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Additive Manufacturing of 3D Connecting Elements in the Building Industry

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ABSTRACT

Climate change and energy scarcity, as well as changing socio-demographic structures and new user needs, will drive major changes in the design, construction and operation of buildings towards sustainability. As the building sector accounts for 35% of global energy consumption and 38% of global CO2 emissions, the energy efficient and sustainable design and maintenance of buildings will also be one of the most effective levers for creating sustainable living conditions for the future.

The research project discussed in this paper aims to integrate different engineering disciplines to develop holistic, environmentally friendly and innovative solutions for the buildings of the future. This will be done by developing advanced building components for existing and new buildings using additive manufacturing (AM) with recycled materials. The use of additive manufacturing to produce building components transfers knowledge from the engineering sector to the construction sector, which can help drive technological progress in this area. The use of recycled materials for additive manufacturing will reduce CO2 emissions and ensure a circular economy.

This paper focuses on the development of a sustainable, energy-efficient, topologically optimised facade bracket. By optimising the topology of components through bio-inspired design, which uses nature as an inspiration for efficient and sustainable structures, the amount of raw material required can be minimised. In addition, optimised facade brackets can minimise thermal bridging in the building envelope, improve building energy efficiency, and increase the flexibility and adaptability of building structures.

Keywords: Sustainability, steel construction, circular economy, additive manufacturing

1 INTRODUCTION

The European Commission's "Green Deal" aims to counter the existential threats posed by climate change and environmental degradation and to develop Europe into the first climate-neutral continent. Central measures for a more efficient use of resources and thus for the transition to a clean and circular economy are anchored in an action plan. The construction industry plays a key role in this context, as it accounts for 35% of global energy consumption and 38% of global CO2 emissions (1). As only a fraction of the materials used in the construction industry originate from a circular economy, the enormous consumption of resources is associated with a considerable amount of waste and corresponding pollutant emissions. The total stock of construction works in Germany can be regarded as a repository of recyclable materials in which, according to the Federal Environment Agency, 50 billion tons of valuable resources are tied up for varying lengths of time. In the future, in addition to the development of solutions for energy efficiency, it will be increasingly important to design and build buildings that are as material-efficient, easy to dismantle and recyclable as possible. The reuse of building components and recycling of building materials can reduce waste, CO2 emissions, energy requirements and land consumption (for raw material extraction and landfill). (2)
At European level, a "Circular Economy Package" including an action plan was adopted in 2015, in which the transition to a circular economy is described as a key lever for a "sustainable, low-carbon, resource-efficient and competitive economy". At national level, the German Resource Efficiency Program II (3) aims to tap into untapped recycling potential and recover secondary raw materials under the term "resource-efficient circular economy" in addition to waste prevention. It is becoming increasingly important to keep raw materials in a high-quality condition once they have been extracted from the earth and to use them for as long as possible. (4), (5)
The research project discussed in this paper aims to integrate different engineering disciplines to develop holistic, environmentally friendly and innovative solutions for the buildings of the future. The use of additive manufacturing (AM) to produce building components transfers knowledge from the mechanical engineering sector to the construction sector, which can help drive technological progress in this area. The main objectives of the research project are to develop topology optimised connection components to minimise thermal bridging effects and improve building energy efficiency, and to promote the circular economy in the construction industry by using steel scrap for additive manufacturing.
This paper focuses on the development of a sustainable, energy-efficient, topologically optimised facade bracket. Using recycled materials for the production of the façade bracket reduces CO2 emissions and the recycling of the facade bracket for its further life cycle ensures Circularity. This requires the collection, categorisation and processing of waste – steel scrap to be more precise – for additive manufacturing. By optimising the topology of components through bio-inspired design, which uses nature as an inspiration for efficient and sustainable structures, the amount of steel scrap required can be minimised. In addition, the optimised components will help to minimise thermal bridging in the building envelope and improve the energy efficiency of the building, as well as increasing the flexibility and adaptability of building structures.

