063-0606-22L : Computational Structural Design II

Structurally-informed Materialisation

Lecture 3

Digital Fabrication in Architecture Engineering and Construction

Thursday, April 28th, 2022

Arch. Serban Bodea

ETH Zürich DARCH BRG

Pioneers in Form-Finding and Materialization

Digital Fabrication in the AEC

Additive Manufacturing (AM)

Subtractive Manufacturing (SM)

Hot Wire Cutting (HWC) and Diamond Wire Cutting (DWC)

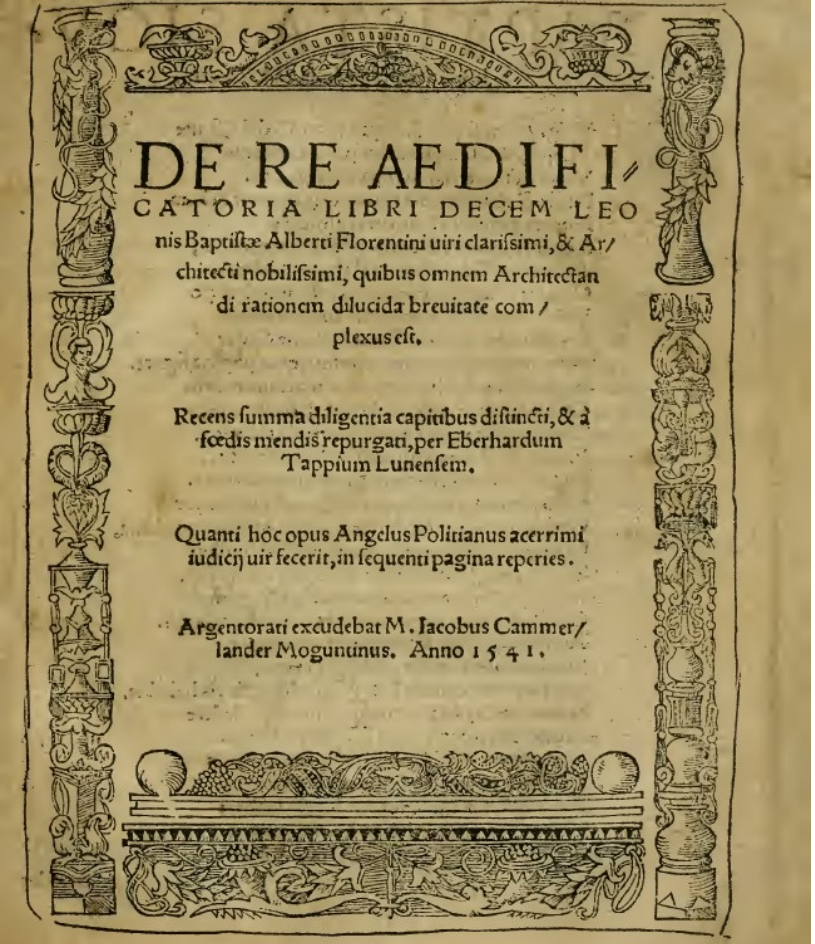
Milling and Sawing

Assignment of the Fabrication Module

Module		Week	Hr	Topic	Instructor	Assignment
I	Form finding	Week 1 (2/24)	1	**Lecture 1**	**Form finding of Funicular Shell Structures**	**Dr. Juney Lee**	
			2	Tutorial 1	Form finding with compas-RV2	Dr. Juney Lee	
			3				
II	Geometry	Week 2 (3/3)	1	Tutorial 2	Procedural thinking: logic diagrams, flow charts, pseudocodes, Introduction to Jupyter Notebook, Introduction to the Python programming language	Serban Bodea and Chaoyu Du	
			2				
			3	Work Session 2	*Ex. 2.1 Cost of cablenet elements* *Ex. 2.2 Check voussoir weight*	Chaoyu Du	
		Week 3 (3/10)	1	Tutorial 3	Coding in Python: data types, for-loops, conditionals	Serban Bodea and Chaoyu Du	Assignment 1 (individual)
			2	Work Session 3	*Ex. 3.1 Organising your design data* *Ex. 3.2 Managing your design data*	Chaoyu Du	
			3				
		Week 4 (3/17)	1	Tutorial 4	Introduction to computational geometry in COMPAS Geometry and Class in COMPAS	Serban Bodea and Chaoyu Du	
			2				
			3	Work Session 4	*Ex. 4.2 Visualising Geometries using the Compas Plotter*	Chaoyu Du	
		Week 5 (3/24)		Seminar week			
III	Materialisation	Week 6 (3/31)	1	**Lecture 2**	**Geometry, Rationalization & Materialization**	**Dr. Juney Lee**	
			2	Tutorial 5	Introduction to The Mesh Half-edge data structure	Dr. Juney Lee and Chaoyu Du	
			3	Work Session 5	*Ex. 5.1 Segmented shell from Mesh Half-edge data structure* *Ex. 5.2 Visualizing the Mesh Half-edge data structure with COMPAS Viewer*	Dr. Juney Lee and Chaoyu Du	
		Week 7 (4/7)	1	Tutorial 6	Operations with the Mesh Half-edge data structure	Dr. Juney Lee and Chaoyu Du	
			2	Work Session 6	*Ex. 6.4 Mesh Topological Modification on vertices and faces* *Ex. 6.4a Topology modification through deletion* *Ex. 6.4 Mesh Topological Modification on vertices and faces* *Ex. 6.4b Topology modification through subdivision*	Dr. Juney Lee and Chaoyu Du	
			3				
		Week 8 (4/14)	1	Tutorial 7	Geometry rationalization and materialization methods for funicular structures: Case Studies	Dr. Juney Lee and Chaoyu Du	Assignment 2 (individual)
			2	Work Session 7	*Ex. 7.1 Rationalization and materialization methods for meshes*	Dr. Juney Lee	
			3				
		Week 9 (4/21)		Easter			
		Week 10 (4/28)	1	**Lecture 3**	**Introduction to Computer Assisted Manufacturing for Architecture Engineering and Construction**	**Serban Bodea**	
			2	Tutorial 8	Introduction to Hotwire Cutting	Selina Bitting	
			3	Work Session 8	*Ex. 8.1 Orient Block for Cutting* *Ex. 8.2 Add Geometry of Cutting Material* *Ex. 8.3 Place Block w/ Cutting Material on Machine Bed* *Ex. 8.4 Generate Wire Cutter Path & Output*		
IV	Fabrication	Week 11 (5/5)	1	Work Session 9 Work on the Assignment 3	*Form Finding and Design Iterations* *Geometry, Rationalization and Materialization*	Dr. Juney Lee, Serban Bodea, Selina Bitting, Chaoyu Du	Assignment 3 (in groups)
			2				
			3				
		Week 12 (5/12)	1	Work Session 10 Work on the Assignment 3	*Material selection* *Process workflow*	Dr. Juney Lee, Serban Bodea, Selina Bitting, Chaoyu Du	
			2				
			3				
V	Dissemination	Week 13 (5/19)	1	**Lecture 4**	**Guest lecture: Dr. Catherine De Wolf**		Presentations
			2	Work Session 11	Group presentations of assignment 3		
			3				

Filippo Brunelleschi Loggia, Duomo Santa Maria del Fiore, Florence

Leon battista Alberti, Galleria degli Uffizi, Florence



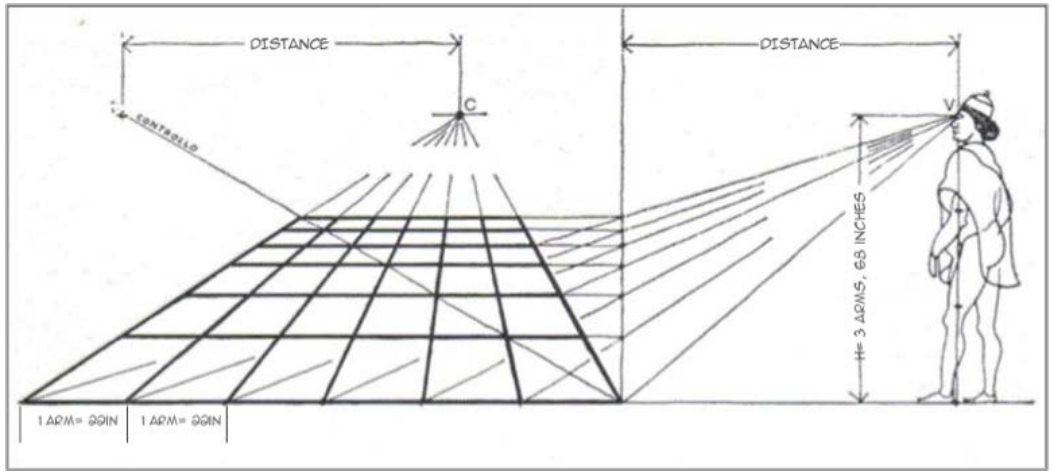
DE RE AEDIFI-
CATORIA LIBRI DECEM LEO
nis Baptistæ Alberti Florentini uiri clarissimi, & Ar-
chitecti nobilissimi, quibus omnem Architectan
di rationem dilucida breuitate com-
plexus est.

Recens summa diligentia capitibus distincti, & à
fœdis mendis repurgati, per Eberhardum
Tappium Lunensem.

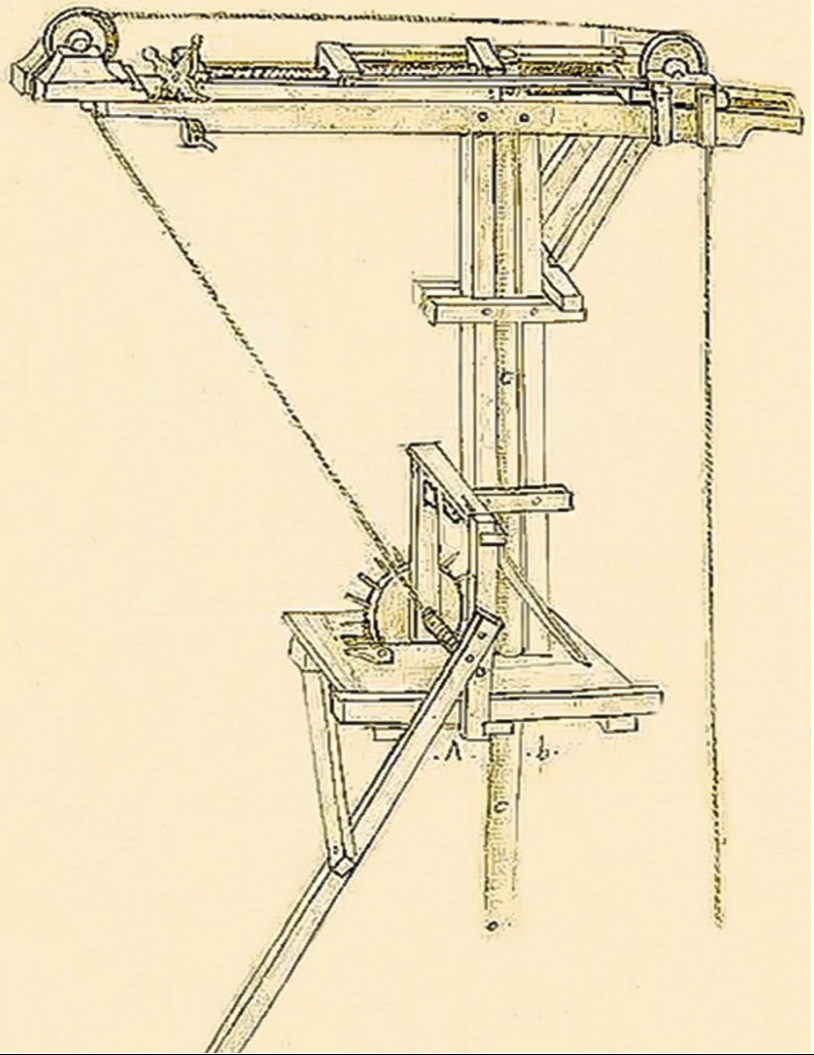
Quanti hoc opus Angelus Politianus acerrimi
iudicij uir fecerit, in sequenti pagina reperies.

Argentorati excudebat M. Iacobus Cammer-
lander Moguntinus. Anno 1541.

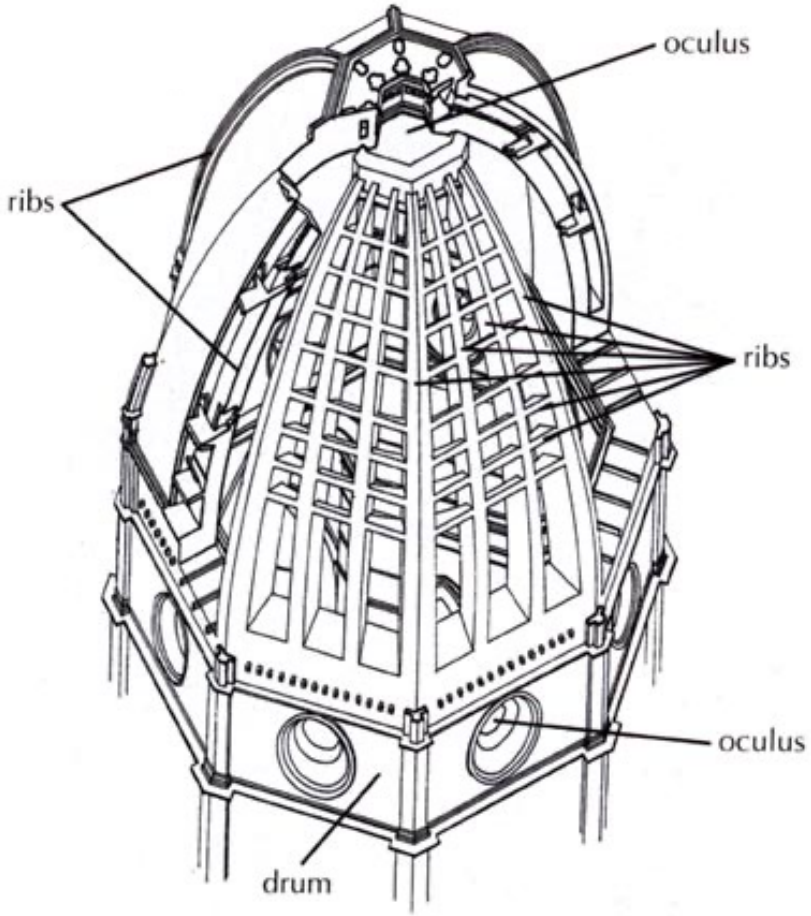
Leon Battista Alberti: Plate from the De re aedificatoria (On the Art of Building). Source: Sivlia Minguzzi



Alberti's Perspective. Source: Sivlia Minguzzi



Filippo Brunelleschi: Revolving Crane. Source: Ariana Eskew



Filippo Brunelleschi: Revolving Crane. Source: Zakaria Aissa

“…certainly it is enough if you give honest Advice, and correct Draughts such as to apply themselves to you. If afterwards you undertake to supervise and complete the Work, you will find it very difficult to avoid being made answerable for all the Faults and Mistakes committed either by the Ignorance or Negligence of other Men.”

Leon Battista Alberti, De re Aedificatoria (1452)

In contemporary architectural practice this abstraction of design from construction is no longer necessary.
Digitalization of design, fabrication, and in-situ construction will transform the industry.

“If I was to realize new buildings I should have to have new a technique. I should have to so design buildings that they would not only be appropriate to materials but design them so the machine that would have to make them could make them surpassingly well.”

