ADDITIVE FORMWORK IN PRECAST CONSTRUCTION

Agent-based Methods for Fabrication-aware Modularization of Concrete Building Elements

DAVID STIELER[1], TOBIAS SCHWINN[2] and ACHIM MENGES[3]
[1,2,3]*Institute for Computational Design and Construction (ICD), University of Stuttgart, Germany*
[1]*david.stieler@icd.uni-stuttgart.de, 0000-0002-3854-0016*

Abstract. This paper presents the geometric foundations for an agent-based modeling (ABM) approach to modularize concrete building elements for prefabrication via additive formwork. The method presented extends the functionality of existing planning tools for concrete prefabrication to addresses the manufacturing characteristics of additive formwork production using fused deposition modeling (FDM), and negotiates these with the structural requirements of its underlying building geometry. First, a method to classify building components according to fabrication methods using a probabilistic feature-based Naive Bayes classifier is presented. This classification allows to automatically assign the most suitable production method to every individual building element within a given building model. Following this classification, elements identified for the production using additive formwork are modularized in an automated, agent-based process. The modularization process utilizing a voxel-representation of the initial building element geometry is described in detail. An agent-based method to simulate multiple modularization variants is presented and the integration of feedback from iterative negotiation processes between fabrication expenditures and structural behaviour outlined. The approach presented fosters material-saving construction and production processes in planning and therefore directly addresses crucial issues of the agenda for global Sustainable Development Goals (SDGs).

Keywords. Agent-based Modeling; Modularization; Prefabrication; ABM; Volumetric Modeling; Additive Formwork; SDG 9; SDG 12.

1. Introduction

In construction, twice as much concrete is used as all other building materials combined. In comparison to the amount of all materials used in general, concrete is second only to water (Gagg, 2014). While fluid concrete can take almost any shape, it needs formwork to support it during its curing process. In many cases, the cost of formwork itself can exceed the combined total cost of labour, reinforcement materials

and concrete used (Robert H., 2007). This imbalance between the cost distribution of the temporary formwork and permanent concrete structure leads to a paradoxical approach on how to design and build with concrete. To keep the construction process cheap and quick, concrete elements often follow the formal dictate of simple formwork and thereby the actual cost of built structures is reduced by using more material than needed (Jipa & Dillenburger, 2021).

For concrete construction to achieve the Global Sustainable Development Goals (SDGs) (UN, 2020), formwork plays a crucial role on two levels. On the one hand, formwork that allows for a variety of geometries enables targeted differentiation of building components and thus material savings in concrete; on the other hand, the use of recyclable materials for the production of formwork itself can avoid the disposal of building component-specific formwork. This directly addresses the goal of sustainable consumption and production. A promising fabrication method to overcome formal and thereby performative limitations imposed by traditional formwork construction is 3d printing (Han et al., 2020). While current research both in academia (Naboni & Breseghello, 2019) and practice (Roschli et al., 2020) explores the potential of 3d printed formwork (3DPF) from a formal, performative, and fabrication point of view, the integration of this fabrication method into planning processes and design to manufacturing workflows is less explored. To avoid shifting the manual labour needed to construct physical freeform formwork to digital drafting processes, the potential to automate and simulate the still-discrete steps of building modularization, formwork planning, and respective print path generation needs to be addressed. Existing Building Information Modeling (BIM) software include features that allow designers and planners to modularize planar building elements into standardized building modules of given dimension and mass (Peticila, 2017). While these features enable the modularization of standard geometries and building elements, they are unable to modularize freeform geometries. Yet, it is exactly these freeform and load-adapted geometries that have the potential to reduce material usage of concrete and offer a promising field of application for 3DPF (Jipa et al., 2018). In combination with prefabrication in a controlled environment, and, therefore error-free production, this can significantly reduce the negative impact of construction activities on the environment (Mark et al., 2021).

