economy solutions sustainably. Circular economy offerings can fundamentally change the role of consumers. Often, they no longer purchase products but rather use them for a specific period without becoming owners. Examples include electronic devices (e.g., Grover) or bicycles (e.g., Swapfiets). This blurs the line between supply and demand: consumers participate as both providers and interested parties on exchange and resale platforms like Vinted or eBay.

Such changes in the role of consumers result in questioning existing insights into consumer behavior in the context of the circular economy. We need to better understand the drivers and barriers for demand in the circular economy.

Science can particularly support through empirical behavioral research. For instance, TUM is represented as a partner in the Consumer Insight Action Panel (CIAP) working group for electronic devices. CIAP aims to better understand consumer behavior regarding circular economy offerings for electronic devices through experiments and pilot studies, and optimize offerings accordingly. In the food production sector, the "Freewalk" project examines the concept of the Circular Economy, focusing on the acceptance of reusing waste products from agricultural production in food manufacturing.

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To further advance the Circular Economy and identify barriers and solutions, a better understanding of consumer behavior is needed, through observation or economic experiments. In addition to potential uses of residual materials in food production, applications include biobased materials, recycling and re-use in clothing consumption, as well as the use of leasing models for electronic devices and the acceptance of used and refurbished equipment.

4.6 Governance and Participation

Circular economy is about much more than just recycling. It involves how products are designed, how often they are reused, how easy they are to repair, and how sustainable their material use is. Social, economic, and political factors can either promote or hinder the adoption of circular economy principles. Overcoming barriers, acting collectively, avoiding unintended side effects, and achieving goals such as the Sustainable Development Goals (SDGs) require joint efforts and coordination.

In this endeavor, policymakers, businesses, and society can draw on a proven repertoire of private and state govenance—from better informing citizens and creating material or other incentives to legislative and regulatory requirements.

Some examples illustrate this:
Researchers at TUM are investigating funding programs, action plans, and implementation strategies for the circular economy at local, national, and international levels. These studies identify effective and ineffective approaches, contributing to the development of better solution strategies. Researchers from the Chair of Environmental and Climate Policy have also published on the governance of fundamental transformations in general, contributed to the Task Forces on Green Transition and Sustainable Development, as well as Green Consumption and Production of the China Council for International Cooperation on Environment and Development, and discussed the promotion of circular economy within the European Environment and Sustainable Development Advisory Councils.

The transition to a circular economy requires significant investments of resources, energy, and ideas but must not become a luxury phenomenon. If circular economy products become unaffordable for lower-income populations, the circular economy will not realize its full economic potential and may provoke social and political resistance. Therefore, it must be socially equitable and politically sustainable. It is crucial to ensure that the necessary changes have broad societal support and do not lead parts of the population to feel that their interests are disregarded in the liberal-democratic political and economic system. It is inevitable that there will be winners and losers. However, suitable political measures can ensure that such changes do not endanger the social and political fabric of society. Addressing distribution conflicts and exploring ways to overcome them are core tasks of two key research units at the Munich School of Politics and Public Policy at TUM: Comparative Political Economy and Social Conflict Research.

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To reflect the economic, climate protective, and societal benefits of the circular economy in accounting and evaluation (see 4.4), new standards must be developed to assess benefits and long-term risks that would otherwise arise without the circular economy. This can be partly achieved through private initiatives, particularly given the strong societal interest in effective solutions to mitigate climate change and strengthen sustainability. However, it also requires government regulation and possibly support. In any case, it is crucial to understand the development of standardized measurement methods and technical standards not only as an engineering and technical challenge but also as a social and political process.
Social and economic researchers at TUM with extensive expertise in this field can accompany the development of standards and, building on current best practices, propose new approaches to avoid foreseeable difficulties.

In order for end consumers to adjust their consumption behavior and thus create incentives for producers, they need transparent information about circular economy offerings, production processes, materials, construction methods, and possibilities for circularity (see 3.2, 4.2, 4.3, and 4.5). Ideally, this information should be made accessible to consumers in understandable form on product packaging.

Only then can they stimulate the development of more circular products through their consumption behavior. Unfortunately, studies on other product attributes (e.g., energy efficiency) show that such consumer empowerment only works to a limited extent due to unclear or non-informative information. This requires expertise in communication science. TUM is currently building such expertise in research and education, particularly in the School of Social Science and Technology, the think tank at the School of Politics, in the School of Management, and at the Institute for Life-Long Learning.

