CFab1 – Fabricating Complex Intersections on Planar Materials

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Abstract

Producing freeform structures on an architectural scale based on curvilinear geometry, constraints of manufacturing limitations are pushed in two ways. First, exploring new means of (mass-) fabricating curved components, and second, developing constructions that translate curved geometry to planar members. Whereas the development of curved components remains a topic for material and production engineers, developing algorithms for the use of simple sheet materials can be resolved using the programming interfaces available in contemporary CAD software. The fabrication tool, CFab1, developed in the laboratories of the Vienna Arsenal, is facilitating a construction method driven by the ambition to process complex geometrical models to be executed with simple (clandestine) sheet and planar materials and so facilitate the design of freeform structures in low-tech manufacturing settings.

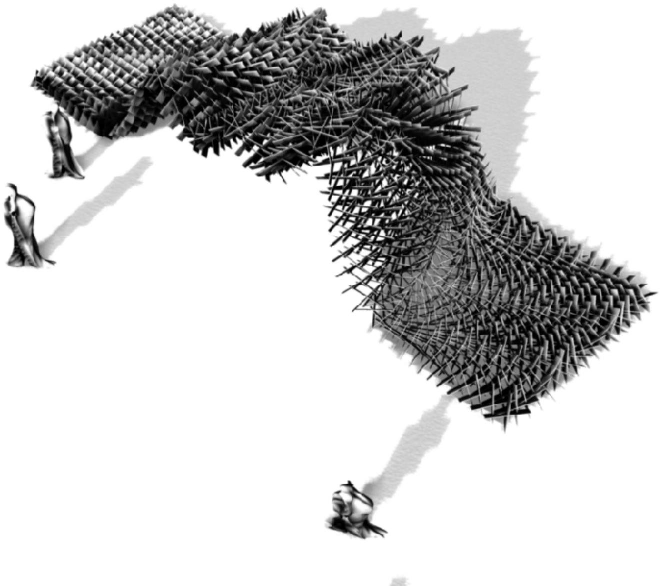


Figure 1. A structure of 2,340 interlocking members. The ambition to execute this design triggered the development of CFab1. Specifications of the tool were tailored to meet the needs of this structure.

1 Introduction

The content of this paper is intended to work on three levels: first, to transmit the experiences and insights gained in the process of assembling a comprehensive fabrication tool, expanding it from a simple routine to a system of automated detailing, second to elaborate on the functionality and purpose of the tool itself, and third to postulate the relevance of fabrication tools in contemporary architectural practice.

Working towards the realization of an architectural vision, an urban form with proliferating free-form structures and complex forms, currently one bottleneck in executing such designs can be diagnosed on the border of modeling and fabrication. Whereas contemporary design tools make the design of non-rational, asymmetric, aperiodic forms relatively simple, such designs mostly generate great challenges to production and are more often than not abandoned due to the costs generated by inadequate production processes. The initial research question that led to the development of CFab1 was, if there could be a method to link the design of complex form to simple, market available production technology by means of using computational intelligence.

2 Setup and tool specifications

Scanning contemporary means of production, it became apparent, that the vast majority of all production process in building practice involved planar materials (including formwork for concrete structures, insulation panels etc.) is formatted by means of cutting. A multitude of cutting machines and tools absolve the main act: From circular saws to foam-cutters to plasma-, water- and laser cutters.

Focusing the investigation on a cost efficient use of CNC cutting machines, in experiments with 3 axis routers it turned out that constraining to a production technique limited to vertical cuts and simultaneously maintaining a high diversity of the cut pieces leads to an optimum in design liberty and production effectiveness. Further supporting the setup, it became evident that the majority of standard cutting devices are either limited to exclusively deliver non-skewed cuts, orthogonal to the materials' main surface or the tilting of the cutting angle would substantially impede the velocity of progress. On the same token the question towards non CNC-production means, involving manual operation of low-tech machinery was raised, in the quest to facilitate the production of complex structures in reduced clandestine production environments.

CFab1 was developed on the premise to explore the intelligent use of cutting technology and to resolve a type of structure that is entirely made of planar materials and in the same instance intersections of the members could be resolved to act as connection details.

In order to manufacture designs comprising of intersecting and interlocking prismatic elements such as panels, blocks or sheets, two major steps have to be absolved. First, to design the details of the piece intersections, and second, to produce adequate fabrication documents for manual or CNC equipped production processes. Only through the automation of these steps can the design of irregular structures with a larger number of such members become economically feasible. Thus constraining to fabrication through cuts perpendicular to the material plane, increases fabrication efficiency and expands the palette of available means of production.

