Numerical modelling and data-driven approaches as valuable tools for the development of new 3D printable inks

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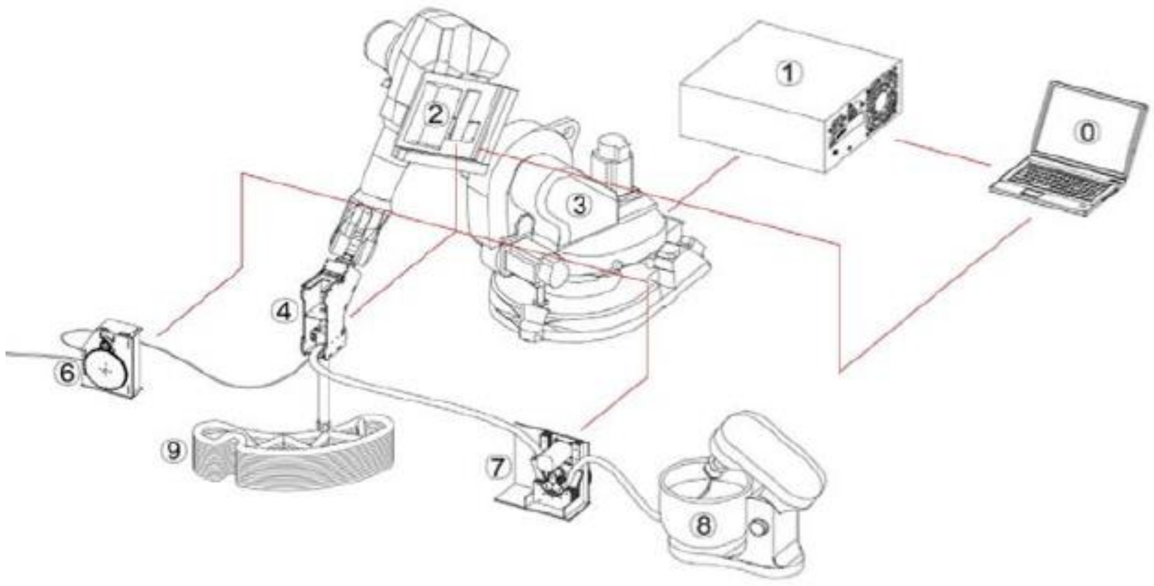
Plan of the talk

- Introduction
- Frequent issues in 3DCP
- Standard solutions and beyond
- Proposed tool
  - Flow table test
  - Numerical model
  - Artificial neural network
- Conclusions

What is **3D Concrete Printing**?



1 = robot controller

2 = robotic arm

4 = printhead + nozzle

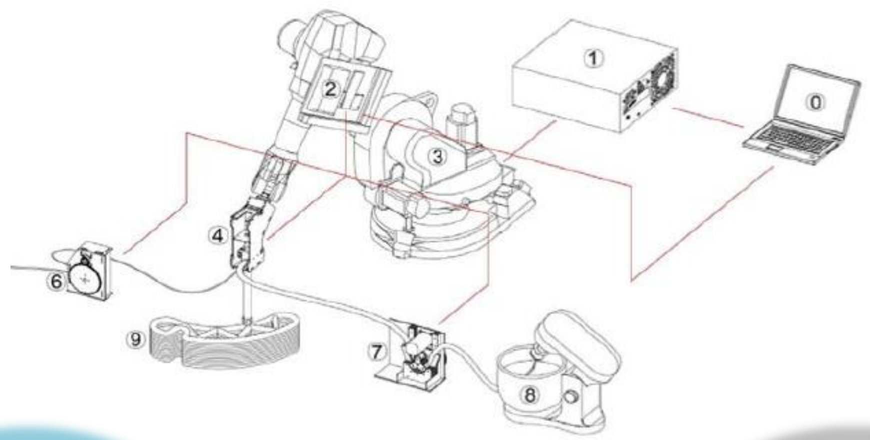
9 = 3D printed object

Striatus bridge
Block Research Group, ETH Zurich

3D Concrete Printing

Materials

- Aggregates
- Rheology
- Sustainability
- High-performance concrete



Structure

- Optimized shapes
- Durability and maintenance

Process

- Printing velocity
- Extrusion velocity
- Toolpath

Reinforcement

- Automatization
- Seismic conditions

At the scale of the object:

Elastic buckling
R. J. M. Wolf (2019)

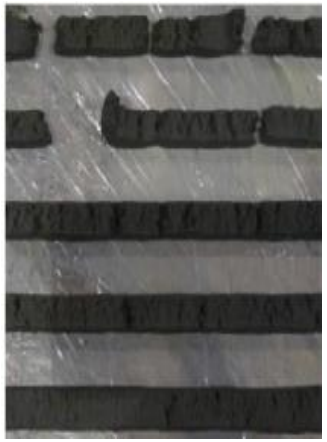
Plastic collapse
Concre3DLab Ghent

Plastic shrinkage and cracking

Weak bonds and cold joints

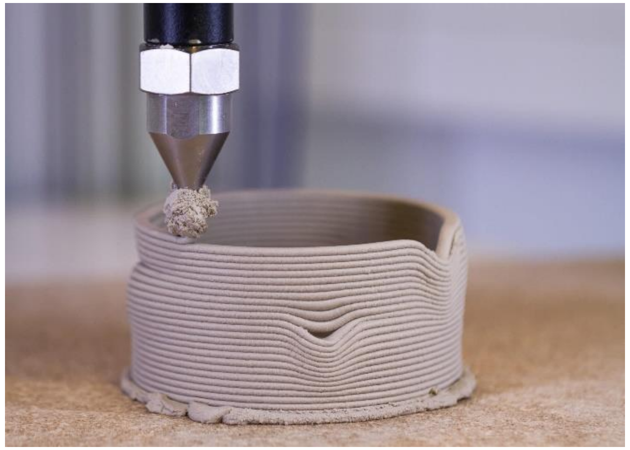
Frequent issues in 3DCP

At the scale of the filament:



Filament tearing
Ramyar et al. (2022)

Uneven layer's height
TechnoMagazine



Under-extrusion

Over-extrusion

Standard solutions and beyond

1) The trial-and-error approach

- Relying on the experience of the workers
- Huge amount of time and resources

2) Experimental test

- Time-consuming
- Not considering the process

3) Numerical simulations

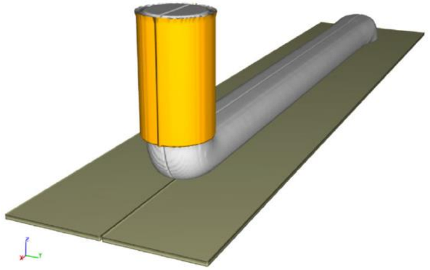
- Quantitative outputs
- Softwares are under development)
- Accuracy is related to experimental test

4) Online monitoring through sensors and digital twins

- Accurate results and online correction of the printing/material parameters
- Under development

1)

2)



3)

4)

IDEA

To develop a tool to help control the extrusion process and to develop new 3D printable mixes.

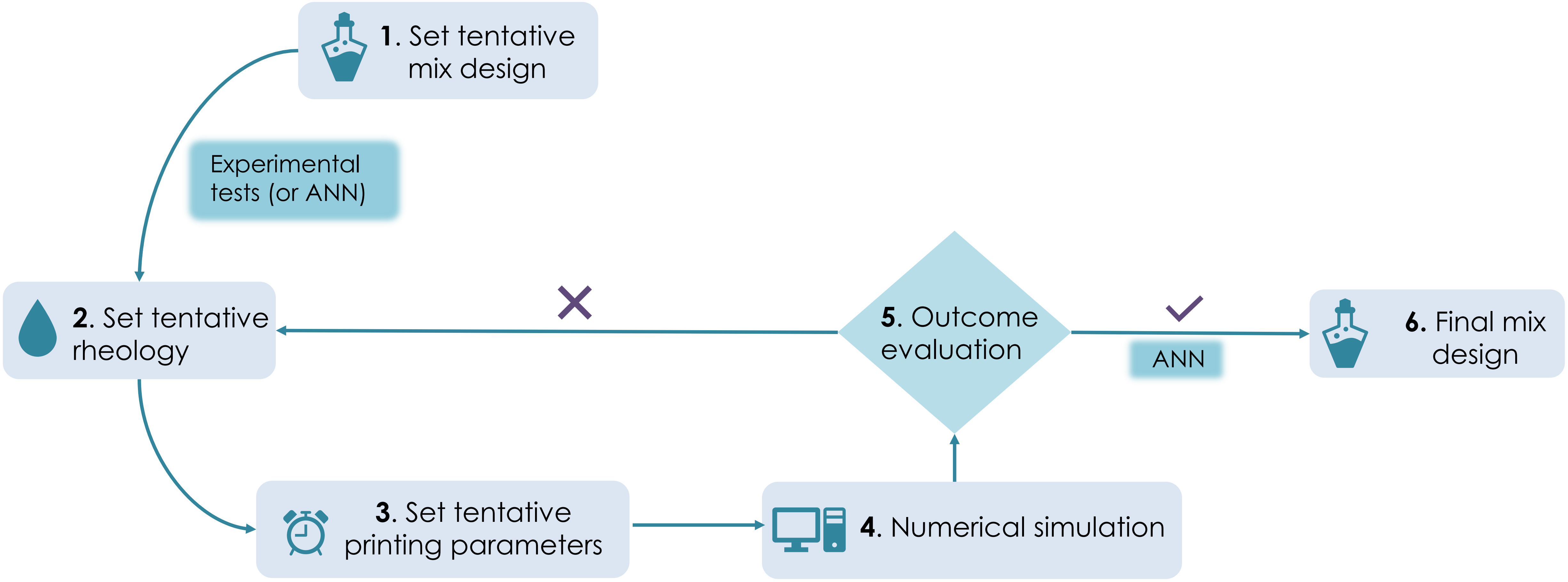
WHY?

