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SAMSax—An Innovative Living Lab for the Advancement of a Circular Economy through Additive Manufacturing Technologies

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Abstract: The sustainable development of products is of great interest to both industry and consumers due to various factors, such as anthropogenic climate change and the scarcity of resources and materials. In response to this, the simul$^+$ Living Lab Sustainable Additive Manufacturing in Saxony (SAMSax) has been established as a physical experimental space aimed at improving the sustainability of products. This includes selecting resource-efficient manufacturing processes, using renewable materials, reducing energy consumption during use, and designing for recyclability. The innovative approach of the lab also integrates an open innovation process, involving present and potential stakeholders. Collaborating closely with stakeholders from industry, academia, and government fosters idea generation, provides solution approaches, and enhances acceptance and practical implementation. Methodologically, SAMSax focuses on upcycling organic and inorganic residues as well as by-products from industry and agriculture, reintegrating them as innovative components in industrial production using additive manufacturing ("3D printing"). The Living Lab provides a space for networking and active knowledge transfer through digital technologies, analyses, and collaborative developments, enabling the testing and evaluation of innovations in a real-world environment. Several potential waste materials suitable for additive manufacturing and new products have already been identified. In addition to industrial residues, materials, such as paper and wood dust; industrial by-products, such as sand; and agricultural residues, like harvest residues, are being analyzed, processed, and tested using additive manufacturing in the laboratory. In this way, SAMSax can contribute to an integrated and consistent circular economy. The research aims to demonstrate that the SAMSax Living Lab is a crucial driver of innovation in the field of additive manufacturing. Furthermore, this study contributes by presenting the Living Lab as an application-oriented research environment, focusing on innovative implementation in small- and medium-sized enterprises.

Keywords: Living Lab; additive manufacturing (AM); sustainability; circular economy; innovation process; digitalization

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1. Introduction

Contemporary challenges, such as resource scarcity and environmental impacts, require a paradigm shift in material production and utilization [1,2]. Sustainable product development, gaining significant interest from both industries and consumers [3], employs various approaches to enhance product sustainability. These include resource-efficient manufacturing processes, low energy consumption during the usage phase [4], and design-for-recycling principles [5,6]. These approaches emphasize the need for disseminating new knowledge through real-world laboratories (Living Labs), to create a substantial impact [7,8]. Living labs serve as open and collaborative innovation networks, providing diverse research opportunities for stakeholders in research, government, business, and society [9,10] by including novel approaches to sustainable development [11].

This article introduces the simul^{+} Living Lab SAMSax (Sustainable Additive Manufacturing in Saxony), addressing challenges in sustainable additive manufacturing in Saxony. Additive manufacturing is seen as a technological innovation for recycling-oriented circular business models [3,5]. With the rising importance of resource-efficient production and waste minimization, the SAMSax Living Lab pioneers research and implementation of sustainable additive manufacturing principles. The joint pilot project involving three technical universities in Saxony (Technical University (TU) Bergakademie Freiberg, Chemnitz University of Technology, and Dresden University of Technology) aims to facilitate networking and knowledge transfer through digital technologies, establishing a Living Lab as a physical experimentation field.

SAMSax Living Lab aims to establish a low-threshold access to expertise and infrastructure for small- and medium-sized enterprises (SMEs) in Saxony that are engaged in digitally integrated manufacturing. In the region of Saxony, the business landscape is predominantly composed of small- and medium-sized enterprises, which lack the innovation capacity (both in terms of manpower and financial resources) often seen in larger corporations. According to data from the Saxon State Agency for Civic Education, in 2017, there were 147,736 businesses with fewer than 10 employees, accounting for 89.5% of the total, and only 618 companies with more than 250 employees, constituting just 0.4% [12]. This places the proportion of large enterprises in Saxony at 4% in comparison to the national average [12]. The relative scarcity of larger firms, with their well-funded research departments, translates into limited capacities in both financial and human resources for the development of use cases. Furthermore, Saxony faces specific challenges in the field of sustainable additive manufacturing, as there is a lack of a global solution for material optimization to minimize energy consumption and waste [13]. To address these challenges, the SAMSax Living Lab aims to leverage the experimental spirit of Saxon entrepreneurs, offering them a low-threshold access platform through the Living Lab to benefit from the scientific insights available from Saxony's technical universities in the field of future technologies. In this context, the term "low-threshold access" in SAMSax primarily refers to the provision of an easily accessible and user-friendly resource for all stakeholders, enabling them to acquire relevant information and knowledge without significant barriers at any time. This is achieved, among other things, by developing and providing easy-to-understand materials on the topics of the Living Lab using a knowledge management platform. A detailed discussion of this platform is provided in the subsequent sections of the paper.

SAMSax involves diverse SME partner groups and an extensive network of local authorities and societal actors. The lab generates value and sustainability by combining digital technologies, additive manufacturing, and materials produced sustainably and regionally from residues. By charting, educating, and connecting local Saxonian material providers, technology providers, and end users, unused material (waste) streams can be utilized for high-margin parts in a local industrial environment. Value is generated by both creating a market for residue material and upcycling the lower-cost material into high-value parts. Reducing waste and replacing "fresh" or fossil-sourced by "upcycled" or bio-based material contributes to sustainability and helps to progress towards a circular economy. The laboratory also addresses critical issues of digitization, circular economy, and climate change, providing impetus for attractive, future-proof work. One of the challenges lies in identifying and addressing the management of waste materials. One focus is on the reuse and recycling of waste substances instead of their energetic use (burning it). This keeps them in the cycle longer, thus supporting ecological change. Such a transformation necessitates a comprehensive approach to effectively contribute to environmental protection. Another challenge involves lowering the carbon footprint by recycling and using bio-based instead of fossil-based materials. Integrating these sustainable materials into industrial processes can lead to significant progress in reducing greenhouse gas emissions. At the same time, digitalization plays a crucial role in managing knowledge transfer and networking among involved stakeholders. The integration of digital technologies is crucial to fully exploit the potential of the SAMSax Living Lab. Optimizing processes, communication, and collaboration not only enhances efficiency but also lays the foundation for sustainable development. Overall, these challenges are closely interconnected and require an integrated approach. The holistic consideration of reuse, recycling, the use of sustainable materials, and digitalization within the framework of SAMSax offers a promising perspective for sustainable development in various industrial contexts. In relation to additive manufacturing technologies and future work, this implies, for example, aligning the properties of residual materials with suitable part properties/demands. Additionally, additive manufacturing technologies can be further developed to process residual materials, e.g., with varying/fluctuating properties. Binder/matrix combinations can be developed and processed for the production of high-strength parts that are either biologically degradable or bio-based.