Figure 2. Prototype of 8 pieces, right: assembly vectors on 3D model, left: cut model

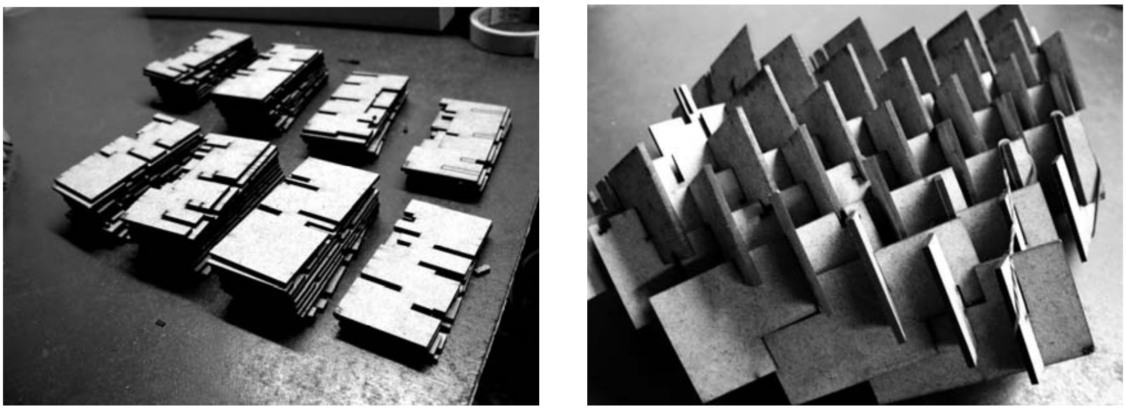


Figure 3. A prototype of 68 pieces, 3mm panels laser-cut, before and after assembly.

Project:	CFab1
Category:	Fabrication tool
Purpose:	Detailing of intersection geometry and generation of fabrication documents of constructions consisting of intersecting planar or sheet material of different material thicknesses by means of cuts orthogonal to the material's main surface.
Prerequisite:	Surface model of neutral planes of the pieces, object layer set to material thickness
Environment:	McNeel Rhinoceros 4
Language:	Rhino VB script

3 Working in large numbers

Whereas the logic of CFab1 is fairly simple and was developed at a fast pace, the initial specification of the tool was to be able to provide construction plans for a structure of 2.340 pieces. Constantly increasing the number of pieces per model, a wide range of new challenges emerged due to the increased intensity of the 3D geometry model impairing the possibility of manual adjustments but also as logistical considerations became more relevant.

First of which regards the order of surface pieces. The test structure of 2340 pieces built in a scale of 1:5 takes 36 sheets of plywood of 80x40 cm, the size of a laser-cutter bed. In a worst case, two adjoining pieces are located on the first and last cut panel, halting the assembly process until all pieces have been fabricated. A sorting operation module was installed guaranteeing proximity of structure pieces on the cut plan. Having assembled the first prototypes, the lesson learned on the logic of plug-and-socket structures was that with increasing number of interlocks the order of assembly becomes increasingly rigid. To master the labor of mounting the pieces, a precise diagram plan had to be extracted from each project, leading to the automated generation of assembly plans. In iterative processes optimizations to the model imply changes. Working in large numbers this means to depart from manual manipulations in favor of an associative model, where relations between pieces are stored as additional data. Subsequently, as detailing the joints of pieces naturally implies bringing two pieces in relation in one another, altering the detail geometry of piece 1 results in a necessary adjustment of a joining piece 2. Further live association needs to be maintained between the three dimensional model of the structure’s geometry and the two dimensional cut plan spread, whereby due to the density of information on the 3D geometry model, only on the 2D spread can be used to evaluate the initial results taking decisions on further optimization. In order to trace back and to facilitate updates in the project, a full reporting scheme has been implemented using external tables, recording object handles, the methods applied per intersection, and data relevant for assembly.