- Increase reliability and geometrical accuracy of the printed objects.
- Optimize the process while ensuring good layer quality.
- Develop of new and more sustainable mixes.

HOW?

Combining in a single framework experimental tests, numerical simulation and AI techniques.

Proposed tool



Proposed tool: flow table test

1. Set tentative mix design → **2.** Set tentative rheology

Flow table test

we want a simple and fast test, to compute the yield stress!

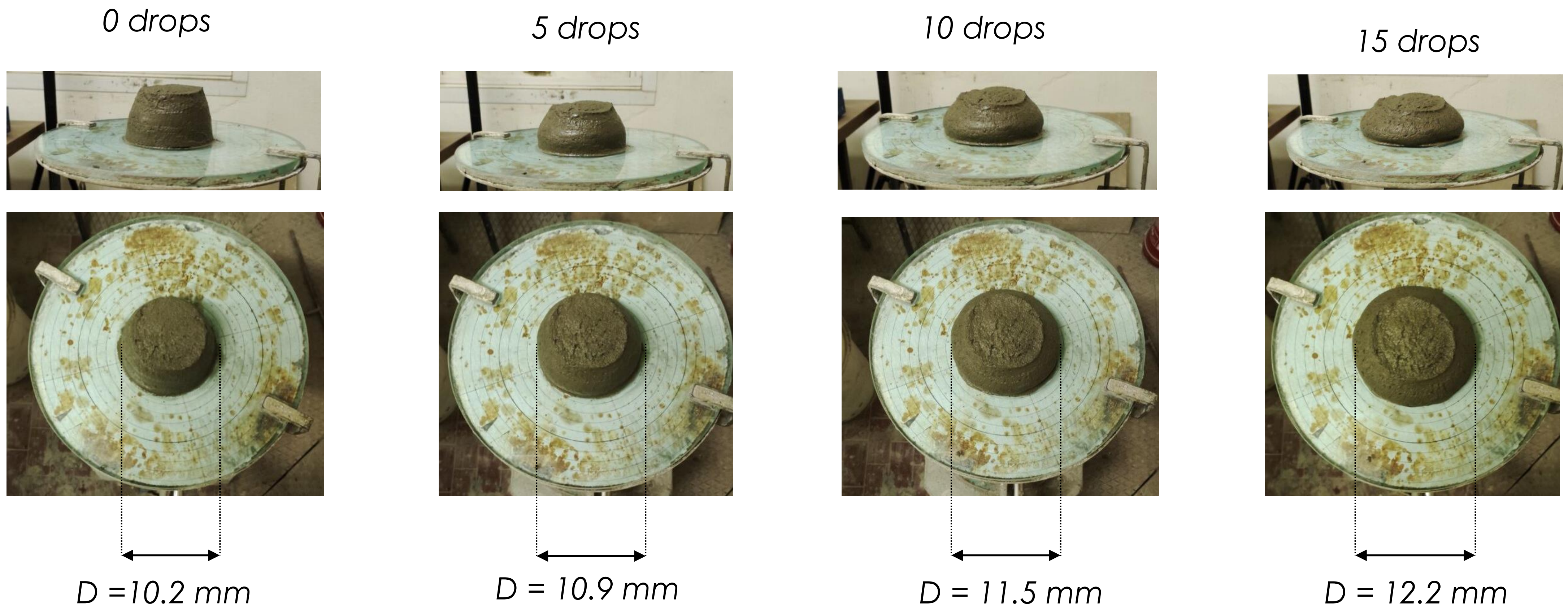
Mix 288	
Binder	894.66 kg/m^3
Water	295.24 kg/m^3
Aggregate	1118.32 kg/m^3
Superplasticizer	1.79 kg/m^3
Water/Binder	0.33
Aggregate/Binder	1.25
Aggregate dim.	1.50

Mix density: 2310 kg/m^3

Flow table test

Cone volume: 344 cm^3

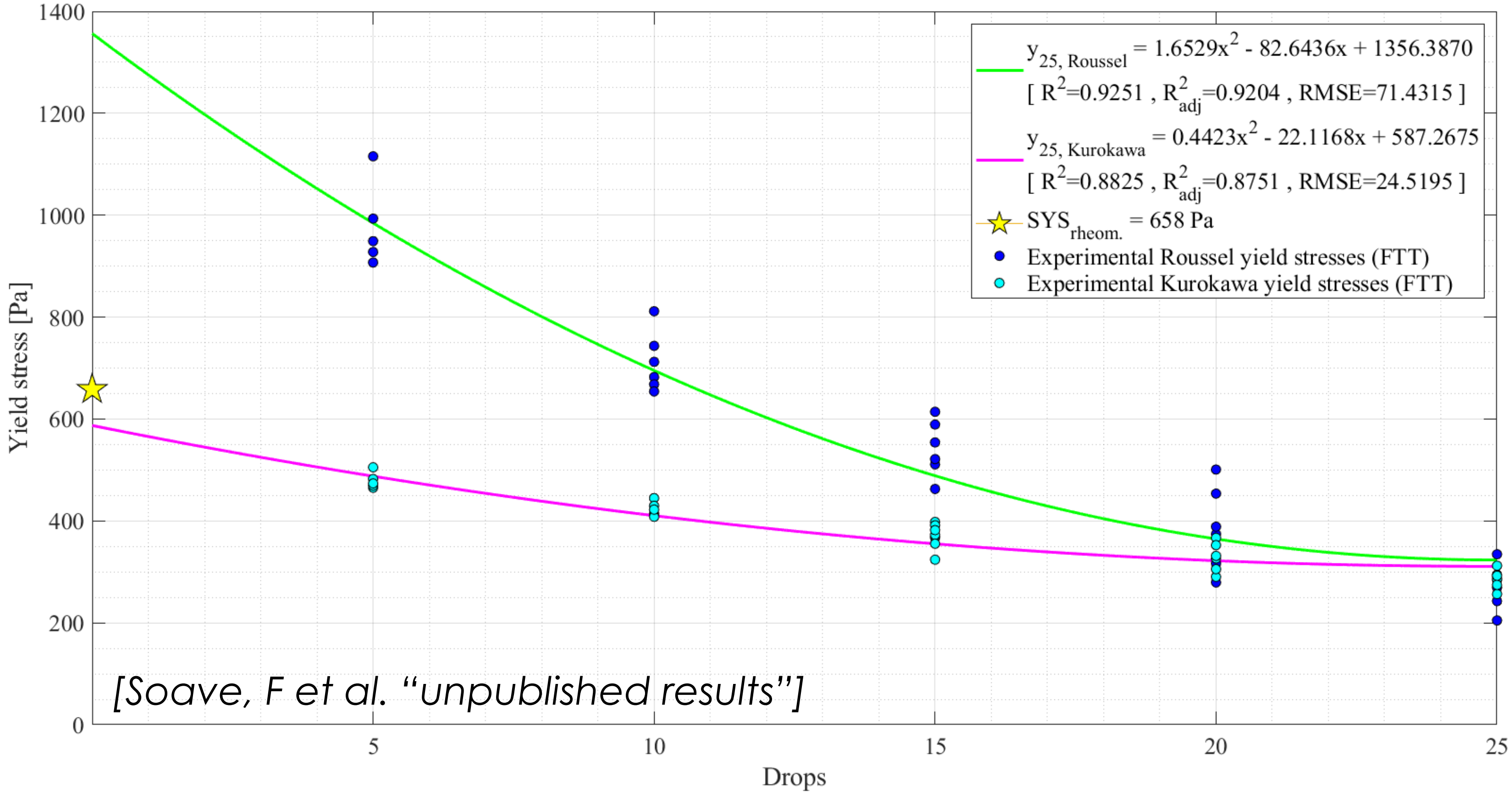
Proposed tool: flow table test



In the literature, some formulas have been proposed to correlate the paste's static yield stress with the spreaded concrete's diameter.