2 ANALYSIS, COLLECTION AND CATEGORISATION OF STEEL SCRAP

The construction sector, and in particular the dismantling of buildings, is one of the largest producers of waste in Germany. Sustainable processes and methods should reduce the volume of waste. In the past, recycling processes have found ways to reuse raw materials as far as possible at the material level. The building substance to be dismantled was interpreted as a raw material mine - a deposit of important resources.
Facade brackets are usually made of metal or plastic. In this project, recycled steel is used for additive manufacturing of building components, so the construction waste being assessed is steel scrap. An analysis of the current demolition process has been carried out to determine which construction waste can be directly recycled and processed as raw material for additive manufacturing. In addition to

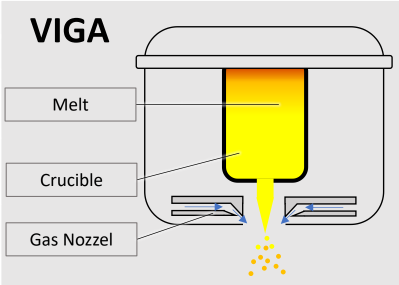
regular steel scrap, steel scrap that is not typically recycled should also be used. This is the case, for example, with reinforcing steel from smaller buildings, which is not normally economically viable to recover. This is one of the steel scraps with the highest loss rate in the material cycle, as it is embedded in concrete structures and it is particularly difficult to separate small residues from construction waste. Even modern processing plants equipped with magnetic separators cannot remove 100% of the reinforcing steel. The loss is between 3% and 5% of the reinforcing steel contained in the concrete. Hydraulic magnets (refer to *Figure 1* on the left) are utilised for this project with the expectation of enhancing the separation process and consequently improving the recycling rate. The additional steel residues collected are particularly suitable for the pulverisation process. Structural steel and steel products from the last 100 years accumulate during dismantling work. The steel quality is very heterogeneous. By separating steel waste from the deconstruction sector from various projects, the suitability of structural steels from different eras can be tested. In addition to reinforcing steel, other steel scrap, such as steel beams (as shown in the *Figure 1* right), are also conceivable raw materials for 3D printing. The samples are categorised according to age (0-25 years to >75 years), component type (beam, reinforcement, cast material) and condition. Material tests are then carried out to determine whether the samples most suitable for preparation for pulverisation are also suitable for the process from a material technology point of view. Finally, sufficient quantities of the identified suitable materials must be separated to produce the intended test specimens.

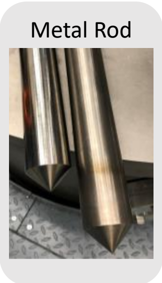
Figure 1: Steel scrap collected with a hydraulic magnet (left) and steel beams collected for recycling (right)

3 TRANSFER OF CONSTRUCTION STEEL SCRAP INTO RAW MATERIAL FOR ADDITIVE MANUFACTURING

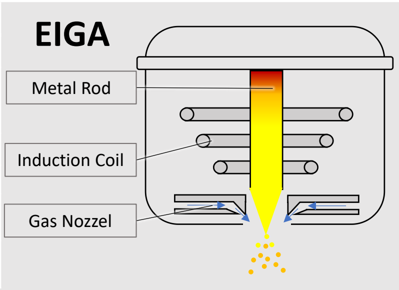
Metal-processing Laser Powder Bed Fusion (PBF-LB/M) is a standard additive manufacturing (AM) process in multiple industries, offering geometric freedom, functional integration, high accuracy, and the production of complex structures. (6). PBF-LB/M is a powder bed-based process, whereby the powder bed consists of metal-particles in the grain size range of 15 - 50 µm. In order to achieve grain sizes within these fractions, molten metal is atomized and then sieved. The atomization process can be carried out using different approaches, e.g. water or gas-atomization, among others (7). This process has hardly been established in the field of steel construction due to high costs and time constraints. But with advancing technology, the production of larger components from new materials is making additive manufacturing in construction more viable. (8), (9), (10).
Two frequently used atomization processes are the VIGA (Vacuum Induction Gas Atomization) and EIGA (Electrode Induction Melting Inert Gas Atomization). In the VIGA process, metal ingots are melted in a ceramic **crucible**. As soon as all the metal is liquid, the crucible is opened at the bottom so that the molten metal flows out and the atomization process begins. In the EIGA process, a continuous induction melting of a **rod-shaped ingot** precedes atomization with inert gas. (11), ref. *Figure 2*.

