

Bespoke Cast Facade

Design and Additive Manufacturing
for Cast Aluminum Facade Elements

Mania Aghaei Meibodi
DBT, ETH Zurich

Marirena Kladeftira
DBT, ETH Zurich

Thodoris Kyttas
DBT, ETH Zurich

Benjamin Dillenburger
DBT, ETH Zurich



1

ABSTRACT

This paper presents a computational design approach and a digital fabrication method for a freeform aluminum facade made of prefabricated bespoke elements. The fabrication of customized metal elements for construction remains a challenge to this day. Traditional fabrication methods, such as sand casting, are labor intensive, while direct metal 3D printing has limitations for architecture where large-scale elements are needed.

Our research investigates the use of Binder Jetting technology to 3D print sand molds for casting bespoke facade elements in aluminum. Using this approach, custom facade elements can be economically fabricated in a short time. By automating the generation of mold design for each element, an efficient digital process chain from design to fabrication was established. In search of a computational method to integrate casting constraints into the form generation and the design process, a differential growth algorithm was used. The application of this fabrication method (3D printed sand molds and casting) in architecture is demonstrated via the design and fabrication of a freeform facade-screen. The paper articulates the relationship between the fabrication process and the differential growth algorithm with a parallel process of adaptive design tools and fabrication tests to exhibit future potential of the method for architectural practice.

1 Impression of the final cast
facade after assembly

BACKGROUND

Cast Metal Facades

Metal casting allows for the production of elaborate facade elements with a wide array of shapes and designs, for example freeform panels with dynamic variation in depth, angles, thickness, and detailing in multiple scales. Cast iron was a prominent material for building facades in the mid-1800s. During that time, elegant and ornate exterior facades could be picked right out of a catalog and mass-produced economically using a prefabricated kit of cast-iron parts (Davey 2009) (Figures 2, 3, 4). The Soho neighborhood in New York City showcases more than two hundred historic buildings with such cast iron facades. Today, there are only a handful of architecture projects that use cast metal, and they usually avoid intricate detailing due to limitations of current fabrication methods, notably because the fabrication of the molds for sand casting is very labor intensive, and hence, expensive.

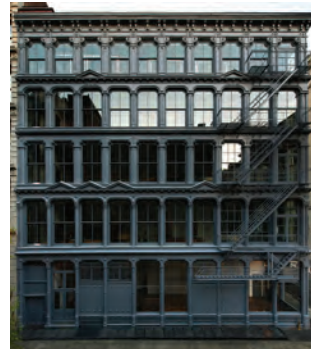
Fabrication of Bespoke Metal Elements:

Traditional Sand Casting and Metal 3D Printing

The degree of geometric complexity achievable in a metal element necessarily depends on the complexity of the casting mold. Conventional sand casting involves significant investment in making a pattern—a replica of the object to be cast—needed for the fabrication of the mold. Sand molds are then formed via packing sand around the pattern. The popularity of sand casting in the mid-1800s was partly due to the economies of repetition and modularity: a pattern that was used to produce thousands of similar parts. This traditional way of making a mold, especially the fabrication of the necessary pattern, is very labor and time intensive, particularly for the production of custom elements.

Contemporary processes of the material formation such as thermo-vacuum forming and CNC milling for the production of patterns have expanded the application of casting for custom elements. Digital fabrication of patterns has enabled architects to realize especially complex surfaces and architectural elements. An example is the cast facade of 40 Bond Street by Herzog & de Meuron, where the patterns were milled with a CNC controlled machine into 1:1 sized foam blocks and then packed with moist sand to produce molds (Pell 2010). During the casting process, the hot aluminum melted the foam away, and after cooling, the individual elements were formed, resulting in a custom 39-meter-long grid (Figure 5). While CNC Forming and subtractive fabrication of patterns can be used to cast complex metal elements, mold-making in this way is slow and produces a lot of material waste.

