In recent years, architecture has been influenced by the capabilities of CAD software for the design of structures and shapes. A direct link can be made between the building envelope design and the increasing sophistication of CAD software. The wall has evolved from the massive homogeneous wall, to the curtain wall facades, to utilised systems with integrated and decentralised technology. It now needs to further evolve and become 'digital' envelopes — dynamic skins. The built systems however, remain more or less in planar and orthogonal orientations. The technology for facade systems has advanced and is highly technologically detailed. Improvements have been made in lowering u-values (heat conduction of building elements) and in better building physics performance rather than in revolutionary new developments.

When there is a freeform shape involved, it is usually transformed to a near-net-shape, but still consists of orthogonal members that are then tessellating the shaped geometry. In the last twenty years, Additive Manufacturing (AM) has started to offer the possibility of directly realising physical parts and detailed representations from CAD files.

It is already state-of-the-art in some industries, but the building industry has approached the changes conservatively and has failed to adopt new ways of generating products layer by layer. AM removes most limitations inherent to traditional production processes such as milling, cutting, moulding, etc., and opens up the real world of toolless production of individualised parts of any shape.

AM has come a long way since its conception in the 1980s and is now addressing materials and solutions for standardisation and quality management. Materials used in these processes range from numerous plastics, to special materials for tooling applications, and to a wide range of metals. What started as a support for product designers to discuss intermediate design proposals on a real part rather than on the computer screen has turned to the production of end-use parts. The architecture industry has shown much interest in this. Every architect is aiming for the one-off solution with an outstanding and recognisable appearance. AM offers the chance to individualise and realise products and parts that are out of the range of the standards.

Although production of facades is not the main use of AM in architecture, it has been used in many one-off showcases that have alerted the wider industry to its capabilities.

**Research in cooperation with the industry**

The research project was conducted in cooperation with Kawneer-Alico, a strong partner related to facade systems made from aluminium profiles, and the Delft Technical University, where the Facade Research Group is pushing the limits of recent facade technology. Also involved is the University of Applied Sciences in Detmold, Germany, where main parts of the work were fulfilled. The findings and inventions being produced during the two-year project also resulted in the dissertation of the author in the field of AM and architecture.

As stated above, this new way of producing parts opens new ways of thinking about details, components or construction units. Economic considerations based on improved design efficiency such as material usage can almost be impossible to achieve by hand in one step with no extra tooling, labour, or assembly. Based on this background, the research project's initial aim was to develop new parts for building envelopes step-by-step. Beginning with the detailed solution for the existing facade system, then to a new application for freeform facades, and finally to the facade of the future — the printed AM envelope — covering innovation for today, tomorrow and for the future.

**The Scope of research**

What was revealed after the first look at the current product catalogue from Kawneer is the fact that some items from the highly developed systems are only being produced to fit into one specific application — and are therefore seldom used. In the traditional production of extruded Aluminium profiles, the tools that are needed for the extrusion lead to an initial investment. This leads to stockholding with an uncertain pay-back period. These tools need to produce a certain amount of 'products'.

In this case we talk about mass-production, where the investment by the producer can result in maximum profit by selling as many parts as possible. As such, many approaches to altered or new parts, even ones with improved performance or other benefits, were refused in the first step because of these high initial costs of investment. By using AM this limitation can be denied due to the fact that production is looked upon to be a tool-less process.

The adoption of the advantage of 'on-demand-production' in low batch numbers was the first attempt to integrate AM technologies to the production chain of Kawneer. The first ideas combine these advantages with others such as better performance, integrated angles and savings on material. To make full use of the..
potential of AM parts, people’s awareness of AM must grow. The designers have to reset their “design-for-production” approach to a “design-for-function” approach.

AA-100 connector
A commonly used connector for the mullion-and-transom system, connecting both members of the system and transferring loads from the transom to the mullion, was examined closely. This connector is efficient if it is applied in an orthogonal system, but doesn’t cope well with non-90° angles.

By applying AM to re-model this connector the aim was to achieve better rigidity of the joints in a non-orthogonal system, use less material and The re-interpretation of the existing facade part was first prototyped on a Stratasys FDM machine at the University of Applied Sciences in Detmold, and then later made.