Within this paper, we therefore present a method that classifies building elements according to suitable fabrication method and that allows for the simulation and evaluation of modularization results early on in the design process. The method thereby extends the functionality of current planning tools for the modularization of buildings geometries for prefabrication. To integrate feedback from later fabrication stages into early design steps, we present an agent-based approach to the modularization of freeform concrete building elements. In agent-based modeling (ABM), a system is modeled from the perspective of its constituent units, where each individual agent assesses its situation and makes decisions and interacts based on a set of rules (Bonabeau, 2002). Therefore, ABM has become a popular method to model and understand complex and non-linear systems, used across a variety of disciplines whenever individuals interact with each other and their environment (Macal, 2016). Previous research investigated such behaviour-based strategies to facilitate the synthesis of computational design and fabrication aspects with regards to performative

lightweight timber plate structures (Schwinn et al., 2014) and façade elements (Gerber et al., 2017). Within the research presented in this paper, ABM is used to similarly synthesize computational design and fabrication aspects, but with a focus on fabrication-informed segmentation of non-standard concrete elements. In the model, pairs of agents represent single concrete modules following specific and adjustable behaviours to extract solid modules from hollow design input models. To make the modularization process independent of the boundary representation type of its input geometry, we present a voxel-based approach using constructive solid geometry (CSG) techniques to decompose an input design model into non-intersecting, space filling modules.

2. Method

2.1. WORKFLOW INTEGRATION

To demonstrate our approach, we use a section of an early design stage model as shown in Figure 3 (1). Within the concept of the six levels of model development (LOD) in BIM, ranging from 100 (symbolic or generic representation) to 500 (model has been validated with constructed building) (Borrmann et al., 2015), this model is situated at LOD 200. Size, dimension, form, position and orientation of elements are approximately known, what is yet to be defined is the precise modularization of building elements and semantic information regarding production, assembly and installation. Situating our classification and modularization approach early in the design process, aims to visualize and understand better the consequences of early design decisions on later production expenditures. Current formwork classifications focus on the architectural function of the element they are intended to form, e.g., a slab, a wall, a column and are thereby unable to address non-standard geometries and 3DPF as production type (Hickert & Knaack, 2016). Therefore, we propose a geometry-based classification of building elements that automates the process of assigning the most suitable production process to each building element based on its geometric features. We consider production types for three different kinds of elements (Figure 1, from left to right):

- Standard elements: Planar hollow-core elements, elements from planar shuttering tables, or cylindrical elements with standardized cross-sections.

- Combinatorial elements: One or more sides consist from printed elements (center).

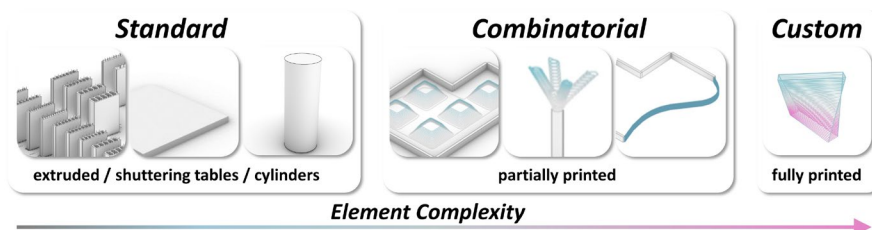- Custom elements: Formwork is fully printed.

Figure 1. Production types considered for building element classification
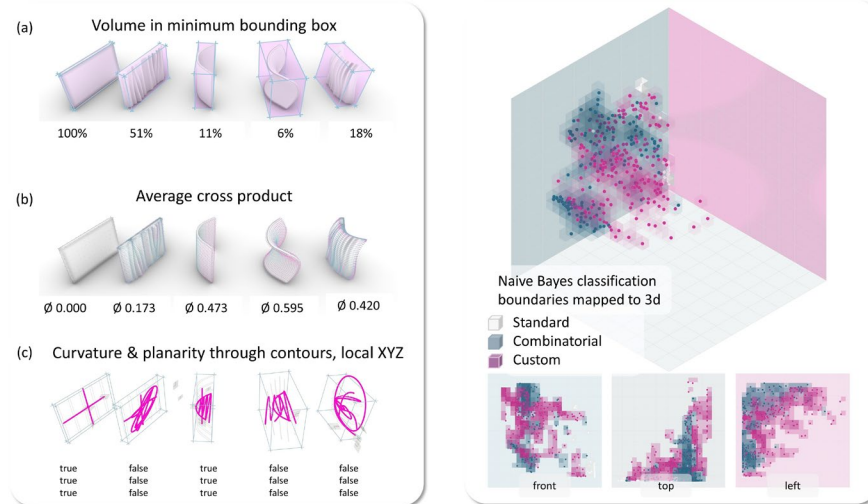
2.2. ELEMENT CLASSIFICATION