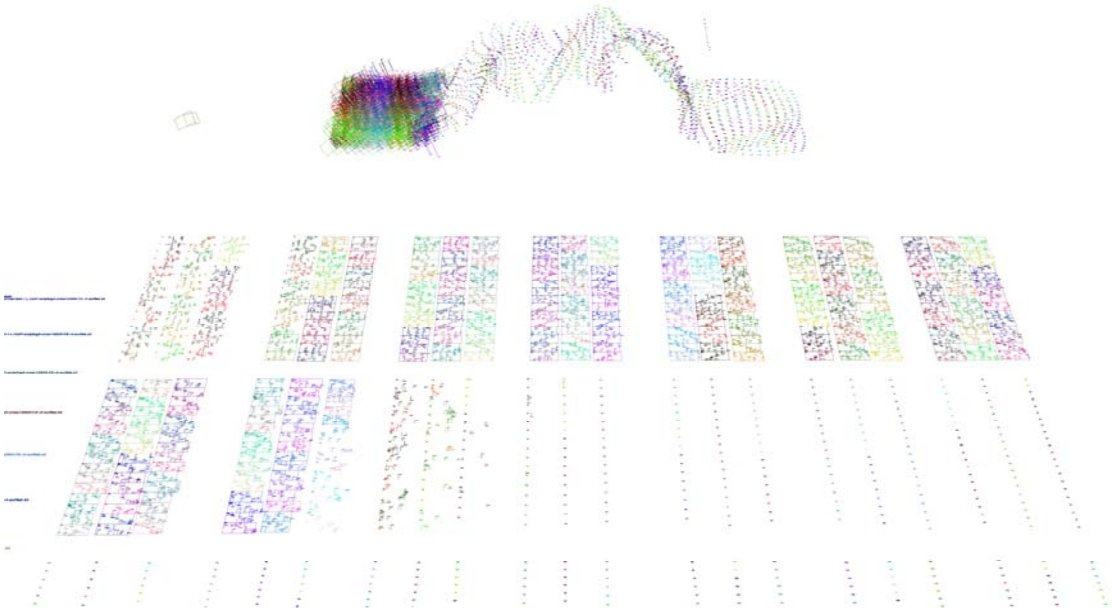
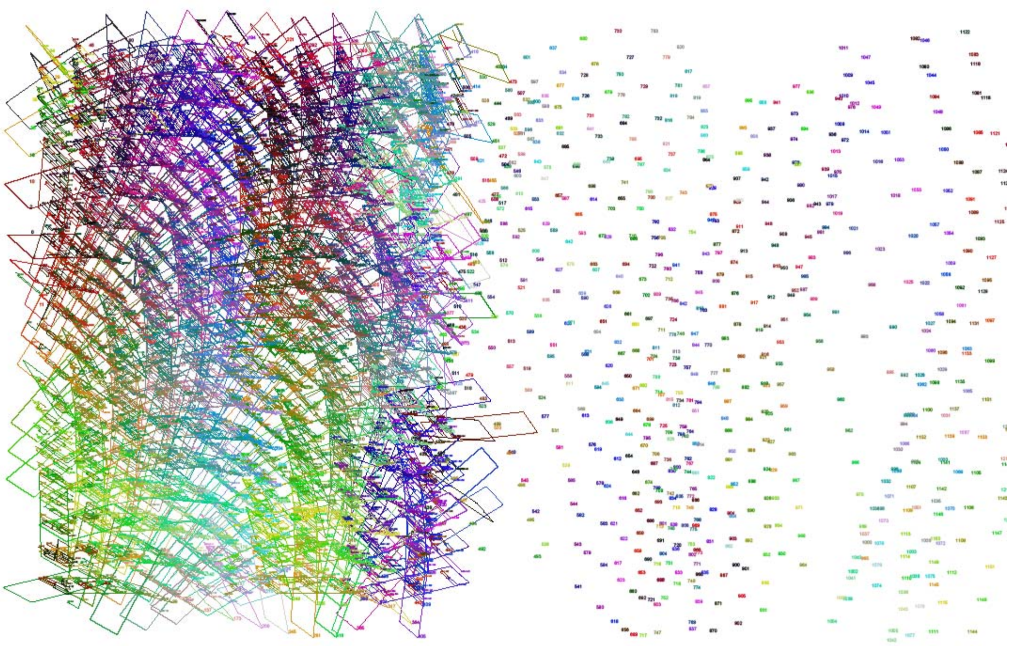


Figure 4. Progress of detailing a structure of 2340 members. Top: 3D surface model and cut file overview, bottom: detail of 3D model.



4 Resolving complexity – techniques and modules used in CFab1

Use of rhinoceros as a tool environment – CFab1 is nested entirely in the rhinoceros 4.0 environment and is programmed using the VB interface in rhino script. Using rhino script bears different scripting methods. Main philosophy in the development of the tool was to give preference to logical operations over object operations, avoiding direct object manipulation. This at first has proved useful in increasing productivity, as vector operations are absolved comparably in a faster pace, but also provides for a relative autonomy of the tool, not being dependent on rhino specific object handling algorithms, allowing for translating the tool to other design platforms. For the survey of internal processes a debug mode was implemented for each module consisting of the display of the operations in form of construction geometry.