The results from the optimisation of the ‘AA-100’ connector are: The ability to mount it like the standard part, no new tools or templates for the facade manufacturers (customers) needed; all drillings and fittings are the same as the standard connector; improved rigidity can be achieved with the implementation of organic struts; AM allows for an optimised design material is located only where it is needed, i.e., at the locations of the distributed loads in the part and not where the extrusion process distributes it, the notch stress of all participating corners and edges is reduced with ‘advanced’ notches.

Material savings of 25% were possible with the use of the so called ‘Soft Kill’ Option by Matheck.

One step further — the Nematox facade node
As introduced earlier, the goal after the enhanced details for the project was to find an advanced way to realise free-form facades. To virtually intersect the required profiles and model them in any desired shape was the initial idea for the facade node — the Nematox. To fulfill this task an initial fifty hours of CAD engineering was done to gain the ‘.stl-files for Nematox’. The nodal point was based on the so called ‘Next Facade Profile’ and should have been realise in Aluminium on an SLM-based system.

Because of the size of this part, the mock-up realisation was not possible and from that point another sixty hours of CAD engineering was done to adjust the profile size to a smaller product. The Nematox II was then realised in Aluminium and in Alumide (a special AM material consisting of Polylactide and Aluminium). This prototype verified the performance of the initial design concept. The project ended with convincing results for the nodal point.

All parties agreed on the following advantages of the AM part: design, implementation and project-realisation of the node match in one progressive product; if the Nematox II was to be applied to a facade, the pre-production for most of the construction would be possible; when AM is applied, the digital planning steps allow visualisation before production in mock-ups and CAD-models, minimising the risk of having major faults in assembly and conversion of the planned project; highly integrated product-features are possible, such as force-following material distribution, enhanced rigidity and snap-on features for easy mounting.

Results from the Project
The presented solutions for facades with AM-produced parts show that a ‘CAD-CAM Process’ is possible in this context. All required functions can be implemented in the digital file for the nodal points. By digitally assigning every node, easy mounting is made possible. Each facade intersection can then be dealt with individually, as every AM-node can be different without increasing the costs. A detailed optimisation for non-linear loads can be realised. The required 3D-data comes from the already available CAD-software, which can make use of the existing digital catalogue.

After realising the Nematox II, it can be stated that there is a future for AM in the building industry. The impact might not occur tomorrow, as AM might well need more time to reach all participating parties. Results from this project highlight the route to push the development of AM for facades further. There are current limitations in its applications for facades because of the limitations in the state of the development of layered fabrication, which will be overcome in the near future. Material properties like UV-resistance, fire resistance, performance in tension and compression and repeatability in different batches need to be further developed.

The available sizes of the building envelope on the AM-systems need to be upgraded to fulfill building construction requirements. This determines the possible size of the parts and is therefore crucial. The building speed needs to be adjusted for bigger batch production, as it currently takes hours to days to ‘print’ a part, depending on its size. To proceed further with the use of AM for facades it is necessary to differentiate the use of AM in terms of the different states of facade system applications: production, storing, mounting and performance of members.

Everybody involved in the process has to gain knowledge about the possible extra value from AM, for example, better performance, material consumption (production and in total), integrated functions (Snap-On and Lock-In), optimised storage capacities (on-demand fabrication) and digital design (digital angles, freeform shape and force following shape).

It became obvious that there is a strong need for a design-guideline. This is needed for each specified AM-system, as they all lead to different parts, performance and materials. If AM is implemented into the production chain of an existing industry, the customer, the designer/planner and the engineer needs such a guideline to find limitations and mitigate any associated risks of the technology.

The potential of AM for future facade systems has to be verified by more end-use applications. By doing so, we push facades towards dynamic envelopes.

Conclusion
The change in the way we are producing products and parts in our environment is not to be underestimated. There will be a strong move towards ‘design for function’ and a step-back from the limitations in the ‘design for production’. Parts will be developed based on their required performances and not from the available production technologies. Looking at the common tencencies towards virtual realities, 3D modeling and further developed CAD-CAM software, the way we design will change, but also the products we design will change.

These shown potentials of AM for building construction and facades is at the moment only a small piece in the broad range of facade developments. It shows how technology transfers and how new emerging technologies can have a significant effect on core-businesses and standard applications. Things will change!