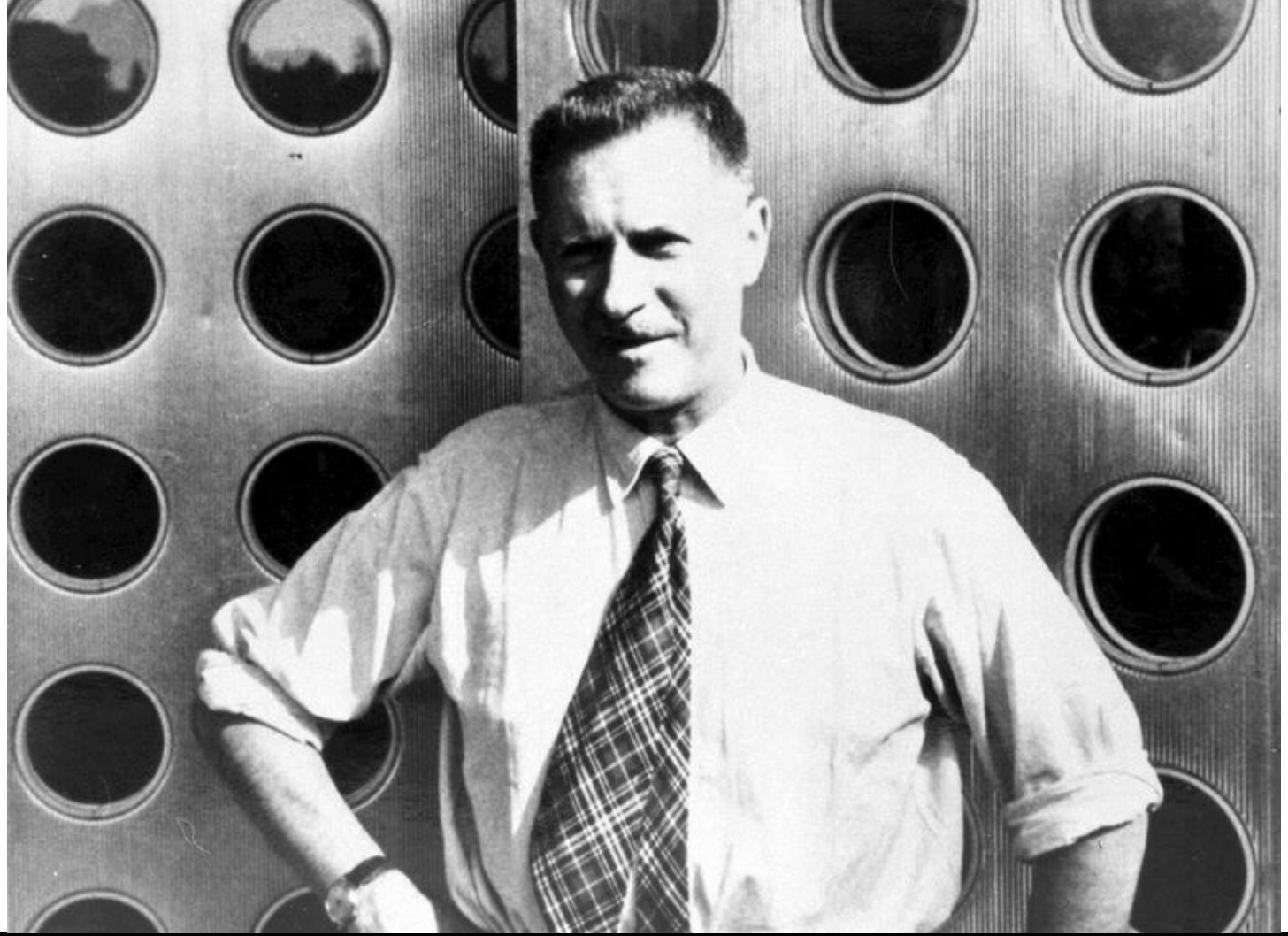
Frank Lloyd Wright, An Autobiography, 1943

Buckminster Fuller in front of the Montreal Biosphere geodetic Dome.
Source: Bettmann/Corbis

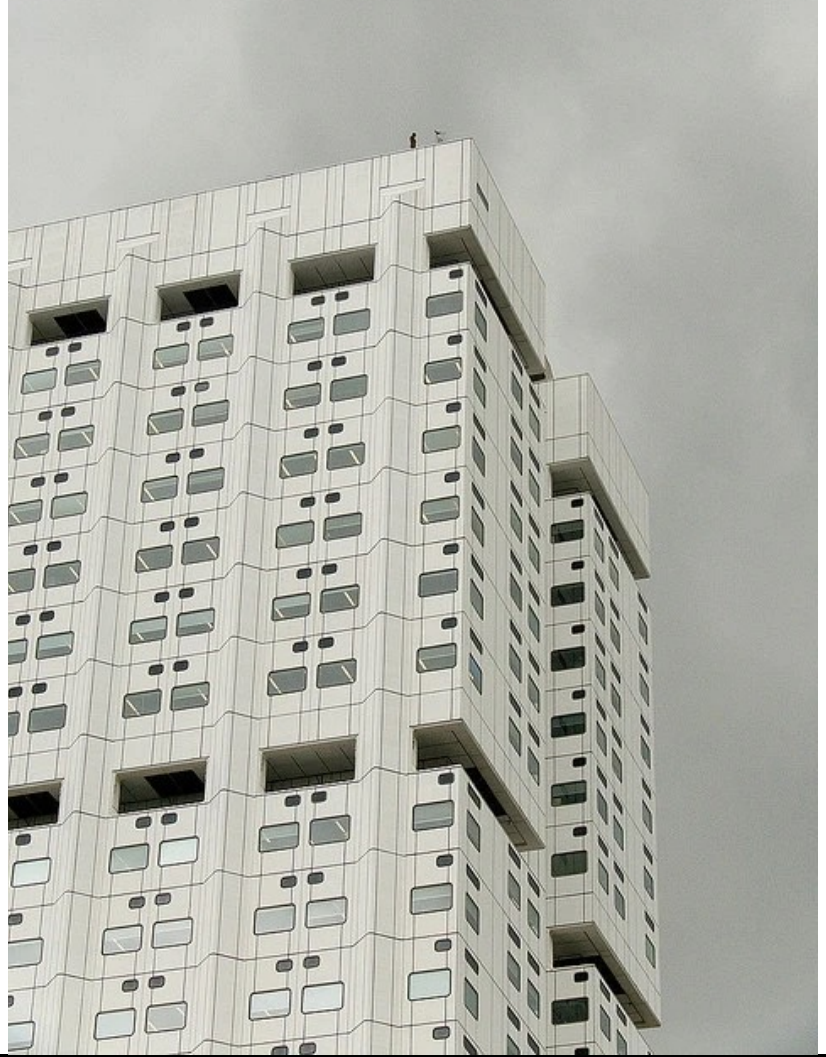
Dymaxion House, Source University of Oregon

Frei Otto, Montreal, Canada. Source; Jorg Schlaich Archive

M,annheim Multihalle. Source: Bauwel.det



Jean Prouvé, Vitra Design Museum, Source: Vitra



Erashus Hospital, Rotterdam. Source: Reinier de Jong

Charles and Ray Eames in front of The Molded Plywood Airplane Fuselage.
Sorce: Eames office

Kazam! Machine for making moulded plywood chairs. Source: Vitra

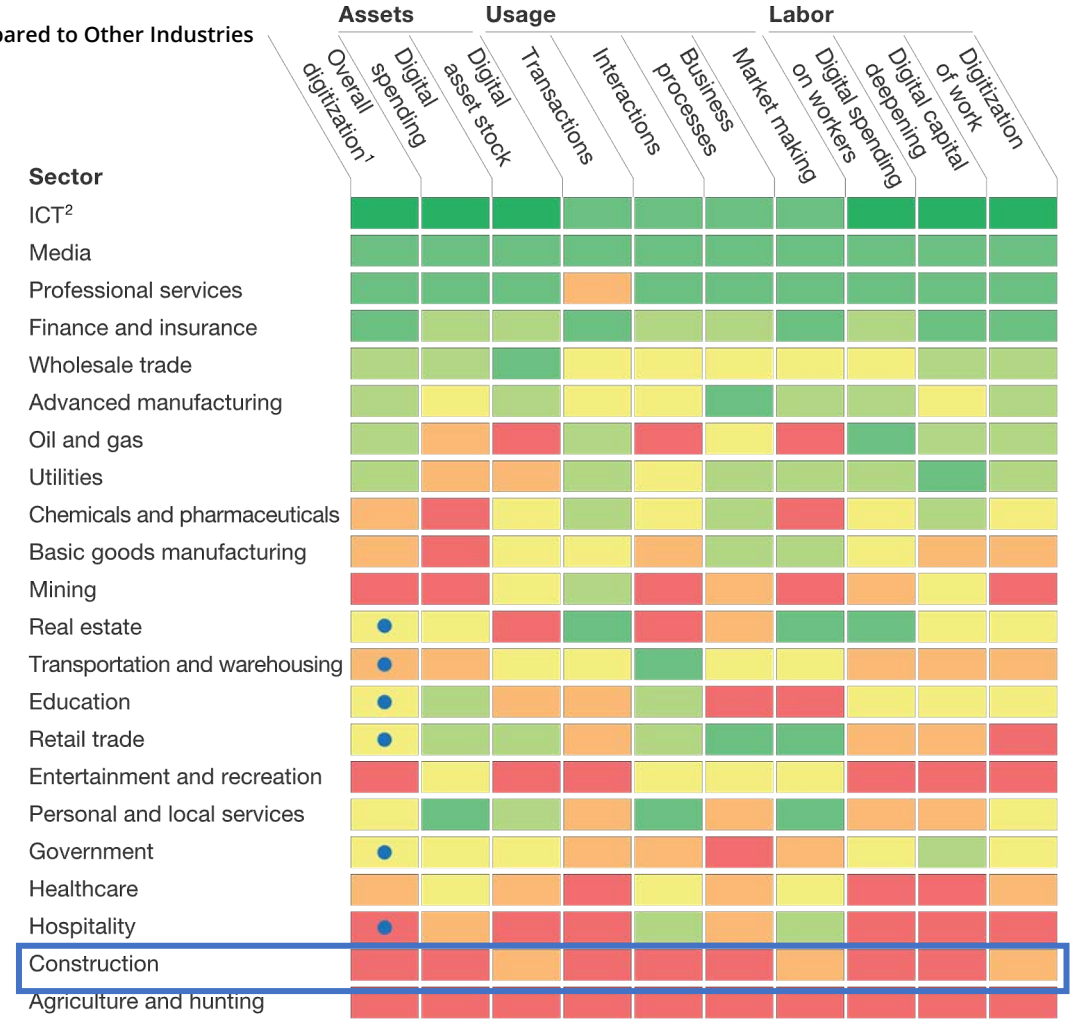
Bernard Cache. Source: Natalie Seroussi

Digital Fabrication in AEC

Contemporary construction is a process of delivery and modification of contemporary buildings that is widely regarded by both owners and building professionals as being **inefficient**, **risky**, **expensive** and often an incomplete or inadequate realisation of the project's original intent (...) through drawing conventions that date back centuries.

Anthony Hauck / Michael Bergin, Autodesk. Fabricate (2017)

Construction Digitization Level Compared to Other Industries



Source: McKinsey Global Institute Analysis


+ 2.1 Bn
Sha Tin
沙田
Tsim Sha Tsui & Hong Kong
尖沙咀及香港
GET IN LANE
選定行車綫

Pollution (CO_2)

The building sector is one of the biggest contributors to climate change, with more than **30%** of human-caused CO_2 emissions and **40%** of global Green-House-Gas emissions.

(UN and International Agency, 2017)

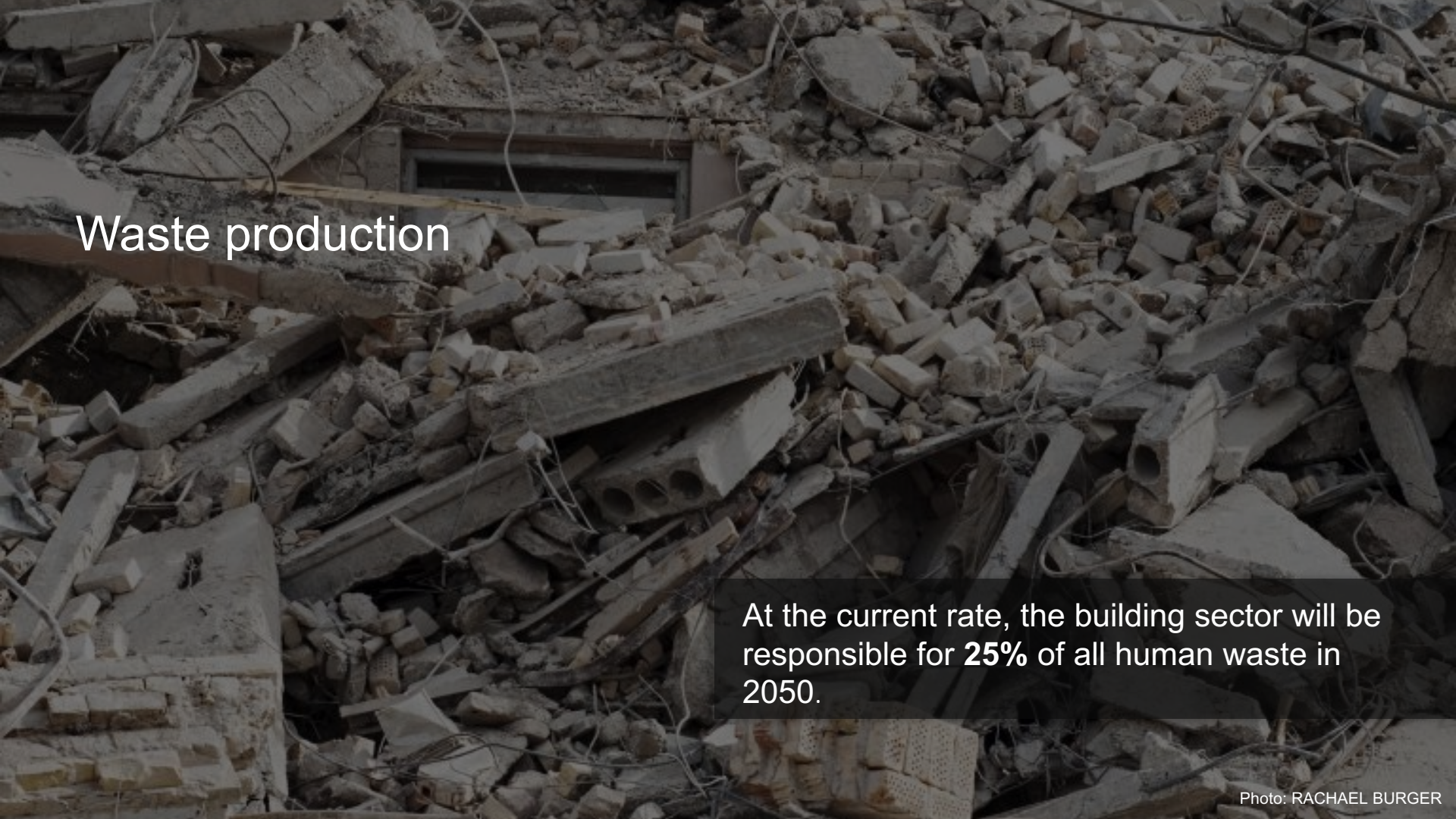
Photo: The Travelers Indemnity Company

Resource depletion

Construction Industry is responsible for **40%** of global resource consumption. More than **10 billion** tons of concrete are currently used every year and it will reach **60 billion** tons in 2050.