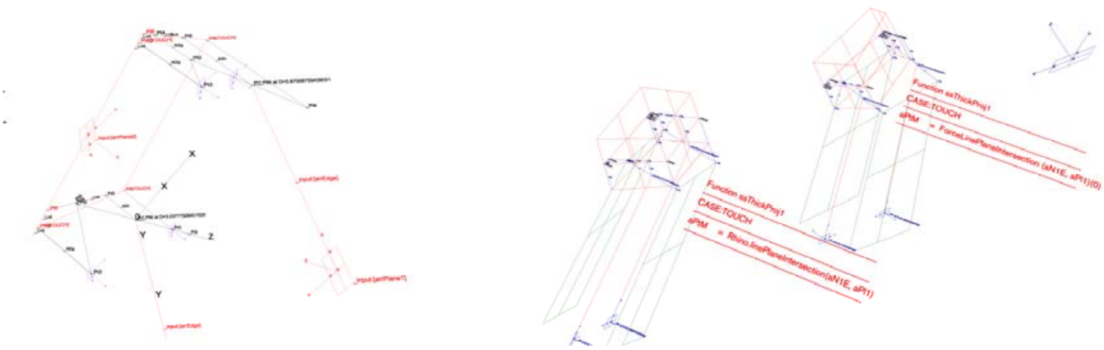


Figure 5. left: *thicknessProject* algorithm construction geometry, right: intersection evaluation extruding resulting geometry to material width.

CFab1 consists of a core of quasi-syntactic geometrical operations: intersections, projections etc., around which a substantial semantic level has been implemented. In the process, the semantic modules analyze and classify a series of events and intersection types and prescribe the appropriate detailing method. Treating two intersecting planar pieces not only as pure geometry, but also taking constructive and design considerations into account, such as the logic of assembly, the minimization of material loss and the avoiding of critical sections, has turned the development into an iterative process, as some of these parameters at cases can stand in opposition to each other. The operations of the semantic modules were informed by results obtained from built prototypes and adjusted.

Converging to satisfactory results, what has become apparent is that the contradictions in the governing parameters can only be resolved entirely through an unproportional investment of means. Especially when working with a large amount of pieces a small percentage of interpretation mistakes needed to be taken into account. Forming the pragmatic layer, the designer operator needs to remain as an auditing instance of the result. Whereby tweaking the tool has at times has to be accompanied by tweaking the design itself. Maintaining sufficient ways to observe and manipulate the project led to the development of a variety of distinct views on the project model.

The core algorithm of CFab1 labeled *thicknessProject*, is a generic operation comparable to standard geometry operations such as *project* or *offset*. Here mapping the intersecting volume of two planar members onto the material planes of each piece under the condition of maintaining edge surfaces orthogonal to the respective material planes. Slit widths and contours are generated in the way that planar piece 2 can slide into planar piece 1 and vice versa under the angle originally set out in the model. The algorithm allows the detailing of plug-and-socket joints of two intersecting pieces of distinct material thicknesses. *thicknessProject* delivers the intersection domain on both pieces. The intersection domain then is further processed by a semantic level, controlling the distribution of the common overlap volume to the respective pieces and delivering the cut detailing of the intersection. In the course of analyzing and classifying the different conditions under which two planar pieces can interlock, five distinct detailing methods involving the articulation of plug-and-socket details have been developed and assigned to the collision events.

4.1 Techniques

OHOP – Overhang: The intersection domain is symmetrically distributed, a plane perpendicular to both material planes is introduced at the overlap center and forms the saddle surface, on which both pieces join firmly. The detailing is derived from the technique of cutting a slit from the material edge halfway into each material. Pieces can be slid into each other in direction of the plane-plane intersection axis (PPIa).

OHSC – Overhang short closed: A derivate of OHOP, the overlap domain is halved by the saddle plane, slits do not extend until surface edge, but enclose the other member's intersection edge. Pieces can be slid into each other perpendicular to the PPIa.

INTR – Intrusion: Flap and hole: the intruded material piece receives a hole, the intruding material two flaps are carved into. The pieces join on 2 saddle planes and slide into each other perpendicular to PPIa

MTTH – Multiteeth: an array of saddle planes is introduced; both materials receive a toothed detail either along the edge or inside the surface area. Pieces slide laterally, perpendicular to PPIa. Teeth of at least one piece need to be edge adjacent and open.

PARL – Parallel and Lowangle: whereas in case of two members parallel no PPIa can be determined, in case of low angle collisions PPIa can take odd directions. Here the intersection is resolved without the use of saddle planes. The intersection domain is distributed to each pieces minimizing material loss.