The SAMSax Living Lab's approach is based on recycling locally generated bio-based, natural, and industrial residues, such as paper dust or wood dust, and by-products, like textile and agricultural residues (e.g., coffee husks) from both industry and agriculture. These materials are reintegrated into industrial manufacturing using additive manufacturing processes. While traditional additive manufacturing relies on plastics, resins, ceramics, and specially processed metals [14,15], SAMSax explicitly integrates natural or industrial residues. The insights from in-depth material analyses serve as the foundation for developing and realizing new applications and products or prototypes as well as small series. This innovative and sustainable approach aligns with the concept of a comprehensive and consistent circular economy, contributing to a necessary shift toward sustainability and ecological transformation in Saxony's industry and beyond.

To connect potential residue suppliers, users, and multipliers, digital technologies serve as enablers. Some manufacturers specialized in certain products often exhibit a knowledge gap in the realm of potential materials. They frequently lack awareness of available bio-based material alternatives and the constructive or mechanical adaptations necessary for their efficient use. At the same time, Saxony has many potential material providers of renewable raw materials, which often occur as by-products and could in principle serve as raw materials for production. However, a problem in this supply chain is that many of these suppliers are unaware that their previously disposed of by-products could be economically and ecologically valuable. As there has been little communication between the manufacturers and suppliers, the potential for synergies between the two groups remains largely untapped. A key element in unlocking this potential is the digital networking of suppliers and users. For this reason, the SAMSax Living Lab utilizes digital technology in the form of an online platform, which in this context serves not only as a source of education and information but also facilitates networking and exchange among the various stakeholders. Furthermore, multipliers support the project by linking their own networks with that of SAMSax and utilizing the online platform. Thus, a systematic exchange of information and knowledge is to be established, enabling the optimal use of existing resources and promoting new, sustainable production methods in Saxony.

The SAMSax Living Lab is methodically embedded in an open innovation process involving current and future stakeholders. This ensures an optimal representation of industrial needs and solutions from the planning stage. With careful guidance, the establishment of an innovation community comprising providers, manufacturers, and researchers becomes possible and is supported by the tailored presentations of scientific requirement analyses from the participating universities.

In summary, the overarching goal of the project is to establish the SAMSax Living Lab for the future testing of regional value creation from locally available, renewable resources (ideally residue materials) for additive and digital manufacturing technologies. Within the scope of regional value creation, the utilization of locally available residual materials in Saxony represents a key approach for generating added economic value. This is achieved through the reuse, processing, or transformation of materials that would otherwise be classified as waste. Such an approach not only supports and strengthens companies in the region, such as the theatre in Chemnitz, through their projects and initiatives in the Living Lab, but also contributes to the promotion of a circular economy. This manifests in a reduction in the need for new raw materials and a minimization of waste. Moreover, this strategy offers the potential to develop new business models, especially in small- and medium-sized enterprises, which in turn can contribute to the economic diversification of the region in Saxony. As previously emphasized, this process also enhances innovative capabilities. This is achieved through the development and implementation of suitable technologies for the utilization of residual materials, which offer not only ecological but also economic benefits. This also involves building a digital knowledge base and networking capability to simultaneously promote circular economy and regional economic growth.

This article clarifies the conceptual framework and aims of the SAMSax Living Lab. It delves into the preliminary outcomes of the project, such as the analysis of residual materials. Additionally, it includes a case study derived from a theatrical context. The article is structured as follows. After the introduction, the Section 2 discusses additive manufacturing, Living Labs, and the digitalization of the circular economy. Subsequently, the Section 3 details the individual steps of the innovation process concerning the SAMSax Living Lab. The Section 4 highlights the current research status and achieved milestones in the Living Lab's innovation process. Finally, the paper concludes with an outlook on planned activities in the SAMSax Living Lab.

2. Additive Manufacturing, Living Labs, and Digitalization of the Circular Economy

Additive manufacturing processes, also known as 3D printing, have undergone significant development in industrial production in recent years. This innovative technology allows for the layer-by-layer construction of three-dimensional objects, enabling not only the realization of complex structures but also the efficient production of customized products [16,17]. In the context of the challenges posed by sustainable development, concepts, such as Living Labs and the digitalization of the circular economy, are increasingly coming into focus. Living Labs serve as test environments for the practical testing of new technologies and concepts, providing the opportunity to experiment with innovative ideas in the real world and analyze their impact on the environment, economy, and society [18]. In the context of additive manufacturing, Living Labs can contribute to optimizing the integration of this technology into existing production processes and understanding its implications for the circular economy [19]. The digitalization of the circular economy involves the use of digital technologies to efficiently utilize resources, reduce waste, and promote a closed-loop system of products and materials [20,21]. Specifically, 3D printing plays a crucial role in this context as it enables the production of customized products, minimizing resource waste [13,22–24]. In this evolving landscape of production technologies, additive manufacturing processes, Living Labs, and the digitalization of the circular economy offer new perspectives for a sustainable and efficient industrial future. However, it is important to note that there are also some disadvantages associated with additive manufacturing technologies. In accordance with [25], the disadvantages are listed as follows. The layered structure of additively manufactured components introduces several complexities, such as anisotropy, where the properties of the material can vary depending on its orientation. Additionally, the surface quality of the finished product is highly dependent on the alignment of these layers, often resulting in a stair-step effect that can affect the aesthetic and functional aspects of the component. One significant drawback of this method is its time-consuming nature, which often renders it uneconomical for producing large batch sizes. A further issue in the field of additive manufacturing is the lack of standardized methods for testing these uniquely produced components. In terms of cost, additive manufacturing typically incurs comparatively high material costs, especially for common AM materials.

This contrasts with the use of residues, which can be more cost-effective. Moreover, the machinery involved in additive manufacturing is not only expensive but also requires skilled labor to operate, which is still in limited supply. The high machine costs add a significant barrier to entry for many companies, particularly small- and medium-sized enterprises. Additionally, the scarcity of skilled labor capable of operating these machines and optimizing the manufacturing process further limits the growth and adoption of additive manufacturing technology [25].

2.1. Additive Manufacturing

According to [26], additive manufacturing (AM) is a process that produces components from 3D model data by binding material together, usually layer by layer, in contrast to subtractive and forming manufacturing methods. AM therefore belongs to the main group of manufacturing processes known as primary shaping [27].

Additive manufacturing processes are an integral part of the product creation process. They are used in industry to manufacture prototypes, tools, and, to a growing extent, end products. AM offers several benefits, including the ability to produce complex geometric shapes, develop prototypes quickly and cost-effectively, enable customization and reduce production times. In addition, additive manufacturing technologies are also used as a cross-sectional technology in many industries, including aerospace, healthcare, automotive, architecture and more, due to its versatility and innovation possibilities [26].

Additive Manufacturing with Sustainable Materials Based on Residues

Additive manufacturing using sustainable materials based on residues represents an innovative approach that translates the fundamental principles of the circular economy into the realm of AM technologies. The concept of the circular economy is based on key principles, such as waste prevention, the development of circular products and materials, and the regeneration of natural systems [28]. In this context, the use of sustainable residual materials plays a crucial role. Such materials, for example, agricultural by-products or waste from production processes, can be reintegrated into the production cycle instead of being discarded. This enhances resource efficiency, as resources are maximized before being considered waste. The circular economy also emphasizes the importance of closed loops, in which products and materials are kept in circulation longer through reuse, refurbishment, reprocessing, and recycling [28]. Sustainable residuals can be incorporated into these loops, thereby reducing the need for new raw materials and minimizing environmental impacts. Utilizing residuals in various applications helps to decrease overall waste generation and move away from the conventional linear economic model of take, use, and dispose. The use of sustainable residuals, often as by-products of other processes, reduces the need for natural resources. This supports the preservation of ecosystems, protects biodiversity, and lessens the environmental impacts associated with resource extraction.