Effective communication and democratic-political sustainability also require broad societal participation. Through their fundamental research on participation and legitimacy, as well as their practical experience ranging from local to international levels, the political scientists at TUM can accompany and promote the development of participatory governance for the circular economy.

Shaping the Sustainability Transformation of Economy and Society

CirculaTUM aims to shape the sustainability transformation in research, education, and society on a global level.

5.1 Research on the Conceptualization and Implementation of the Circular Economy

Fundamental research as well as the rapid development and implementation of practical solutions: this is what CirculaTUM aims to achieve, and for this purpose, TUM consolidates research within an excellent professional framework. The sustainability challenges we face as a society are proactively addressed using inter- and transdisciplinary approaches. The scope of work ranges from fundamental research on the concept of the Circular Economy, its potentials and barriers, necessary key technologies and scaling, to questions of implementation within the framework of sustainable economic and societal transformation.

Thematically, the focus is on the three described key areas: industrial value creation, the built environment, and natural cycles and bioeconomy, as well as the six described areas of expertise. In addition to classical approaches, new methods are also pursued: impact- driven, open, and participatory concepts, such as Living Labs, are to be used to enable mutual learning between science and society within co-creative experimental spaces and to quickly implement practical solutions. This is essential as the tasks are urgent.

To achieve this, pioneering project ideas are identified within the research themes and areas of expertise and strategically developed and implemented as flagship projects. The vision of the Circular Economy is thus realized through innovative and responsible research aimed at solving clearly defined challenges. In doing so, TUM addresses key content aspects of its Sustainable Futures Strategy 2030. Additionally, the integration of economic, ecological, and social perspectives in research, as described in the strategy, is implemented in concrete use cases.

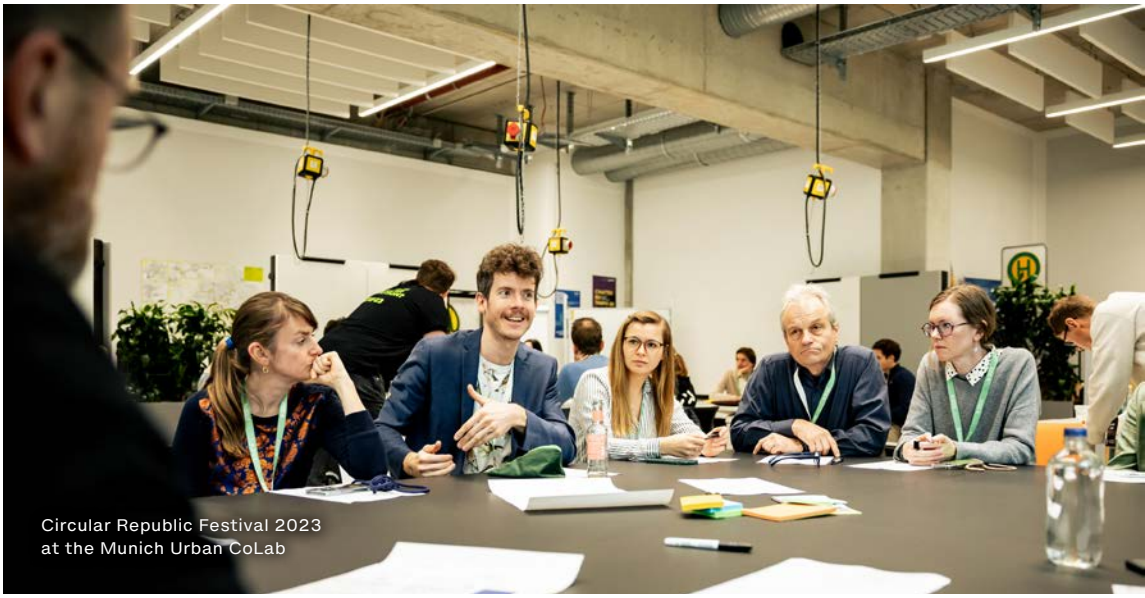
First TUM Sustainability Day 2022

5.2 Teaching Sustainability, Holistic and Systemic Thinking

In the field of education, the qualification goals of all Bachelor's and Master's programs aim to impart fundamental sustainability-related competencies, systems thinking, and inter- and trans-disciplinary problem-solving skills..