Figure 2. Feature extraction, Naive Bayes Classification and mapped decision boundaries

While an intuitive approach to classify elements to standard and custom production methods would be to measure curvature, either in mesh or NURBS geometries, this would not allow the categorization of elements to the class of combinatorial formworks, where building elements are described by a variable number of planar and non-planar sides. Here, not only curvature is a factor that impacts the choice of a suitable production method, but also the question how many sides of an object are curved, how much the deviation is from its bounding box, and if the objects cross-section is constant or not. To be able to evaluate these factors and thereby universally classify models independent of the geometry type used to model design inputs, we use a retopologized mesh representation of each respective input model. The following three features shown in Figure 2 (left) are used to numerically describe the properties mentioned above and form the basis for the probabilistic classification utilizing a Naive Bayes Classifier (Claster, 2015):

- (a) Ratio between the volume of the input model and its minimum bounding box (MBB) volume as an indicator for object planarity and variations in cross section.

- (b) Average of the cross product of all face normals to the local coordinate system derived from the building element's MBB X, Y, or Z vector, measuring the vector which is closest in direction. This serves as an indicator for surface texture and relief-like structures.

- (c) Contours are extracted from the input model in MBB X,Y, and Z directions. The center points of contours for each direction are interpolated with a curve. Planarity of the resulting curves serve as a rough indicator for the overall element curvature.
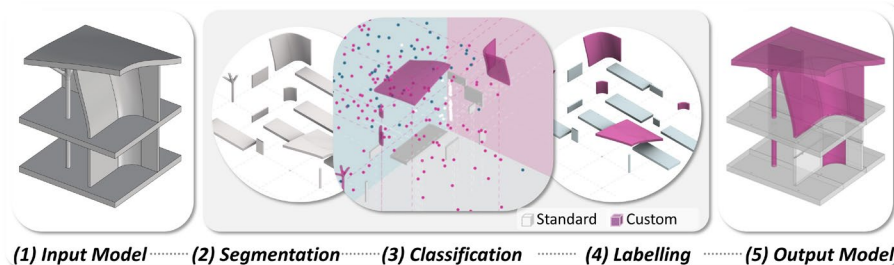
(1) Input Model ········· *(2) Segmentation* ········· *(3) Classification* ········· *(4) Labelling* ········· *(5) Output Model*

Figure 3. Classification applied to sample model

The Naive Bayes classifier is an efficient approach to calculate class probabilities given a set of features (Sammut & Webb, 2017). Figure 2 (right) shows the distribution of data points from 500 manually labelled input geometries that served as training data for this supervised classification. The labelled input data is used to make a prediction about the likelihood of any new, unlabelled building element being a member of one of the categories shown in Figure 1. Figure 3 shows the integration of the classifier into the modularization workflow starting from the input design model (1), applying the modularization possible in given BIM software (2), classifying the resulting elements (3), and transferring the production information back into the initial model (5). The output model in Figure 3 (5) serves as the basis for the modularization of non-standard building geometries.
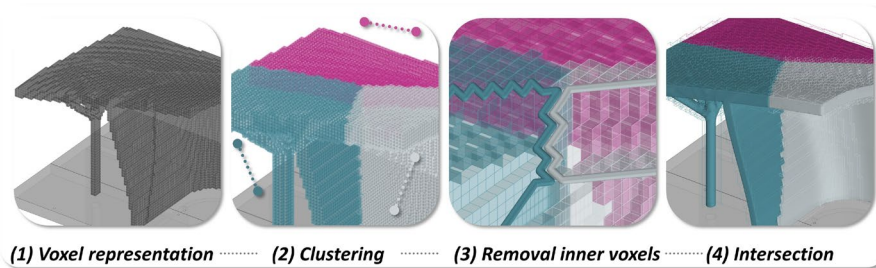
2.3. VOXEL BASED MODULARIZATION