Photo: Adam Ferguson

Waste production

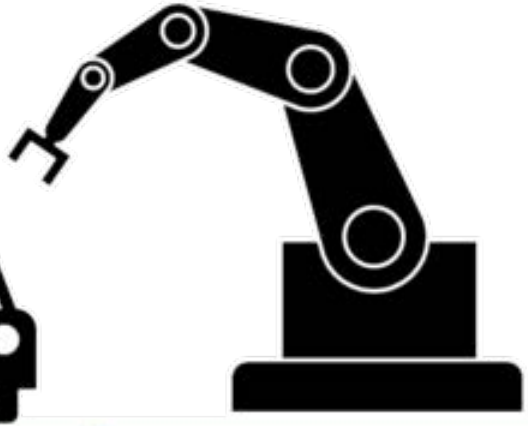


At the current rate, the building sector will be responsible for **25%** of all human waste in 2050.

Photo: RACHAEL BURGER

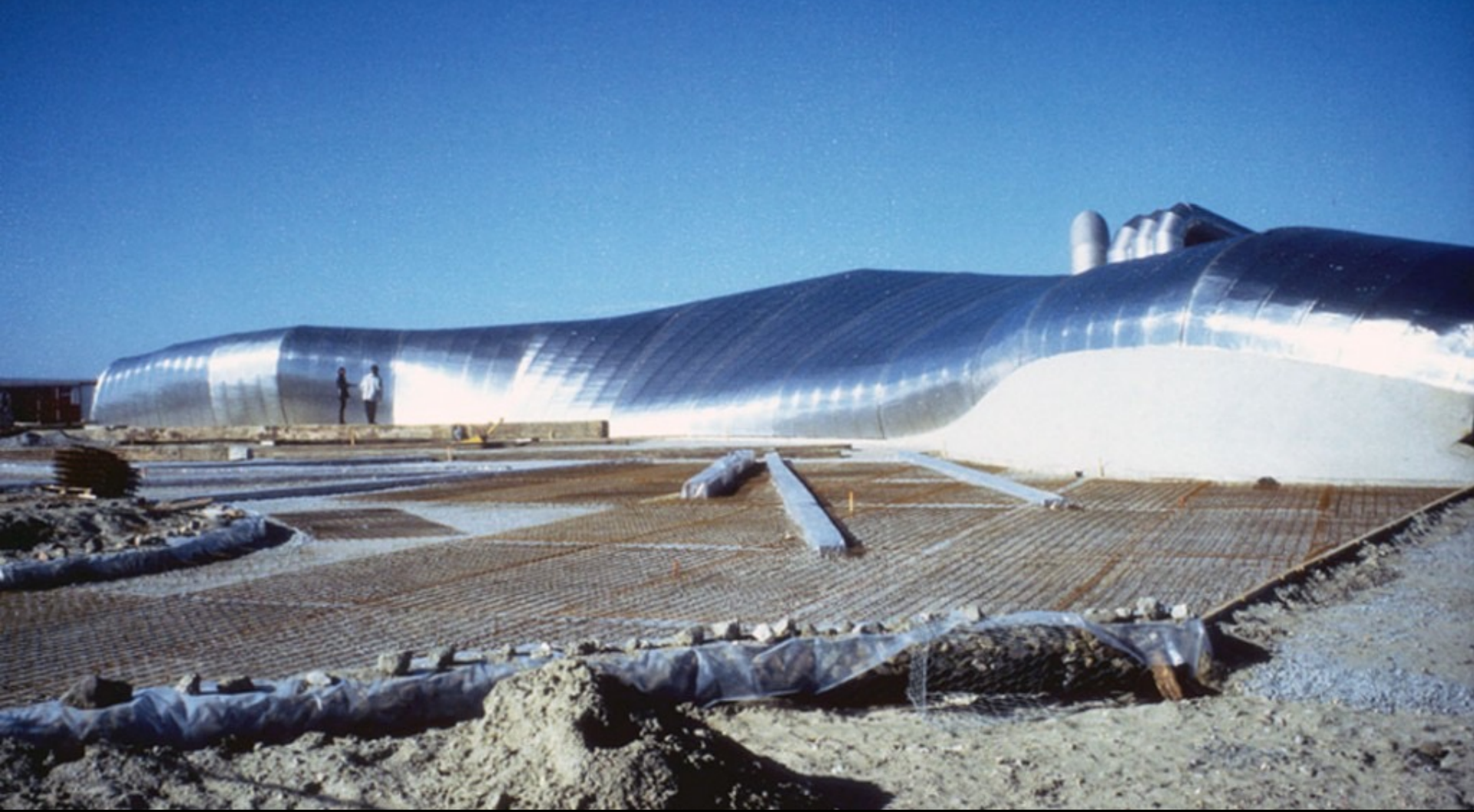

We need to change the way we **design** structures
We need to change the way we **build** structures

Manufacturing is not a mechanical problem like for Brunelleschi but an intellectual one and that is interesting for engineers and architects



1st	2nd	3rd	4th
Mechanization, water power, steam power	Mass production, assembly line, electricity	Computer and automation	Cyber Physical Systems

FORBES, 4th Industrial Revolution. Source: Christoph Roser



Fresh Water Pavilion, by NOX Architekten, 1997

Salt Water Pavilion, by ONL, 1997

Balna, Budapest, by ONL, 2013

Gantenbein Vineyard Façade, Gramazio & Kohler, 2006

Swatch Headquarters, Biel, 2019, Designed by Shigeru Ban Architects Consulting: Design to Production Timberwork: Blumer-Lehmann AG

Cambridge Mosque, 2020, Designed by Marks Barfield Architects | Consulting: Design to Production | Timberwork: Blumer-Lehmann AG

NCCR D-fab research: D-fab House Unit, EMPA NEST, 2021

NCCR D-fab research: D-fab House Unit, EMPA NEST, 2021

Source: Block Research Group

NCCR D-fab research: HiLo Unit, EMPA NEST, 2021

Source: Block Research Group

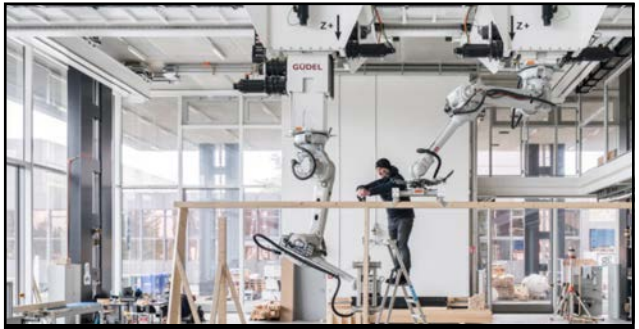
NCCR D-fab research: HiLo Unit, EMPA NEST, 2021

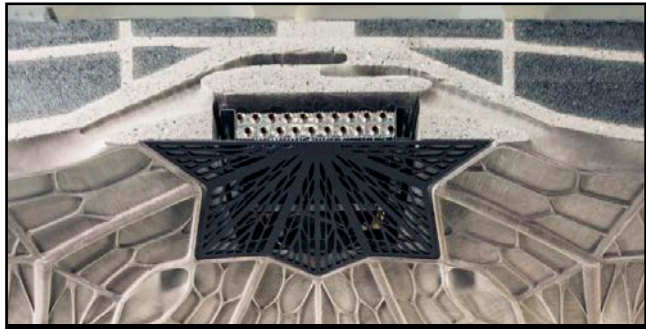

Lightweight Flexible Formwork


Large-span Self-supporting Assemblies


Construction Robotics

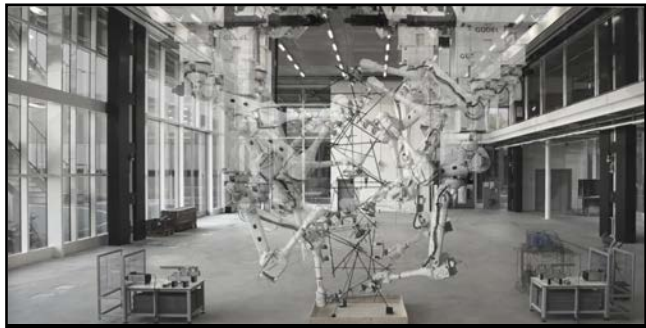

Mouldless Shaping of Concrete Elements


Spatial Timber Assemblies


Performance-integrated 3D Printing


Fostering Implementation: Sustainability, Performance, and Applicability


Computational Methods


Robotics Fundamentals: Perception, Mobility, and Dexterity


Lightweight Flexible Formwork


Large-span Self-supporting Assemblies


Construction Robotics

1. On-site digital fabrication


Mouldless Shaping of Concrete Elements

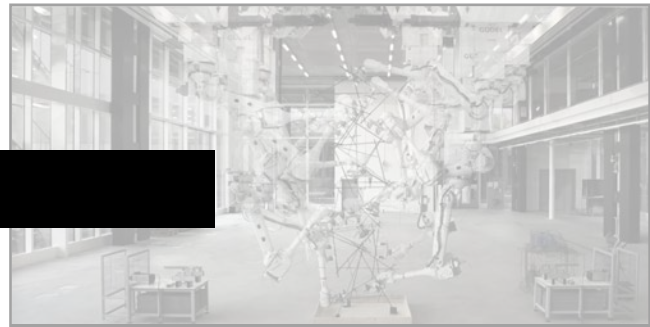

Spatial Timber Assemblies


Performance-integrated 3D Printing

2. Bespoke digital prefabrication


Fostering Implementation: Sustainability, Performance, and Applicability


Computational Methods


Robotics Fundamentals: Perception, Mobility, and Dexterity

3. Cross NCCR topics

Additive Manufacturing

Additive manufacturing (AM) is defined (...) as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”.

S. Anand Kumar, R.V.S. Prasad

https://doi.org/10.1016/B978-0-12-822056-6.00012-6

BUGA Fibre Pavilion. Sorce ICD, University of Stuttgart

Concrete Coreography. Source: DBT, ETH Zurich

LivMats Pavilion. Sorce: ICD, University of Stuttgart

Hybrid Tower. Source: CITA, Royal Danish Academy Copenhagen

KnitCandela. Source: BRG, ETH Zurich

MeshMold D-FAB House. Source: GKR, ETH Zurich

Striatus Bridge. Source: BRG, ETH Zurich

Smart Dynamic Casting. Source: GKR, ETH Zurich

HiLo Slab, Hilo. Source: NCCR D-FAB, ETH Zurich

BUGA Fibre Pavilion. Sorce ICD, University of Stuttgart

Concrete Coreography. Source: DBT, ETH Zurich

LivMats Pavilion. Sorce: ICD, University of Stuttgart

Hybrid Tower. Source: CITA, Royal Danish Academy Copenhagen

KnitCandela. Source: BRG, ETH Zurich

MeshMold D-FAB House. Source: GKR, ETH Zurich

Winding, Knitting, and 3D Printing

Striatus Bridge. Source: BRG, ETH Zurich

Smart Dynamic Casting. Source: GKR, ETH Zurich

HiLo Slab, Hilo. Source: NCCR D-FAB, ETH Zurich

BUGA Fibre Pavilion. Sorce ICD, University of Stuttgart

Source ICD ITKE

LivMats Pavilion. Sorce: ICD, University of Stuttgart

Source: Block Research Group

KnitCandela. Source: BRG, ETH Zurich

Source: Block Research Group

Striatus Bridge. Source: BRG, ETH Zurich

Subtractive Manufacturing

“Subtractive manufacturing is an umbrella term for various controlled machining and material removal processes that start with solid blocks, bars, rods of plastic, metal, or other materials that are shaped by removing material through cutting, boring, drilling, and grinding.”

formlabs

https://formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing

BUGA Wood Pavilion. Sorce: ICD, University of Stuttgart

NEST HiLo Floor. Source: BRG, ETH Zurich

Stereoform Slab. Source: SOM and ODICO Robotics

Hyperbody MSc.2 Prototype. Source: Hyperbody, TUDelft

Armadillo Vault. Source: BRG, ETH Zurich

Theater Zuidplein. Source: Studio RAP

Sagrada Familia. Source: Prototyping for Architects, M. Burry, J. Burry

Carrara Marble Diamond Wire Cutting. Source: Jelle Feringa, ODICO Robotics

Cambridge Moschee. Source: Designtoproduction, Blumer Lehmann

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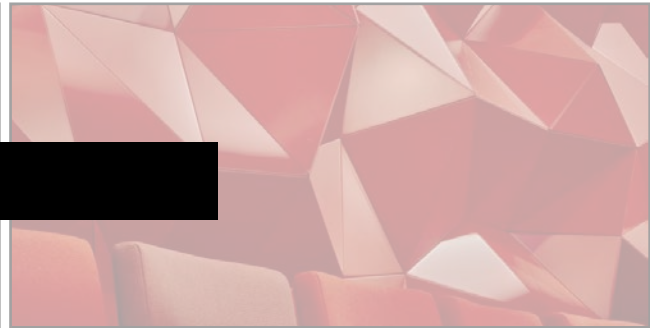
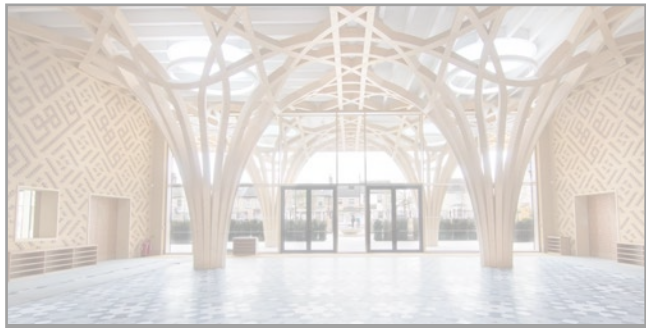


Theater Zuidplein. Source: Studio RAP

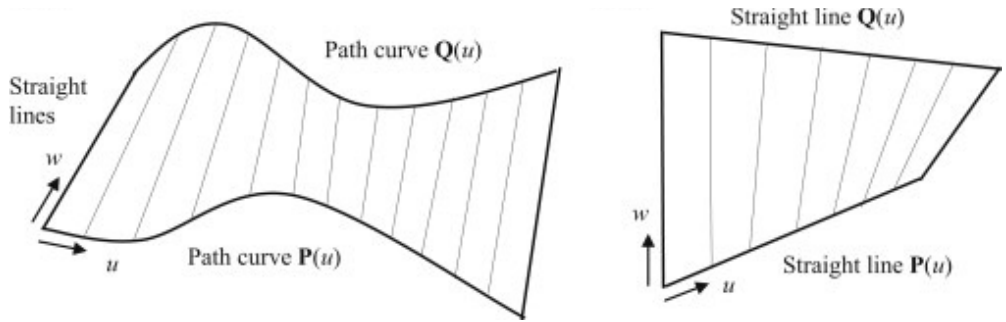
Robotic Wire Cutting

Sagrada Familia. Source: Prototyping for Architects, M. Burry, J. Burry

Carrara Marble Diamond Wire Cutting. Source: Jelle Feringa, ODICO Robotics



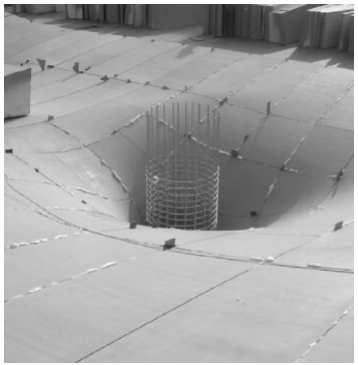
Cambridge Moschee. Source: Designtoproduction, Blumer Lehmann



Ruled Surfaces types. Source: https://doi.org/10.1016/C2009-0-63076-2

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

EPS foam and Stone



Top Left: Figure 1. Finalized CNC milled and assembled formwork for casting; Top Right: View under the Spencer Dock Bridge by Amanda Levete Architects. Source: Digital Concrete: Opportunities and Challenges DOI: 10.21809/rilemtechlett.2016.16; Bottom; EPS foam Formwork for reinforced concrete. Source: https://toiib.com