Due to its additive nature, AM has thus far offered a relatively underexplored potential in research for utilizing, e.g., biogenic residues existing in particle or fibred form, presenting opportunities to save fossil resources and reduce CO_2 emissions. Materials, such as grass, wood, or (fruit) kernel flour, represent a promising and addressable resource group. TU Bergakademie Freiberg and the Dresden University of Technology are working towards transforming these residues, conventionally destined for disposal or, at best, energetic utilization (combustion), into high-quality, environmentally friendly, and cost-effective products and components, with extensive trials already conducted on bio-based materials [29–32].

For instance, investigations on Miscanthus grass show values such as 1.5 g/cm^3 solid density, 0.12 g/cm^3 bulk density, and 0.16 g/cm^3 component density after 3D printing, with strengths comparable to polystyrene. These are material properties that could not previously be achieved in the field of AM with standard materials and processes. In combination with AM, these sustainable materials therefore offer material properties with which completely new applications can be conceived (acoustic and thermal insulation and mechanical damping applications). Similar results are expected for straw and flax. Crucial to this process is a particle size distribution suitable for manufacturing/build-up, which must be adjusted, along with an appropriate powder-binder system. Research interest in this field is expanding [33], with literature reviews indicating the suitability of new materials derived from biomass waste or by-products for extrusion-based additive manufacturing processes [34], and agricultural bio-wastes, such as wood, fish, and algae cultivation residues [35], being deployable in additive manufacturing processes. Additionally, wood residues from conventional wood processing can be used as material for 3D printing, upgrading low-value residues often used as fuel or even disposed of in landfills [36]. The described residues generated during the process are utilized for both assessing printability and material characterization [34], as well as for prototype manufacturing. On the other hand, these materials find applications in various sectors, including "[. . .] "buildings and architecture", "furniture", "equipment", "accessories", "prosthetics and medical", "packaging, and "bioengineering" [. . .]" [34]. Based on the existing literature overview [34], the application domains of "building and architecture", "furniture", and "equipment" are particularly prevalent. Within these domains, diverse products are manufactured as a proof-of-concept through 3D printing. Furthermore, efforts are made to develop sustainable, recyclable, and biodegradable 3D printing filaments from the generated bio-waste [35]. These residues also find utility in various industries, including the production of bone tissue [37], food packaging [38], construction [39], wastewater treatment plants [40], the electrical industry, the manufacture of pharmaceutical components [41], the furniture industry [42,43], and the automotive industry [44].

The concept of using renewable resources in the SAMSax Living Lab extends not only to the actual powdered building materials but also includes the necessary binders. Currently, polymeric materials, like polyvinyl alcohol (PVA), are used in the lab. Furthermore, alternative substances, such as gelatin or binders based on tree resin/rosin, are being used and developed. By using bio-based binders, renewable raw materials can be utilized to create fully bio-based and most often biodegradable parts. In addition, the binders mentioned are recyclable and can be recycled as well. SAMSax is committed to advancing and executing tailored machine concepts designed for the utilization of natural raw materials. These concepts are engineered to withstand and adjust to the diverse array of properties inherent in such materials. Operating at the intersection of material science, machinery, and technology, SAMSax particularly focuses on applications demanding good biodegradability and, consequently, a short service life.

This promising approach of the SAMSax Living Lab has the potential to offer both ecological and economic benefits. On one hand, materials that are usually considered waste can be utilized as valuable resources. By reusing and reintegrating these residues into industrial production, the living lab demonstrates that waste quantities can be reduced, and limited resources can contribute to efficient utilization. Consequently, the ecological footprint of small- and medium-sized enterprises can be minimized. Additionally, the reuse of residues in additive manufacturing can also provide economic advantages by minimizing waste disposal costs, while simultaneously creating new business models through the production of sustainable products. A further advantage of additive manufacturing with sustainable residues is the reduction in costs for AM materials. Another advantage is the potential for local use of AM technologies. This local application translates into lower transportation costs and shorter delivery times, making it a more responsive and agile manufacturing method. Additionally, the local use of AM reduces dependency on international markets. Moreover, additive manufacturing can provide a competitive advantage by producing sustainable products. In today's environmentally conscious market, the ability to manufacture goods that are sustainable, both in terms of the materials used and the manufacturing process, can differentiate a company from its competitors. Additive manufacturing with sustainable residues fosters innovation in material science and manufacturing technology. The search for suitable residues, their analyses, and transformation necessitate solutions, contributing to the development of new materials and manufacturing processes. SAMSax

Living Lab's objective is to strengthen the circular economy, where materials are not only used from extraction to disposal but circulate in a closed loop. Depending on the material used and its associated binder, the customized products can be recycled and reprinted after fulfilling their purpose.

2.2. Living Labs

In recent years, Living Labs have gained increasing importance as an innovative research methodology [9,11,45]. These interdisciplinary experimental spaces enable the practical exploration of complex societal challenges and the development of solutions in real-world environments [11,46]. Living Labs are particularly well-suited for addressing and understanding challenges in innovation development by directly involving stakeholders in experimentation [18]. These labs are conceived as platforms for collaboration among various participants from research, government, industry, as well as citizens working together to seek solutions and innovations for specific problems or questions [9–11,18,47]. The concept of the Living Lab was first documented by the Massachusetts Institute of Technology (MIT) as a methodology capturing, validating, refining, and creating prototypes for complex solutions in different and evolving real-life contexts [48]. Over time, various definitions of Living Labs have been proposed [49]. According to [47,50], a Living Lab encompasses four key activities: (1) analysis of context and user behavior as well as identification of cultural, legal, technical, and market-specific conditions; (2) collaborative development of innovations by bringing together users and developers; (3) conducting experiments within real usage scenarios; and (4) evaluating products and services in actual environments [47,50]. Living Labs for sustainable development aim to promote environmentally friendly innovations in production and consumer systems by involving users and stakeholders [47]. They are viewed as instruments to support the transition to a society based on the principles of the circular economy, bio-based approaches, and environmentally friendly practices [11]. While sustainability has gained global significance, many Living Labs do not have this topic in their focus [9]. This is surprising as they could address sustainability issues by prioritizing the use of environmentally friendly processes and materials to minimize social and economic impacts [51].

The SAMSax Living Lab (see Figure 1) is designed to pursue and implement this approach. In this context, SAMSax is a lab made accessible to the general population by science. Experimental work takes center stage, with a particular focus on extending into the digital realm. The goal is to collaboratively test and analyze residues that can be transformed into new applications using additive manufacturing processes.