Furthermore, students in advanced disciplinary and interdisciplinary Master's programs should be able to acquire competencies in Circular Economy. This will be implemented through project weeks, plug-in modules, or micro-credentials as outlined in the new TUM teaching constitution. Additionally, specializations for doctoral students will be developed in collaboration with university partners from the EuroTech network and other internationally leading universities.

In the field of Life Long Learning for TUM employees and leaders from business and society, work in Circular Economy also makes significant contributions, such as through the Certificate Program in Sustainable Management and Technology and other emerging programs.



Circular Republic Festival 2023
at the Munich Urban CoLab

5.3 Shaping the Transformation of Economy and Society through Entrepreneurship

As challenging as the industrial and societal transformation to a Circular Economy may be, this fundamental shift also offers one of the great entrepreneurial opportunities of the 21st century. Through the close integration of research and teaching activities with UnternehmerTUM and the TUM Venture Lab Sustainability and Circular, as well as intensive collaboration with partners from industry and society, it is ensured that scientific findings are developed in close alignment with practical needs and that the solutions generate scalable impact.

UnternehmerTUM, as Europe's largest center for entrepreneurship and innovation, is poised to play a key role in realizing and commercializing regenerative materials and technological solutions for the Circular Economy, as well as supporting and empowering established companies in their entrepreneurial transformation. To this end, the Circular Republic Initiative has been established within UnternehmerTUM to support the sustainability transformation through Circular Economy in collaboration with society and industry. As a thriving startup hub, with strong partners and outstanding implementation capabilities, the entrepreneurial ecosystem of TUM and UnternehmerTUM can become an ideal breeding ground for circular innovations and startups that will sustainably transform our industry and society.

It is essential to win the minds and hearts for the Circular Economy, to inspire students and researchers to start their own ventures, and to work together with the industry to identify and strategically address the crucial action areas that will help the Circular Economy break through in specific sectors or across the entire industry. At the same time, a Circular Economy can only succeed if it is embedded in a corresponding societal framework and an appropriate regulatory environment. Being the initiator and solution provider for this comprehensive industrial and societal effort will be the significant task for CirculaTUM, the TUM as a whole, and UnternehmerTUM in particular.

5.4 Achieving More and Faster Together

With CirculaTUM, TUM pursues an inclusive and participatory approach. Together with all relevant stakeholders from business, society, and politics, as well as our excellent network of national and international research partners, we aim to identify relevant questions and challenges. Our goal is to collaboratively develop and implement solutions swiftly.

Here, collaborations are particularly leveraged with partner institutions at the TUM locations to collectively develop and implement regional solutions for the circular economy. At the same time, these partners are actively involved in activities related to research, teaching, and knowledge transfer.

CirculaTUM collaborates closely with leading national and international research institutions focusing on the circular economy. To achieve this, it leverages the existing excellent networks of TUM and its members, such as the leading European technical universities (EuroTech) and global flagship partner universities. These networks are intentionally expanded to include prominent partners.

5.5 Taking Global Responsibility

The TUM, as a leading academic institution, is aware of its global responsibility and pioneering role in the field of Circular Economy. To initiate and actively shape a transformation towards a Circular Economy at an international level, CirculaTUM has already formed effective alliances with renowned partners.

The TUM, TUM Asia, and CirculaTUM, together with the Plastics Recycling Association Singapore (PRAS), have signed a Memorandum of Understanding (MOU) on plastic recycling. The aim is to provide training and foster closer collaboration in the area of mechanical recycling of large-volume plastic waste, the processability of high-quality recycled granulates, and the promotion of higher recyclability of plastics. This commitment continues the longstanding cooperation with Singapore in an innovative research field, contributing to addressing global challenges.

A similar partnership exists with the Kwame Nkrumah University of Science and Technology (KNUST) in Ghana on the topic of sustainable electronic waste recycling. The KNUST-TUM consortium collaborates with local stakeholders from politics and society to develop environmentally friendly recycling strategies that consider local health and working conditions. Specific challenges will be addressed within third- party funded projects to establish a long-term collaborative effort.

“Health & Disease”

The healthcare sector in OECD member states, such as China and India, accounts for nearly 5 percent of the national CO_2 footprint, with two-thirds of these emissions originating from supply chains. Additionally, due to its high societal standing, the healthcare sector plays a crucial role as a model for implementing Circular Economy practices in sustainable production and consumption of materials. The healthcare sector has the potential to become a driving force for the transformation towards a healthier planet, a prerequisite for a healthier population.