Top: Marble Quary, Carrara, Italy. Source: National Geographic Society

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

EPS and Stone - Structure and Shape

Top Left: EPS Foam stock material; Source: https://www.atlasfoam.com/foam-materials/eps-foam-packaging ;

Carrara marble form and structure. Source: https://www.yokokubrick.com/carrara-marble

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

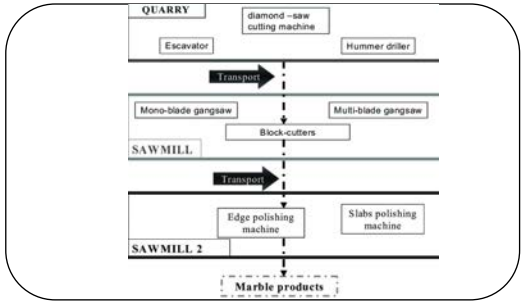
tools

A

B

A: Industrial 3-Axies Hot wire cutting machine. Source: cnc-multitool.com;
B: Robotic 6-Axes Hot wire cutting machine. Source: instructables.com

A



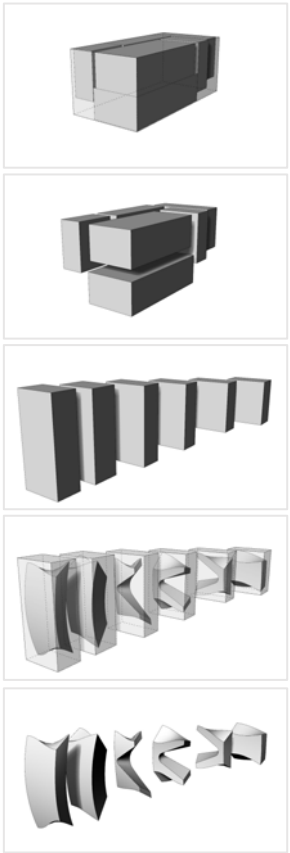
B

C

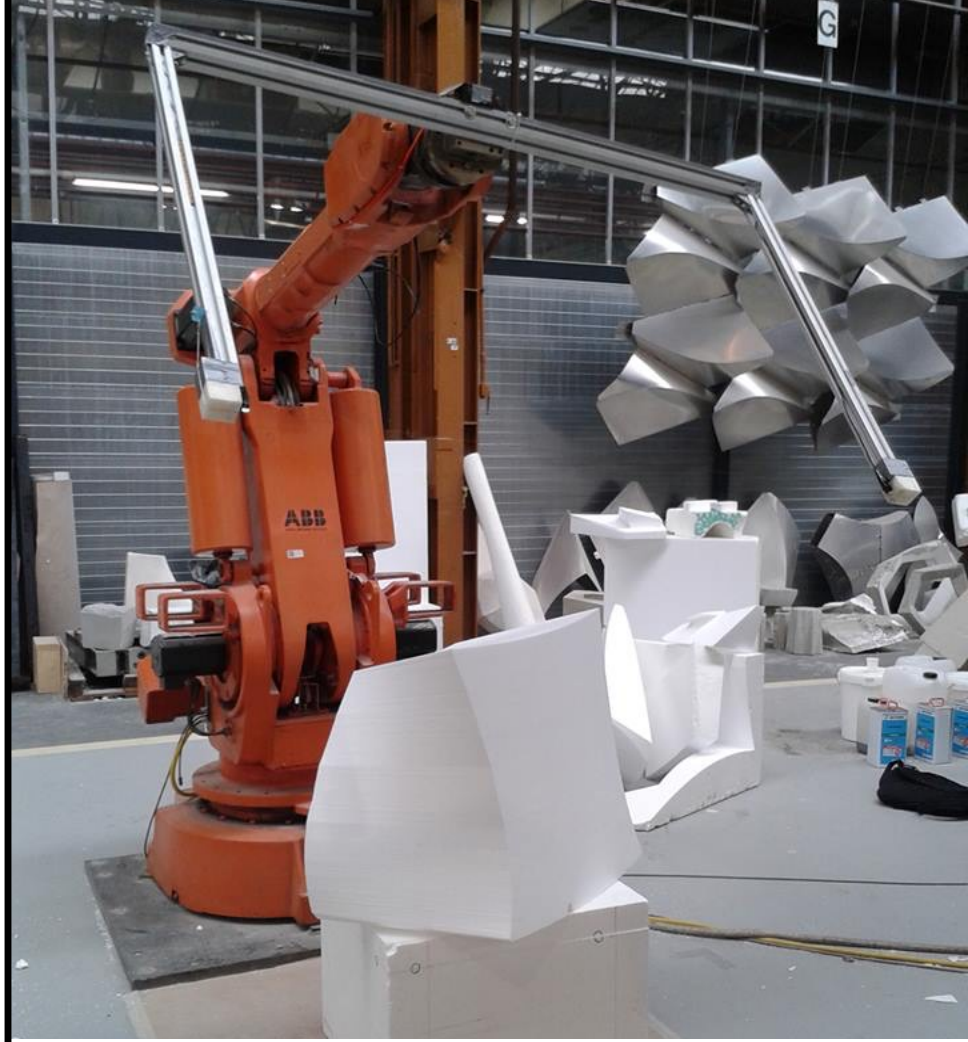
A: Processing Stone. Source: Marble quarrying: an energy and waste intensive activity in the production of building materials.DOI:10.2495/EEIA080201;
B: Cutting and polishing of natural stone slabs. Source: Cararra marble;
C: Robotic diamond wire stone cutting. Source: Jelle Feringa/ Odico robotics

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

Basics of HWC



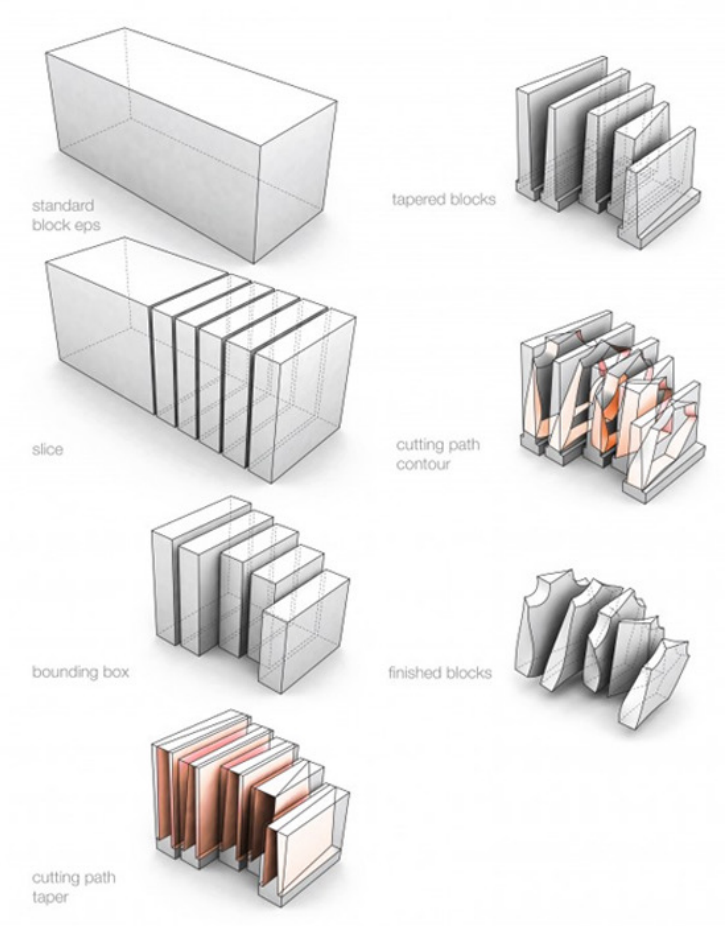
Robotic HWC.
Source http://multimod.hyperbody.nl/index.php/project05:Studio



Robotic HWC.
Source http://multimod.hyperbody.nl/index.php/project05:Studio

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

Basics of DWC



Robotic diamond wire stone cutting. Source: Jelle Feringa/ Odico robotics

- **Cutting speed** [m/min] (RPM)

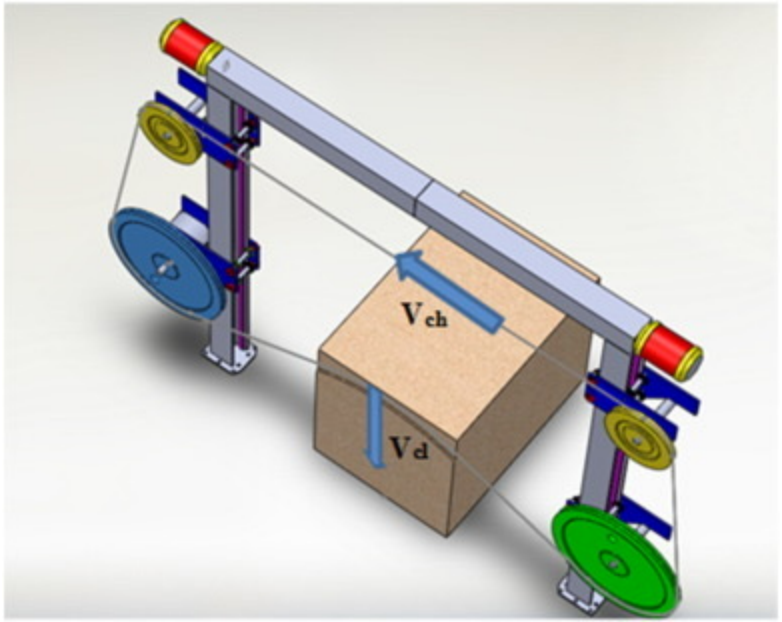
- **Feed Rate**
  - -Feed per Tooth [mm/tooth]
  - - Feed per Revolution [mm/Rev]
  - - Feed per Unit of Time [feed/min] [feed/sec]

- **Depth of cut** [mm]

- V ch – Horizontal Cutting Velocity[m/min]
- V cl – Linear Cutting Velocity[m/min]

Material load

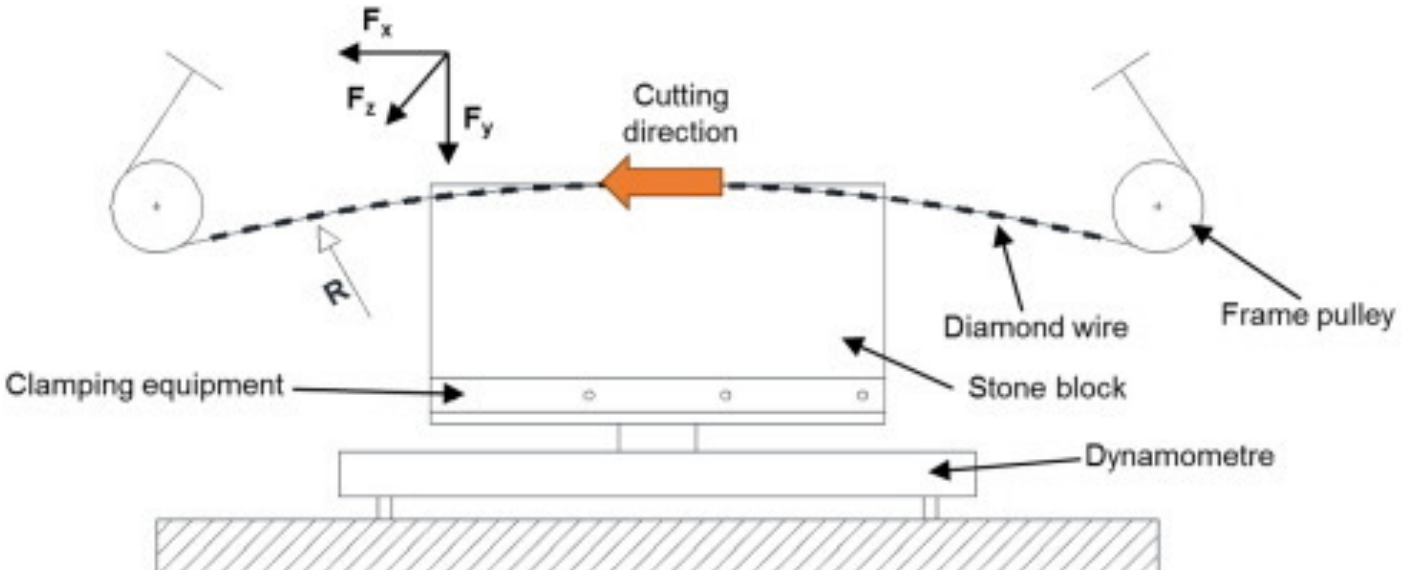
amount of material (load) each flute cuts during each revolution (every chip)



General Principle of DWC. Source: DOI https://doi.org/10.1007/s10064-021-02381-5

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

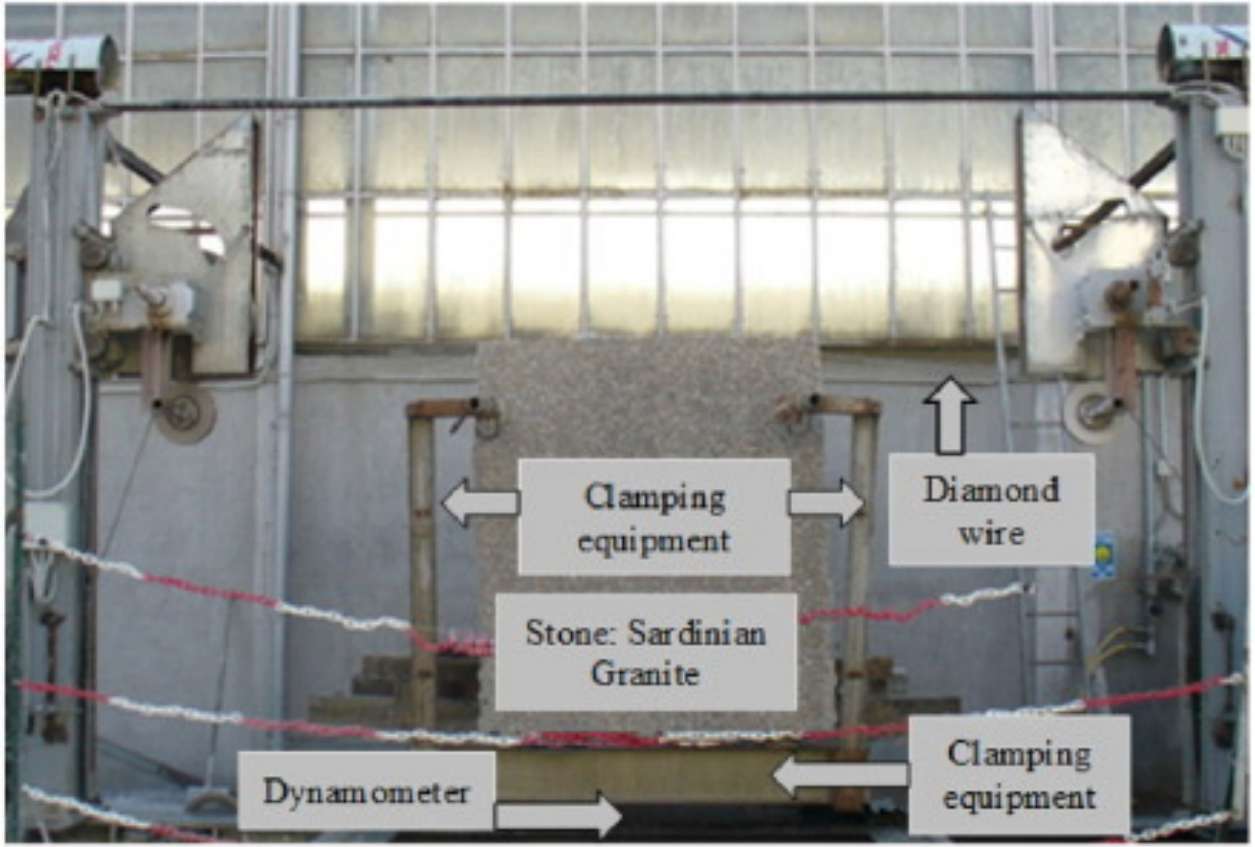
Tools : Milling cutters



DWC setup for stone cutting. Source: A method to optimize the diamond wire cutting process, https://doi.org/10.1016/j.diamond.2016.11.016