Figure 1. A look inside the SAMSax Living Lab. ©Crispin Mokry.

As mentioned earlier, the SAMSax Living Lab aims to facilitate a sustainable and ecological shift in the industry of Saxony. The lab focuses on the recycling of biobased, natural, and industrial residues and by-products from both industrial and agricultural sources, reintegrating them into industrial manufacturing through additive manufacturing processes. This innovative and sustainable approach enables a comprehensive and consistent circular economy. The innovation of the Living Lab lies in the development and expansion of additive manufacturing processes specifically for printing with residues as well as the general analysis of the feasibility of using residues as potential materials for various applications.

Another aspect, the circular economy, is considered in the SAMSax Living Lab from both a machinery and material perspective to foster progress. The use of renewable resources as alternatives to established conventional materials offers relevant approaches that could actively reduce waste and CO_2-emissions, supporting climate protection (sustainability). However, the different properties of these materials require adjustments in manufacturing and processing techniques as well as components. This presents a significant knowledge gap that is also addressed in the Living Lab.

Furthermore, many waste emitters are unaware of the potential of their residues. This gap can be bridged by digital technologies that connect, educate, and support stakeholders. Digital technologies can also add value to new products, ensuring complete traceability or facilitating recycling. In the SAMSax Living Lab, all interested stakeholders can initially test their own best practice example at SAMSax free of charge before establishing the expertise within their own companies.

In summary, it can be said that SAMSax is contributing to climate goals by showing options for climate- and resource-friendly industrial production. Since it simultaneously addresses key manufacturing technologies, it is of great importance for the state of Saxony, which is defined by small- and medium-sized enterprises. The topic of sustainable AM is not only to be implemented in prototypes and lighthouse projects, but broad educational and further training programs will be performed. As one expected outcome, sustainable AM will be applied in SME and industry both for ecologic and economic benefit. In addition to the implemented and published individual projects, a further education and networking platform is to be developed, which will enable easy uptake of the results by industrial users.

2.3. Digitalization of the Circular Economy

The convergence of digital technologies and sustainability has initiated a transformation that not only improves the efficiency and accuracy of resource utilization but also opens up new possibilities for waste stream management and the promotion of a circular economy [52,53]. Digitalization plays a crucial role as a driver of the circular economy by increasing the transparency and intelligence of products and resources. It enables, for example, monitoring of locations, conditions, and availability of assets [20]. The term "digitalization" describes the connection between people and objects as well as the merging of the physical and digital worlds through information and communication technologies [54]. Digitalization will be a key driver of innovation in the coming decades, enabling not only new, intelligent market services but also revolutionizing entire value systems [55]. The focus is particularly on the importance of digital innovations, i.e., products or services that arise or are supported by digital technologies [56].

Digital technologies are important for improving circular economy practices by providing solutions for resource optimization [57]. The use of digital technologies, such as intelligent devices, big data, the Internet of Things (IoT), and artificial intelligence (AI), allows companies to implement the principles of the circular economy more effectively. These technologies facilitate the maximization of product reuse, reduction of energy waste, and conservation of capital [57,58]. A critical aspect of this is the capacity of digital technologies to monitor and manage the entire lifecycle of a product, leading to more efficient restoration and recycling of products, components, and materials.

The deployment of smart manufacturing systems, supported by digital innovations, not only optimizes business resources but also promotes necessary changes in corporate governance and legislation to realize an effective circular economy [57]. Additionally, a framework for intelligent circular economy aids in translating circular economy strategies into specific digital technology requirements. This enhances resource efficiency and productivity in manufacturing companies, contributing to a more sustainable mode of operation [58]. Overall, digital technologies enable a more precise and efficient implementation of the circular economy, offering both ecological and economic benefits.

For the SAMSax Living Lab, the comprehensive establishment of a circular economy based on local residues is considered a crucial aspect to increase regional value creation through extensive digitalization. However, to ensure the sustainable implementation of a circular economy, it is important to consider specific requirements such as minimizing waste and pollution and maximizing the lifespan of products and materials. One challenge lies in the increased coordination of material and information flows as well as the networking of suppliers and users. Furthermore, it is crucial to effectively generate, collect, process, and provide relevant information about the material composition of products, their usage behavior, and their fate in the waste system. Digital applications, such as product passports, resource mappings, and consumer information, can help to close these gaps and make the paths of products and materials traceable [59]. One such example from a very different domain is the introduction of blockchain-based tracking systems for different food groups, pioneered by Carrefour and Nestlé to enable consumers to trace origins and ingredients of products like mashed potatoes, milk and baby formula [60]. In the research by [61], which examines the role of blockchain technology (BCT) in the context of circular economy practices and its impact on the organizational performance of companies, the results indicate that BCT has a significant and positive influence on circular economy practices. Specifically, the study supports the notion that the integration of BCT into business processes enhances circular economy practices, thereby contributing to the promotion of sustainability. BCT makes a substantial contribution by providing a high level of security, ensuring transparency, and improving traceability throughout the entire product lifecycle, which positively affects the efficiency and effectiveness of circular economy initiatives [61].

Within the Living Lab framework, the networking of manufacturers and suppliers, as well as cross-sector collaboration within Saxony, is intended to serve as the basis for numerous regional economic cooperation. This is to illustrate that even smaller companies can actively shape future manufacturing. The digital core components in the SAMSax Living Lab include a knowledge management platform on topics such as residue processing, circular economy, sustainability, and additive manufacturing processes; a database for material and application information; and an integrated networking option among the involved stakeholders.

3. Innovation Process

The initiative of the SAMSax Living Lab to promote regional value creation through innovations faces significant challenges. A central task is to distill complex scientific concepts of the circular economy into formats that can be effectively conveyed to businesses in Saxony. This transfer is intended to be realized through an open innovation process. Traditionally, the innovation process has been viewed as a predefined sequence of stages encompassing idea generation, selection, development, introduction, dissemination, and distribution [62]. According to [63], the concept of open innovation is defined as an approach that promotes targeted knowledge exchange within and outside an organization, aimed at enhancing the internal innovation process and simultaneously expanding the markets for externally applied innovations. This process is founded on the principle that companies, in their pursuit of technological advancement, should and can rely on both external and internal ideas as well as market strategies within and outside the organization. Specifically, within the framework of the SAMSax Living Lab, the open innovation process is employed to place a stronger emphasis on collaboration and networking among stakeholders. The primary goal is to develop, evaluate, and translate ideas into innovative applications within the Living Lab, in collaboration with relevant stakeholders. This approach underscores the importance of cooperative development and implementation of solutions in a practical, experimental environment. Following the framework proposed by [64] (p. 9) and the early phases of the innovation process based on [65], the innovation process for the SAMSax Living Lab (see Figure 2) is defined as follows:

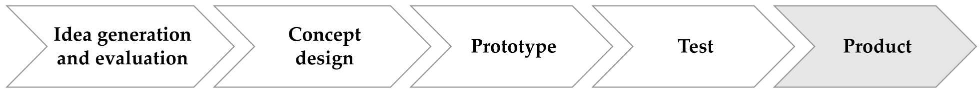


Figure 2. Innovation process based on [64] (p. 9) and [65].