Proposed tool: flow table test

- Roussel relation: $\tau_y = \frac{225\,\rho\,g\,V^2}{128\,\pi^2 R_t^5}$
- Kurokawa relation: $\tau_y = \frac{1}{\sqrt{3}}\sigma_v = \frac{1}{\sqrt{3}}\frac{\rho\,g\,V}{A_{spread}\,[m^2]} = \frac{1}{\sqrt{3}}\frac{\rho\,g\,V}{A_{spread}\,[cm^2]}\cdot 10^8 = \frac{\rho\,g\,V}{100\sqrt{3}\pi R_t^2}\cdot 10^8 = \frac{\rho\,g\,V}{25\sqrt{3}\pi D_t^2}\cdot 10^8\ Pa$



[Soave, F et al. "unpublished results"]

As expected, for low-slump mixes, the Kurokawa relation performs better:

$$\tau_{y,Roussel} = 1356\ Pa$$

$$\tau_{y,Kurokawa} = 587\ Pa$$

Giving a result closer to that obtained from rheometer tests:

$$\tau_{y,rheometer} = 658\ Pa$$

Proposed tool: numerical model

2. Set tentative rheology → **3**. Set tentative printing parameters

Material parameters: $\rho = 2100\ kg/m^3$ $\mu = 7.5\ Pa \cdot s$ $\tau_0 = 630\ Pa$

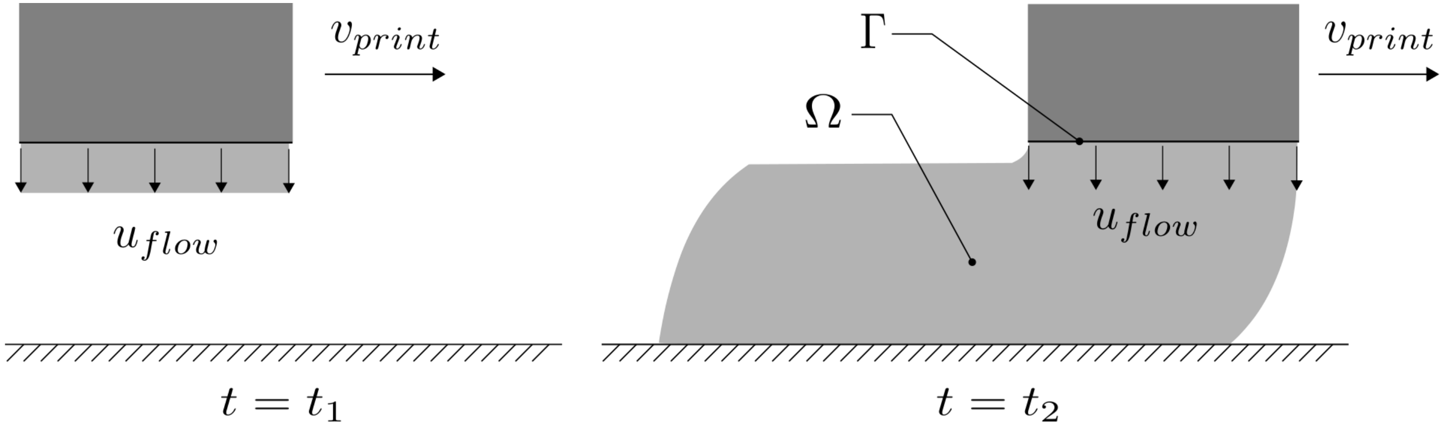
Printing parameters

$v_{flow} = 33.6\ mm/s$

$v_{print} = 30\ mm/s$

$d_{nozzle} = 25\ mm$

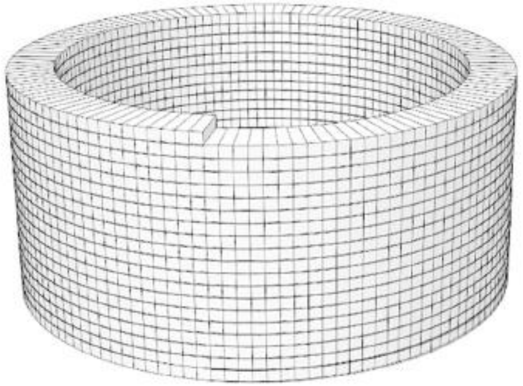
$h_{nozzle} = 12.5\ mm$



Proposed tool: numerical model

3. Set tentative printing parameters → **4**. Numerical simulation

Numerical methods for 3DCP are still under development:

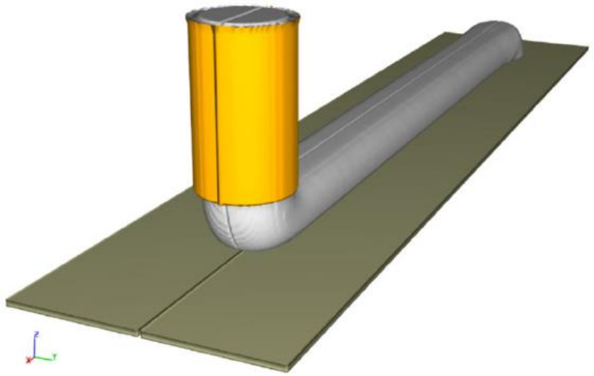


T. Ooms et al. (2021)

Solid continuum models

E. Ramyar et al. (2022)

Discrete models



R. Comminal et al. (2020)

Fluid continuum models

Proposed tool: numerical model

Navier-Stokes equations

Balance of linear momentum

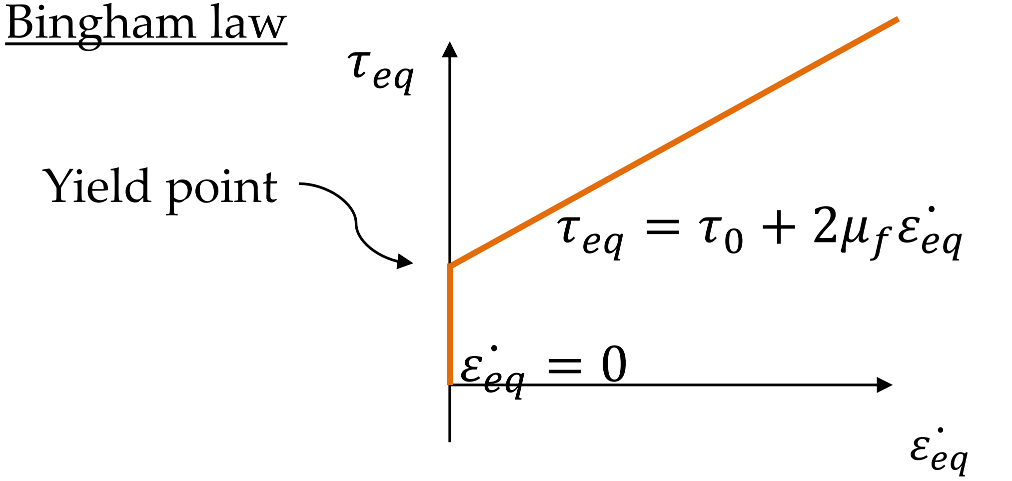
$$\nabla_{\boldsymbol{x}} \cdot \boldsymbol{\sigma} + \rho \boldsymbol{b} = \rho \left(\frac{\partial \boldsymbol{u}}{\partial t}\Big|_{\boldsymbol{X}} + (\boldsymbol{c} \cdot \nabla_{\boldsymbol{x}}) \boldsymbol{u} \right) \quad \text{in } \Omega_t \times [0, T]$$

Balance of mass

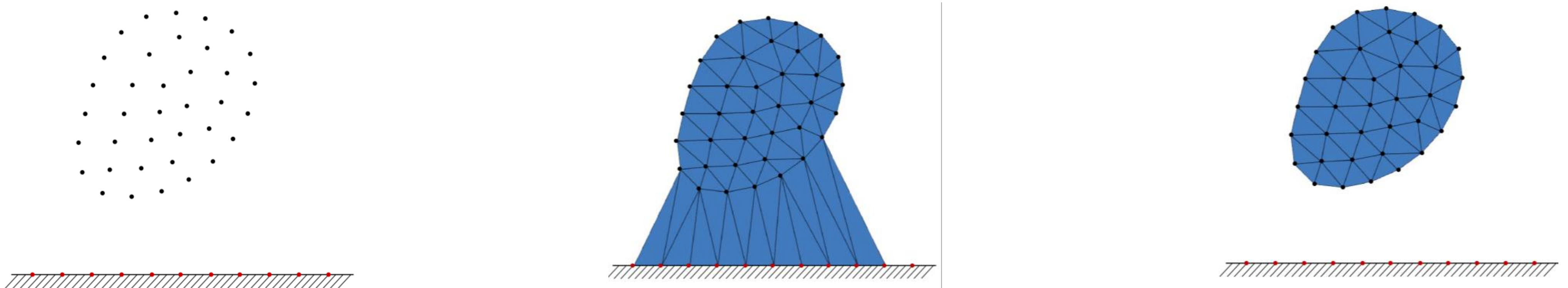
$$\left(\frac{\partial p}{\partial t}\Big|_{\boldsymbol{X}} + \boldsymbol{c} \cdot \nabla_{\boldsymbol{x}} p \right) + K \nabla_{\boldsymbol{x}} \cdot \boldsymbol{u} = 0 \quad \text{in } \Omega_t \times [0, T]$$