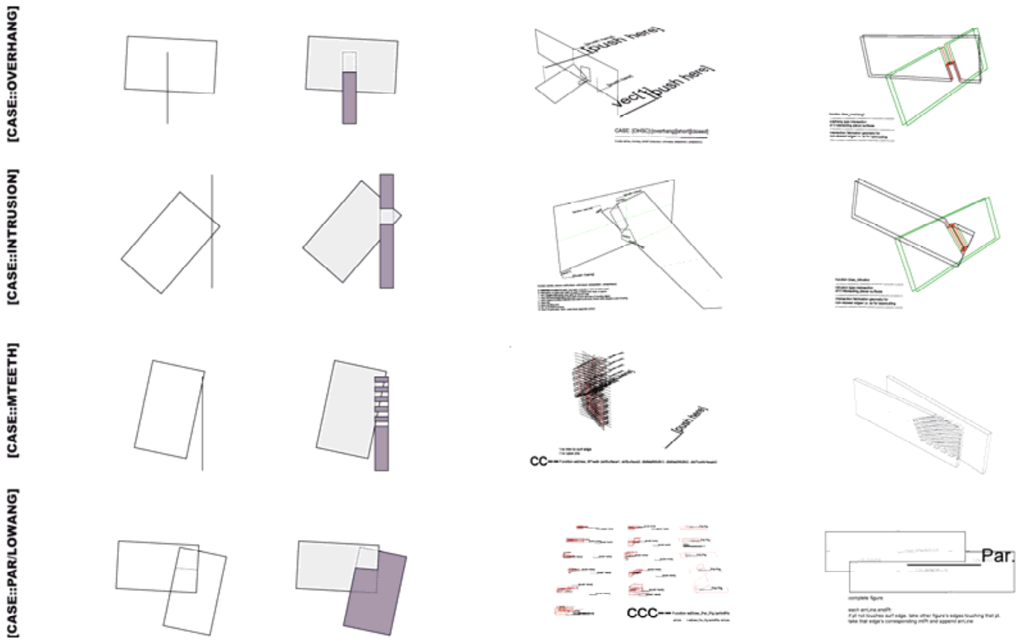


Figure 6. Intersection detail techniques

4.2 Modules

Analytic Module – Accounting for a variety of collision events, in the analytic module a range of detection operations is condensed. Distinguishing between full intersection and touch type intersection, detecting intrusion type event, in which not one edge of piece 1 is intersected by the piece 2, and reporting the angle under which two pieces intersect constitute the most prominent influencing parameters leading to the prescription of a detailing method.

Draw Modules – Clear distinction between modules authorized to alter model geometry and unauthorized, essentially logical modules is necessary to maintain control over the entire tool. All changes need to be tracked back, similar to a quality management system. Draw modules carry the core detailing algorithms and report on conditions and resulting drawing/deletion interventions. Each draw module operates for a pair of surfaces and delivers resulting geometry projected respectively onto the poly-surfaces representing a piece. The kernel module *thicknessProject* delivers the domain, within which detailing will be inserted. The *toothing* module places saddle planes perpendicular to both surface planes. Cut edges of two pieces coincide on a saddle plane, when put in position the pieces join firmly on the saddle edge surfaces. Further draw modules are devised for detailing *overhang*, *intrusion*, *multiteeth* and *parallel* intersection situations.

Optimize Module – Each intersection event is treated independently leading in case of multiple intersections and overlapping intersection domains on one piece to a redundancy in the cut plan in form of overlapping slit contours. To reduce cut paths to the resulting outline of a detailed piece, the optimize module uses a turtle logic algorithm to generate a streamlined continuous cut path per piece. In the practice of working with a laser cutter, this reduces machine time up to 35%.

Visualize Module – In detailing mode at no times the entire volume of a piece is rendered visible. Detailing work is conducted with reduced representations and numeric values. To facilitate means of visual evaluation of the result, the visualize module generates models of the pieces in a project as watertight volumes. These volumes can then be submitted to visual control by rendering or producing rapid prototyping models.

Assembly-plan Module – The puzzle-like structures have an inherent logic of order in assembly. Taking this into account, the order of assembly is closely monitored, recording the sliding vectors, under which two pieces can be mounted. Contradictory assembly vectors result in dead-locking constructions and need to be resolved. Understanding that similarly oriented vectors prescribe a predecessor-successor relationship, assembly plans in form of flow-charts are generated for accomplished projects.