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

DWC setup

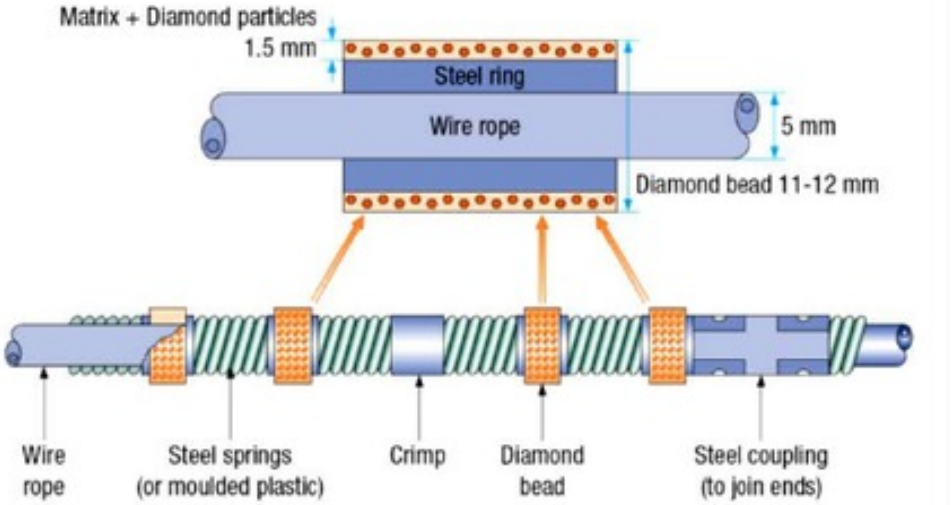


DWC setup for stone cutting. Source: A method to optimize the diamond wire cutting process, https://doi.org/10.1016/j.diamond.2016.11.016

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

Tools

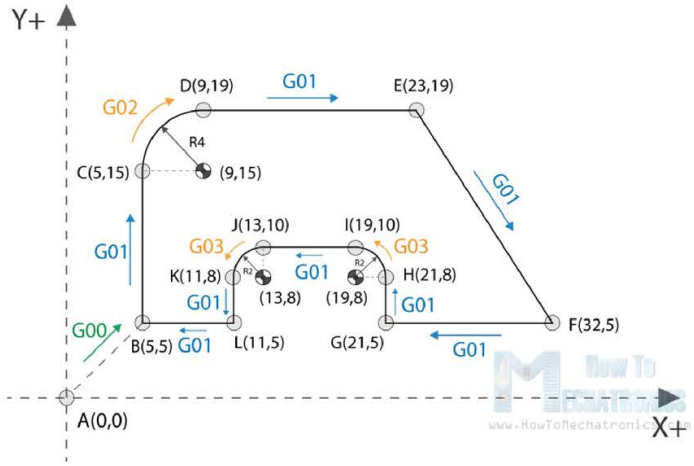
DWC chain for stone cutting. Source: A method to optimize the diamond wire cutting process, https://doi.org/10.1016/j.diamond.2016.11.016



Composition of the DWC chain. Source: Optimum distance between cutting machine and working face in travertine exploitation with diamond wire cutting method. https://www.researchgate.net/publication/276025292_Optimum_distance_between_cutting_machine_and_working_face_in_travertine_exploitation_with_diamond_wire_cutting_method

Hot Wire Cutting(HWC) / Diamond Wire Cutting(DWC)

Programming G-Code



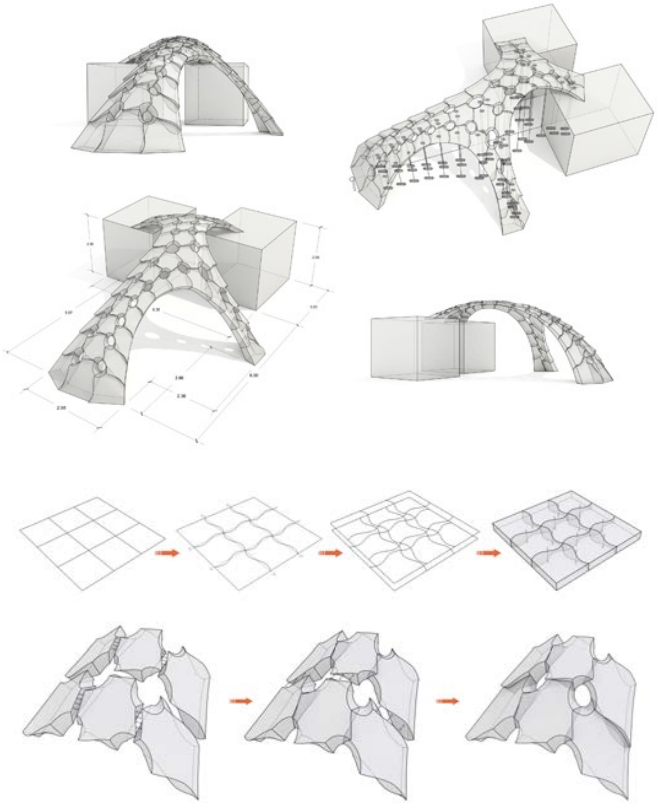

```
%                                   Code initialization. This character (%) is always present at the beginning and at the end of the program.
G21 G17 G90 F100                    Safety line: Set programming in metric system (all dimensions in mm), XY plane, absolute positioning and feed rate of 100 inches/min.
M03 S1000                           Spindle on clockwise at speed of 1000 RPM.
G00 X5 Y5           ; point B       Rapid positioning to B(5,5).
G01 X5 Y5 Z-1       ; point B       Controlled motion on the same position, but lowering the tool to -1.
G01 X5 Y15 Z-1      ; point C       Linear cutting movement to position C(5,15).
G02 X9 Y19 Z-1 I4 J0 ; point D      Clockwise circular motion to point D(9,19), with center point at (9,15).
G01 X23 Y19 Z-1     ; point E       Linear cutting to point E(23,19).
G01 X32 Y5 Z-1      ; point F       Linear cutting to point F(32,5).
G01 X21 Y5 Z-1      ; point G       Same straight cutting to point G(21,5).
G01 X21 Y8 Z-1      ; point H       One more straight cutting to point H(21,8).
G03 X19 Y10 Z-1 I-2 J0 ; point I    Counterclockwise circular interpolation to position I(19,10), with a center point at (19,8).
G01 X13 Y10 Z-1     ; point J       Linear cutting to point J(13,10).
G03 X11 Y8 Z-1 I0 J-2 ; point K     Counterclockwise circular cutting to position K(11,8), with a center point at (13,8).
G01 X11 Y5 Z-1      ; point L       Linear cutting to position L(11,5).
G01 X5 Y5 Z-1       ; point B       Final linear cutting movement to position B(5,5).
G01 X5 Y5 Z0                        Rise up the tool.
G28  X0 Y0                          Go to home position.
M05                                 Spindle off.
M30                                 Main program end.
%
```

G-Code programming Syntax – generic. Sorce: howtomechatorincs.com

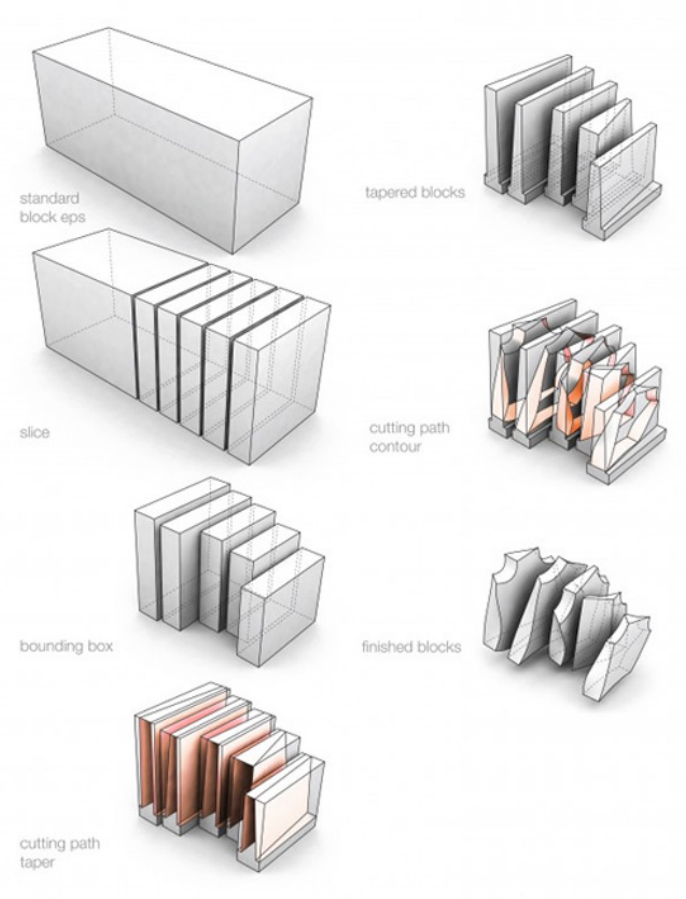
RDM Pavilion

Hyperbody and ROK

Source: http://designplaygrounds.com/deviants/msc2-studio-at-hyperbody-at-tu-delft/



ODICO pavilion RDM With ROK. Source: http://designplaygrounds.com/deviants/msc2-studio-at-hyperbody-at-tu-delft/



ODICO pavilion RDM With ROK. Source: http://designplaygrounds.com/deviants/msc2-studio-at-hyperbody-at-tu-delft/

RDM pavilion

Hyperbody and ROK

ODICO pavilion RDM With ROK. Source: http://designplaygrounds.com/deviants/msc2-studio-at-hyperbody-at-tu-delft/

NEST HiLo Floor

Dübendorf, Switzerland | 2011-2021

Innovation

Block Research Group, ETH Zürich
Chair of Architecture and Building Systems, ETH Zürich

Architecture

ROK Architekten
Block Research Group, ETH Zürich

Selected Planners and Contractors

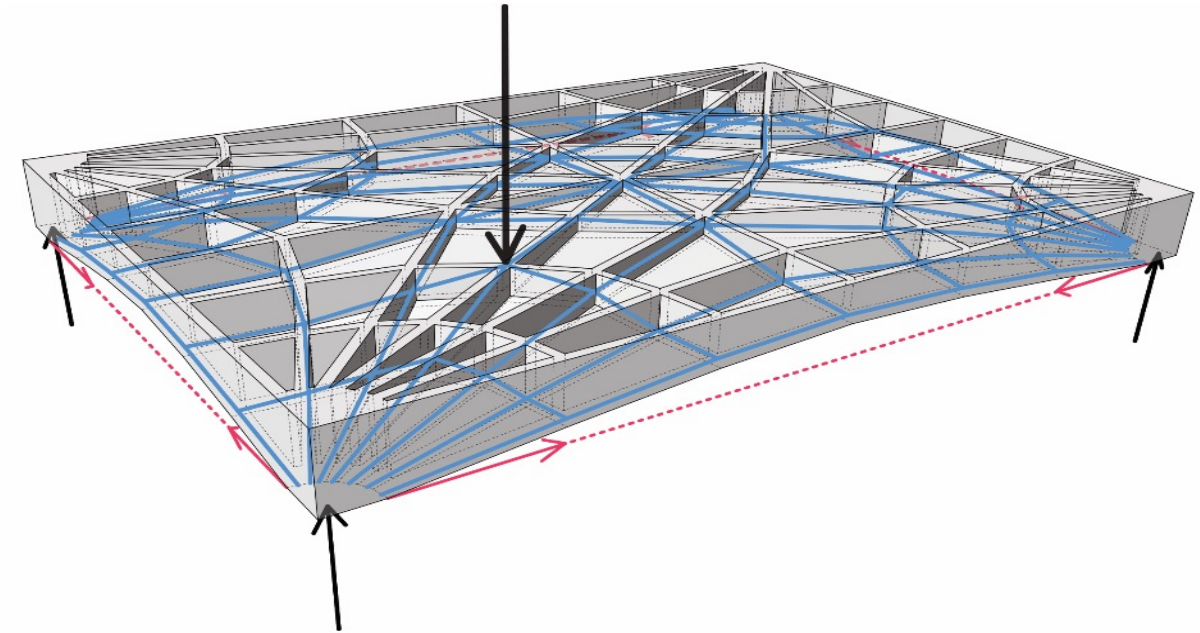
Buergin Creations
Dr. Schwartz Consulting AG
Marti AG
Pletscher Metallbau AG
Künzli Holz AG
Kaufmann Spenglerei & Sanitär AG Holcim Schweiz
Mitsubishi Electric

Financial support

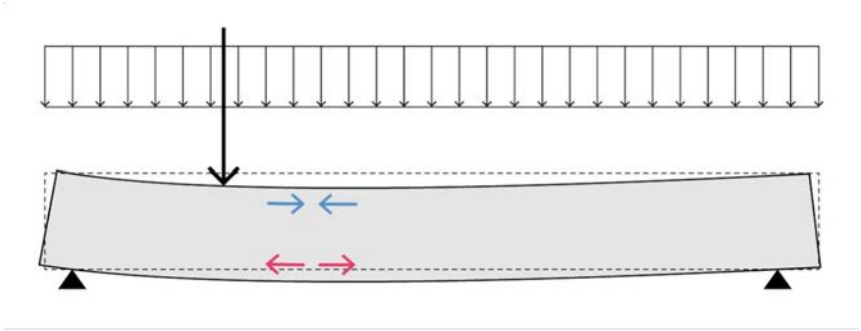
ETH Zürich
Dr. Max Rössler / ETH Foundation Empa
NCCR Digital Fabrication
Holcim Schweiz
Mitsubishi Electric