Process Parameter	VIGA
Max. melt temperature	1900 °C
Max. melt mass	14,4 kg [at ρ = 7.2 g/ccm]
Power	40 kW
Inert gas pressure	10 – 40 bar
Mass flow/atomization rate	8-15 kg/min
Processable particle size	30 – 80 µm





Process Parameter	EIGA
Max. Melt temperature	2400 °C
Max. Melt weight	55,5 kg [at ρ = 7.2 g/ccm]
Power	120 kW
Inert gas pressure	10 – 40 bar
Mass flow/atomization rate	5,5 kg/min
Processable particle size	60 – 120 µm



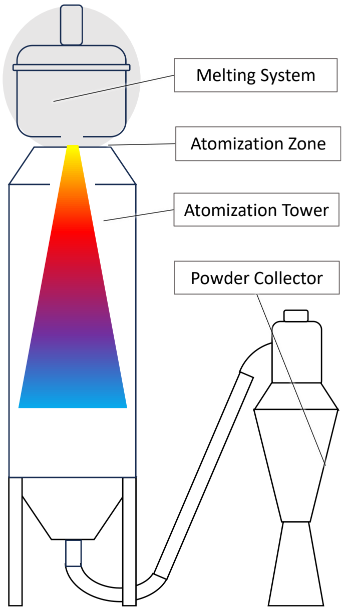


Figure 2: Manufacturing processes for metal powders **(12)**, **(13)**

Powder produced by gas atomization of a melt stream has a spherical particle shape. The very high initial cooling rate during solidification ensures excellent flow properties of the powder. The rapid solidification process results in a uniformly homogeneous microstructure. The produced particle sizes range is typically between 0 and 400 µm and highly depends on the used process parameters.

The VIGA method was deemed more suitable due to its capability to handle a diverse range of metal scrap forms and compositions in a crucible obtained from these sources than the EIGA process. The versatility of VIGA allowed for efficient atomization of the extracted materials, producing high-quality metal powders with a variety of shapes and sizes without casting an ingot ahead. This adaptability is crucial when dealing with the heterogeneity inherent in construction waste, enabling the transformation of assorted metal scraps into finely atomized powders suitable for diverse applications, such as additive manufacturing and powder metallurgy. The used atomization equipment was an ALD VIGA 2B from ALD Vacuum Technologies GmbH. Otto-von-Guericke Platz 1. 63457 Hanau.

The preparation of the metal scrap extracted from construction waste involved a systematic approach with distinct stages as shown in *Figure 3*. Initially, the materials were separated based on their chemical composition to ensure a homogeneous feedstock for subsequent processes. The size of the metal scrap was assessed and categorized to optimize the efficiency of the VIGA process. Accessibility and quantity considerations led to the chopping of the metal scrap into smaller, manageable chunks, facilitating the subsequent stages. The cleaning phase was essential, involving the removal of minerals, oxide layers, paint, residuals from concrete and other construction materials using sand blasting. This enhances the purity of the metal feedstock. In the sorting stage, the scrap parts were organized according to the specifications of the VIGA process, and, when necessary, stapled in the crucible.

Following the atomization process, the resulting metal powder exhibits a diverse range of particle sizes ranging from 0 to 400 µm. Subsequently, an air filtration step is employed to extract ultra-fine particles, typically below 10 µm, enhancing the powder's purity. The next phase involves sieving, with the first stage filtering particles above 315 µm and the second stage focusing on those above 90 µm. After these preparatory steps, the powder proceeds to the quality control stage, where analyses encompass particle size distribution (PSD), chemical composition assessment, and flowability analysis are conducted. This thorough workflow ensures the production of a high-quality metal powder with precise characteristics suitable for a myriad of industrial applications.