Today, multiple technologies of metal 3D printing exist



2



3



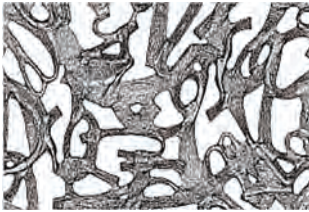
4

- 2 Examples of historic cast facades: The cast iron facade of Judd Foundation, Soho, New York
- 3 Cast iron detail of Haughwout building's facade, New York
- 4 Bronze-plated cast iron ornamental facade in the entrance to the Carson, Pirie, Scott and Company store by Louis Sullivan

for the moldless fabrication of bespoke elements with complex geometry. A commonly used technology is Powder Bed Fusion (such as SLM, EBM, and DMLS), in which each powder bed layer is selectively fused using laser or electron beam. While this technology is used for the manufacturing of small-volume complex metal parts (Bhavar 2014), its application for the building industry still has major limitations: small build volumes, long printing times, limited range of materials, and high cost. Another technique is Wire Arc Additive Manufacturing (WAAM), which allows additive manufacturing (AM) of large-scale parts by welding metal wire in layers. However, this technique requires expensive post-processing to reach a high-quality surface finish and is still limited to certain printable forms.

BINDER JETTING TECHNOLOGY FOR RAPID CASTING

Instead of forming a sand mold via packing sand around a pattern or printing the metal parts directly, we explore the 3D printing of sand molds for casting metal in any shape desired. While there are a few different types of AM technologies, Binder Jetting technology, where a liquid agent selectively binds sand layer by layer, is the most suitable one to fabricate sand molds. Binder Jetting technology with sand offers a unique combination of geometric freedom, resolution of parts, large print-bed dimension, and fast printing time. It not only speeds up the fabrication process by eliminating patternmaking and reducing material waste, but also enables the production of large-dimension sand molds regardless of their geometric complexity.



5a



5b



5c

- 5 Design geometry generated from graffiti drawings, CNC milled foam pattern to be used for mold making and cast parts before post-processing (Pell 2010, 137)
- 6 Diagrammatic section of a closed mold with the gating system

In recent years, we have seen a growing interest in integrating Binder Jetting AM technology into the metal casting industry to produce molds and cores (Lynch et al. 2017) for small-cast parts and car engines. However, this process has not yet found its application for the fabrication of architectural elements. In 2017 the authors, together with a group of students from the Master of Advanced Studies Program in Digital Fabrication (MAS DFAB) for 2016-17 at ETH Zurich, designed and built a space-frame structure with 189 bespoke and light-weight complex joints that showcased the benefits of this fabrication method for the mass customization of architecturally expressive joints (Aghaei Meibodi et al. 2018).

To further explore the potential and challenges of this method in architecture, the authors engaged the research in their teaching and together with the students of the MAS DFAB 17-18 designed and built an experimental facade screen, the Deep Facade, from bespoke cast aluminum elements using 3D printed molds.

Closed Mold Casting

The typical fabrication method used in the industry for cast metal parts is the production of closed sand molds. A closed mold has a cavity that is entirely enclosed by the mold, accommodated with a passageway (called the gating system) that controls and directs the flow of the molten metal from the external pouring point to the cavity. The gating system ensures the smooth and continuous flow of the liquid metal to the mold cavity. It also ensures the slow drop of the metal temperature. The gating system is composed of the pouring basin, sprue, sprue well, runner, and ingates (Figure 6).

While parts with complex three dimensional geometry must be cast using a closed mold system, parts that have a flat side can also be fabricated with an open mold system,

which does not require the top side of the mold and the gating system; the metal is poured directly into the cavity.

CASE STUDY: DEEP FACADE

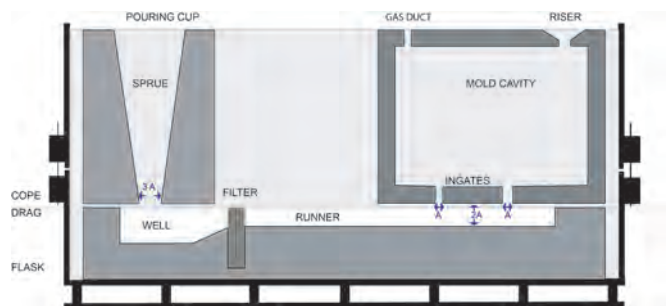
The Deep Facade is a custom 1:1 cast aluminum screen that showcases the potential of additively manufactured open sand molds for casting facade elements (Figure 7). The aluminum screen covers a glass surface area of $3.5 \times 2.7 \text{ m}^2$ and has a variable thickness of 55 to 110 mm. The facade screen expresses the structural tensile strength of cast aluminum through the geometry of elements that are very thin and suspend locally in the air (Figure 8). It is a lightweight and self-supporting screen that takes its structural load through changes in the density of elements and the precisely calculated connectivity of the elements. Its interaction with daylight creates a dynamic atmosphere, casting intricate shadows in the room. It controls the transparency of space and vision through the density of its winding members and their angles.