Surface-sort Module – In an effort to increase productivity, proximity of intersecting pieces on the final cut plan allow for the temporal overlap of fabrication and assembly. The production order needs to follow an emerging assembly order, more so with increasing piece count.

Query and Update Modules – Detail generation is an automated process which runs autonomously for a theoretically infinite number of construction pieces. At the end of a detail-run, the logical integrity of a structure might include inconsistencies, due to arising critical sections or impasses in assembly, requiring the optimization of certain joint details. To prepare for selective adjustments after the main detail-run, the tool has been equipped with pre-scripted query modules leaning onto the logic of querying relational databases with SQL tools. I.e. to rework all *intrusion*-type intersections as *closed overhang*, or to highlight all pieces that have a critical section below a given minimum.

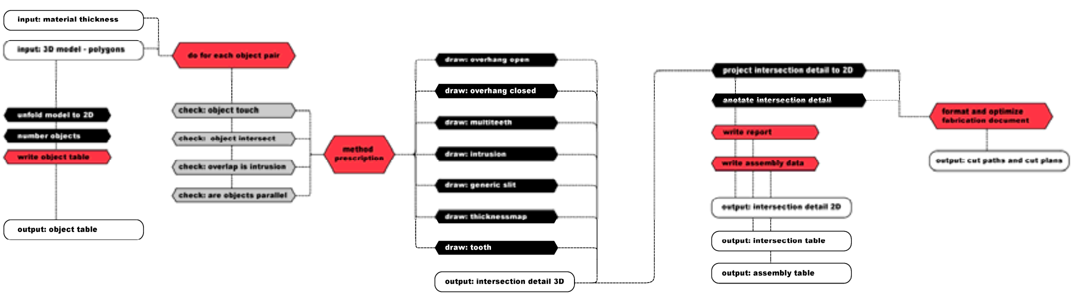


Figure 7. CFab1 – interoperation of the modules within the fabrication tool

5 CFab1 - Modus operandi

Input – The tool operates using planar poly surfaces marking the neutral centre plane of a material piece. Material thicknesses are assigned using object layers. Detailing projects can be done in separate batches, by creating a new project or resuming or updating existing detailing projects.

Output – Main output is a two-dimensional cut plan. Pieces are numbered, each intersection is annotated automatically. Further an assembly plan in form of a flow diagram is generated for completed projects. Both output parts are drawn directly in the model file. Due to the need of working with a large number of intersecting pieces, each intersection event is duplicated in the double-check matrix allowing for a visual revision. External tables as ASCII report files are populated, recording intersection geometry curve handles, material thicknesses, intersection methods. Direct manipulation of these tables is supported for optimization purposes.

Geometrical representational conventions – Detailing of a piece takes place in form of a) introducing slits and cuts into the contour line of the piece and b) introducing polygonal holes within the domain of the piece surface. Searching to simplify representation of the members in the working model, a logical duplicate was given preference over a full descriptive replica. Since the tool is geared to expose the pieces to cuts orthogonal to the surface plane, these are reduced to planar surface representatives. Details are carried through as two-dimensional line geometry. Only for the purpose of visual evaluation of the resulting detailing the pieces are re-extruded to 3 dimensional solids.

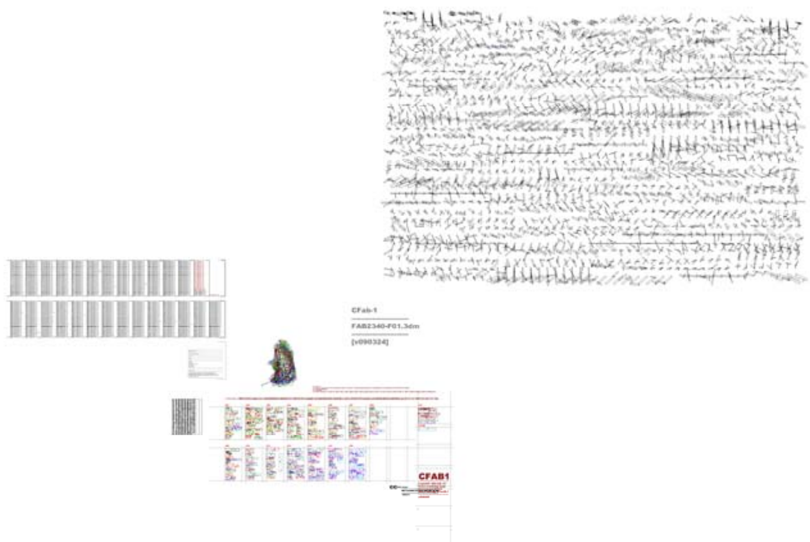


Figure 8. Overview of the model zone of a structure of 330 members. Top left: report log, top right: double-check matrix, center: 3D model, bottom section: cut plan spread.