Rheological/constitutive law

Bingham law



Particle Finite Element Method



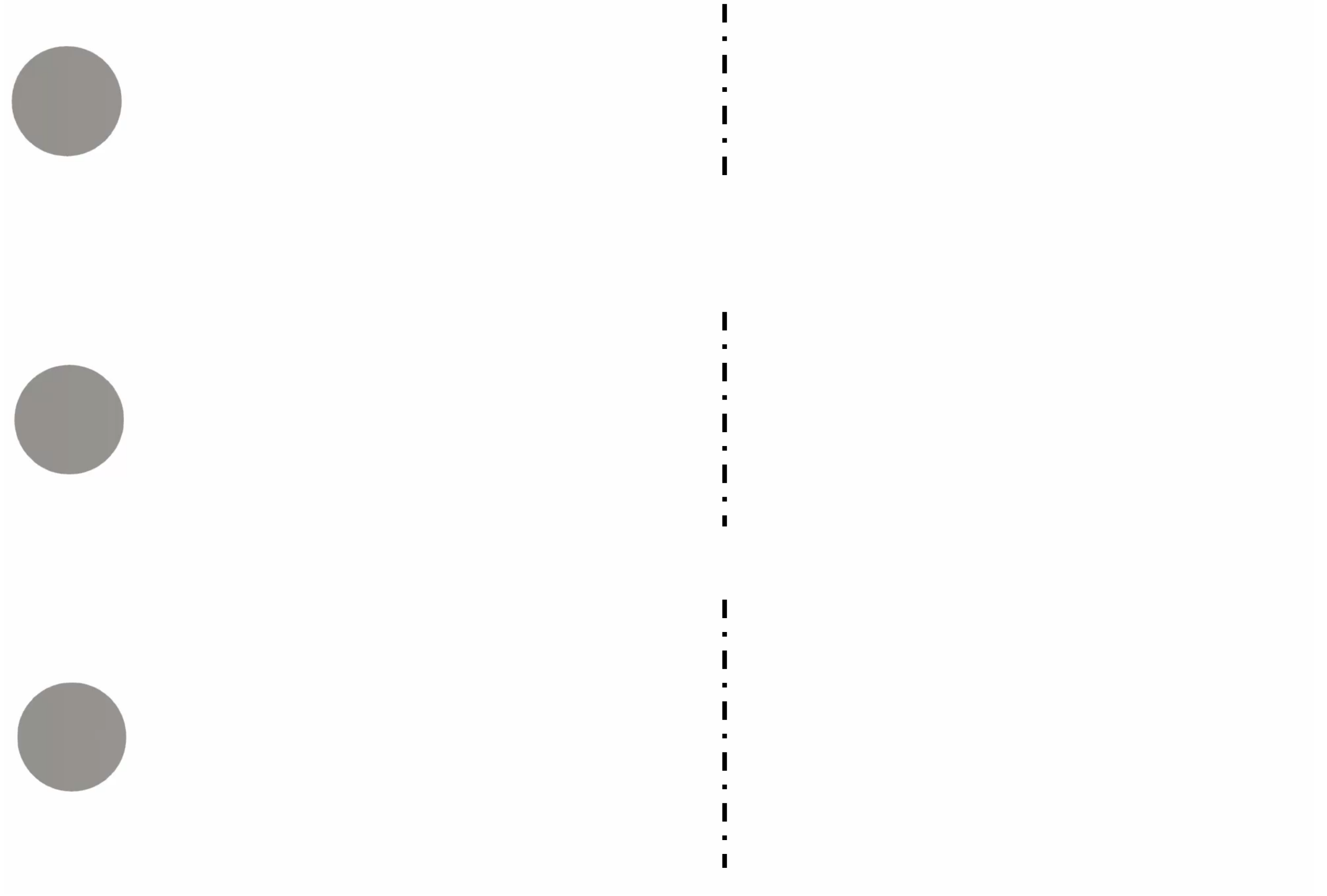
(a)
Remove the previous mesh, obtaining a set of points.

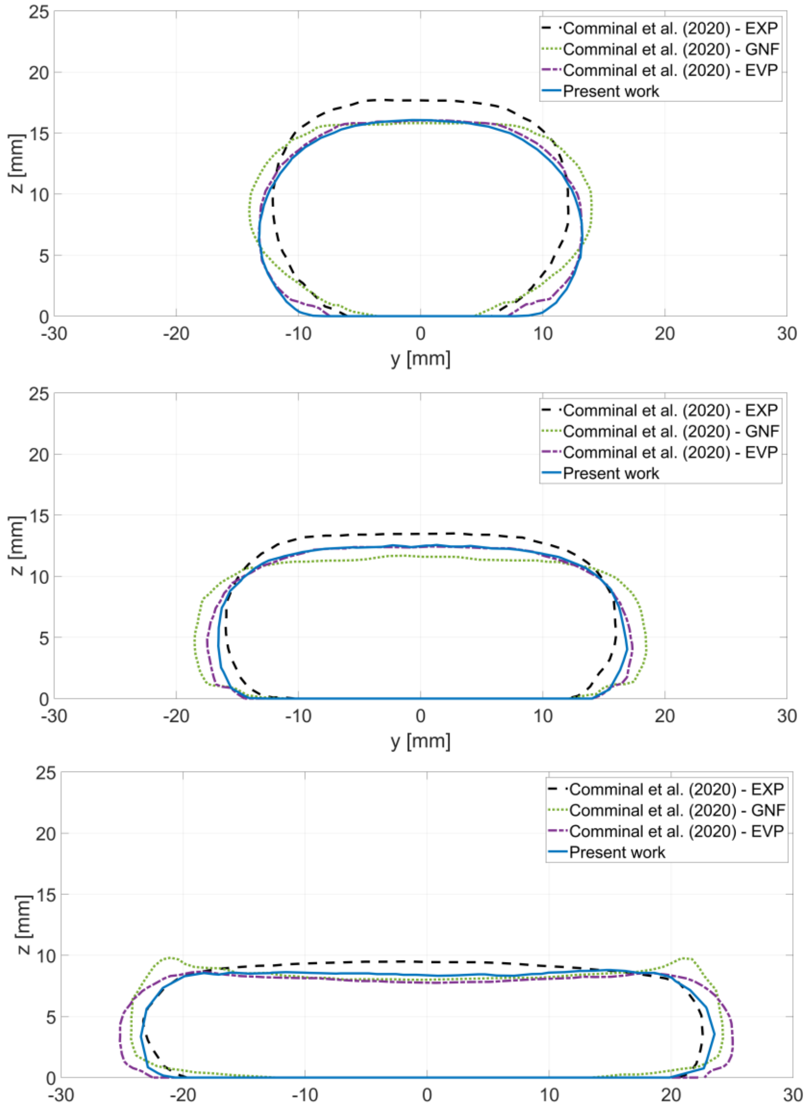
(b)
Delaunay triangulation is performed.

(c)
The alpha-shape method removes overly distorted elements.