The COVID-19 pandemic underscored the healthcare sector’s heavy reliance on global supply chains. Adopting a Circular Economy approach can enhance supply chain resilience and reduce emissions in the healthcare sector.

With its strong interdisciplinary research capabilities,the Technical University of Munich offers the ideal prerequisites for developing new concepts in healthcare and prevention that extent beyond material research and conversion technologies. Integrating medical and life sciences research with social, political, and economic sciences is essential to meet the unique challenges in healthcare.

Examples include:

- Developing decarbonization strategies in the healthcare sector, focusing on material supply, particularly in prevention through sustainability assessments for manufacturing (e.g., hygiene products).
- Establishing sustainable local approaches to implementing circular concepts across the value chain, including in Global Health contexts with partner institutions like Kwame Nkrumah University of Science and Technology (KNUST) in Ghana, TUM’s partner university in Africa (e.g., waste management, integration of new sterilization methods, etc.).

5.6 Advancing the Circular Economy in a Flexible and Evolving Network

After its inception, a lean and agile organizational structure was established for the TUM Mission Network Circular Economy. However, given the scale and urgency of the challenges, this structure is not intended to be set in stone. The Mission Network is consciously designed as a learning network that evolves continuously to adapt to the latest insights and changing circumstances.

CirculaTUM is coordinated by a core team that promotes regular exchange within the network at all levels. The team consists of the academic management by Prof. Dr. Magnus Fröhling (Chair of Circular Economy) and Prof. Dr. Johannes Fottner (Chair of Materials Handling, Material Flow, Logistics), the coordinator Ann-Christin Kessler and the research assistants Vanessa Heinrich and Merve Emir.

Together with the members, the CirculaTUM team continuously develops the network and enables an inclusive exchange with an external impact. The team is responsible for the organization of events, network management and administration, the acquisition of funding for research projects as well as marketing and communication in order to promote cooperation and the exchange of knowledge within and outside the network.

On the occasion of the publication of our brochure, we would like to sincerely thank all members for their participation and contributions.

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Shaping Technological Change Together

Outlook and Perspectives

With the TUM Mission Network Circular Economy (CirculaTUM), we are developing a center for Circular Economy in research, education, and knowledge transfer to contribute our part towards achieving sustainability and climate protection goals.

The Circular Economy is a key strategy for achieving sustainability and climate protection goals at global, national, and regional levels. While the fundamental idea may seem straightforward at first, it requires not only individual excellence but also complex systems thinking and collaboration across disciplinary boundaries. The challenges are immense, necessitating rapid scaling and adaptation of solutions within the society. This is a significant task, requiring fundamental research, development of technologies and materials, new business models, adapted regulations, and importantly, societal acceptance and transformation. It is also crucial to embed the necessary circular and sustainability-oriented systemic thinking and interdisciplinary approaches in both university and non-university education and training, without compromising disciplinary excellence. Only in this way can the transformation towards a Circular Economy succeed.

Through the TUM Mission Network Circular Economy, we aim to connect our excellent researchers and students at TUM who are working on relevant topics within the field, to collectively, actively and visibly shape the development and implementation of the Circular Economy. Together with the TUM Venture Lab Sustainability and Circular Economy, UnternehmerTUM, and the TUM Think Tank, TUM is uniquely positioned to provide the necessary disciplinary breadth and depth to approach Circular Economy holistically, integrating ideas with a focus on rapid scaling and implementation. Embedded within the unique entrepreneurial ecosystem around our locations, with a vibrant startup scene, medium-sized enterprises, and large industries, as well as in collaboration with cities, particularly in Munich and Straubing, and the region, we aim to create a unique hub for Circular Economy. While continuing to pursue already proven and effective approaches, we also seek to explore new pathways in research, education, and knowledge transfer.

We aim to do this in a participatory manner. I therefore warmly invite you to join us on this journey. Discuss with us the opportunities and challenges. Collaborate with us on sustainable and practical solutions. Let us implement these together in practice. In doing so, we can achieve the goals and harness the potentials offered by the concept of Circular Economy, contributing to a sustainable way of living and economic activities in harmony within the limits of our planet.

We look forward to engaging with you.

Prof. Dr. sc. techn. Gerhard Kramer

Executive Vice President for Research and Innovation

Impressum

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