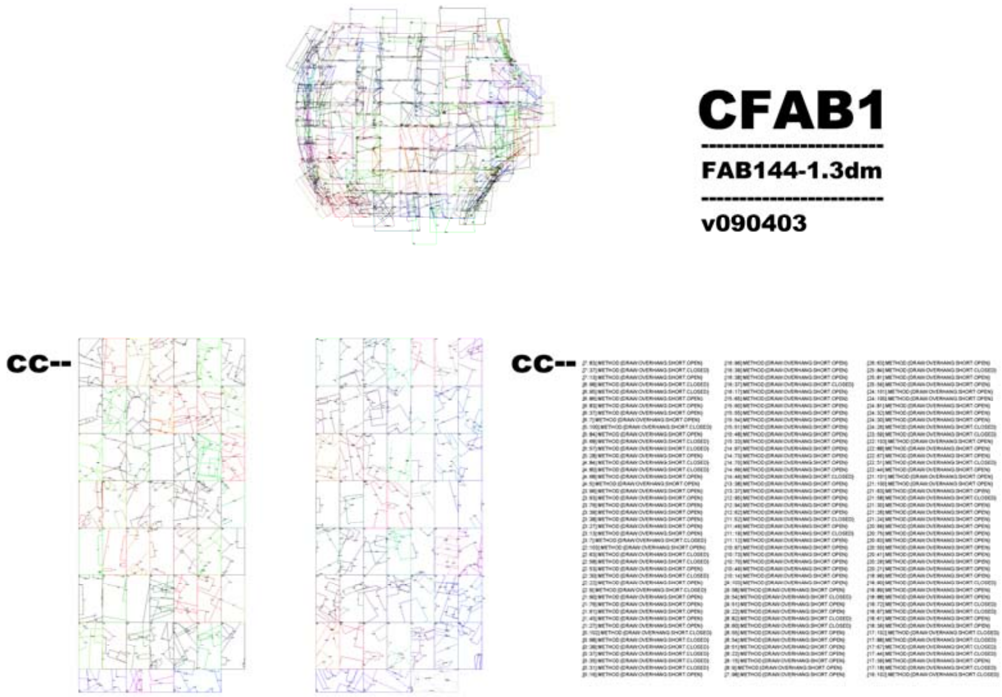


Figure 9. Detail of the model zone of a structure of 104 members. Top: 3D geometry model, bottom left: cut file spread, bottom right: report log.

The model space – Model space within the CAD environment is vesting distinct operational zones. Data is stored in the drawing file and in external tables. Conceptual views from different angles into the structure of the project are organized in the CAD environment into zones:

1. *Workbench* contains the 3D surface model.

2. *Double-check matrix* contains a spread of each intersection event for visual revision.

3. *Report log* is recording method applied for each intersection event.

4. *Assembly diagram* is a 3D flowchart containing the order of assembly organized in predecessor-successor relationships per interlocking pair of members

5. C*ut-geometry-spread* contains a clone of each surface in the model, unfolded and laid out for the cut plan. Intersection geometry is mirrored on the surfaces. In this zone the cut plans are formatted and populated.

Use of External Tables – External data holding additional information on geometry, reporting methods and assembly relevant data are linked to the project.

1. *Surface Table* links surface to material width and cut file clone, uniquely identifies surface pieces, holds object handles and numeric thicknesses.

2. *Intersection Geometry Table* links surface pairs to generated intersection geometry, contains information on the detailing method applied.

3. *Assembly Table* contains assembly relevant information per intersecting surface pair, contains assembly slide vectors.

4. *Outline Table* identifies the resulting cut path poly-line associated to each fabrication piece.