(1) Voxel representation ········· *(2) Clustering* ········· *(3) Removal inner voxels* ········· *(4) Intersection*

Figure 4. The use of voxel clusters as input independent cutting proxies to define modules

In the next step, building elements identified suitable for 3DPF are prepared for further modularization. Previous research highlights the strength of quadrilateral meshes to rationalize freeforms to be built from planar elements (Pottmann, 2013). However, the modularization of freeform concrete elements without altering the surface of the initial design geometry requires a different geometric approach. This approach should be able to create solid, space-filling, non-intersecting geometries from hollow design models, regardless of input geometry type and form.

Therefore, we propose a geometric approach that relies on a voxel representation of the initial design geometry, where voxel clusters serve as proxy geometries to

generate cutting elements and subsequently extract modules from the input geometry. Figure 4 shows the voxel representation of the building elements identified for 3DFP (1), three voxel clusters formed by grouping the closest voxels based on the distance to three randomly distributed lines (2), the hollow representation of the clusters (3), and the resulting element geometry after intersecting the voxel clusters with the initial building geometry (4). For preview purposes, the voxel resolution at this step is kept low, which leads to jagged module interfaces, in the following section voxel resolution is increased.

2.4. MODEL DESCRIPTION AND SIMULATION

The goal of this simulation approach is the evaluation of multiple modularization variants and the negotiation of fabrication expenditures, structural impact of modularization, and the adherence to a certain size of resulting modules. The computational foundation for this model is formed by the ABM framework developed at the Institute for Computational Design and Construction (ICD) at the University of Stuttgart (Groenewolt et al., 2018). While the process of clustering voxels and their intersection with the input geometry forms the geometric basis for modularization, locomotion behaviour mechanisms as described by Reynolds (Reynolds, 1999) form the conceptual basis for simulating different modularization variants and their evaluation.
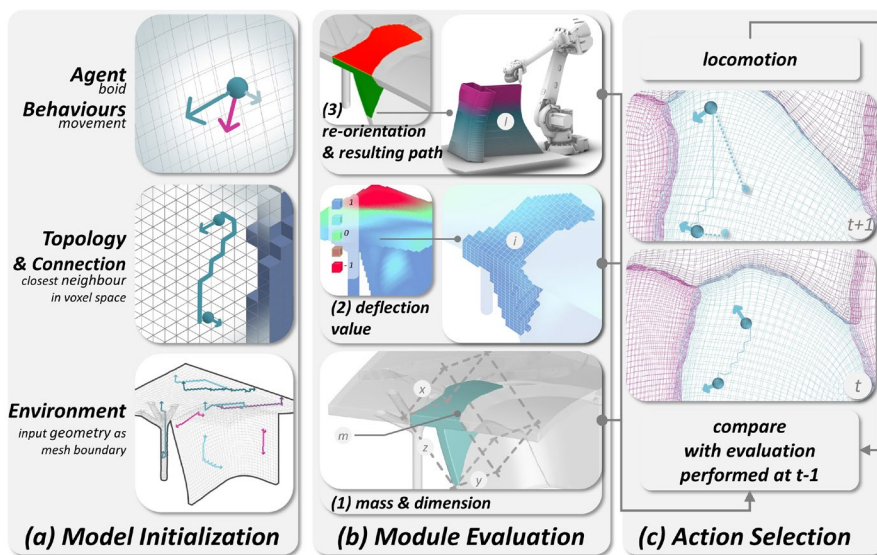