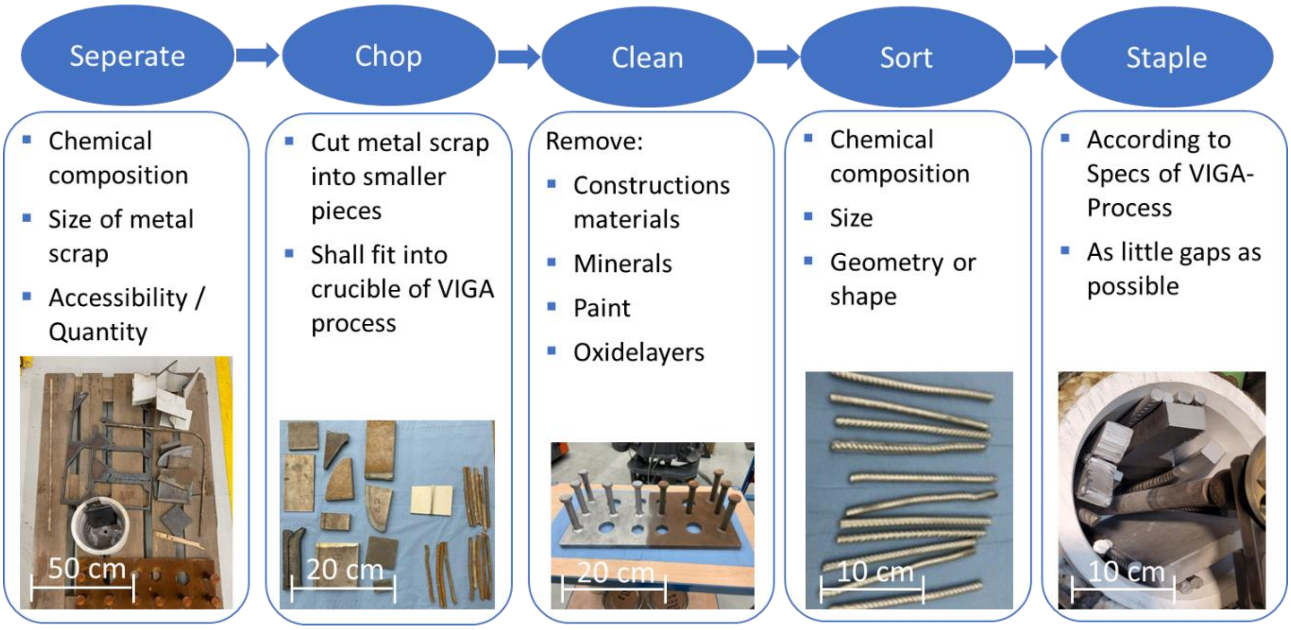


Figure 3: Illustration Workflow for recycling the procured construction scrap for further processing and alloying of the steel as well as atomization of the material to produce the powder for the LPBF process

Throughout the study, various parameters were systematically adjusted to probe their impact on the welding process. This included varying the melt temperature, gas nozzle gap, gas pressure, and nozzle stone diameter. Gas heating remained off consistent. These controlled variations enabled a thorough investigation into their effects on process outcomes and material characteristics.

The particle size distribution of the metal powder obtained through atomization is intricately linked to these process parameters. Adjusting these parameters allows for a precise control over the size range of the resulting particles. However, the efficiency of the atomization process can significantly vary, as the suitability of the powder for specific applications, such PBF-LB/M processes, depends on the particle size distribution. Fine particles below 10 µm and large particles exceeding 90 µm may not be optimal for PBF-LB/M, leading to inefficiencies and potential defects in the final product. Therefore, a delicate balance in process parameters is crucial to tailor the particle size distribution to the desired specifications, ensuring the efficiency and success of subsequent manufacturing processes. The post-atomization PSD deviates from the required working fraction because particles of up to 400 µm were found in comparison to the targeted range of 15-45. This discrepancy necessitates additional processing steps to sieve out the top and bottom grains, aligning the powder with the desired specifications. However, this sieving process inevitably reduces throughput, potentially affecting production efficiency. Hence, careful consideration and optimization of particle size distribution are paramount to ensure optimal performance and quality in the AM-process. Approximately 50 kg of metal scrap underwent atomization, yielding distinct fractions after sieving between 90 µm and 315 µm. From this process, 27.8 kg of particles finer than 90 µm were extracted, while particles ranging between 90 µm and 315 µm accounted for 14.1 kg. Additionally, particles larger than 315 µm constituted approx. 1.8 kg of the total yield. Notably, a portion of the output, approximately 3.1 kg, comprised flakes rather than molten material, indicating variations in the atomization process. The PSD graph (Figure 4) offers a detailed view of particle size distribution obtained through Microtrac Camsizer X2 analysis for the >90 µm Batch.

This instrument, compliant with ISO 13322-2 standards, allows precise measurement of particle size distributions, circularity, and convexity. Whereas within the batch a median particle size of more than 50% (d50) are smaller than 39.5 µm the grainer batch indicates a d50 of 151.7 µm. These insights are crucial for optimizing powder properties in additive manufacturing.