Rib-stiffened funicular floor system

Source: BRG

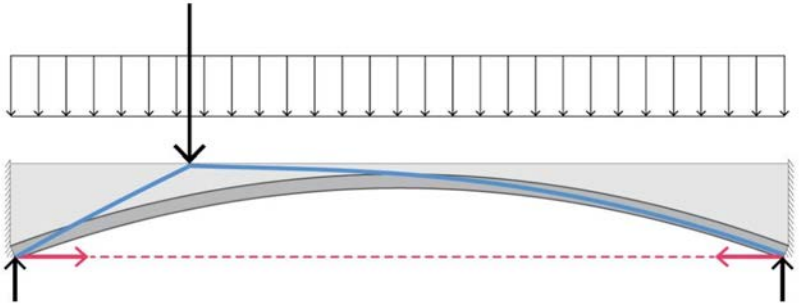


Source: BRG



Concrete Floor Slab

In bending



Funicular Floor System

In compression

- 70% concrete

- 90% reinforcement

Source: BRG

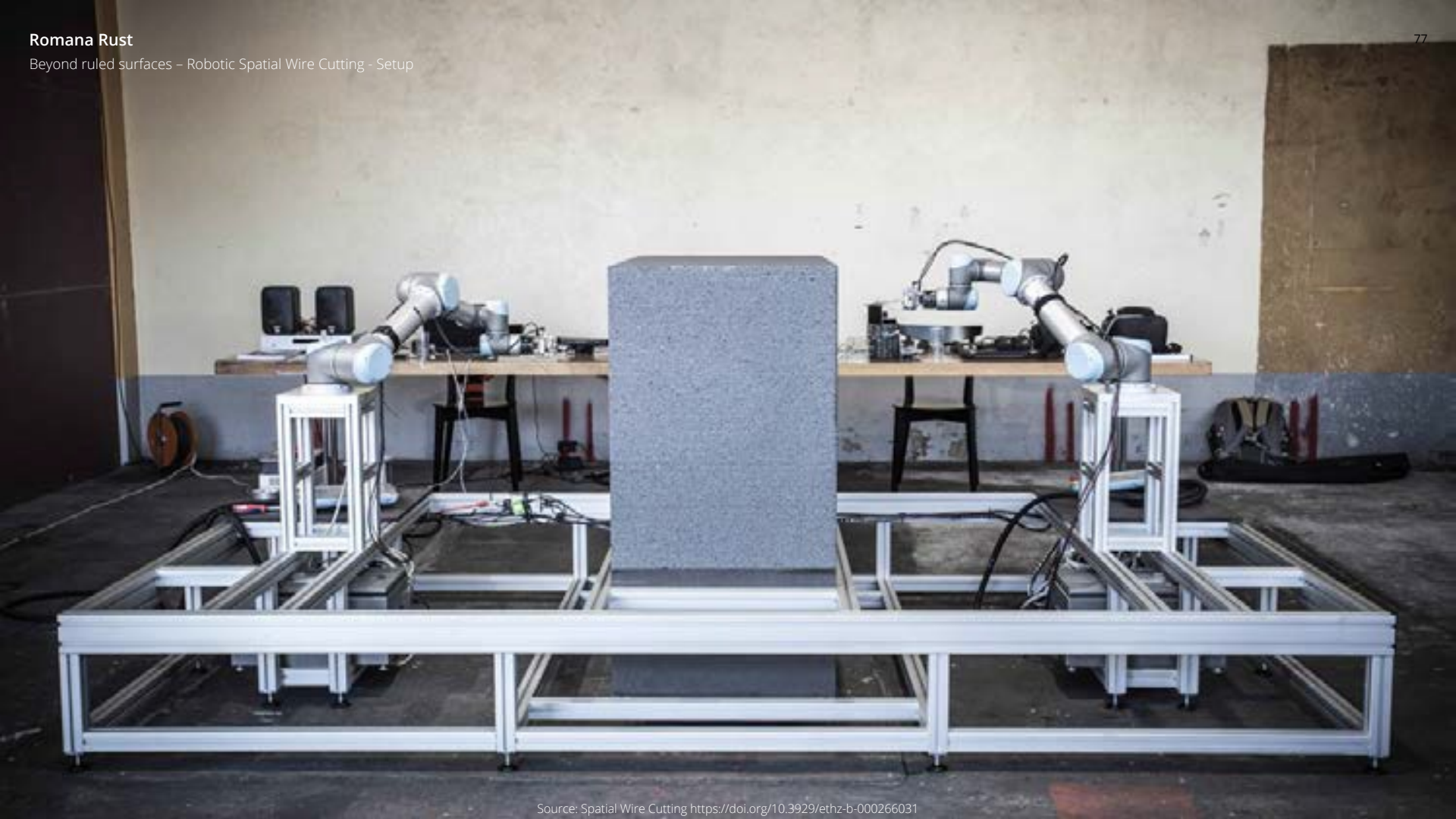
Photo Juney Lee

Photo Juney Lee

Photo Juney Lee

Photo Juney Lee

Photo Juney Lee



Source: Spatial Wire Cutting https://doi.org/10.3929/ethz-b-000266031

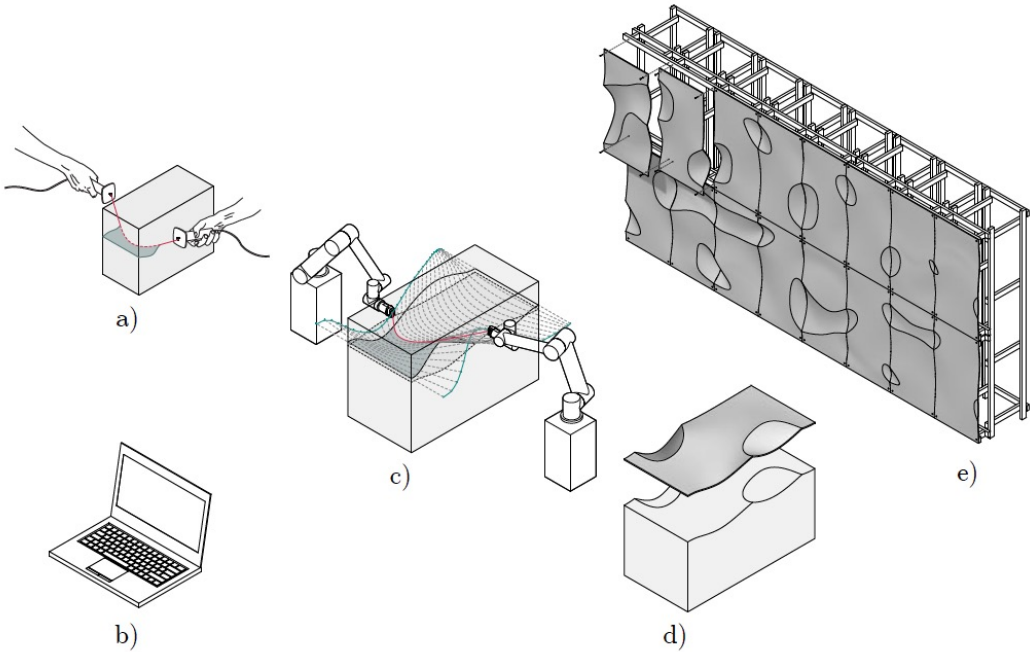


Fig. 4.13: Workflow: a) manual testing b) computational design c) robotic fabrication, d) manual lamination e) assembly

Source: Spatial Wire Cutting https://doi.org/10.3929/ethz-b-000266031

BUGA Wood Pavilion. Sorce: ICD, University of Stuttgart

NEST HiLo Floor. Source: BRG, ETH Zurich

Stereoform Slab. Source: SOM and ODICO Robotics

Hyperbody MSc.2 Prototype. Source: Hyperbody, TUDelft

Armadillo Vault. Source: BRG, ETH Zurich

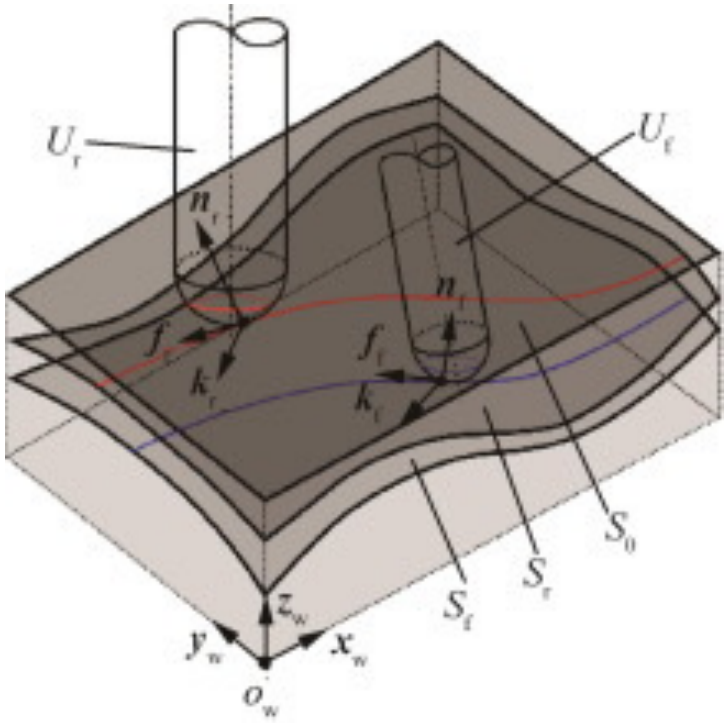
Theater Zuidplein. Source: Studio RAP

Milling

Sagrada Familia. Source: Prototyping for Architects, M. Burry, J. Burry

Carrara Marble Diamond Wire Cutting. Source: Jelle Feringa, ODICO Robotics

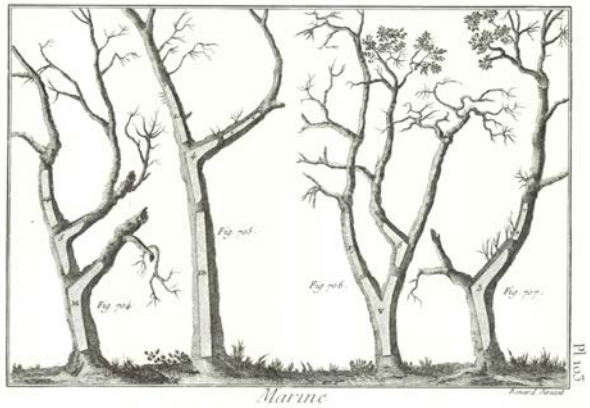
Cambridge Moschee. Source: Designtoproduction, Blumer Lehmann

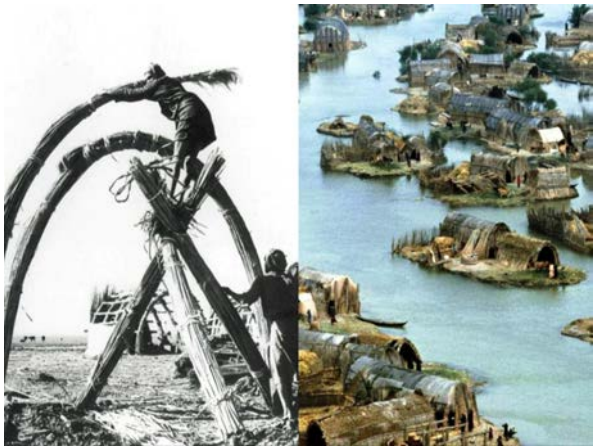


Source: https://doi.org/10.1016/j.cja.2017.07.004

Milling Wood and Stone

Overview



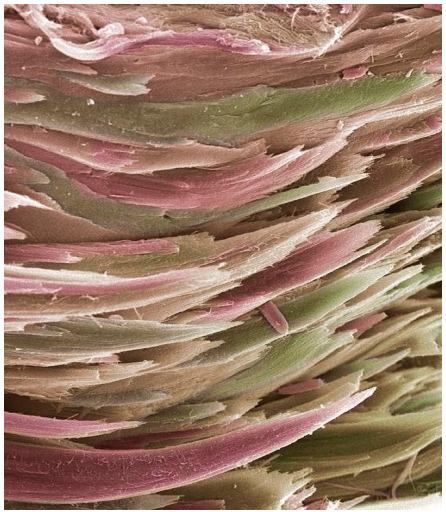


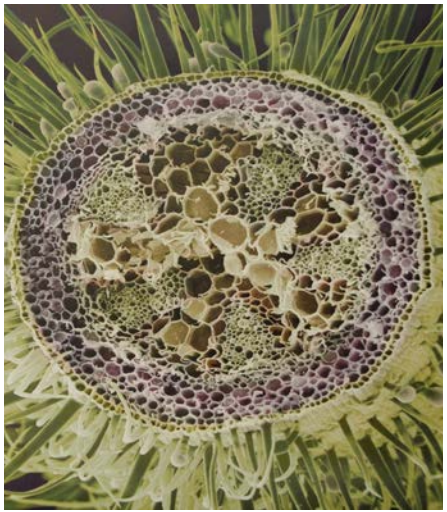
Top: Plate 103 from the Encyclopédie Méthodique: Marine (1798)
Bottom: Vernacular architecture in the Euphrat Delta Region in Iraq (Paul Oliver)

Top: Marble Quary, Carrara, Italy. Source: National Geographic Society

Milling Wood and Stone

Structure and Shape

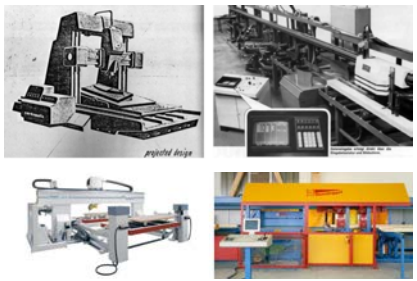




A

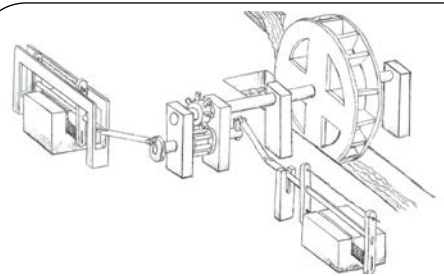
B

C



A

B



C

A: Ancient Hand Tools and Their Equivalents Today; B: Bandsaw from 1875; C: Early and modern CNC and wood processing machines

A: Stonemason's chizzle kit B: Hierapolis sawmill, Roman machinery, 3rd century AD ; C: Modern CNC and wood processing machines

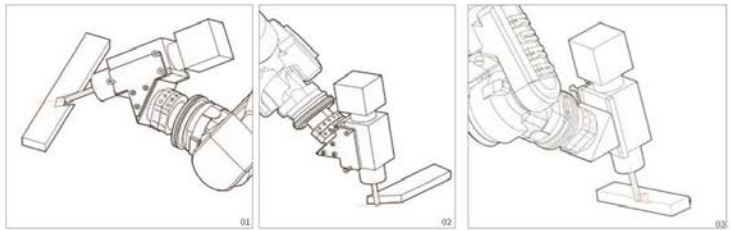
Siemens Sinumerik CNC panel, 1979 Source: Carlos Vieira, 2006

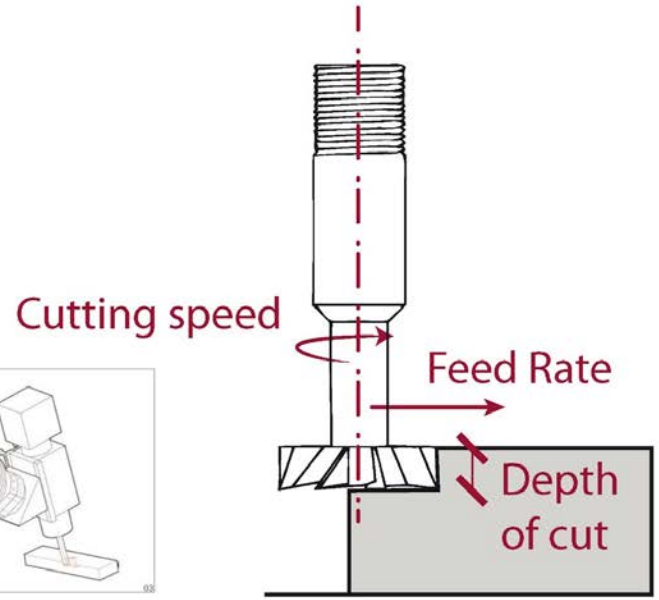
- **Cutting speed** [m/min] (RPM)

- **Feed Rate**
  - -Feed per Tooth [mm/tooth]
  - - Feed per Revolution [mm/Rev]
  - - Feed per Unit of Time [feed/min] [feed/sec]

- **Depth of cut** [mm]