Proposed tool: numerical model

Code validation

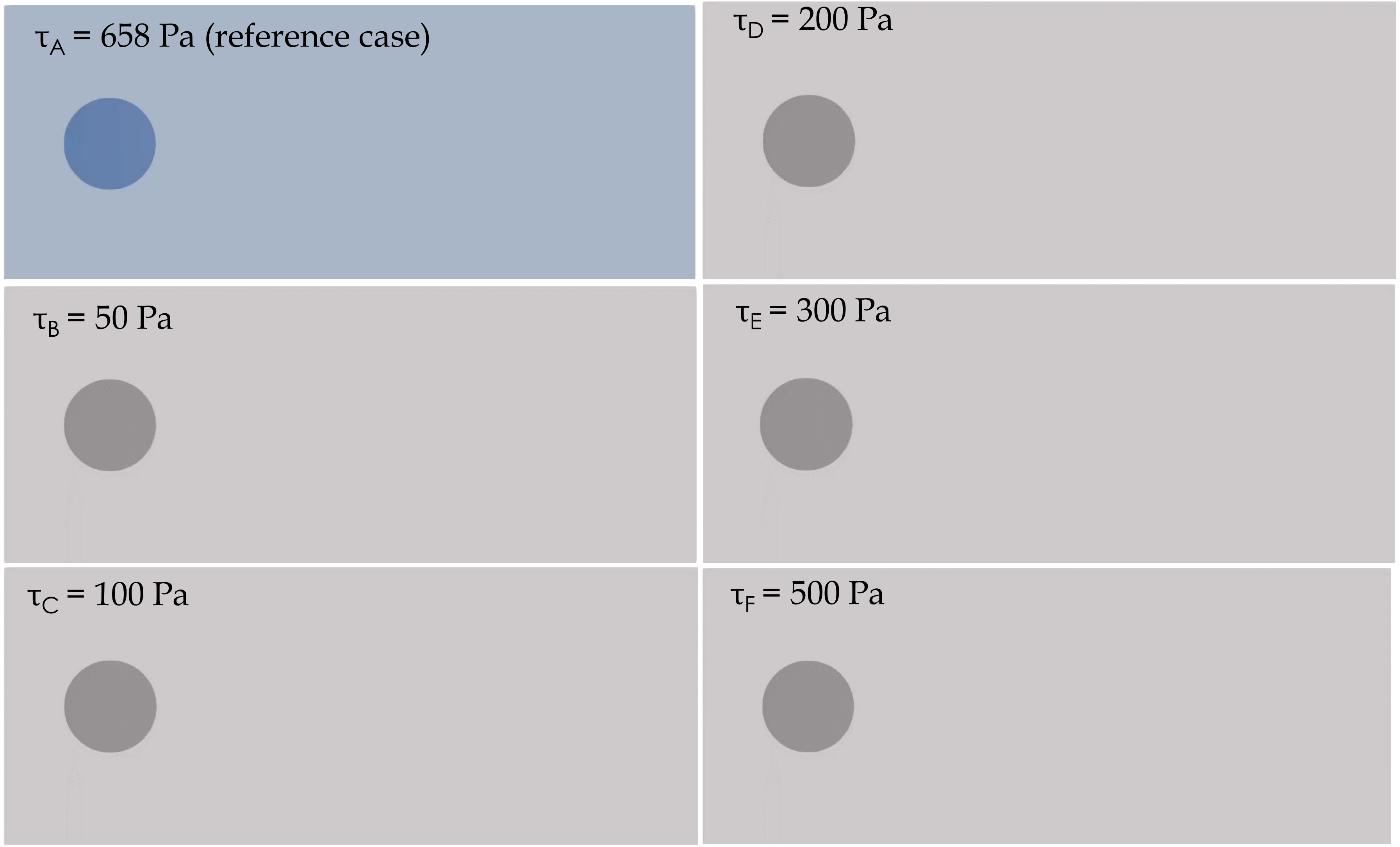




*Rizzieri, G., Ferrara, L. & Cremonesi, M. "**Numerical simulation of the extrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method**." Comput Mech (2023). https://doi.org/10.1007/s00466-023-02367-y*

Proposed tool: numerical model

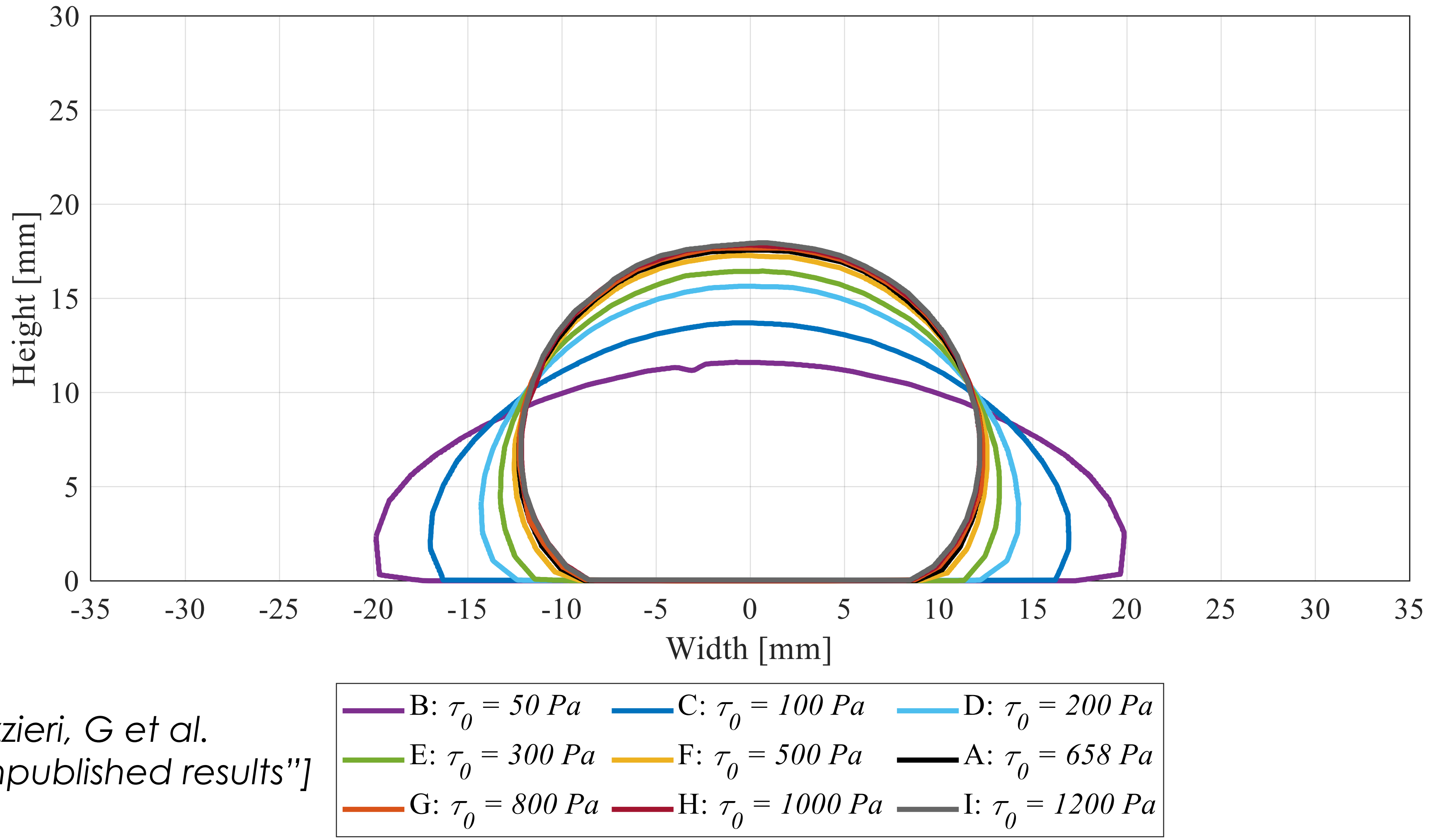
Different yield stress values

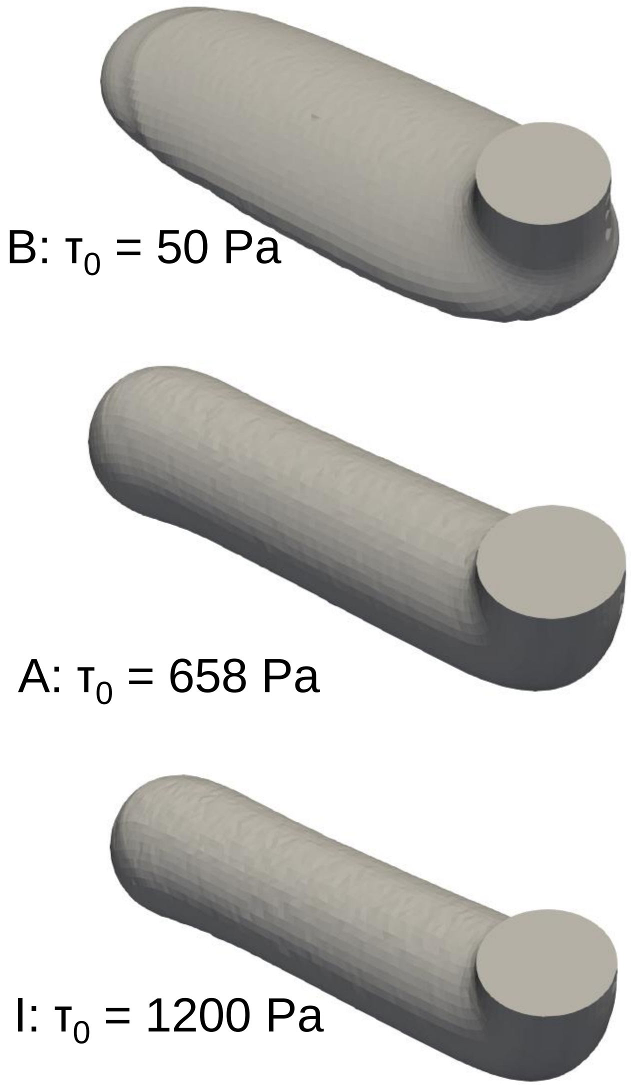


[Rizzieri, G et al. "unpublished results"]

Proposed tool: numerical model

Different yield stress values





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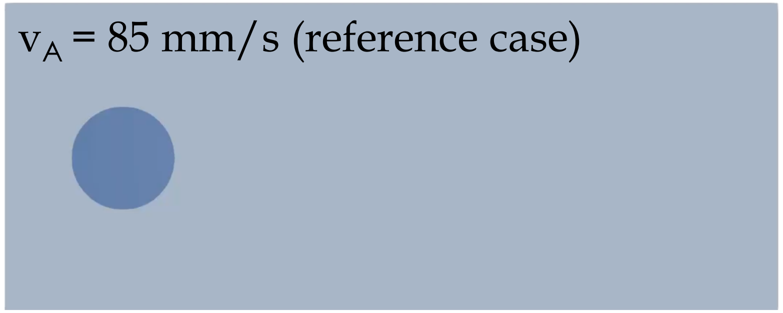
Proposed tool: numerical model