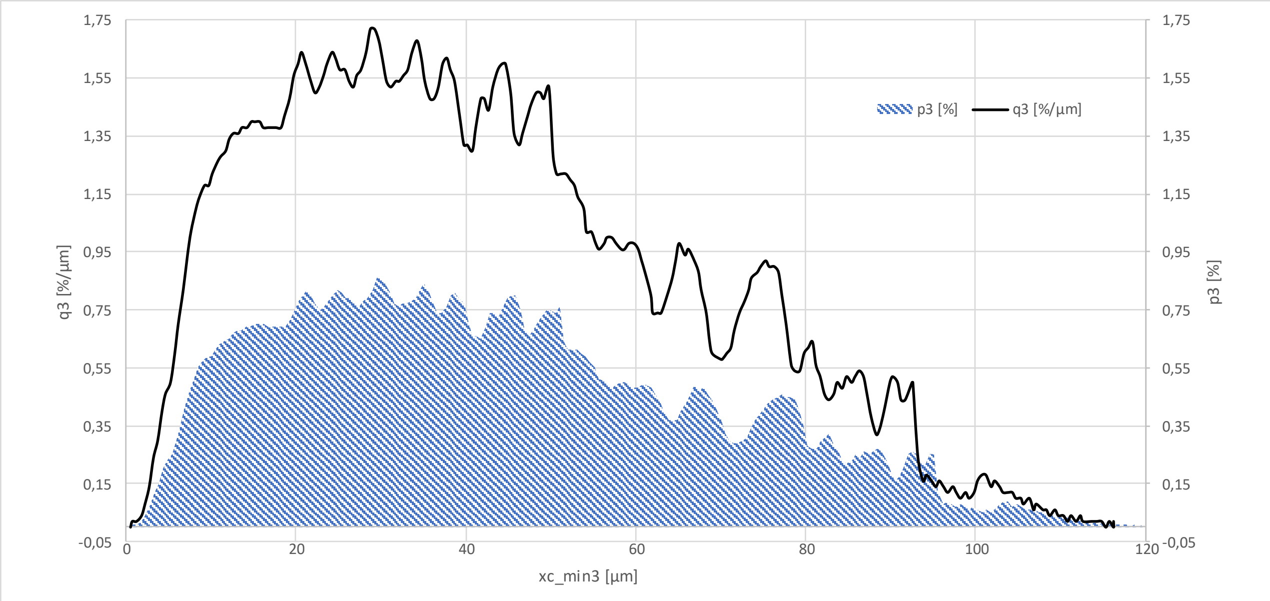


Figure 4: Comparison: PSD<90 µm of atomized steel scrap

4 DESIGN AUTOMATION FOR OPTIMIZED AND ADDITIVELY MANUFACTURED COMPONENTS

Since AM technologies rely on the layerwise and toolless production, geometrical restrictions as tool accessibility do not apply. This approach allows for the creation of functionally advanced components with a high degree of function integration, lightweight structures as well as highly customized and specialized components. The AM process of PBF-LB/M starts with a 3D geometry that is usually prepared using CAD-software. The 3D model is then sliced into a collection of 2.5D representations (layers) of the geometry. The geometrical layer information and suitable process parameters (layer thickness, laser power, hatch distance, scanning speed etc.) are transferred to the manufacturing machine to physically build the part. For this, the current layer of powder is selectively melted based on the slice information. Subsequently, the powder bed is recoated with a new powder layer with a thickness corresponding to the sliced layer thickness. These steps will be repeated until the part is completely solidified. Since AM manufacturing allows for the economical production of geometrically complex parts with a lot size of one, parts can be designed and optimized for every specific application and load case as well as using complex and freeform geometries at no additional manufacturing costs. (14)

These advantages can be helpful for the building industry either to build optimal parts with a high material efficiency (saving material and energy during the production process and life cycle), to produce consolidated parts (decreased assembly effort) or to increase the architectural design freedom by providing individually fitted (connecting-) parts.

Façade brackets have various requirements which vary depending on the building size, regional area, cladding type and other architectural features. They need to maintain mechanical integrity and since they penetrate the insulation layer, they act as thermal bridge, increasing the thermal transmittance of the façade and leading to an increased energy demand of the building (15). To decrease the direct and indirect environmental impact of façade connecting elements during their life cycle, they need to be material efficient, manufactured from commonly used mono-materials to facilitate recycling and exhibit a low effective heat conduction. Currently used façade brackets from systemized solutions are not individually adapted to the building and therefore are limited considering architectural freedom and optimal dimensioning in regard of material efficiency and thermal bridges. Considering individualized bracket designs, the parts can better meet the requirements respectively, potentially leading to less assembly effort, high material efficiency due to geometrically and load case adapted parts as well as a reduced thermal bridge effect.