To produce the Deep Facade, we used an open mold system. The flat side of the facade screen, that is attached to the building, corresponds to the open top surface of the mold, where the aluminum is cast from. The motivation to use an open mold system was to save 3D printed material and to facilitate the assembly of the printed parts by minimizing the number of parts, as well as reduce print time and cost.

The open mold is extremely beneficial as it saves 190 mm in height from the printed material on the flat side of the mold and an additional $225 \times 10^2 \text{ mm}^2$ of mold footprint. At first glance, this might not seem like a significant gain, but this can result in up to a total of $3.5 \times 10^8 \text{ mm}^3$ volume gain per cast element.

Computational Design for a Metal Facade

In order to exploit the potential of the fabrication method, a computational workflow was generated for the design of the Deep Facade. The computational design of the facade involved two interdependent steps: generating 2D lines using a differential growth algorithm and dynamically



6

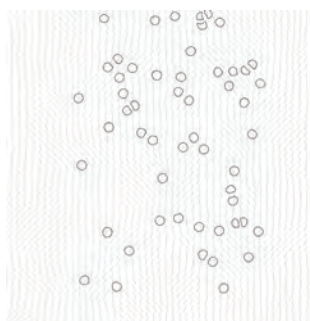


7

forming them in 3D space in accordance with design parameters.

A Custom Differential Growth Algorithm for Facade Elements

Surprising emergent forms inspired by biology and morphogenesis can today be created with algorithms and would be impossible to create without digital technology (Lomas 2014). The roots of genetic algorithms were laid already in 1967 by John Holland and his colleagues (Goldberg 1989), but it was only after 1991 that knowledge in evolutionary design started to grow and develop more systematically in various scientific fields (Jong et al. 2004). Since then, generative design algorithms have been used in graphics (Pedersen and Karan 2006), as well as in architecture and other areas of design (Caldas 2001, 40-43).



9a



9b



9c



9d

For this case study a custom 2D differential line-growth algorithm was developed—building upon existing examples (Giachino 2017)—with the following control parameters:

- maximum edge length
- growth force
- growth speed
- maximum distance
- separation cohesion
- flow field intensity

The differential line-growth algorithm was chosen for multiple reasons as the main design method. The seamlessly grown curve displays fabrication advantages for metal casting, as it provides a continuous path for uninterrupted material flow. Also, overhangs can be integrated into the structure as the tension is delivered through the material strength in the line path. Additionally, it allows the simultaneous development of a variety of design criteria, which often contradict one another, such as the structural capacity, reduction of weight, and a high level of transparency.

The input of the algorithm is a set of closed polygonal chains in a 2D manifold (Figure 9) that corresponds to single elements of the overall structure in the processing

7 Deep Facade project by the MAS DFAB Students 2017/18; Final full scale prototype of the facade

8 A detail showing thin suspending parts

9 A set of closed polygonal chains, corresponding to the number of facade elements, are growing following the flow field generated from the image mask on 9d



8



10 Structural analysis of cast connections and mechanical element-element connections: The internal stress of the facade is displayed in a color gradient to show the intensity of material stress at any given point; it also highlights the path through which the forces travel through the screen to the ground

environment. In subsequent iterations, these curves grow according to a varying flow field, which is generated based on the transparency value mapping of a predefined image mask to a two-dimensional constructed vector grid.

When the curves reach full growth, tightly packing the given surface, a series of additional editing steps take place in order to achieve the 3-dimensionality of the facade and also ensure fabrication success.

The first immediate step is to identify the connections needed between and within the individual elements. To ensure stability, a parametric computational method is generated that analyzes the stress of the material and maximum deformation of the structure using the Karamba 3D tool. In the first iteration, a set of random connections between the curves is generated and fed to the structural analysis, which then, in a feedback loop, rearranges the position of said connections, until the desirable state of minimal deformation, within expected tolerances for fabrication, is reached (Figure 10).