Figure 5. Model constituents, module evaluation and action selection

The initial model by Reynolds was built to simulate the flocking behaviour of birds in computer graphics. Reynolds decomposes the task of constructing motion behaviours into a three level hierarchy of: Action selection, steering, and locomotion. Here, actions are mainly based on distances between single individual agents. Therefore, in the context of modularization, we augment the layer of action selection with information about the current state of the concrete module each agent is associated

with:

- Action selection: Agents observe the state of the module they are associated with and perceive changes in module mass, dimension, deflection value, and resulting print path length for the module's formwork. These perceptions form the basis for the respective goal selection.

- Steering: Goals selected from the previous step are coordinated with the agents' internal rules and translated to steering signals.

- Locomotion: steering signals are converted into motion parameters.

Figure 5 shows the model constituents (a), the analysis for one module at a given timestep (b), and a zoom in on two consecutive iterations with resulting agent positions, locomotion vectors, their connection in voxel space, and resulting module boundaries (c). The initial state of the model at t = 0 starts from the distribution of a given number of agents from random starting points within the given geometry that serves as environment for the agents to move in. At initialization, for each agent its nearest neighbouring agent in voxel space is found. Their connecting graph within the voxel space functions as reference curve to measure voxel distances to. Voxel clusters are formed by the closest distance from voxel position to connecting graph. By using voxel space, not euclidean distances, it is ensured that for each agent pairing, exactly one module, and not multiple, can be created. From this initialization step, the first modularization variants are evaluated and the following parameters stored in the action selection layer:

- (1) Mass & dimension: Mass is directly derived from each modules volume, dimension considers the longest side of each module's MBB.

- (2) Deflection value: Derived from a deflection analysis of the unsegmented input model. Deflection values are stored in the voxels forming the clusters and the average value considered for each module's deflection value at every timestep.

- (3) Print path length: Due to fabrication constraints of FDM, modules are automatically oriented to reduce surface areas with overhangs larger than 45 degrees. For areas over 45 degrees, print supports are generated and the additional material needed is considered in the module evaluation.

Instead of studying the dynamic movement of swarms, we seek to achieve a dynamic equilibrium, meaning that no agents are moving once all set requirements are met and the model converges to a steady-state. Behaviours described by Reynolds include cohesion and separation which can be used to create an even distribution of agents in their environment. While an even distribution in size is desirable, the control over size to stay within a given domain should be ensured. Therefore, the larger the module size, the larger the attraction force between two agents composing one module, resulting in smaller module sizes. Conversely, with decreasing module size, separation force between agent pairings helps to keep spacing consistent. Figure 5 shows the resulting locomotion vectors for different timesteps (right). While the behaviour affecting module size is directly influenced by the steering directions resulting from agent positions, the behaviours affecting deflection value and print path length rely on a metaheuristic approach, meaning a comparison of each module's evaluation from

previous timesteps and their current state. Locomotion direction is stored and results from the evaluation at timestep t-1 is compared with evaluation at timestep t. An improvement, meaning less print path or a lower deflection value, results in no modification of the steering vector. If the values deteriorate, the direction is adjusted to steer towards the last position with better values. Conceptually, this approach is known from particle swarm optimization (PSO), which is used to search for a solution to an optimization problem by iteratively moving a population of candidate solutions through a search space (Eberhart & Sixth, 1997). The final locomotion vector results from the addition of cohesion and separation behaviours amongst all neighbouring agents, the directed cohesion between agent pairings, and the memory-based approach to steer towards previous positions. On the system level, this allows for the observation of multiple modularization variants, their effect on fabrication expenditures and their influence on structural behaviour.