Printing faster than the reference v_p



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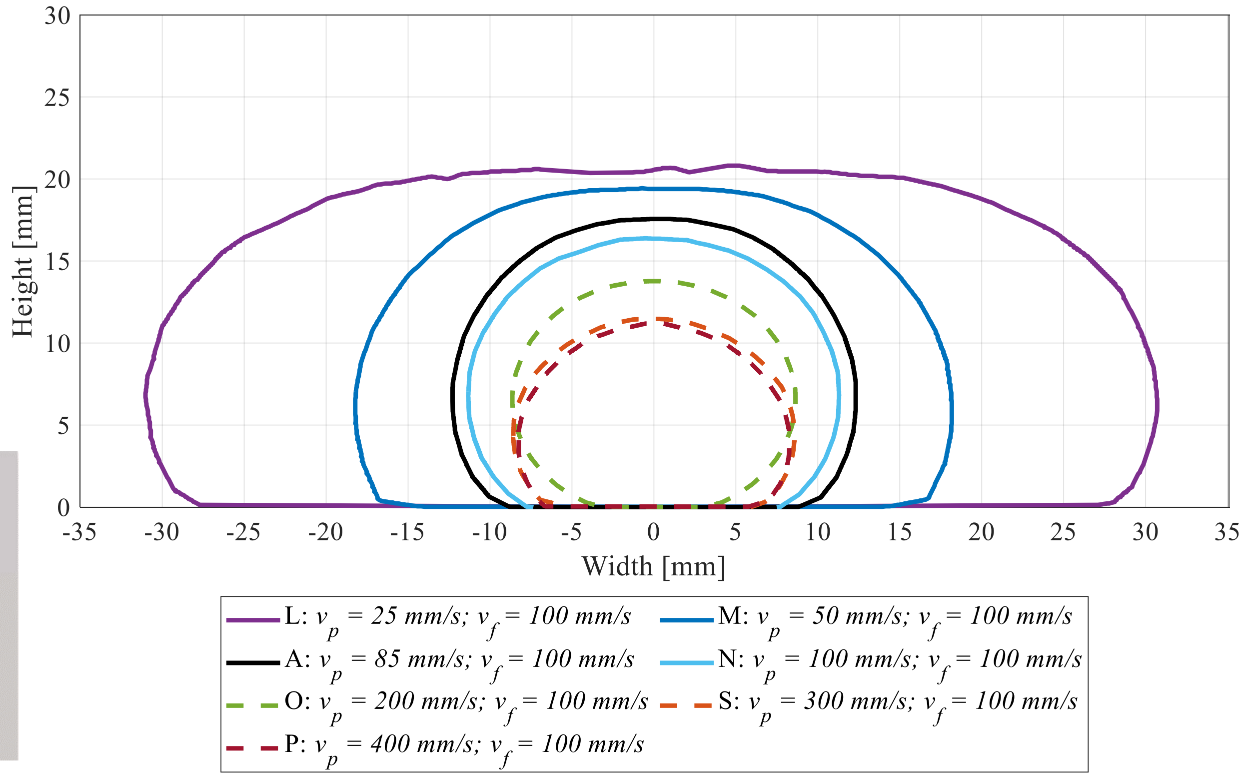
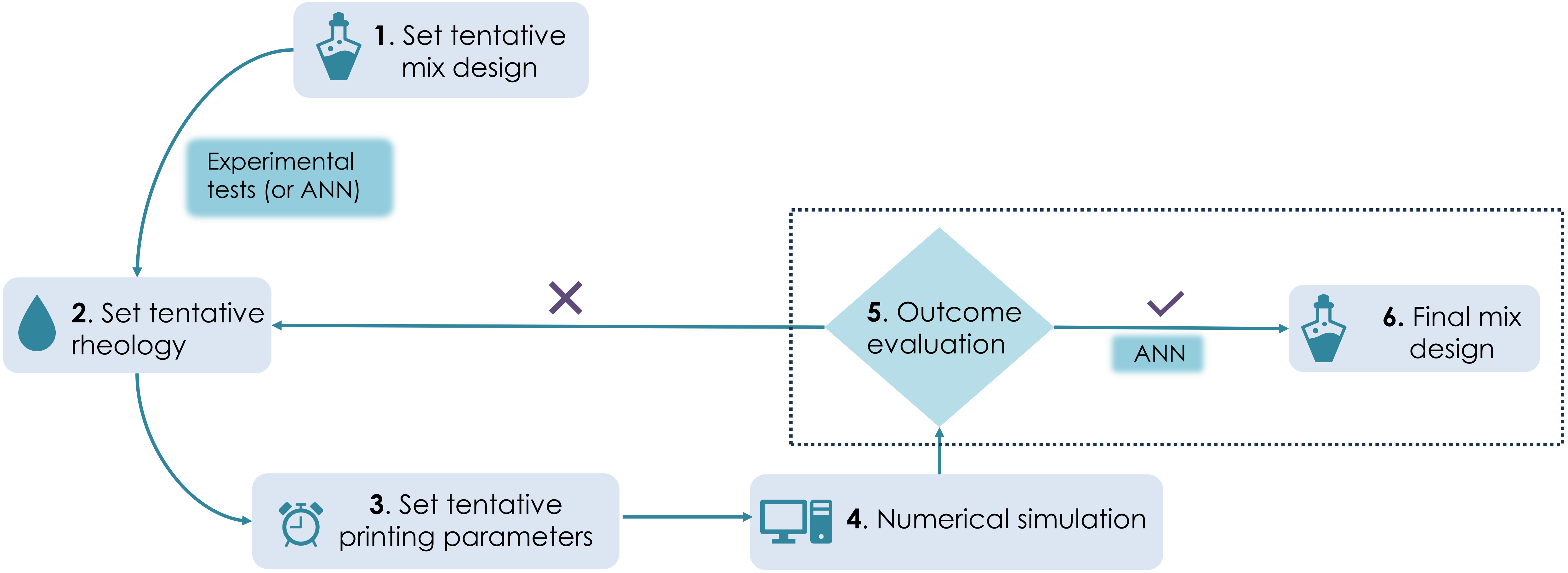
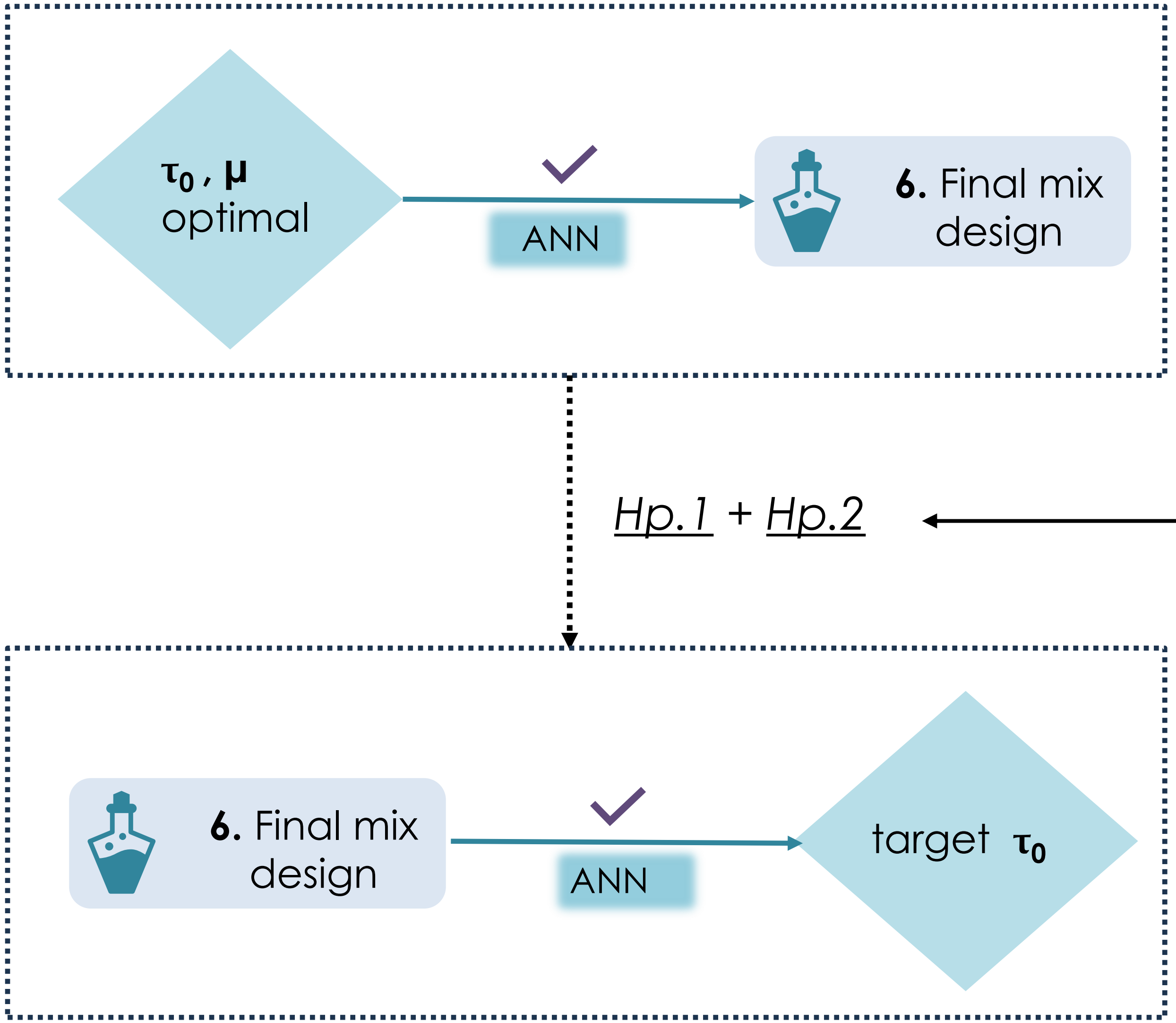