Additional parameters in this step are the length of the connections—what length the connection line needs to span to connect two vertices—and a minimum amount of connections per element. Since element-to-element connections in many cases do not suffice to stabilize the structure—due to the fact that the algorithmic growth is to a certain extent unpredictable, and given that the cantilevering of very long elements can cause serious deformations—some cast connections are designed within each element. These cast connections are identified selectively between points of a curve-element, and in terms of design language, are treated in a similar way to element-to-element connections. The element presented in Figure 8 showcases three such cast connections.

As soon as the positions of the connections are set, the initial curve elements are transformed in the initial algorithm in such a way that the connected elements meet in a tangential relationship at the connection moment. This provides an interface where elements can be screwed together, in the case of element-to-element connections, while at the same time the connection appears to be seamless and organic, as it almost disappears within the vast collection of flowing curves.

From a 2-Dimensional to a 3-Dimensional Structure

The second step in the process, which relates directly to the 3-dimensional quality of the cast elements, is to define the width, depth, and directional extrusion of the generated linear geometry based on various design concepts such as vision control, structural capability, and fabrication constraints such as minimum castable thickness.

The width of the extrusion also varies depending on the extrusion angle and the depth and vertical position of the cast element. Closer to the glass, the cast aluminum facade gains thickness and thins out toward the exterior view for a slender appearance (Figure 11). This also helps to maintain the center of gravity toward the connection to the main frame of the building, so that the cantilevering weight is reduced to a minimum. The thickness is also very much dependent on the vertical position of each element, as in this case study the facade is mainly self-supported and attached to the ground. The main load transfer is vertical and not horizontal to the building attachments, leading to the decision to make the lower elements thicker and the very upper ones as lightweight as possible, which increases significantly the stability of the overall structure.

A second image mask is used as an input to parametrically dictate the intensity of the extrusion and the directionality. The alpha value of the bitmap is again the primary source of information, as the alpha range of 0 to 255 is mapped to a perpendicular extrusion range, defined by fabrication tests that are executed in parallel. The perpendicular vector is then redirected according to a flow field generated from the same image mask, resulting in the final extrusion vector for every vertex of the curve.

MOLD DESIGN AND AUTOMATIC GENERATION OF MOLD DATA

The intricate geometry of the Deep Facade can only be fabricated through digital means. For this reason, a parallel computational workflow was created to automate the process of mold making. However, to define this computational process it is important to address the challenges the



11a



11b



11c



11d

11 Final cast elements with various thicknesses, extrusion depths, and angles

open mold system posed for the Deep Facade in the design and fabrication of the molds.

Challenges of Open Mold Making

When casting with an open mold, one of the biggest challenges is the oxidation of liquid aluminum during casting. Contrary to a closed mold, which minimizes the contact between the molten metal and air, in an open mold the liquid aluminum is in immediate contact with air. This results in higher oxidation of the aluminum which prevents its smooth flow throughout the mold cavities (Figure 12). Therefore, in using the open mold system, the casting time and travel paths of the material need to be minimized. To overcome this challenge, multiple pouring sources are introduced in a single mold thereby reducing material travel distances (Figure 13). However, this solution does not come without shortcomings. In moments where material from different pouring sources meet, a cold joint is formed due to the different local temperature of the two (or more) flows. More importantly, when the meeting occurs in opposing directions, the cast can be extremely weak and brittle, to the point of structural failure. For this reason, the position of casting sources was carefully decided in order to minimize those failures.

Another challenge when using an open mold is the need for high pressure at the pouring point to ensure the successful flow of material throughout the mold, while avoiding overflow, as the mold is open from above. This challenge was addressed in the Deep Facade with the introduction of an additional off-shelf sand sprue, locally, where the pouring sources are found (Figure 13). These are premade low-cost sand parts that are used in foundries and facilitate the casting process. For the Deep Facade the production company offered circular sprues of 250 mm diameter.

While traveling through the open mold, the aluminum cools down and its viscosity changes—cooling starts at the outer surface and moves inward. This causes significant shrinkage of the shape. Therefore, the time the material travels has a direct relation to the geometry of the mold. If channels are too narrow, or if the metal cools down too early, then the mold is not fully cast (Figure 14). In order to identify the minimal dimensions and minimize the shrinkage, several prototypes with varying curve thickness, depth, and sharpness of curvature were tested. Here, the parametric model allowed the integration of constraints in distances and dimensions relevant to a smooth flow of the molten aluminum in the mold design.