Figure 6 shows the modularization of the non-standard area within the initial building design model (a), the oriented modules to reduce overhangs (b), and respective information for each resulting module (c).
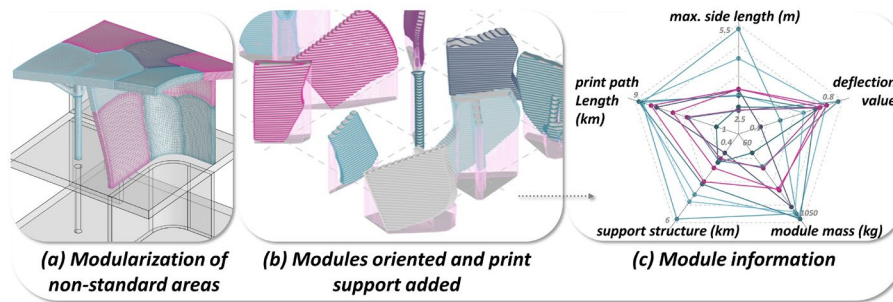

(a) Modularization of non-standard areas   **(b) Modules oriented and print support added**   **(c) Module information**

Figure 6. Non-standard modules within the initial building geometry, resulting modules oriented for printing, and module information

3. Discussion, Limitations, Outlook

Within this paper, we presented an automated workflow to identify building elements where 3DPF is applicable. We demonstrated the decomposition of hollow input models into solid, space-filling modules using voxels as proxy geometry and embedded this geometric approach into an agent-based model.

Since it is a common goal to reduce overhangs in 3d printing processes (Luo et al., 2012), the model presented could also be used to modularize geometries for concrete 3d printing. While this universality of the presented method presents an addition to planning tools also for other production processes, some main aspects of formwork planning remain unaddressed at this stage. So far, formwork is conceived as a monolithic shell around building modules. Some research has shown the successful demoulding of thin monolithic formwork (Burger et al, 2019), However, this is the exception rather than the rule. Therefore as the next step, formwork segmentation, the connection of single formwork elements, and general demouldability of building elements need to be addressed.

The voxel-based segmentation approach is in itself independent from the constituents of the input design model. In the research presented, the voxel structure was also used to transport analysis results from an initial deflection analysis performed on the input model to resulting modules. For now, this deflection value is simply mapped to a domain between 1, largest deflection detected, to -1, least deflection detected. Values from the input mesh are stored in each voxel based on spatial proximity and serve as indicator for expected stresses on module interfaces. While we demonstrate the transfer, storage, and analysis of values obtained from an input model to resulting modules, the analysis itself needs further refinement to adequately inform position and design of module interfaces and the requirements for connecting elements. So far, the design of module interfaces is not addressed. However, module interfaces can clearly be identified in voxel space, and therefore the voxel unit could potentially be beneficial in locally defining variable interfaces between modules. To test connections and interfaces and consider production tolerances in the modularization process, physical prototypes directly resulting from the proposed approach are part of ongoing research.

3DPF offers the potential to combine the efficiency of prefabrication with the formal freedom and performance of freeform concrete structures. This research presents a modularization approach to address the vast field of geometric solutions enabled by 3DPF, therefore addressing planning methods that show a possible path for concrete construction to meet the SDGs. On the simulation level, the approach allows for further refinement of agent behaviours to better understand the effects different modularization variants have on the building system level. By automating the steps necessary for modularization, this research seeks to make freeform modularization more accessible and thereby widening the design space of prefabricated concrete.

Acknowledgements

References

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(SUPPL. 3), 7280–7287.

Borrmann, A., Koch, C., König, M., Beetz, J. (2015), *Foundations & Practice in Building Information Modeling*.

Claster, W. B. (2015). Naïve Bayes classifier. *In Data Mining Algorithms* (pp. 118–133). John Wiley & Sons, Ltd.

Eberhart, R., & Sixth, J. K. (1997). A new optimizer using particle swarm theory. In: *Proceedings of the IEEE Symposium on Micro Machine and Human Science*, Nagoys, Japan, 39–43.

