Università degli Studi di Pavia

Facoltà di Ingegneria
Dipartimento di Ingegneria Civile e Architettura (DICAr)

Numerical simulation of bone remodeling based on patient specific 3D models derived from CT images

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Laurea specialistica in **Bioingegneria**
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Presentazione di **Stefano Merli**
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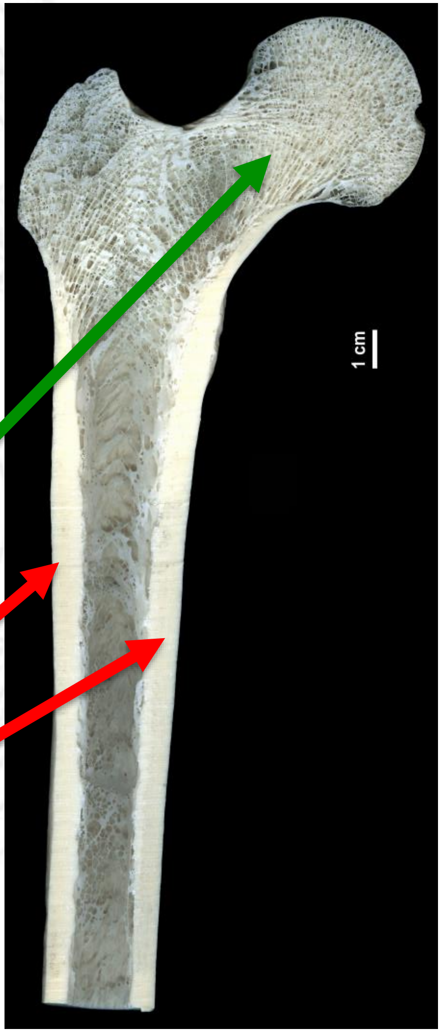
Human femur anatomy

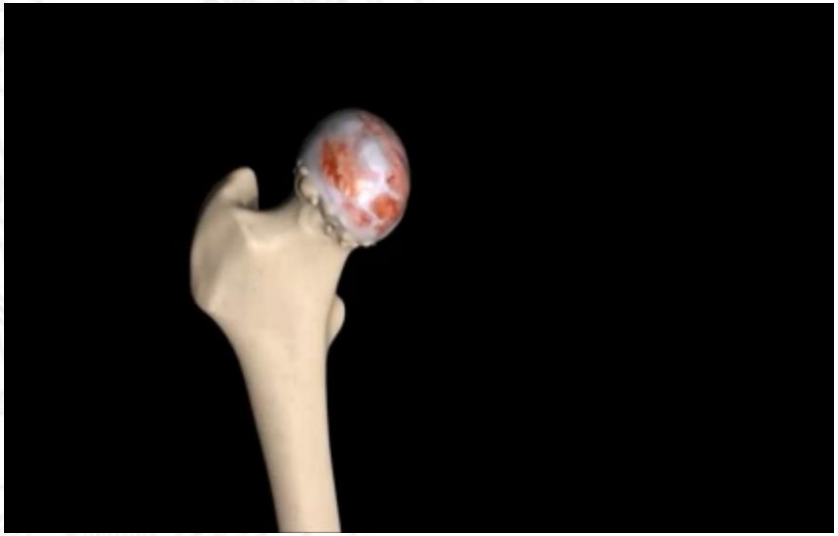
- Femur: longest bone in the human body
- Connects with:
  - Acetabulum of pelvic bone → Hip joint
  - Shinbone → Knee joint
- Composed by two distinct types of tissues:
  - Cancellous (spongy) bone
  - Cortical (compact) bone



Total hip arthroplasty (THA)

- Total Hip Arthroplasty (THA):
  - Hip joint replaced by a prosthetic implant

- Performed when:
  - Bone or soft tissues erosion → severe arthritis pain
  - Hip fractures



- One of the most common surgical procedure in hospitals
- Performed in few hours
- Recovery time of few days
- Patient can return to his daily routine, no limitations for everyday activities.

Hip implant failure

- Some data:
  - Declared lifetime of an implant: up to 25 years
  - Actual lifetime of an implant: up to 12-15 years
  - 300000+ THA are performed each year in the United States
  - Around 52000 revision surgeries in 2006 in the United States
  - The 13% of THA will require a revision surgery as result of bone remodeling and aseptic loosening

Bone remodelling evolution in THA must be investigated

Wolff’s law & mechanotransduction

Bone tissue adapts to the loads under which it is placed to resist with more efficiency

- If the load $\downarrow$ bone density $\downarrow$
- If the load $\uparrow$ bone density $\uparrow$

Mechanotransduction: process used by cells to convert a mechanical stimulus into electrochemical activity