Automation and Features of the Open Mold System

The method of open mold making required a novel computational process. In contrast to the complex process of creating closed molds for metal casting, the open mold that was used in this case study featured none of the systems described in closed mold casting. Since the geometries intended for open-mold casting are shallow, the material can be poured directly in the cavities from the top. In the case of bigger elements, like the ones used in the Deep Facade, central pouring wells were introduced, where the geometry was wide enough. The central wells help to shorten the maximum travel distance of the material and are found within the casting geometry, wherever there is a thicker member or a within-element connection. A casting simulation was also used to pre-visualize the casting and possible cold joints that occur when material flows with different temperatures meet.

To automate the mold production, the mesh of every single element was voxelized with a custom algorithm for robust boolean and offset operations that follow in the process. In a second step, the geometry was offset outward 7 cm in

all directions except toward the top layer, where the mold would remain open (Figure 15). A hollow grid was added at the bottom side of the mold to eliminate breakage while lifting from the print box and support the irregular geometry while handling. Lastly, inlets for placing the off-shelf sprues were formed at the top central wells.



12



13



14

12 Oxidation of aluminum that comes in contact with air in the top surface while casting the pouring points

13 Multiple off-shelf sand sprues were inserted in the identified pouring sources to increase pressure while casting

14 Failed cast due to early cooling of molten aluminum and its quick viscosity changes that resulted from early pressure lost and the thin pathways of the mold geometry

In prior fabrication tests, many cracks in big, slender molds were caused by a combination of factors: complex shape, the fragility of prints, and bending forces. As a countermeasure, lifting details were computationally integrated on the bottom grid to perfectly fit the lifting tools of the foundry.

These details proved to be very helpful for interlocking and safely transferring the printed molds to the de-sanding station. Also, the system with the central wells significantly reduced post-processing labor, as only a few straight cuts using standard machinery were needed after casting.

A nesting algorithm with two-axes freedom was used to place the mold geometries in the fittest position inside the print box. The nested files were sent to the foundry company with automatically generated 3D maps explaining the exact positioning inside the print box to guide the unpacking process and eliminate damage to molds during unpacking.

PROTOTYPING AND FABRICATION-AWARE DESIGN

The overall design process was co-developed with several fabrication tests to ensure a fabrication-aware design.

In order to enhance the understanding of fabrication limitations, multiple sets of small-scale casts were conducted in parallel to the design development. Prototyping was necessary to ensure the high surface quality of the elements (Figures 16, 17) and identify the castable shapes amid the prototyping phase. The latter was enhanced by the use of an infrared thermal camera with a thermal resolution of 80x60 pixels (pixel size 17 μm) and video capture 1440x1080 pixels. During every casting, the infrared camera was used to monitor the material flow inside the molds with a range of 20°C–120°C. Afterward, the fabricated elements were compared to the designed geometries, while the thermal recordings gave crucial feedback on how curvature complexity, depth of extrusion, and minimal thicknesses influenced the resulting cast. In close collaboration with the foundry company, we gradually developed in the prototyping phase a vocabulary for castable shapes, possible extrusion lengths, thinnest member sizes, and steepest castable angles.

FABRICATION AND ASSEMBLY

The final production of the facade was achieved in less than four days. All of the 28 custom molds were produced using only four print boxes, each box with a print volume of 1.8x1.0x0.7 m³. Binder Jetting technology enabled the production of molds with sand-grain surface resolution (0.28 mm) in a very short time.

The fabrication process consists of the following sequence (Figures 18-20):

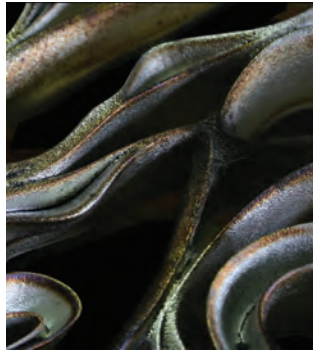
- 3D printing of the molds
- Unpacking and sand removal of printed molds



15 Mold examples generated from the custom algorithm

16 To avoid fast cooling and oxidation, the aluminum was heated over the usual temperature ($>800^{\circ}\text{C}$), which resulted in undesired surface qualities

17 As opposed to a "burnt" surface in Figure 16, this is the desired surface finish of a successful cast



16



17

- Preheating of molds to 300°C with a flame gun
- Casting of preheated liquid aluminum ($700\text{--}800^{\circ}\text{C}$) into the mold from the pouring points
- Cooling
- Removal of sand molds with mechanical force on a vibration platform
- Post processing to remove excess material in the pouring points

The printing time of each box was less than 12 hours, and unpacking the molds from the print box took approximately two hours per box. Casting itself followed the conventional procedure and could be done within minutes. The casting temperature and the type of aluminum alloy are highly relevant for a successful cast.