Step 1–Idea Generation and Evaluation: In the first step, fundamental approaches for processing and utilizing residues are developed in collaboration with representatives from science, politics, business, and society. This is achieved through moderated events in the Living Lab, as well as local engagement in the region with multipliers and businesses. The initial idea generation took place during the project's kick-off event. This event aimed to introduce the project and its concept. An interactive workshop was conducted to extract the participants' expectations for the SAMSax Living Lab, intending to implement them throughout the project. Three central questions were the focus of the workshop and were addressed from various perspectives. The first question delved into the expectations of the associated project stakeholders. Participants were encouraged to discuss benefits, opportunities, challenges, expectations, and ideas. The second question was about the attitude of the stakeholders towards sustainability. Topics of discussion were the importance of sustainability, the need for action, risks and concerns, and available resources. The third question targeted collaboration with SAMSax. Responses were documented, categorized, and summarized based on [66].

In a subsequent user workshop, specific ideas, such as sustainable lightweight panels or custom art, were developed for potential applications using the Six Thinking Hats method [67]. The generated ideas were discussed by participants from various perspectives. Currently, these ideas are being examined in the SAMSax Living Lab for implementation and feasibility using suitable residues and the corresponding additive manufacturing processes.

Simultaneously, a knowledge management platform is established to facilitate long-term networking of business groups beyond the project duration. The promotion of the SAMSax community concept and moderation aims to maximize the potential of this online offering and actively foster collaboration among different companies. The results from the idea generation phase are prepared for knowledge transfer, enabling continued discussion and utilization within a broad network.

Step 2–Concept Design: In the second step, concrete concepts for the processing and utilization of various types of residues are developed in collaboration with knowledge holders in additive manufacturing and the circular economy. Expert focus groups identify specific use cases that demonstrate potentials and application areas for the circular economy community. These use cases are also made accessible to the network through knowledge transfer. Additionally, specific criteria are defined in expert focus groups to assess the success of a concept or prototype. These criteria contribute to defining and evaluating the effectiveness of the developed concepts in the context of the circular economy. This involves evaluating economic factors, such as quantity, cost, and transportation (proof of market), as well as technological aspects, including feasibility and potential for the circular economy (proof of technology). The developed concepts or use cases are then prototypically implemented in Step 3.

Step 3–Prototype: In the third step, a promising use case is prototypically implemented. This circular economy process is experimentally tested in the Living Lab under real conditions without being integrated into a company's production workflow. The flagship project aims to demonstrate an idealized process in terms of manufacturing, processing, and utilization to all involved SAMSax stakeholders, serving as a model for additional use cases. The innovative nature of the SAMSax Living Lab initiative suggests that it should achieve high visibility, serving as a best practice example for future similar projects or initiatives. SAMSax is initiated through the established online platform, with SAMSax project partners providing proactive support to answer questions and overcome challenges. The results of the Living Lab are published in project profiles on the knowledge management platform to make them accessible to a broad audience of businesses. Through this documentation, other companies recognize the possibility of easily repurposing residues, helping to break down barriers and highlighting that participating companies can derive economic benefits from the circular economy by actively contributing to the value chain.

Step 4–Testing to Product: Subsequently, the identified use cases undergo a comprehensive testing phase and are iteratively developed both in terms of material and process aspects. After successful testing, standardization and normalization are sought to facilitate seamless integration into real production environments. Each step of the process is reviewed and assessed according to pre-defined criteria (see Step 2) using guideline interviews and checklists based on the Stage-Gate process with the following stages: scoping, build business case, development, testing and validation, and launch [68]. This approach enables ongoing assurance of goal achievement and supports continuous improvement of the identified process steps.

4. Research Status of the SAMSax Living Lab

The following section describes the research status achieved in the SAMSax Living Lab based on the predefined steps in the innovation process. It highlights significant developments and insights achieved within the experimental space over one year (1 September 2022 to the present).

4.1. Residues for Additive Manufacturing

4.1.1. Differentiation of the Term "Residual Material" from the Term "Waste"

The European Waste Framework Directive defines waste as *"any substance or object which the holder disposes of, intends to dispose of or is required to dispose of"* [69]. On this legal basis, a distinction is made between waste for recovery and waste for disposal. The term "waste for recovery" includes residual materials [69]. Residuals are substances or materials that are generated or left over from treatment and processing operations. Residues are therefore not the primary objective of the production process. In this context, they are often referred to as production residues. Residues can come from a variety of sources, including industrial and agricultural processes. They can therefore be of both organic and inorganic origin.

4.1.2. Technological Analysis of Residual Materials

As part of the project, regionally produced organic and inorganic residues are being technologically analyzed for use in AM processes. To date, the SAMSax Living Lab has received and recorded more than 30 different residual materials from small- and medium-sized enterprises. To date, the following materials have been analyzed for possible use in AM processes:

- ABS regenerate;
- Beech and birch wood;
- Carpet residues;
- Chaff straw;
- Coffee husks and coffee grounds;
- Cotton fluff;

- Folding chips;
- Fermentation residues;
- Glass fibers;
- Jeans dust;
- Leather dust;
- Mineral-wood mixtures;
- Miscanthus grass;
- Paper dust;
- Sanding dust;
- Stone residues (mineral chippings, high-grade chippings);
- Waste from grain cleaning;
- Wood from spruce and poplar;
- Wood shavings.

Information about the residual materials is collected by means of a residual accompanying note. This documentation is crucial for the prototypical construction of the SAMSax database (SAMSaxDB). This includes information on availability, the residual value of the material, disposal costs, and the toxicity and flammability of the materials. Coffee husks represent a type of analyzed residual material, arising as a by-product during the roasting process of coffee beans. The relevant data collected for this material are presented in Table 1.

Table 1. Data collected about coffee husks from the residual accompanying note.

	Specifications
Origin	Kenya, Brazil, Peru, etc.
Availability	1 bag/month (circumference: 75 cm; height: 130 cm)
Flammability	Flammable
Toxicity	Non-toxic
Residual value (€/t)	Unknown
Costs for disposal (€/t)	Free disposal

The technological analysis of the residues focuses on the potential use of the residues in various additive manufacturing processes. Promising AM processes include material extrusion (MEX), fused filament fabrication (FFF), and binder jetting (BJT). Relevant property tests are performed prior to the actual processing. In this context, particle size distribution, residual moisture determination, and image analysis of residual materials are of particular importance for additive manufacturing processes.

4.1.3. Determination of Residual Material Moisture

A moisture analyzer is used to determine the moisture content of the residue. A small quantity of 10 g of the residue to be tested is first weighed on the crucible in the measuring chamber. The chamber is then heated to 105 °C, and the loss of weight due to evaporation of the residual moisture is recorded in parallel. The measurement is stopped when equilibrium is reached or the weight loss falls below a critical threshold. The moisture content can be determined to within 0.01%.