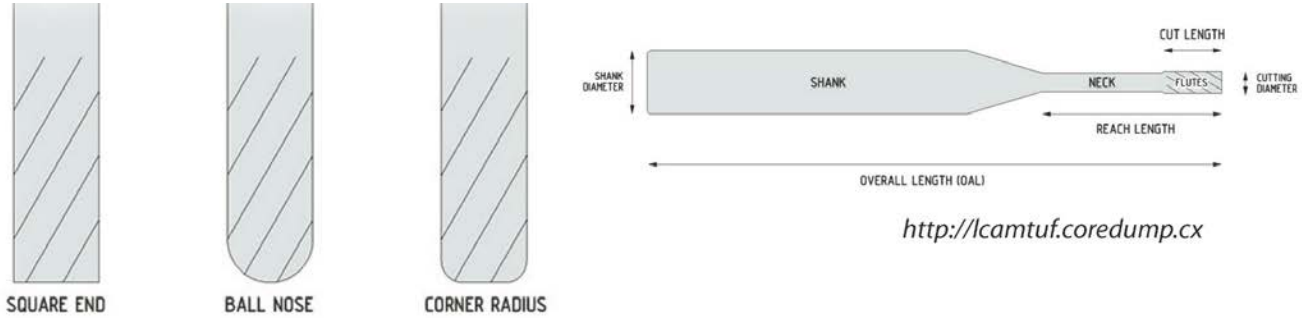
Chip Load
amount of material (load) each flute cuts during each revolution (every chip)



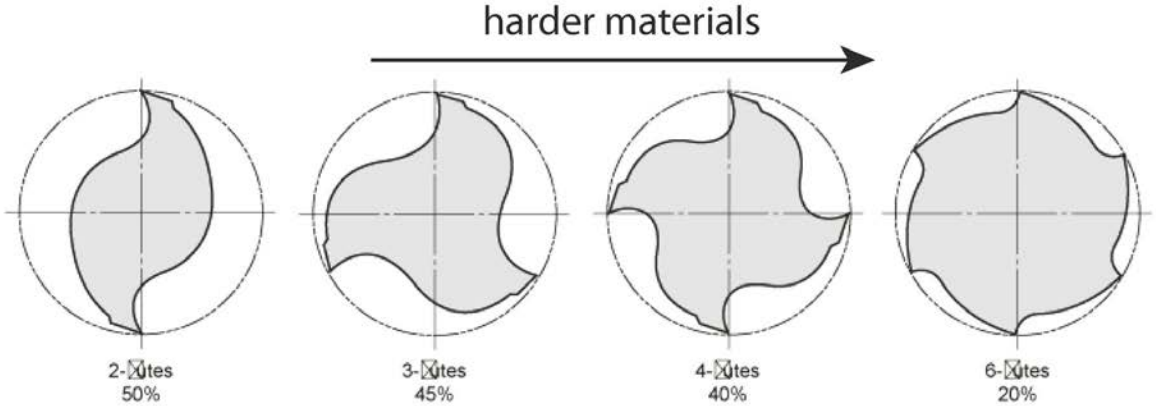


Milling / Sawing

Tools : Milling cutters



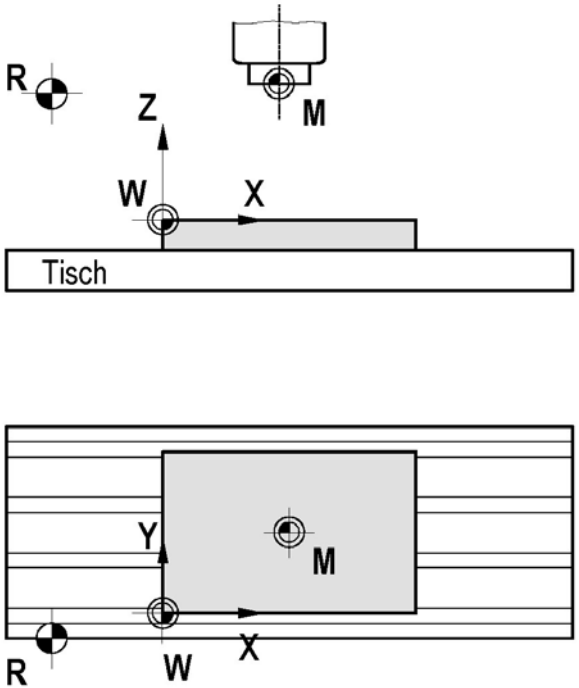
http://lcamtuf.coredump.cx



http://www.mitsubishicarbide.net/

Milling / Sawing

Milling Tools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Y
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W
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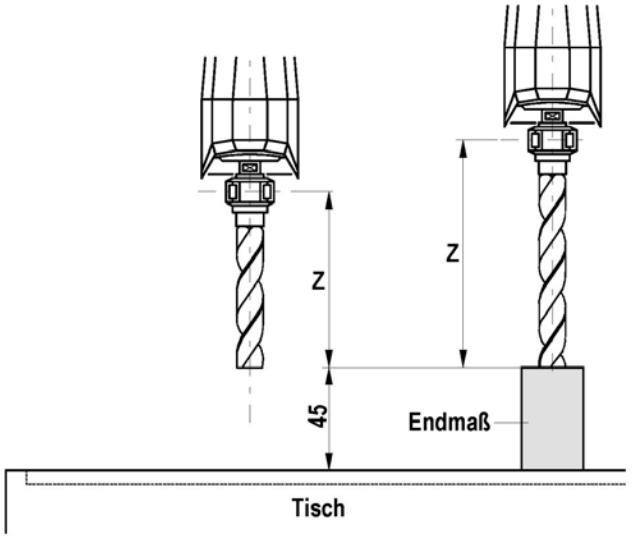
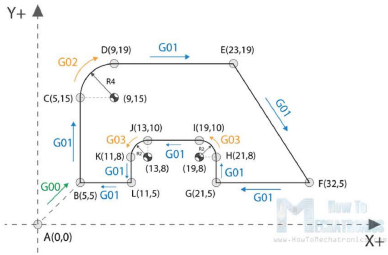

Z
Z
45
Endmaß
Tisch

Milling Wood and Stone

Programming: G-Code




```
%                                  Code initialization. This character (%) is always present at the beginning and at the end of the program.
G21 G17 G90 F100                   Safety line: Set programming in metric system (all dimensions in mm), XY plane, absolute positioning and feed rate of 100 inches/min.
M03 S1000                          Spindle on clockwise at speed of 1000 RPM.
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G01 X5 Y5 Z-1       ; point B      Controlled motion on the same position, but lowering the tool to -1.
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G02 X9 Y19 Z-1 I4 J0  ; point D    Clockwise circular motion to point D(9,19), with center point at (9,15).
G01 X23 Y19 Z-1     ; point E      Linear cutting to point E(23,19).
G01 X32 Y5 Z-1      ; point F      Linear cutting to point F(32,5).
G01 X21 Y5 Z-1      ; point G      Same straight cutting to point G(21,5).
G01 X21 Y8 Z-1      ; point H      One more straight cutting to point H(21,8).
G03 X19 Y10 Z-1 I-2 J0  ; point I  Counterclockwise circular interpolation to position I(19,10), with a center point at (19,8).
G01 X13 Y10 Z-1     ; point J      Linear cutting to point J(13,10).
G03 X11 Y8 Z-1 I0 J-2  ; point K   Counterclockwise circular cutting to position K(11,8), with a center point at (13,8).
G01 X11 Y5 Z-1      ; point L      Linear cutting to position L(11,5).
G01 X5 Y5 Z-1       ; point B      Final linear cutting movement to position B(5,5).
G01 X5 Y5 Z0                       Rise up the tool.
G28  X0 Y0                         Go to home position.
M05                                Spindle off.
M30                                Main program end.
%
```

Let’s take a look at a single line and explain how it works.

G01 X247.951560 Y11.817060 Z-1.000000 F400.000000

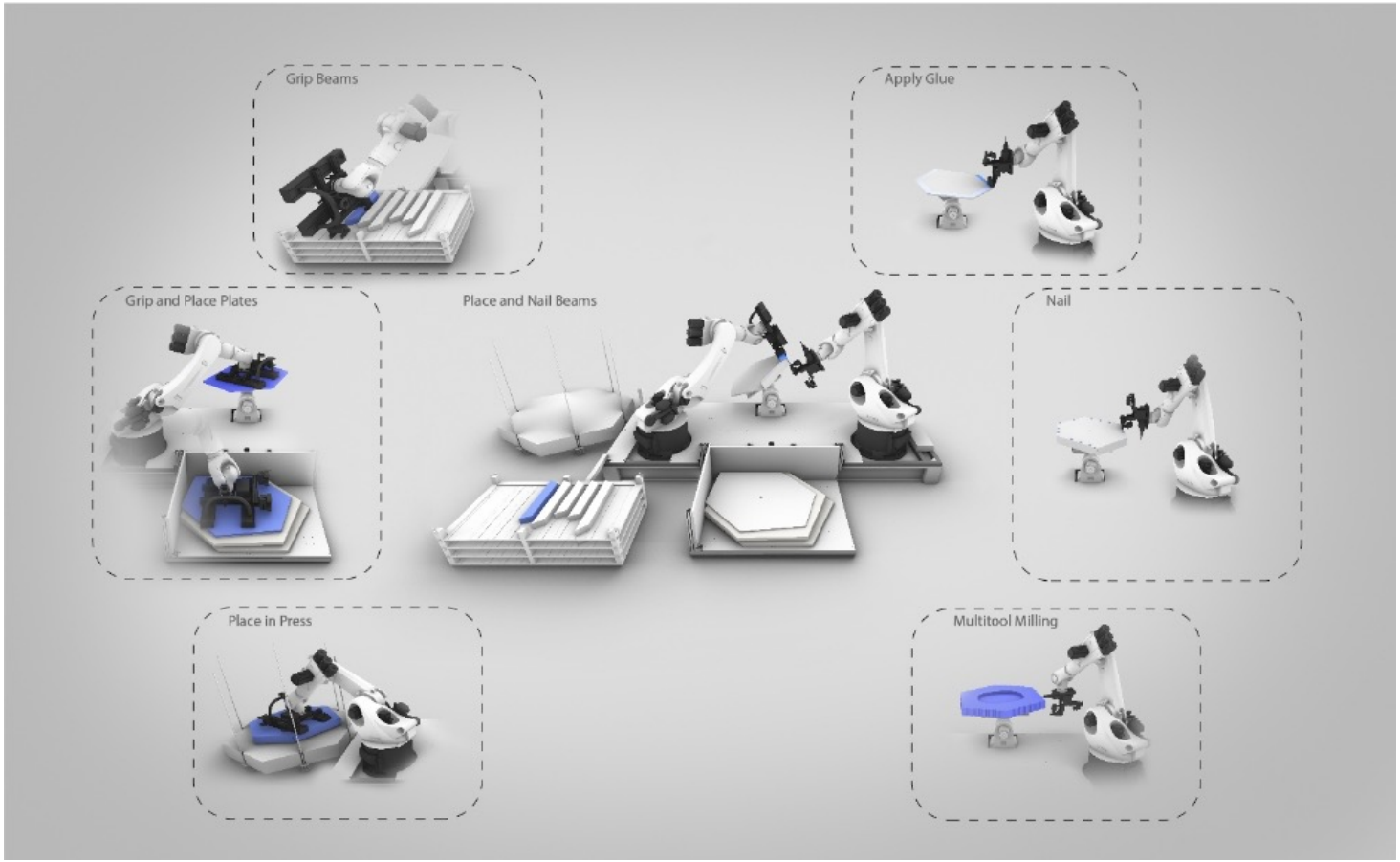
The line has the following structure:

G## X## Y## Z## F##

BUGA Wood Pavilion

By ICD and ITKE University of Stuttgart

Source: https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/



Source: https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/

BUGA Wood Pavilion

By ICD and ITKE University of Stuttgart

Source: https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/

BUGA Wood Pavilion

By ICD and ITKE University of Stuttgart

Source: https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/

Armadillo Vault

Venice Architecture Biennale, Italy | 2016

Structural design and Architectural geometry

- Block Research Group

Structural engineering

- Ochsendorf De Jong and Block (ODB)