The solidification of the cast aluminum took less than two hours per cast element and demolding was only a few minutes of work. In comparison to a closed mold, where post-processing is extremely time-consuming (Aghaei Meibodi et al. 2018), casting with an open mold eliminated the extensive post-processing step.

FUTURE WORK

Through this case study, a number of challenges for casting facade screens were identified that opened up opportunities for further research on the following aspects:

- Integrating an advanced casting simulation to the computational model, including: analysis of speed and

temperature loss as aluminum flows through the geometry can help to identify moments of cold joints in the cast that undermine structural performance; and optimized repositioning of the pouring sources according to the mold geometry can ensure a similar temperature at points where multiple metal flows meet.

- Integrating the installation logic and the assembly sequence as part of the computational design of the cast elements; the interlocking of custom panels and connection details can reduce assembly labor and increase structural integrity.
- Informing the design input with performance and comfort-related data, such as light paths, can couple functional material densities with transparency requirements that result in cast shadows of exquisite nature.

CONCLUSION

This paper discusses a computational design and digital fabrication method for the revival of custom ornate metal elements in architectural practice. The proposed mold system offers the possibility of creating elements with a planar side and a freeform side with ease, allowing for the economical construction of geometrically complex facade panels in a short time. While ensuring high quality castings, this method demands only a small amount of parts for mold assembly, less printing material, as well as minimal post-processing and costs compared to a closed mold system. The opportunity to cost-effectively produce one-of-a-kind, customized, freeform building elements can be applied to a wide spectrum of elements. Moreover, the material chosen, aluminum, is lightweight, strong, and can be almost infinitely recycled and recast, reducing the waste of building materials.

The computational design approach enabled the automatic generation of diversified facade geometries and their required molds. This fast design-to-fabrication pipeline allowed the optimization of the digital model, based on multiple physical prototypes, to minimize casting failures and hence the costs of the mold fabrication.



18



19



20

The experimental freeform facade screen demonstrated that cast elements are strong and precise enough for applications in architecture and the building industry (Figure 21), as the production of parts through 3D printing sand molds is much faster and cheaper than current state-of-the-art mold making or direct metal printing strategies. It also showcases that the combination of the current technology (3D printing) with traditional methods (casting) can open up new possibilities for non-repetitive and aesthetically enriched metal elements in architecture.

Lastly, it should be highlighted that the production of such an amount of bespoke facade elements in less than half a week could not have been achieved using any other methods, neither direct metal printing, nor a conventional mold-making process.

ACKNOWLEDGEMENTS

The Deep Facade screen was designed and fabricated during a three-month course by the students of the 2017-18 Master of Advanced Studies in Architecture and Digital Fabrication Program (MAS DFAB) of ETH Zurich: Sahar Barzani, Fernando Cena, Georgia Chousou, Alexander Enz, Moon Young Jeong, Frank Lin, Matteo Lomaglio, Ioanna Mitropoulou, Haruna Okawa, Rafael Pastrana, Francisco Regalado, Jetana Ruangjun, Jun Su, Nizar Taha, Yao Wang, Zong-Ru Wu, and Angela Yoo.

Special thanks to Christenguss AG and DGS Druckguss-Systeme AG, fabrication partners and sponsors of this research, who made the realization of the Deep Facade project possible. Finally, special thanks to structural engineer Dr. Mario Rinke.

REFERENCES

Aghaei, Mania, Rena Giesecke, and Benjamin Dillenburger. 2018. "Digital Metal: Additive Manufacturing for Cast Metal Joints in Architecture." In First International Conference on 3D Construction Printing in Conjunction with the 6th International Conference on Innovative Production and Construction, edited by J.G. Sanjayan. Melbourne, Australia.