Proposed tool: artificial neural network



[Rizzieri, G et al. "unpublished results"]

Proposed tool: artificial neural network



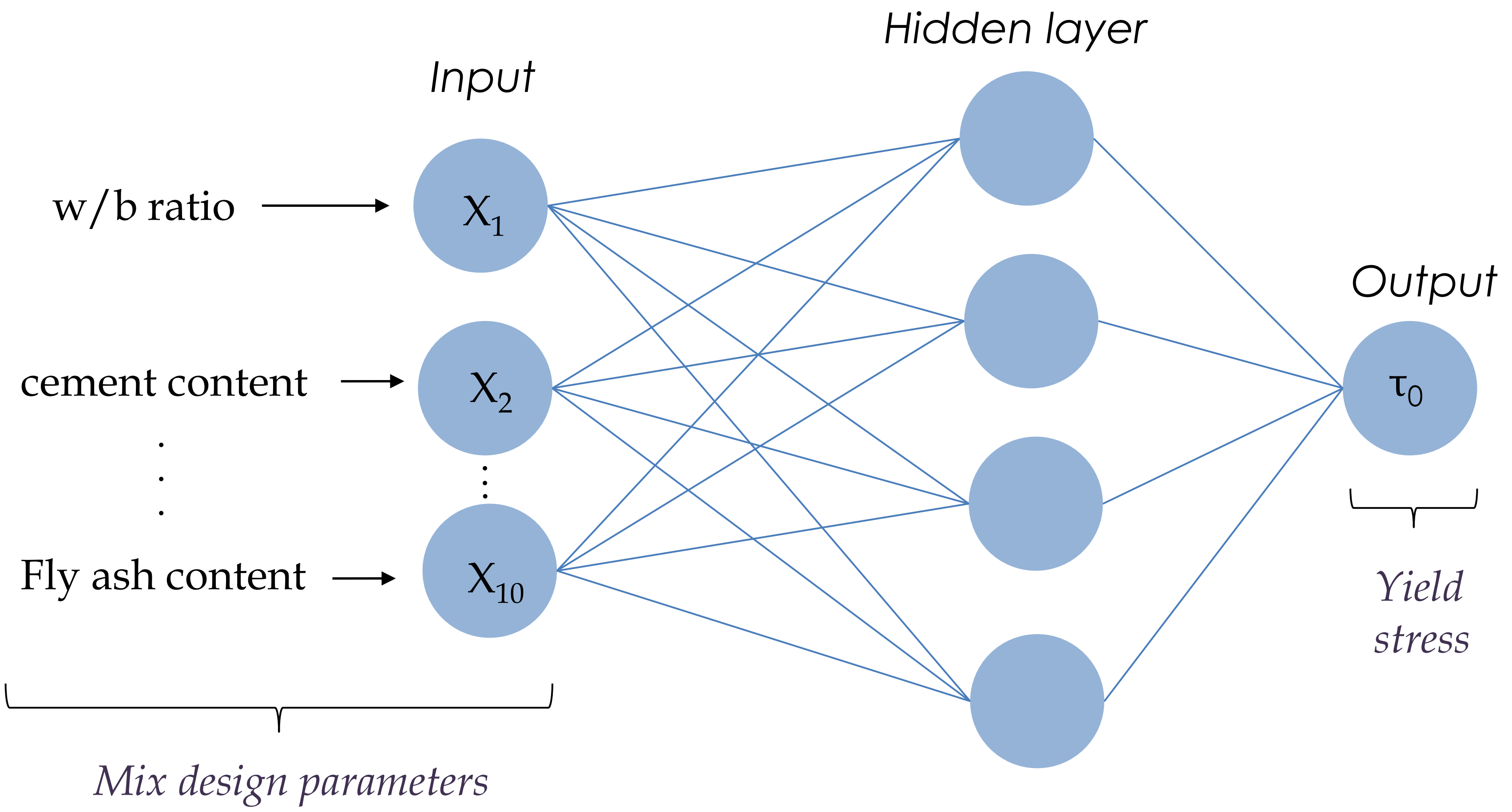
How can we actually create a paste with the optimally computed values of τ_0 and μ ?

*Hp.1) **Reverse the problem**, not only it becomes feasible to use ANN, but also gives the designer more freedom.*

*Hp.2) **Viscosity is disregarded**, as it has little influence on the final layer shape.*

N.B.: the ANN gives almost instantaneous results

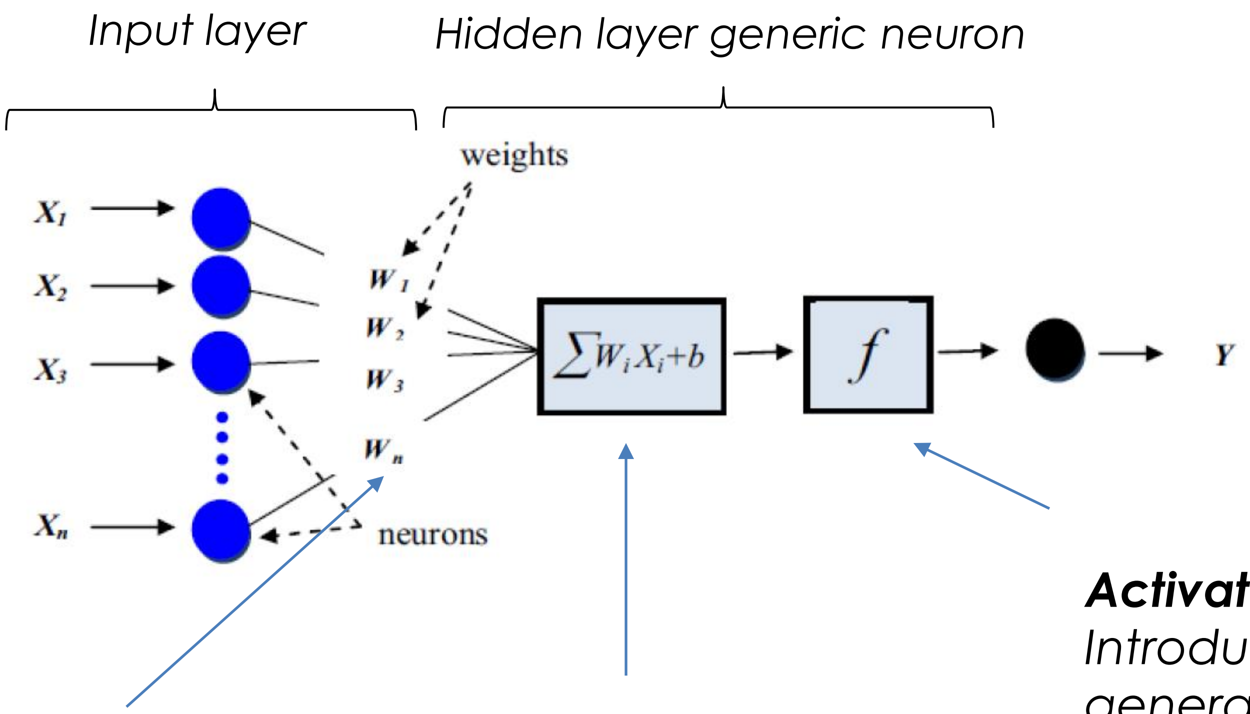
Artificial Neural Network



[Marcucci, A et al. "unpublished results"]