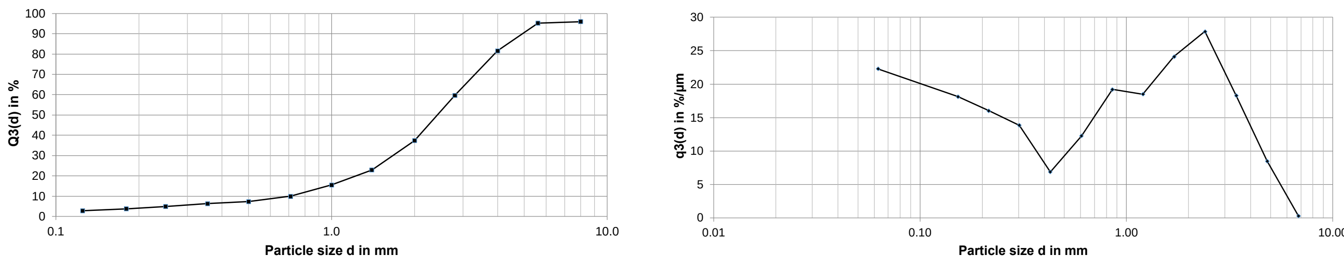
For use in binder jetting or fused filament fabrication, residual moisture levels of less than 10% are generally intended. If the residual moisture content is above 10%, the particles must be pre-dried before application-oriented processing. In the case of the coffee husks already mentioned (see Figure 3), the residual moisture content is 8.33%. This means that the coffee husks are generally suitable for use in binder jetting or fused filament fabrication. The residual moisture content of the other materials analyzed is also below 10%. This means that these residual materials are generally suitable for AM processes.

Figure 3. Coffee husk sample in a received condition.

4.1.4. Determination of the Particle Size Distribution

The sieve fractionation method according to DIN EN 933-1 [70] is used to determine the particle size distribution of residual materials. Depending on the material to be analyzed, a sieve tower is composed of 12 sieve stages, the fineness of which increases from top to bottom. The gradation is 5.6 mm, 4.0 mm, 2.8 mm, 2 mm, 1.4 mm, 1 mm, 0.71 mm, 0.5 mm, 0.355 mm, 0.25 mm, 0.18 mm, and 0.125 mm. Approximately 160 g of the air-dried residue to be analyzed is placed on the top sieve of the sieve tower and agitated for 15 min on a vibrating sieve (amplitude: 0.6 mm). The residue in each sieve insert is then weighed and documented so that the sieve passage can be read and a particle size distribution corresponding to the different sieve fineness can be obtained. The sieving is performed twice for each material to obtain a representative result.

The particle size distribution of the coffee husks (see Figure 4) shows a clear increase in the cumulative particle size distribution from a diameter of 0.71 mm. Only about 8% of the coffee husks are smaller than 0.355 mm. Therefore, only a small proportion of the particles would be suitable for binder jetting, where particle sizes below 300 µm are required. However, crushing (here: grinding) and subsequent sieving of the particle fractions is an option to make these residues accessible for binder jetting. Due to the nature of the coffee husks, grinding was performed using a granulator. Given their brittle nature, only a small amount of energy was required for grinding. Regarding an application in the FFF process or material extrusion, it depends on the nozzle characteristics of the 3D printer and the application. Both coarser and finer particles can be used.



(**a**) (**b**)

Figure 4. Particle size distribution of the coffee husks: (**a**) Cumulative distribution of the coffee husks; (**b**) Distribution density of the coffee husks.

All analyzed screen fractions and their usability in AM processes are systematically recorded in a residue database. The database is being continuously expanded, particularly with regard to the general printability of the materials and their mechanical properties (compressive strength, tensile modulus of elasticity, tensile strength) after printing in the various additive manufacturing processes.

4.2. Production-Related Development of Additive Manufacturing

In order to effectively utilize additive manufacturing for processing residual materials, it is crucial to identify suitable processes or process categories. Certain processes are specifically tailored to handle distinct material groups. For instance, material extrusion using a thermal reaction (MEX-TRB) is particularly well-suited for pure or filled plastic filaments. However, the use of filled filaments presents a challenge, as end-of-life parts manufactured from these materials typically cannot be directed towards traditional recycling. Instead, they must be directed towards energy recovery. In the SAMSax Living Lab, a concerted effort is made to mitigate this scenario. The primary objective is to maintain materials within sustainable cycles, prioritizing alternatives, such as composting, and only resorting to energy recovery in the final stages. When referring to cycles, we encompass existing waste streams (such as paper or glass) or the internal cycles specific to the respective company.

The binder jetting and material extrusion methods using pasty materials share a significant advantage concerning residual materials. Generally, any material can be employed as long as particle properties, including particle size distribution, moisture content, particle shape distribution, etc., meet the necessary criteria. While there are alternative additive manufacturing processes that, in theory, could also accommodate residual materials, the selection of compatible material groups is restricted. Currently, in the SAMSax Living Lab, these other processes are not under consideration, and the focus is solely on the two mentioned processes.

The SAMSax Living Lab has machines for almost all process categories according to ISO 52900 [26] in order to be able to produce the desired prototypes for every SME in Saxony.

Basically, two approaches are pursued in the Living Lab from an AM perspective:

1. Preliminary tests with the processed residual materials.
2. Prototype parts for partner companies (use case).

The preliminary tests are designed to assess the basic processability and printability. For this purpose, the same binders are used for both processes to produce identical test specimens. Machine parameters may need to be adjusted to suit the materials. For the binder jetting process, 15 wt.% polyvinyl alcohol is used as the powder binder, and 15 wt.% alginate is used for MEX with pasty materials. Five cylinders of 20 mm diameter and height are first produced as test specimens. The specimens are used to determine the density, shrinkage, and compressive strength of the material. The aim is to make the properties of the test specimens comparable.

If a residual material is judged to be highly suitable and its use for prototypes seems reasonable, further tests are performed for shrinkage in the x, y, and z directions, and tensile strength is also determined using shortened tensile test specimens.

Below is a list of residual materials that have already been successfully printed in the SAMSax Living Lab. The residual materials are assigned to the processes that are suitable for printing with the following residual materials:

Binder Jetting (BJT)

- Chaff straw;
- Miscanthus grass.

Material Extrusion (MEX)

- Coffee husks;
- Cotton fluff;
- Glass fibers;
- Jeans dust;
- Leather dust;
- Wood from spruce and poplar;

Binder Jetting (BJT) and Material Extrusion (MEX)

- Beech and birch wood;
- Coffee grounds;

- Paper dust.