Aghaei Meibodi, Mania, Rena Giesecke, and Benjamin Dillenburger. 2019. "3D Printing Sand Molds for Casting Bespoke Metal Connections." In Intelligent & Informed: Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2019), Volume 1, edited by M.H. Haeusler, M.A. Schnabel, and T. Fukuda, 1:142. Wellington, New Zealand: Association for Computer-Aided Architectural Design Research in Asia (CAADRIA).

Bhavar, Valmik, Bharat Forge, and Prakash Kattire. 2014. "A Review on Powder Bed Fusion Technology of Metal Additive Manufacturing." In 4th International conference and exhibition on Additive Manufacturing Technologies. Bangalore, India.

Caldas, Luisa Gama. 2001. "An Evolution-Based Generative Design System: Using Adaptation to Shape Architectural Form." PhD diss., Massachusetts Institute of Technology.

Davey, Ali. 2009. "Shopfront Design and Construction: The Use of Iron." *Architectural Heritage* 20(1): 93-104.

Giachino, Alberto. 2017. "Differential line growth with Processing". Accessed May 17, 2019. <http://www.codeplastic.com/2017/07/22/differential-line-growth-with-processing/>.

Goldberg, David E. 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Boston, MA: Addison-Wesley Longman Publishing Co.

- 18 Unpacking of 3D printed sand molds
- 19 Heated mold with multiple pouring spots
- 20 Casting from multiple pouring points at the same time
- 21 Natural light creates a visual interplay between the different angles of the cast elements



21

Jong, Kenneth De, David B. Fogel, and Hans-Paul Schwefel. 1997. "A History of Evolutionary Computation." In *Handbook of Evolutionary Computation*, edited by T. Bäck, D.B. Fogel and Z. Michalewicz, 1-12. Oxford: Oxford University Press.

Lomas, Andy. 2014. "Cellular Forms: An Artistic Exploration of Morphogenesis." In *AISB-50*, edited by R. Kibble. London: Goldsmiths, University of London, UK.

Lynch, Paul C., Chitralekha Beniwal, and Joseph H. Wilck. 2017. "Integration of Binder Jet Additive Manufacturing Technology into the Metal Casting Industry." In *67th Annual Conference and Expo of the Institute of Industrial Engineers*, edited by H.B. Nembhard, K. Coperich, and E. Cudney, 1721-26. Pittsburg: Institute of Industrial Engineers.

Pedersen, Hans, and Karan Singh. 2006. "Organic Labyrinths and Mazes." In *4th International Symposium on Non-Photorealistic Animation and Rendering*, edited by D. DeCarlo and L. Markosian, 79-86. New York: ACM.

Pell, Ben, Andreas Hild, Sam Jacob, and Alejandro Zaera. 2010. *Modulierte Oberflächen: Ornament Und Technologie in Der Gegenwartsarchitektur*. Basel: Birkhaeuser GMBH.

IMAGE CREDITS

Figure 1,7: © DBT, Demetris Shammas, 2017.

Figure 2: © Ksenia Baranova, 2015.

Figure 3: © Michael Daddino, October 12, 2008.

Figure 4: © Steve Minor, Mach 25, 2010.

Figure 5: © Ben Pell, 2010.

Figure 8,11,13,16,17: © DBT, Jetana Ruangjun, 2017.

All other drawings and images by the authors.

Mania Aghaei Meibodi is Co-founder/lead architect of meonia and senior researcher at Digital Building Technologies, ETH Zurich. Mania has a PhD and a master's degrees in Architecture from KTH School of Architecture and Built Environment, Sweden.

Marirena Kladeftira is a PhD researcher at the chair of Digital Building Technologies, ETH Zurich where she researches additive joints for spatial lightweight structures. Her research addresses complexity in architectural components, that can be encoded into design and fabricated through additive manufacturing.

Thodoris Kyttas is an architect engineer, specialized in digital construction processes. He holds a Master of Advanced Studies in Digital Fabrication from ETH Zurich, where he later joined the chair of Digital Building Technologies. His current professional focus is on automation for Building Information Modeling.

Benjamin Dillenburger is assistant professor at the Institute of Technology in Architecture, ETH Zurich. He is leading the research group Digital Building Technologies, which investigates computational design and digital fabrication, with a focus on large-scale additive manufacturing in architecture.