Proposed tool: artificial neural network

Single neuron of the ANN



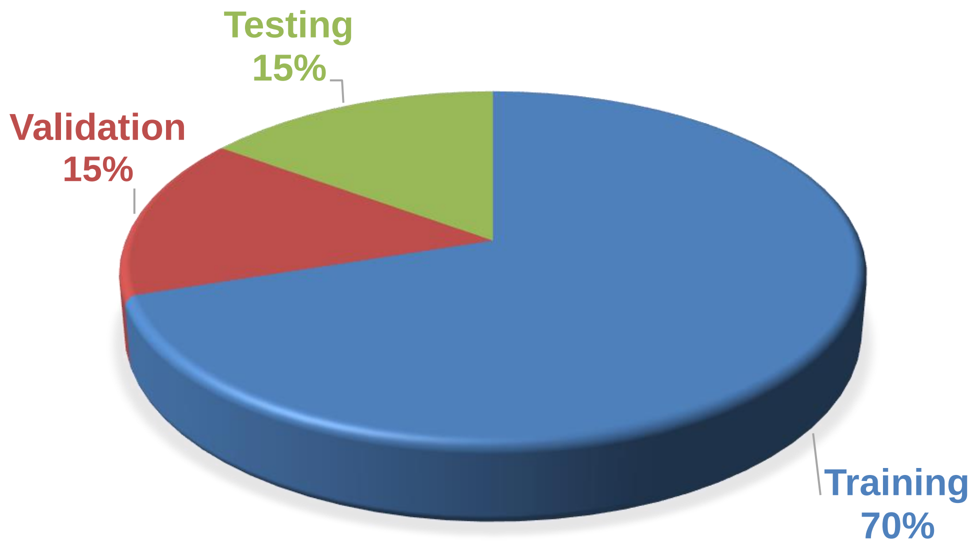
***Weight** of the interpolation, they are changed during the training with the biases*

***Linear interpolation** + bias*

Activation function
Introducing nonlinearity, generally an exponential or easy to be-derived functions

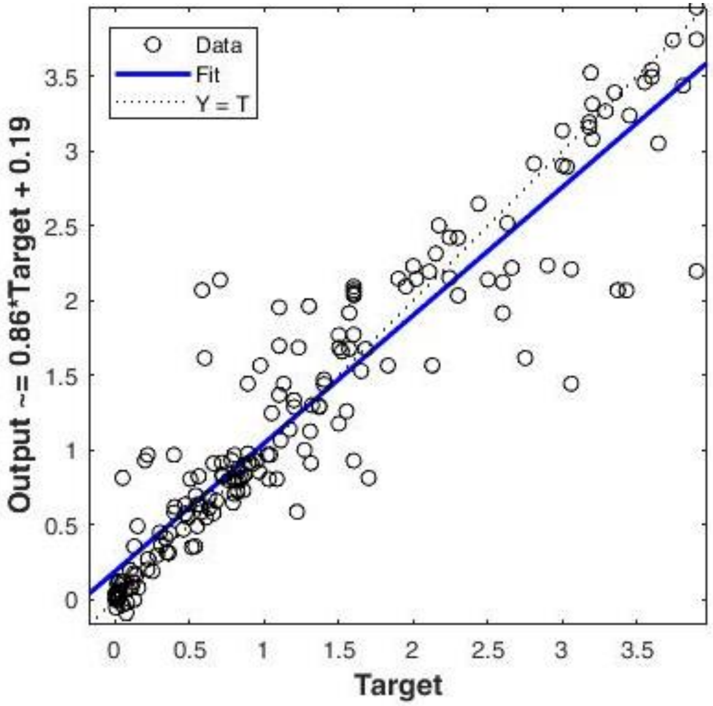
Proposed tool: artificial neural network

Training and validation

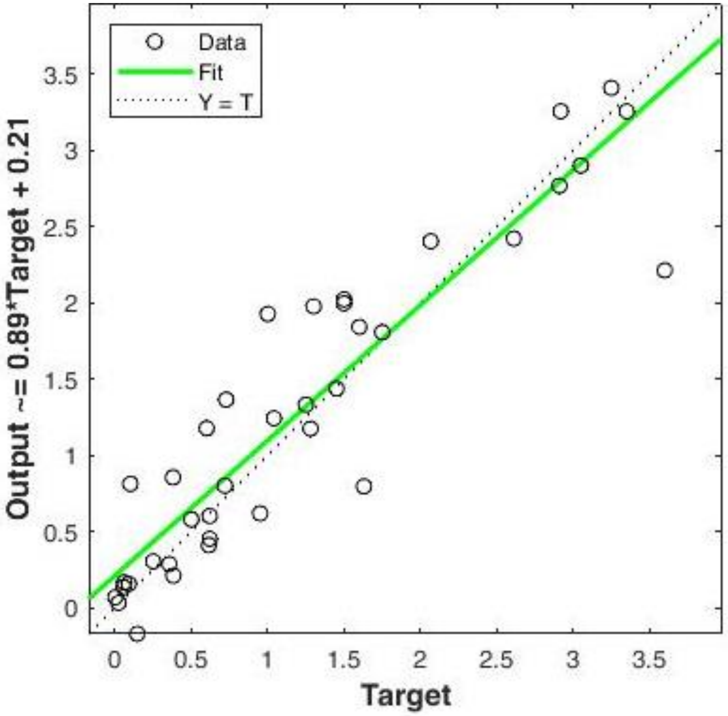


Dataset subdivision (70:15:15 rule)

Network outputs w.r.t. targets values



Training performances

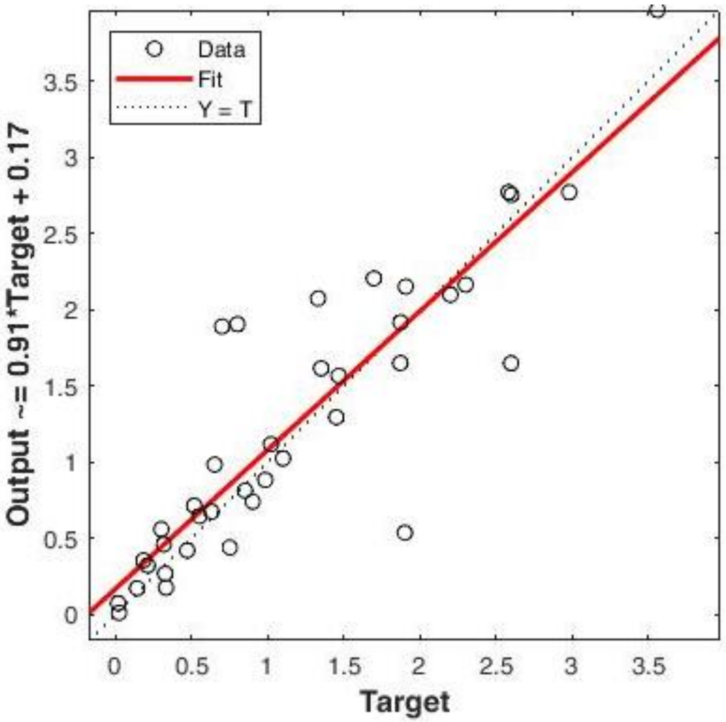


Validation performances

[Marcucci, A et al. "unpublished results"]

Proposed tool: artificial neural network

Network outputs w.r.t. targets values



Testing performances

[Marcucci, A et al. "unpublished results"]

Consideration

The ANN works fine, but has been overfitting a bit. Possible solutions are:

- *Enlarge the dataset*
- *Change network structure/parameteres*
- *Use it in combination, but not to replace experimental tests*

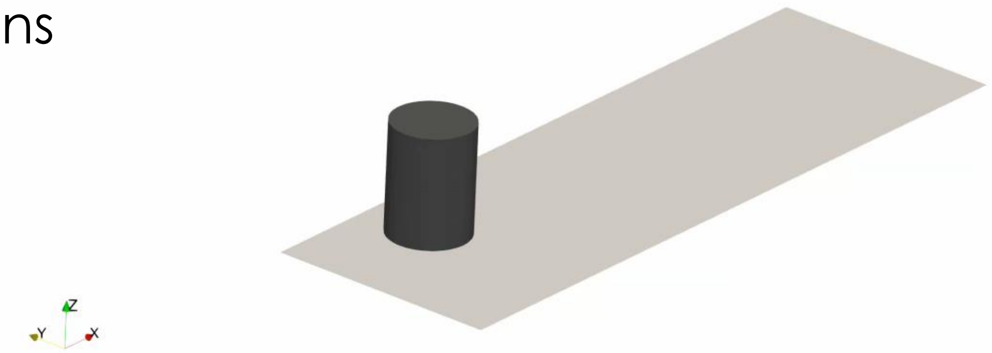
Conclusions

It has been proposed a tool to:

1) Increase reliability and geometrical accuracy of the printed objects

2) Optimize the process while ensuring good layer quality.

3) Develop of new 3D printable mix designs



Future works

1) Increase performances of the ANN and validate it

2) Develop a similar tool that accounts also for “buildability”, i.e., multiple layers

Thank you!

*Rizzieri, G., Ferrara, L. & Cremonesi, M. "**Numerical simulation of the extrusion and layer deposition processes in 3D concrete printing with the Particle Finite Element Method.**" Comput Mech (2023). https://doi.org/10.1007/s00466-023-02367-y*

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