Combining the optimization goals of material efficiency and a low thermal conductivity requires expert knowledge in both mechanical and thermal optimization. Topology optimization for mechanical load cases results in an optimized material distribution within a defined design space (16). This usually leads to force flow oriented solid structures, whereas the most effectively decreased thermal conduction can be found in more porous, filigree or thin-walled structures with air inclusions that do not connect both ends of the part with the shortest path (17). Adapted topology optimization results for brackets considering mechanical load cases, however, show good results in a reduced heat transfer compared to commonly used solutions. For the adaptation, the dominant structures of the optimization result are reconstructed using thin-walled tube-like geometries in a symmetrical layout. Other lightweight structures such as lattice structures or bio-inspired designs are promising to meet both mechanical and thermal requirements and are considered within the project. These structures have a high strength to weight ratio and a rather porous or network-like structure with many small cross-sections within the network instead of one solid connecting geometry, potentially leading to a decreased effective thermal conduction (18).

Although, the production of individualized and geometrically complex parts, as they result from the above design considerations, can be realized using PBF-LB/M, the design of many slightly different parts involving complex geometries is a time-consuming yet repetitive task when commonly CAD software is used. However, it still requires expert knowledge in designing and dimensioning, making it uneconomical due to high labour costs. Automating the design process using design algorithms can not only accelerate this process and making it more affordable, but also the required "expert knowledge" can be implemented into the algorithms, eventually leading to a part configurator enabling also non-experts in designing and AM to generate customized parts. Design automation means that the 3D model of a part is generated using algorithms or automated workflows depending on the user input. These algorithms can consist of e.g. parameterized CAD-models, which can be directly manipulated according to the user input, parameterized CAD-models with a subsequent Finite Element Analysis and feedback loop with a following parameter optimization or topology optimization. Product configurators make use of these algorithms by providing adequate input options, generating parts based on the user information and potentially providing ready-to print files to the user (19). For façade brackets the process is schematically shown in *Figure 5*. Automating the design and dimensioning process opens up the possibility to design a large number of product variants at comparatively low design costs, still, all of them meeting the predefined individual requirements. This facilitates not only the design of optimized and more sustainable parts, adapted to each building, but can also lower the entry hurdle into AM and AM-compatible and optimized design for first time users in the building industry.

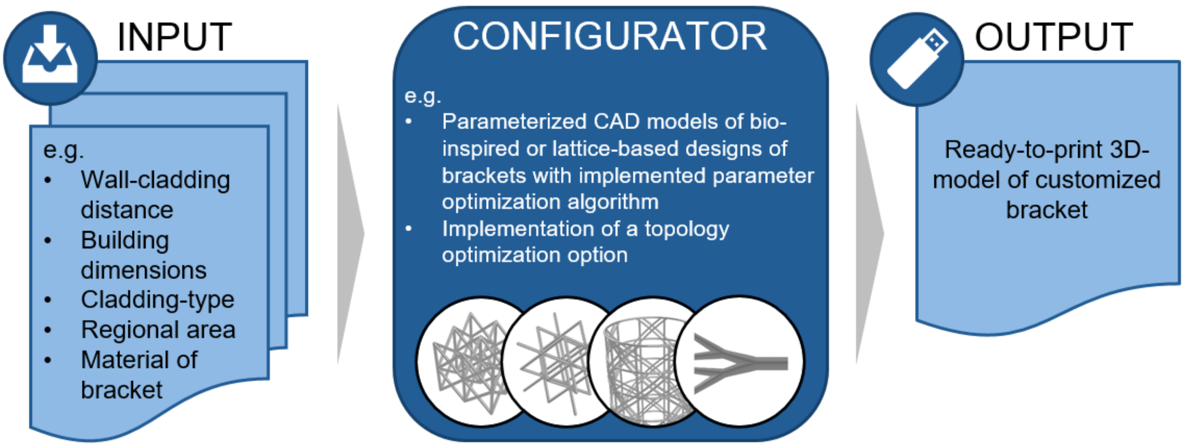


Figure 5: Schematic illustration of an algorithm-based design configurator for facade brackets.