Fabrication and construction

- The Escobedo Group

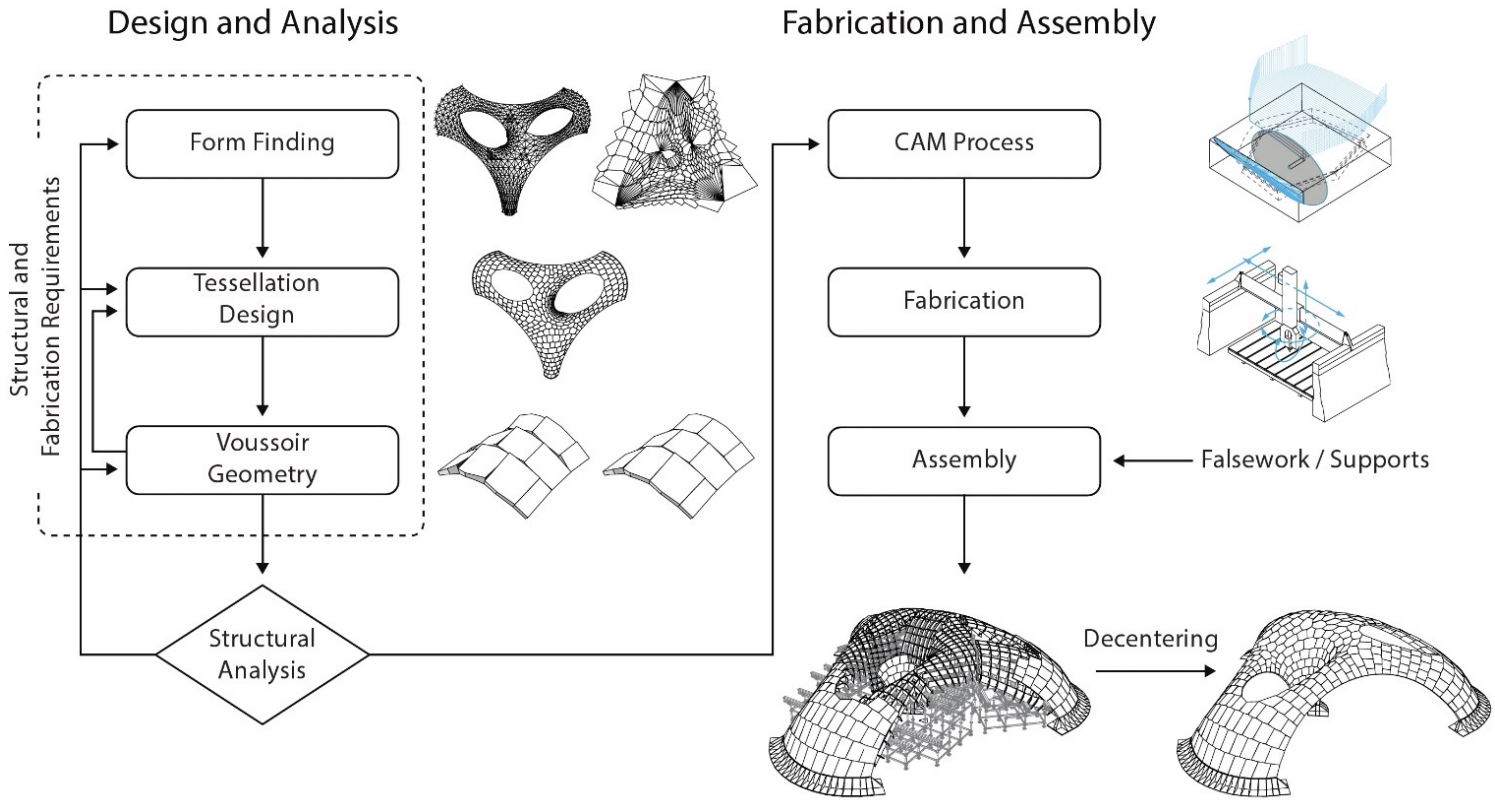
Lighting

- Lichtkometenz
- Artemide

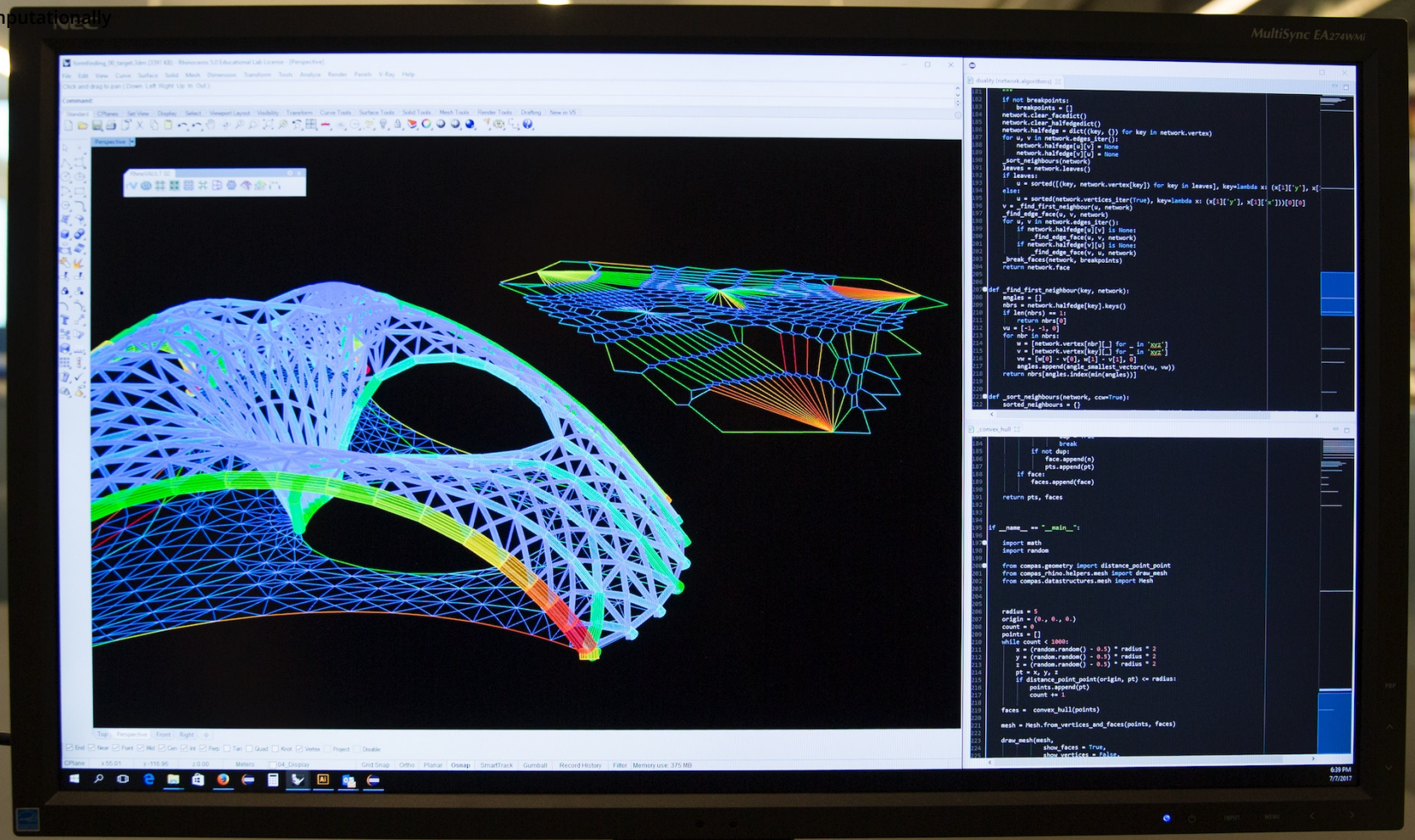
Sponsors

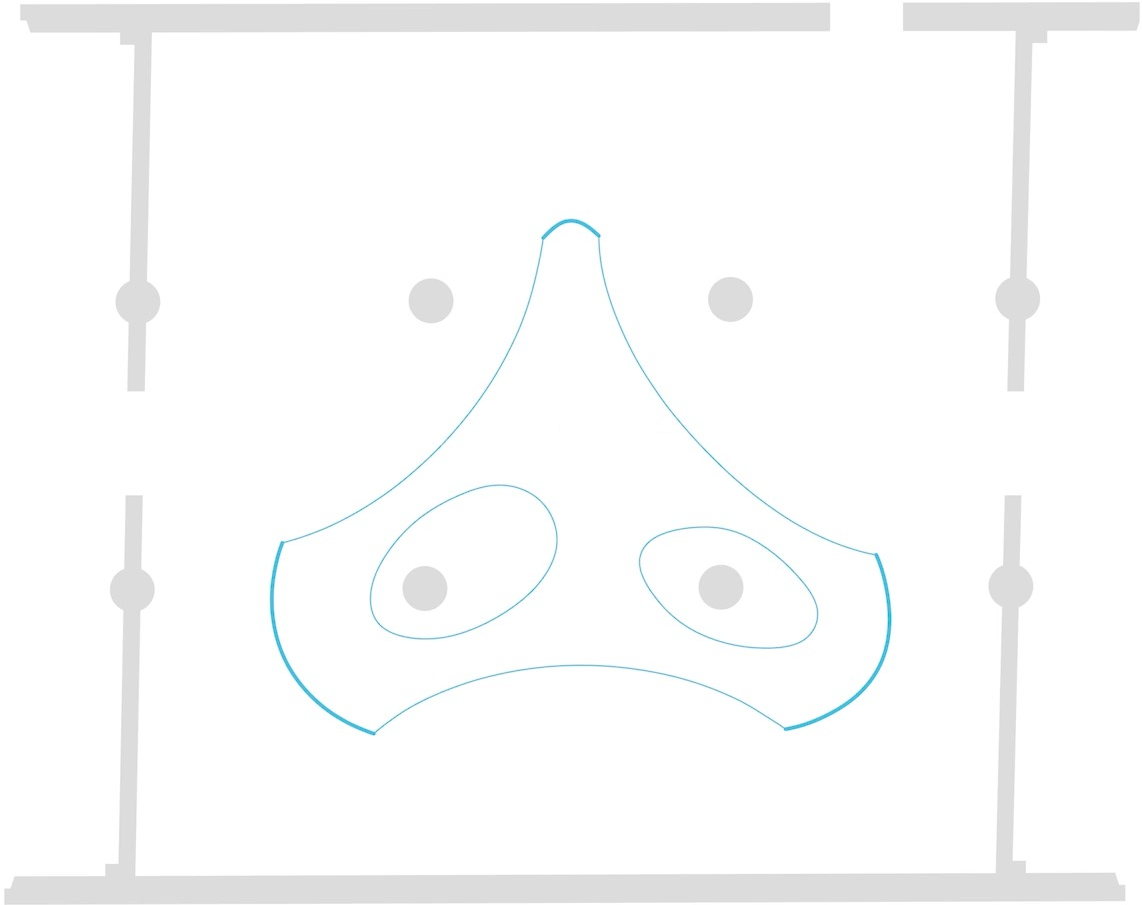
- Kathy and David Escobedo
- ETH Zurich – Department of Architecture
- MIT – School of Architecture and planning
- NCCR Digital Fabrication

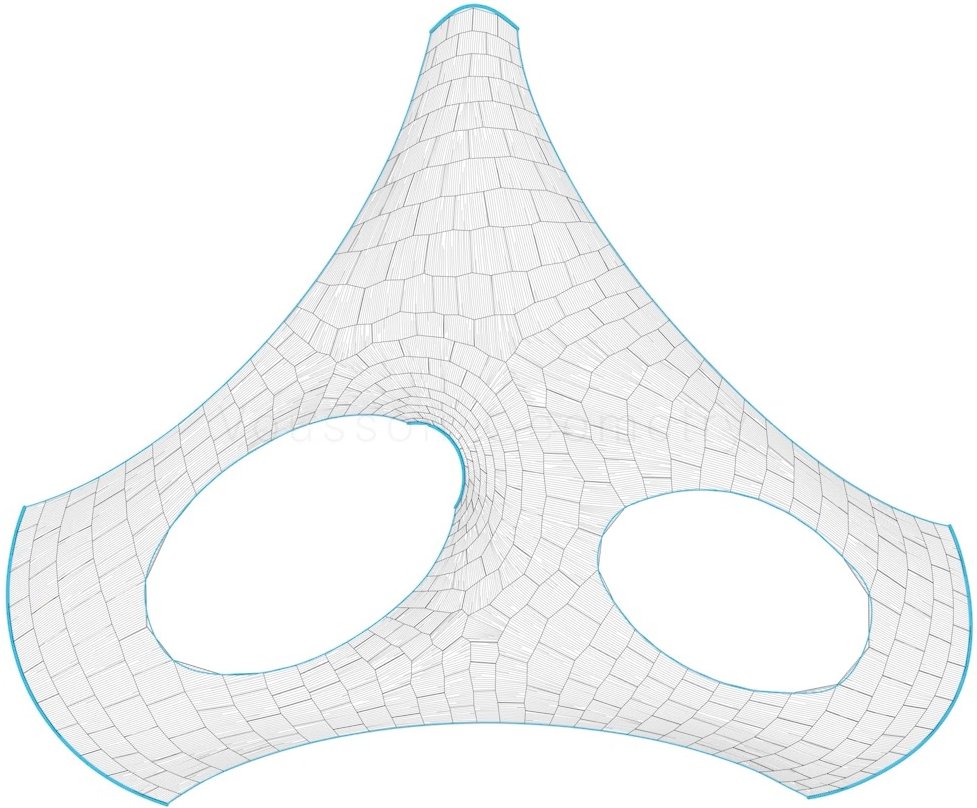
Photo: Iwan Baan



Source: Armadillo Vault Block Reserch Group

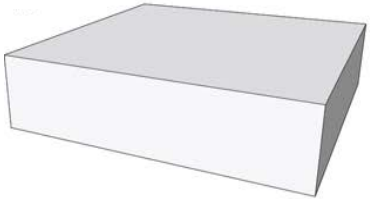

MultiSync EA274WMi

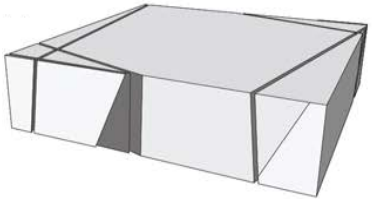


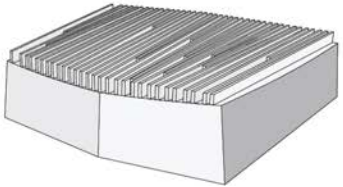


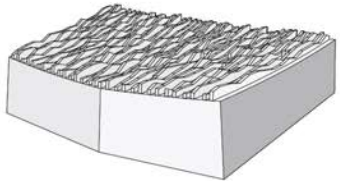
West Texas, USA | January 08, 2016

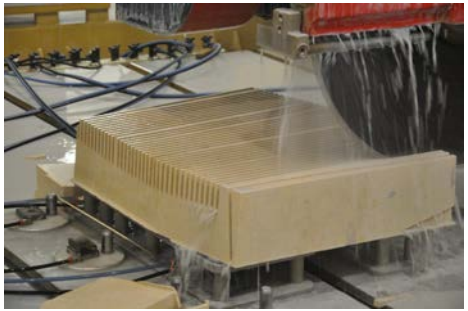
Voussoir Geometry












blade 5
lathe
GROUP
blade 5

Buda, Texas, USA | February 4, 2016

Corderie dell'Arsenale | May 09, 2016


Armadillo Vault
Corderie dell'Arsenale | May 10, 2016

Module		Week	Hr	Topic	Instructor	Assignment
I	Form finding	Week 1 (2/24)	1	**Lecture 1**	**Form finding of Funicular Shell Structures**	**Dr. Juney Lee**	
			2	Tutorial 1	Form finding with compas-RV2	Dr. Juney Lee	
			3				
II	Geometry	Week 2 (3/3)	1	Tutorial 2	Procedural thinking: logic diagrams, flow charts, pseudocodes, Introduction to Jupyter Notebook, Introduction to the Python programming language	Serban Bodea and Chaoyu Du	
			2				
			3	Work Session 2	*Ex. 2.1 Cost of cablenet elements* *Ex. 2.2 Check voussoir weight*	Chaoyu Du	
		Week 3 (3/10)	1	Tutorial 3	Coding in Python: data types, for-loops, conditionals	Serban Bodea and Chaoyu Du	
			2	Work Session 3	*Ex. 3.1 Organising your design data* *Ex. 3.2 Managing your design data*	Chaoyu Du	
			3				
		Week 4 (3/17)	1	Tutorial 4	Introduction to computational geometry in COMPAS Geometry and Class in COMPAS	Serban Bodea and Chaoyu Du	
			2				
			3	Work Session 4	*Ex. 4.2 Visualising Geometries using the Compas Plotter*	Chaoyu Du	
		Week 5 (3/24)		Seminar week			
III	Materialisation	Week 6 (3/31)	1	**Lecture 2**	**Geometry, Rationalization & Materialization**	**Dr. Juney Lee**	
			2	Tutorial 5	Introduction to The Mesh Half-edge data structure	Dr. Juney Lee and Chaoyu Du	
			3	Work Session 5	*Ex. 5.1 Segmented shell from Mesh Half-edge data structure* *Ex. 5.2 Visualizing the Mesh Half-edge data structure with COMPAS Viewer*	Dr. Juney Lee and Chaoyu Du	
		Week 7 (4/7)	1	Tutorial 6	Operations with the Mesh Half-edge data structure	Dr. Juney Lee and Chaoyu Du	
			2	Work Session 6	*Ex. 6.4 Mesh Topological Modification on vertices and faces* *Ex. 6.4a Topology modification through deletion* *Ex. 6.4 Mesh Topological Modification on vertices and faces* *Ex. 6.4b Topology modification through subdivision*	Dr. Juney Lee and Chaoyu Du	
			3				
		Week 8 (4/14)	1	Tutorial 7	Geometry rationalization and materialization methods for funicular structures: Case Studies	Dr. Juney Lee and Chaoyu Du	
			2	Work Session 7	*Ex. 7.1 Rationalization and materialization methods for meshes*	Dr. Juney Lee	
			3				
		Week 9 (4/21)		Easter			
		Week 10 (4/28)	1	**Lecture 3**	**Introduction to Computer Assisted Manufacturing for Architecture Engineering and Construction**	**Serban Bodea**	
			2	Tutorial 8	Introduction to Hotwire Cutting	Selina Bitting	
			3	Work Session 8	*Ex. 8.1 Orient Block for Cutting* *Ex. 8.2 Add Geometry of Cutting Material* *Ex. 8.3 Place Block w/ Cutting Material on Machine Bed* *Ex. 8.4 Generate Wire Cutter Path & Output*		
IV	Fabrication	Week 11 (5/5)	1	Work Session 9 Work on the Assignment 3	*Form Finding and Design Iterations* *Geometry, Rationalization and Materialization*	Dr. Juney Lee, Serban Bodea, Selina Bitting, Chaoyu Du	Assignment 3 (in groups)
			2				
			3				
		Week 12 (5/12)	1	Work Session 10 Work on the Assignment 3	*Material selection* *Process workflow*	Dr. Juney Lee, Serban Bodea, Selina Bitting, Chaoyu Du	
			2				
			3				
V	Dissemination	Week 13 (5/19)	1	**Lecture 4**	**Guest lecture: Dr. Catherine De Wolf**		Presentations
			2	Work Session 11	Group presentations of assignment 3		
			3				

Assignment of the Fabrication Module