As an illustration, the procedure and outcomes of an initial test are outlined, utilizing residual wood dust from spruce and poplar, along with 15 test specimens. Material extrusion (MEX) with pasty material was employed as the process, and a binder of 15 wt.% alginate was added. Water was then introduced to form a pasty mass with approximately 80% moisture content by kneading the powder. The experiments were conducted using a self-modified Ender S3 with a Zmorph extruder. The design closely resembled that of Rosenthal (2023) [71], with the exception of the optimization of die geometry for improved flow properties of the test specimens. Parameters for production included a nozzle diameter of 4 mm, a layer height of 1.5 mm (initially 1.3 mm), extrusion width of 4.2 mm, a speed of 5 mm/s, and a concentric infill of 100%. Slicing was performed using PrusaSlicer 2.7.0 software.

After the production of the test specimens, identical to all other residues, the specimens are dried at 60 °C with 100% air circulation. Once mass stability is achieved (no later than 24 h), the samples are analyzed, as shown in Figure 5. The measured values are presented in Table 2.

Figure 5. Test specimen made of wood dust consisting of spruce and poplar and 15 wt.% alginate.

Table 2. Parameters for test specimens made of wood dust consisting of spruce and poplar and 15 wt.% alginate.

Parameter	Symbol	Unit	Value
Height	h	mm	17.6 ± 0.39
Diameter	d	mm	22.2 ± 1.18
Mass	m	g	1.73 ± 0.18
Density	ρ	g/cm^3	0.25 ± 0.01
Pressure strength	σ_p	N/mm^2	3.61 ± 0.96

Compared to grown solid spruce, which has compressive strengths of 38.7 N/mm^2 parallel to the grain and 4.0 perpendicular to the grain, the values for AM-produced samples are 10% lower than solid timber loaded perpendicular to the grain [72]. The reason for this lies in the nature of the material, i.e., grown fibers always have a higher strength than an artificially produced material made from short fibers. The density of spruce varies greatly and is 0.4–0.62 g/cm^3 depending on the location [73]. The density of printed parts is approximately 50% lower.

The properties attained in the initial tests, coupled with the favorable processability of the residual material and the achieved print quality, pave the way for the continued utilization of the residual material in prototype production.

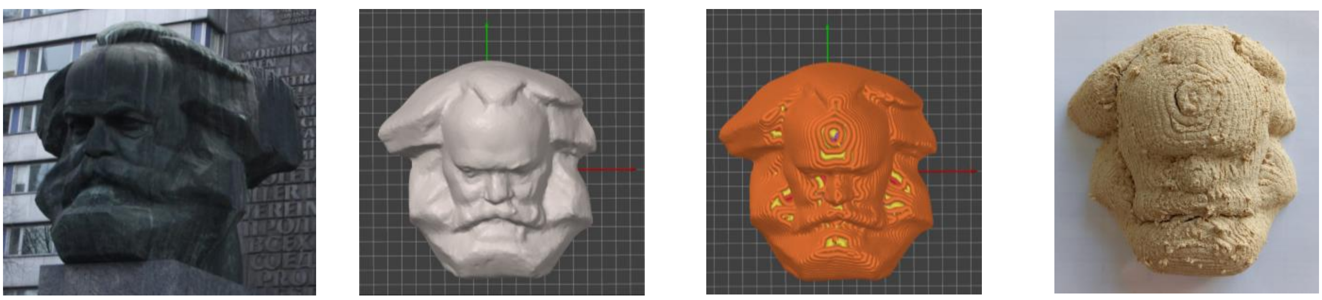
The SAMSax Living Lab has the potential to scale up manufacturing processes. Next to small test rigs for material development, large additive manufacturing machines are in procurement to enable demonstration of scaled-up applications. Binder jetting is then possible up to more than one cubic meter in volume. Another very promising process to date is material extrusion with pasty materials, as is already being used industrially in building construction with concrete. Currently, paste extrusion is possible to 0.4 m^3 at one-meter height.

To realize prototypes for companies, the initial step involves defining the product requirements. The second step is to identify the suitable material, additive manufacturing process, and post-treatment to attain the necessary properties. Only in the third step is the prototype produced. An illustrative example of prototype realization involves the use of wood dust derived from spruce and poplar.

One specific application in mind is the creation of props for the theater. Historically, props were manually crafted by stage sculptors based on specific concepts, often employing materials such as polystyrene foams and epoxy resins. The theater industry is now seeking more sustainable materials that ideally can be recycled after their operational life (often lasting only one season) and repurposed into new props. Another crucial consideration is that some theaters frequently utilize digital stage sets, have the capability to generate computer-aided design (CAD) drawings in-house, and possess access to 3D scanners. The availability of 3D data is essential for 3D printing, as it serves as a prerequisite for generating machine codes (g-codes) from these 3D objects.

The implementation of the use case is underway for theater workshops in Chemnitz, Saxony. The chosen prop is the Karl Marx monument, situated in Chemnitz and standing at a height of 7.1 m. The 3D data are captured using the "Polycam" 3D scanner app (version 3.2.12) and converted into machine code at a scale 1:50 using PrusaSlicer 2.7.0. The printing is done on a WASP 40,100 clay, employing an 8 mm nozzle diameter, 3 mm layer height (initially 2.5 mm), and an 8 mm extrusion width. After printing, the prototype is dried for two days at 60 °C with 100% circulating air.

The completed printed Karl Marx monument Is depicted In Figure 6, with a total mass of 128 g. Subsequently, the theater takes over the prototype for further refinement and design. The printed material allows for intriguing processing possibilities, and the pasty material (similar to that used for 3D printers) serves for levelling. The light-colored and suitably rough surface provides an opportunity for fine-tuning the color. If the prop is no longer required in the future, it can be transformed back into a new printable paste by dissolving it in water. The initial test prints have already been reproduced with the same characteristics, and the theater expresses great satisfaction. Future work includes optimizing the material and process as well as establishing the process directly within the theater.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Representation of the Karl Marx monument: (**a**) Original monument; (**b**) 3D-part of the monument; (**c**) G-code; (**d**) Printed part of the monument using the material extrusion process.

4.3. Digitalization

To achieve the goal of reusing bio-based natural and industrial residues as well as by-products from industry and agriculture, SAMSax has prototypically implemented a central information database named "SAMSaxDB". The software architecture is divided into a backend system that allows SAMSax staff to manage residue data and a frontend system that presents information to interested parties on various platforms (e.g., web browser or mobile phone) and makes it searchable. The SAMSaxDB backend is based on the open-source software PocketBase (version 0.20.7), which enables both the management of residue information and the fine-grained regulation of roles and rights concerning the display, modification, and deletion of residue information. Data storage is achieved through an integrated relational database. For the SAMSaxDB, the functionality has been extended so that a QR code is created for each analyzed residue, directly linking to detailed information that can be scanned, for example, from a mobile phone.

Furthermore, the web-based frontend is provided by the same server, simplifying deployment and software maintenance. An interesting aspect of this approach is that the extensibility of the base platform allows for the implementation of additional processes, such as a marketplace for residues. The primary goal of the SAMSaxDB frontend is to enable easy access to the data in the SAMSaxDB backend. Therefore, the frontend was primarily developed as a web application that accesses data in the backend via a REST API and presents it on the user's device. The presentation of information is adapted to the respective device, meaning there are specific layouts for use in the browser on a computer or on a mobile phone. In the simplest form of interaction, the interested party only needs to scan the barcode on a residue container to receive all relevant information directly from the database (see Figure 7).