6 The role of fabrication tools in contemporary architectural production

Advances in CAD modeling have substantially extended the possibilities in form making, amplifying imagination and the ability to develop unprecedented shapes. A reduction of a resistance which historically kept designs perceivable and on the same token conceivable has taken effect. The most intriguing of which devoid of the possibility to be translated into the material world remain encapsulated in the realm of the visionary digital medium. Working on reconnecting these two realms, one of the strategies leads to the development of a type of software that has one foot in design and one in production. The project presented in this paper represents a research aiming to link design practice with fabrication methods. The emerging software type, as a link between the universal CAD tool and the highly specialized CNC routine, has to retain a high level of specificity. It is best regarded as a virtual building system or tool. In this manner, the predicate tool becomes more than just a slogan, understanding the universality of a tool being born out of the high level of specificity imbued to it. Thus the tool is most strongly linked to an operation or construction. In the case of CFab1 the chosen operation is cutting planar material under orthogonal cut axis, resulting in the construction of plug-and-socket joints. CFab1 can be operated on various scales. In the course of testing, projects included small objects, shells, masks, furniture, spatial dividers and scale models of pavilion structures. Testing different materials and fabrication methods involved cutting blocks with foam cutters, laser cut models and wooden prototypes made with band saws. Yet the tool itself advocates a certain type of construction technology. For certain construction types, i.e. on the field of realizing freeform steel and glass constructions, such tools have already been developed. Yet similar design-production-construction oriented tools can be imagined for mold making, resolving the under-cut constraint of three-axis milling machines, or working with framework structures of equal length members and will eventually find their way into architectural practice.

7 Conclusion

CFab1, the working title of the project is an abbreviation of *Computer Fabrik*, the German equivalent to computer factory. In the first place the name refers to the repetitive, oscillating and quasi mechanic actions one can observe when operating in debug mode: scaffolding construction geometry is erected in milliseconds, used and erased for the next step, reports are produced, and control mechanisms are installed, a hierarchy of network and linear progressive structures is governing the process. But even more, the name should express the enthusiasm in mirroring production type processes in the virtual realm, and thus bridging the practice of design by modeling with the world of material processing and construction. The project has been developed in an academic environment, in a framework where intense development investments could be made, yet the role of extending the practice of the architect into the domain of manufacturing, whereby the architect becomes proactive in the installment of new structural production chains, remains crucial to an innovative design work. The discovery made in the process is, that this involvement is now easier than ever, with CAD-CAM programming environments ready to absorb complexities arising from the work with highly individualized design setups. The economic coefficient of complexity can be substantially reduced when translated into the virtual computational realm. This as a future scenario, points towards the emergence of more virtual factories which in turn can be regarded as a key step towards the proliferation of nonstandard, highly specific design solutions in the realm of architectural production, lowering demands on manufacturing environments and intelligently expanding possibilities of working with low-cost technologies.

Currently CFab1 is in use in architectural education, where through the use of the tool students are learning to handle the intricate relationships between parametric modeling and digital fabrication by developing a design and testing those on fabricated models.

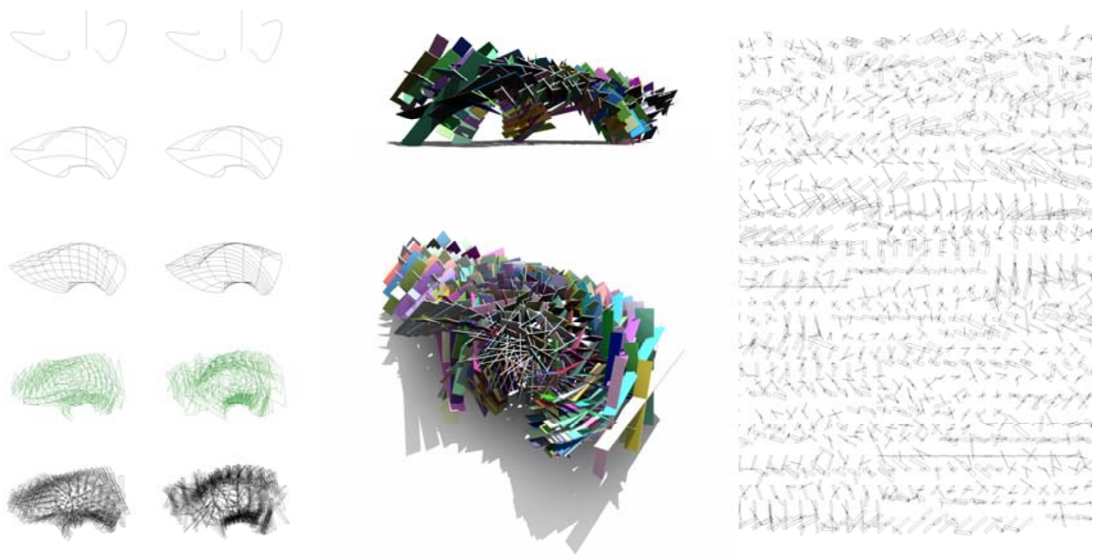


Figure 10. Parametric design and fabrication: Shadow structure of 330 members. Left: parametric model, centre: rendering of structure, right: double-check matrix detail, below: CFab1 cut file detail.