5 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) (20), (21), is an essential part of the sustainability assessment of products, processes and services. It evaluates environmental impacts, potential hazards and energy requirements over a defined period of time and within defined system boundaries. In the construction sector, information can be gathered on the potential environmental impact of the building materials used and the energy requirements over the entire life cycle of a building. Building materials and products are analysed from raw material extraction, through production and use, to disposal. Building Life Cycle Assessments (LCA) are becoming increasingly important as the focus shifts to meeting and achieving climate change targets and demonstrating a holistic approach to sustainable construction. It is establishing itself as the central assessment system in the field of sustainable construction. It helps to compare the contribution of building products and structures to global warming and the acidification or eutrophication of water or soil, for example, in order to make the most ecologically favourable choice.

According to EN 15804 (22), the life cycle of a building/construction product is divided into different phases, as shown in *Figure* **6**. The production stage (A1-A3) covers all processes from the extraction of raw materials to leaving the production site, including transport processes. The construction phase (A4-A5) covers transport to the construction site, the construction and installation process and all associated impacts. Modules B1 to B8 cover the period from the completion of the building to its demolition. In addition to the modules for the use, maintenance, repair, replacement and refurbishment of components (B1-B5), energy and water consumption for the operation of the building (B6-B7) are also listed. Data for B1-B5 are difficult to collect accurately for individual building materials and products and should be considered on a project-specific basis. The disposal process at the end of the building's life is presented in modules C1-C4. C1 and C2 deal with the deconstruction of the building or individual components, including initial sorting and subsequent transport of the materials to the recycling site or final disposal. Module C3 covers waste treatment for materials to be recovered or recycled, while Module C4 covers the processes and impacts of waste disposal. Benefits and burdens outside the system boundary of the building are covered in Module D. The boundary between Modules C3 and D is drawn at the point where materials or components cease to be waste due to the fulfilment of certain conditions. For example, if raw materials are not disposed of because of their high value, but are generally fed into a recycling process, then processing charges and credits should be considered in Module D. In addition to the environmental impact of the materials used in the building, the so-called grey energy and grey emissions, the environmental impact of energy consumption, are also considered. This is done in stages B6, operational energy use, and B7, operational water use. In the past, the energy demand of building use dominated the embodied (grey) energy. In the future, thanks to improved building technology and the use of renewable energy, the environmental impact of the use stage will decrease and grey energy and emissions will move more into focus.

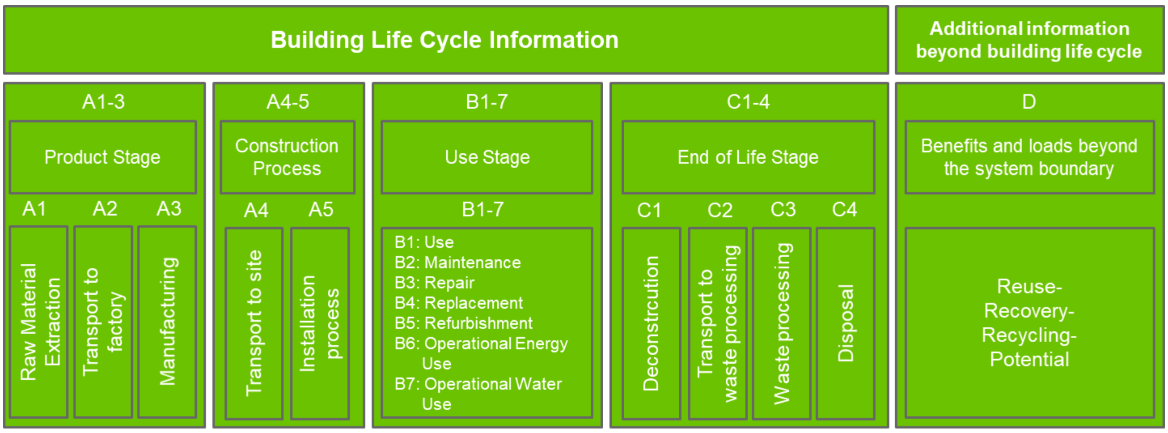


Figure 6: Modular categorisation of the life cycle according to DIN EN 15804 **(22)**

5.1 Production of AM facade brackets

The production stage has the greatest environmental impact on steel products. In the production of primary steel, iron ore is mined, transported to the steelworks and usually produced in the blast furnace. This process is associated with high energy consumption and environmental impacts. If secondary steel is produced using steel scrap in an electric arc furnace, greenhouse gas emissions per ton of steel can be reduced. However, the problem with using secondary steel is the availability of scrap. Current levels of scrap are insufficient to meet the demand for steel produced by this process. (23)