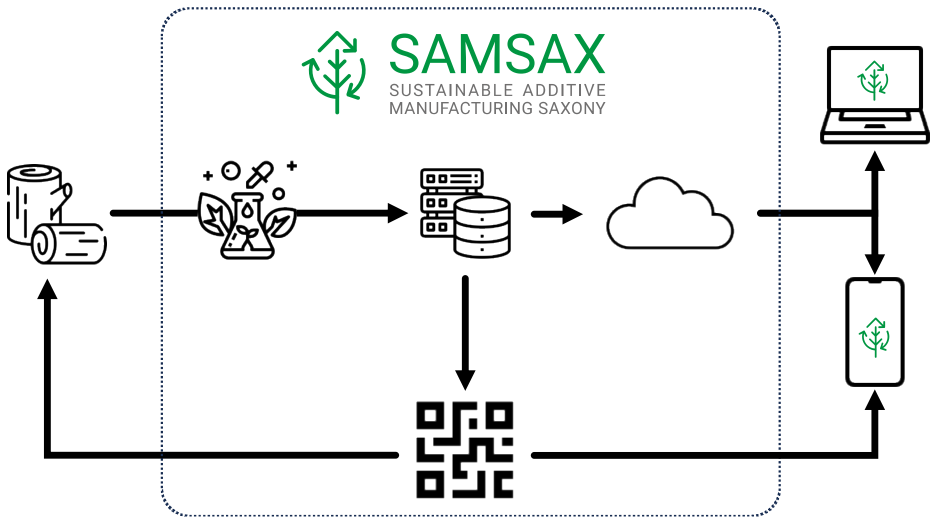


Figure 7. Functionality of the SAMSaxDB. Icons [74].

The frontend also allows residue database searches, either through free-text input or by setting category filters. The corresponding logic for processing search queries lies in the backend. This not only prevents unnecessary data transfer, e.g., to mobile devices, but also allows for capturing and scientifically evaluating interest trajectories in the SAMSax community over their search histories and using them for future functions, such as an algorithm for pricing residues.

In addition to the prototypical implementation of the SAMSaxDB, a knowledge management platform has been established that is accessible directly from the project website. The SAMSax Living Lab also serves as an innovation platform for the circular economy and has prepared a series of courses and videos covering crucial aspects of additive manufacturing and beyond. Currently, various 3D printing processes are in focus: binder jetting, fused filament fabrication, laser sintering, paste extrusion, and bath-based photopolymerization. The courses provide a brief introduction to the topic, describe the functioning of the AM process, and showcase different materials and binders as well as the processing and post-processing steps in the process. Additionally, the advantages and disadvantages of the process are explained. Videos are available for some additive manufacturing processes to better illustrate the concepts. The courses and accompanying videos offer a foundation and insights into different processes used within the SAMSax Living Lab. The knowledge management platform also plays a significant role in providing this knowledge to interested parties and involved stakeholders, contributing to the dissemination and application of this innovative technology. Furthermore, there is an opportunity to exchange and network with participants through the platform. Stakeholders can identify participants on the platform using the provided contact information and engage with them directly for any concerns. If individuals have specific questions or are uncertain, they can send a contact request to the SAMSax team. The staff of the SAMSax Living Lab will either respond to these inquiries directly or forward them to the appropriate companies within the network. The platform's easy accessibility and online exchange not only save time but also reduce the need for personal meetings. This leads to a more efficient and faster coordination and networking among the participants.

5. Summary and Outlook

The current need to address resource scarcity and environmental impacts requires a shift in the approach to material production and usage. Therefore, there is a strong interest in sustainable product development. Various approaches, such as resource-efficient processes and material selection as well as low energy consumption, are in focus. These require the dissemination and development of new knowledge for effective implementation. The concept of a Living Lab provides a testing environment for resource-efficient systems where various actors can cooperate.

The SAMSax Living Lab presents an approach that deals with sustainable additive manufacturing in Saxony. This includes the recycling of organic and inorganic residues in industrial manufacturing, particularly using additive manufacturing processes for new applications. The Living Lab also aims to provide an easily accessible entry point for knowledge and infrastructure for SMEs in Saxony, combining digital technologies with additive manufacturing processes and transferring knowledge to all stakeholders through a platform.

Within the framework of the SAMSax Living Lab, over 30 different residual materials from regional small- and medium-sized enterprises have been collected and examined for their suitability for additive manufacturing processes. The central focus in the lab is the application of two additive manufacturing methods, binder jetting and material extrusion, to process the analyzed residual materials. This work presents initial findings on which residual materials are best suited for which process and demonstrates how they can be utilized in practical applications. A notable example is the use of residual materials at the Chemnitz Theatre for stage props, highlighting the diversity of potential applications. To facilitate effective exchange and networking among stakeholders, such as residual material suppliers, users, multipliers, and research institutions, a knowledge management platform has been established. This platform serves for information and knowledge exchange and is continuously being expanded. In addition, the SAMSax Database (SAMSaxDB) has been prototypically developed to provide stakeholders with detailed information about the analyzed residual materials and their specific properties. These integrated approaches contribute to fully exploiting the potential of residual materials in additive manufacturing processes, thus promoting sustainable and resource-efficient manufacturing practices.

Future steps in the concept of the SAMSax Living Lab involve expanding available residues through close collaboration with small- and medium-sized enterprises. Simultaneously, machines and binders in the SAMSax Living Lab are further developed to broaden the range of application possibilities with residues. Planned workshops and analyses in cooperation with involved stakeholders are expected to yield additional innovative ideas for applications, prototypes, and small series in various industries. The prototypical implementation of the SAMSaxDB will be expanded with new residues and detailed information and tested in practice. Additionally, new courses will be introduced, including other additive manufacturing processes, 3D printing with sustainable materials, the circular economy, recycling, and non-fossil-based filament materials. A primary goal is to expand collaborations with SMEs and institutions to promote comprehensive circular economies and support regional economic growth. The next phase of the established SAMSax Living Lab focuses on broad testing and implementation of the developed concepts in the economy of Saxony.

The SAMSax Living Lab makes a significant contribution to climate protection goals by demonstrating innovative paths for ecological and resource-efficient industrial production. Its relevance is especially high in the Free State of Saxony, a region heavily influenced by small- and medium-sized enterprises. In addition to developing prototypes and flagship projects, the project also encompasses comprehensive education and training programs. It is anticipated that the adoption of sustainable additive manufacturing technologies in small- and medium-sized enterprises, as well as in the broader industry, will bring not only ecological but also economic benefits. The future focus is on integrating the knowledge and expertise gathered in the Living Lab into the industrial landscape of Saxony. Companies are to be empowered to independently realize their projects using existing residual materials. The continuous development of the educational and networking platform as well as the database will make it easier for industrial users to adapt and practically implement the research findings.

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