Gagg, C. R. (2014). Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Engineering Failure Analysis*, 40, 114–140. https://doi.org/10.1016/j.engfailanal.2014.02.004

Gerber, D. J., Pantazis, E., & Wang, A. (2017). A multi-agent approach for performance based architecture. *Automation in Construction*, 76, 45–58. https://doi.org/10.1016/j.autcon.2017.01.001

Groenewolt, A., Schwinn, T., Nguyen, L., & Menges, A. (2018). An interactive agent-based framework for materialization-informed architectural design. *Swarm Intelligence*, 12(2), 155–186. https://doi.org/10.1007/s11721-017-0151-8

Han, D., Yin, H., Qu, M., Zhu, J., & Wickes, A. (2020). Technical Analysis and Comparison of Formwork-Making Methods for Customized Prefabricated Buildings: 3D Printing and Conventional Methods. *Journal of Architectural Engineering*

Hickert, S., & Knaack, U. (2016). Evaluation of free-form concrete architecture, moulding systems and their technical potentials. *Journal of Facade Design and Engineering*, 3(3–4), 273–288.

J. Burger, E. Lloret-Fritschi, F. Scotto, T. Demoulin, L. Gebhard, J. Mata-Falcón, F. Gramazio, M. Kohler, R.J. Flatt. (2019). Eggshell: Ultra-thin 3D Printed Formwork for Concrete Structures. *3D Printing and Additive Manufacturing*. https://doi.org/10.1089/3dp.2019.0197

Jipa, A., Aghaei Meibodi, M., Giesecke, R., Shammas, D., Leschok, M., Bernhard, M., & Dillenburger, B. (2018). 3D-Printed Formwork for Prefabricated Concrete Slabs. *1st International Conference on 3DCP, 2018*. https://doi.org/10.13140/RG.2.2.26722.89280

Jipa, A., & Dillenburger, B. (2021). 3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications. *3D Printing and Additive Manufacturing*. https://doi.org/10.1089/3dp.2021.0024

Luo, L., Baran, I., Rusinkiewicz, S., & Matusik, W. (2012). Chopper: Partitioning models into 3D-printable parts. *ACM Transactions on Graphics*, 31(6). https://doi.org/10.1145/2366145.2366148

Macal, C. M. (2016). Everything you need to know about agent-based modelling and simulation. *Journal of Simulation*, 10(2), 144–156. https://doi.org/10.1057/jos.2016.7

Mark, Peter and Lanza, Gisela and Lordick, Daniel and Albers, Albert and König, Markus and Borrmann, Andre and Stempniewski, Lothar and Forman, Patrick and Frey, Alex Maximilian and Renz, Robert and Manny, Agemar (2021). Vom Handwerk zur individualisierten Serienfertigung. Bautechnik. https://doi.org/10.1002/bate.202000110.

Naboni, R., & Breseghello, L. (2019). Additive Formwork for Concrete Shell. *IASS Annual Symposium – Structural Membranes 2019*.

Peticila, D. (2017). *Structural Precast for Revit – Fast and Accurate Modeling in a Single BIM Model*.

Pottmann, H. (2013). Architectural Geometry and Fabrication-Aware Design. *Nexus Network Journal*, 15(2), 195–208.

Reynolds, C. W. (1999). Steering Behaviors For Autonomous Characters. *Proceedings of Game Developers Conference*, 763–782.

Robert H. (2007). Think formwork – reduce costs. Structure Mag., April, 14.

Roschli, A., Post, B. K., Chesser, P. C., Sallas, M., Love, L. J., & Gaul, K. T. (2020). Precast concrete molds fabricated with BAAM. *Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium, SFF 2018*, 568–579.

Sammut, C., & Webb, G. I. (Eds.). (2017). *Encyclopedia of Machine Learning and Data Mining (2nd ed.)*. Springer.

Schwinn, T., Krieg, O. D., & Menges, A. (2014). Behavioral Strategies: Synthesizing design computation and robotic fabrication of lightweight timber plate structures. *Proceedings of the 34th ACADIA*, 177–188. http://cumincad.scix.net/cgi-bin/works/Show?acadia14_177

UN (2020). *The Sustainable Development Goals Report 2020* (pp.48-49). ISSN: 2518-3915