The aim of this research project is to use additive manufacturing (AM) to produce connection elements and facade brackets from recycled steel scrap, this paper focuses on facade brackets. The technology presented in chapter 2 increases the recycling rate of steel scrap from construction waste. This steel scrap is transferred into raw material for additive manufacturing, see chapter 3. Component optimisation (see Chapter 4) aims to develop topology-optimised facade brackets to replace conventional, mostly full-surface cross-sections made of steel, stainless steel, aluminium and plastic. By reducing the cross-section, less scrap is needed in the manufacturing process. In addition, heat losses through the building envelope can be reduced. This saves CO2 and increases architectural design freedom.

For the life cycle assessment of AM facade brackets, the production process chain must be analysed in detail. The production of an additively manufactured component is divided into four steps, see *Figure 7*.

Figure 7: Additive manufacturing process chains in the production stage

The literature reports an energy requirement of 241-339 MJ/kg for the production of components using 17-4 PH stainless steel powder, which is typically used in additive manufacturing (24), (25), (26). This energy requirement has an environmental impact that depends on the proportion of fossil fuels in the available electricity mix. Data sets showing the global warming potential per kWh of electricity for different electricity mix scenarios are obtained using the Ökobaudat platform (27). The Ökobaudat platform is provided by the Federal Ministry of Housing, Urban Development and Building (BMWSB) as a standardised database for the ecological assessment of buildings. Combining the environmental indicators from Ökobaudat with the energy demand from the literature shows that the environmental impact will continue to decrease in the future, see *Table* ***1***. This is due to the increasing share of renewables in the German electricity mix. The energy required to manufacture the brackets is to be measured in order to better assess the associated environmental impact.

Table 1: Global warming potential for Additive manufacturing

Electricity grid mix scenario	**Global warming potential [kg CO2-Äq. /kg]**
Electricity grid mix scenario 2030, conservative	23,8 - 33,5
Electricity grid mix scenario 2040, conservative	10,4 - 14,7
Electricity grid mix scenario 2050, conservative	8,6 - 12,1
Electricity mix scenario Agora 2030, progressive	13,5 – 19
Electricity mix scenario Agora 2040, progressive	9 - 12,7
Electricity mix scenario Agora 2050, progressive	6,7 - 9,4

A model is currently being developed using the GaBi software to assess the environmental impact and energy requirements of facade brackets manufactured using AM. GaBi is a well-established tool that is suitable for in-depth analysis of product footprints (28). The production of such a bracket has a higher environmental impact than a conventionally manufactured bracket. However, the reduced cross-sections result in lower transmission heat losses through the building envelope and therefore lower heating requirements and lower impacts in Module B6. It will be investigated whether the increased impact in production is offset by savings in Module B6, resulting in an overall better environmental outcome. A reference building is to be used to analyse whether the higher impact during production is compensated for by savings in module B6, and lead to a better environmental result overall.

6 SUMMARY

An analysis of the current demolition process has been carried out to determine which construction waste can be directly recycled and processed as raw material for additive manufacturing. By using a hydraulic magnet, steel scrap that is normally lost can be recovered in addition to normal steel scrap. The collected steel scrap has been categorised and conditioned before being turned into powder through atomization. The VIGA process was considered suitable for the atomization due to its ability to process a wide range of metal scrap forms and compositions in a single crucible obtained from these sources. Various parameters were systematically adjusted to investigate their effect on the welding process, including melt temperature, gas nozzle gap, gas pressure and nozzle block diameter, while gas heating was consistently switched off. These controlled variations allowed a thorough investigation of their effects on process results and material properties. These findings are important for optimising powder properties in additive manufacturing. To automate the design process for the AM facade brackets, a configurator will be developed to provide a 3D model ready for printing. The configurator will use bio-inspired design, which uses nature as an inspiration for efficient and sustainable structures, minimising the amount of waste required by optimising the topology of components. The environmental impact will be assessed using Life Cycle Assessment. The energy required to manufacture the brackets is to be measured in order to better assess the associated environmental impact. So far, initial estimates have been made on the basis of literature values. In the future, a GaBi model will be used to conduct this assessment. Furthermore, a reference building is to be used to analyse whether the higher impact during production is compensated for by savings in module B6, and lead to a better environmental result overall. The transfer of additive manufacturing technology to the construction industry will help drive technological progress in this area and the development of sustainable building components.

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