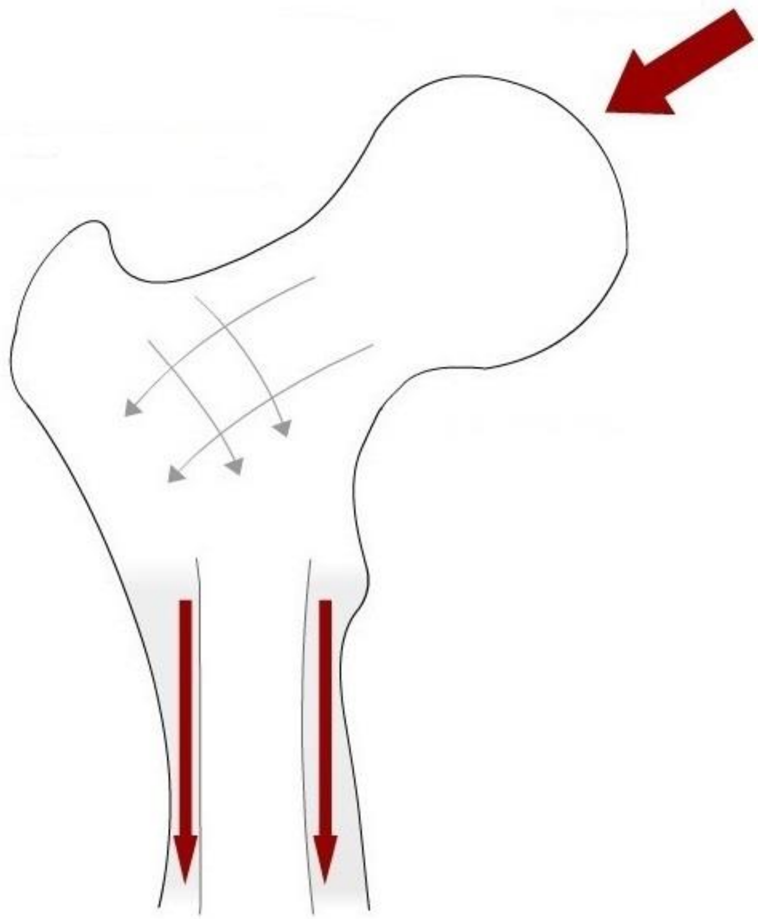
Stress shielding and bone remodeling

Healty femur loaded with typical loading conditions:

- Load applied at femur's head

- Stress is transmitted through trabeculae of cancellous bone

To cortical bone



When an implant is placed we have:

- Since :
  - $\rho_{implant} > \rho_{bone}$
  - $E_{implant} > E_{bone}$

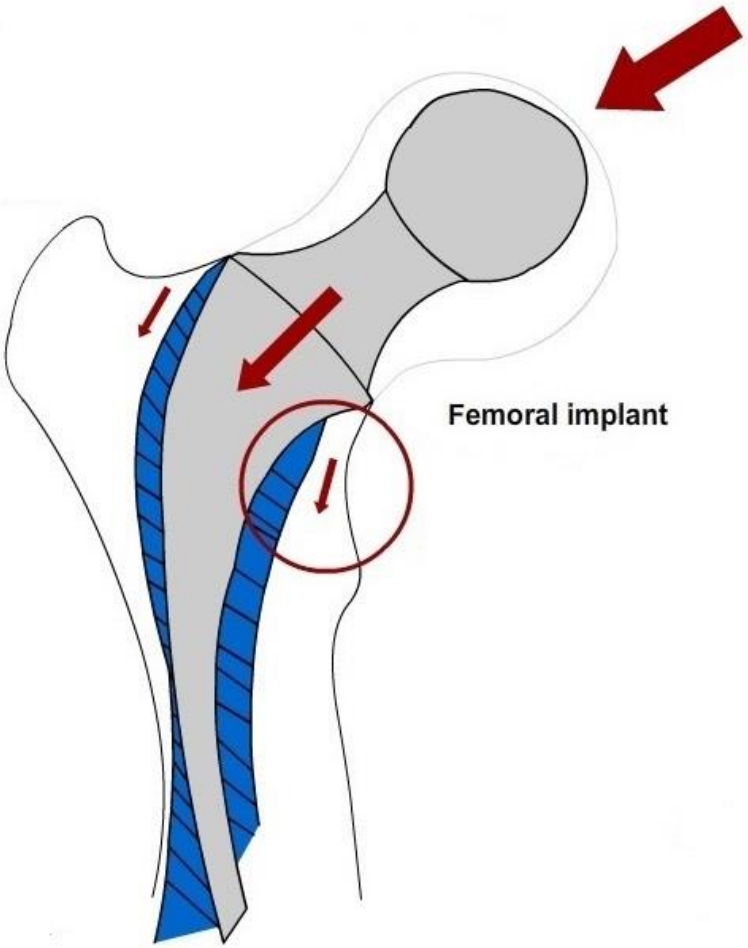
↓

- Stress shielding in bone tissues

Stress shielding and bone remodeling

When an implant is placed we have:

- Load applied at implant's head
- Transmitted through implant's stem
- Stress shielding→ less stress is carried by the bone



Stress shielding and bone remodeling

Discrepancy in mechanical properties of bone and implant

Alteration in stresses distribution in bones

Bone remodeling

Implant failure

Courtesy of: Prof. Benazzo's medical equipe (Ortopedia Traumatologia, IRCCS San Matteo)

- As result, after few months, this situation…

Stress shielding and bone remodeling

Discrepancy in mechanical properties of bone and implant

Alteration in stresses distribution in bones

Bone remodeling

Implant failure

- As result, after few months, this situation…

  …changes into **this** situation

Courtesy of: Prof. Benazzo’s medical equipe (Ortopedia Traumatologia, IRCCS San Matteo)

Aim of this work

- This work aims to:
  - Develop a **computational** mechanical **simulation methodology** to **predict** bone remodeling in THA using **patient specific** models
  - **Understanding** the **mechanisms** and the **variables** involved in this phenomenon
  - Evaluate the quality of prediction by **confrontations with physicians' support**

Innovations brougth by this work

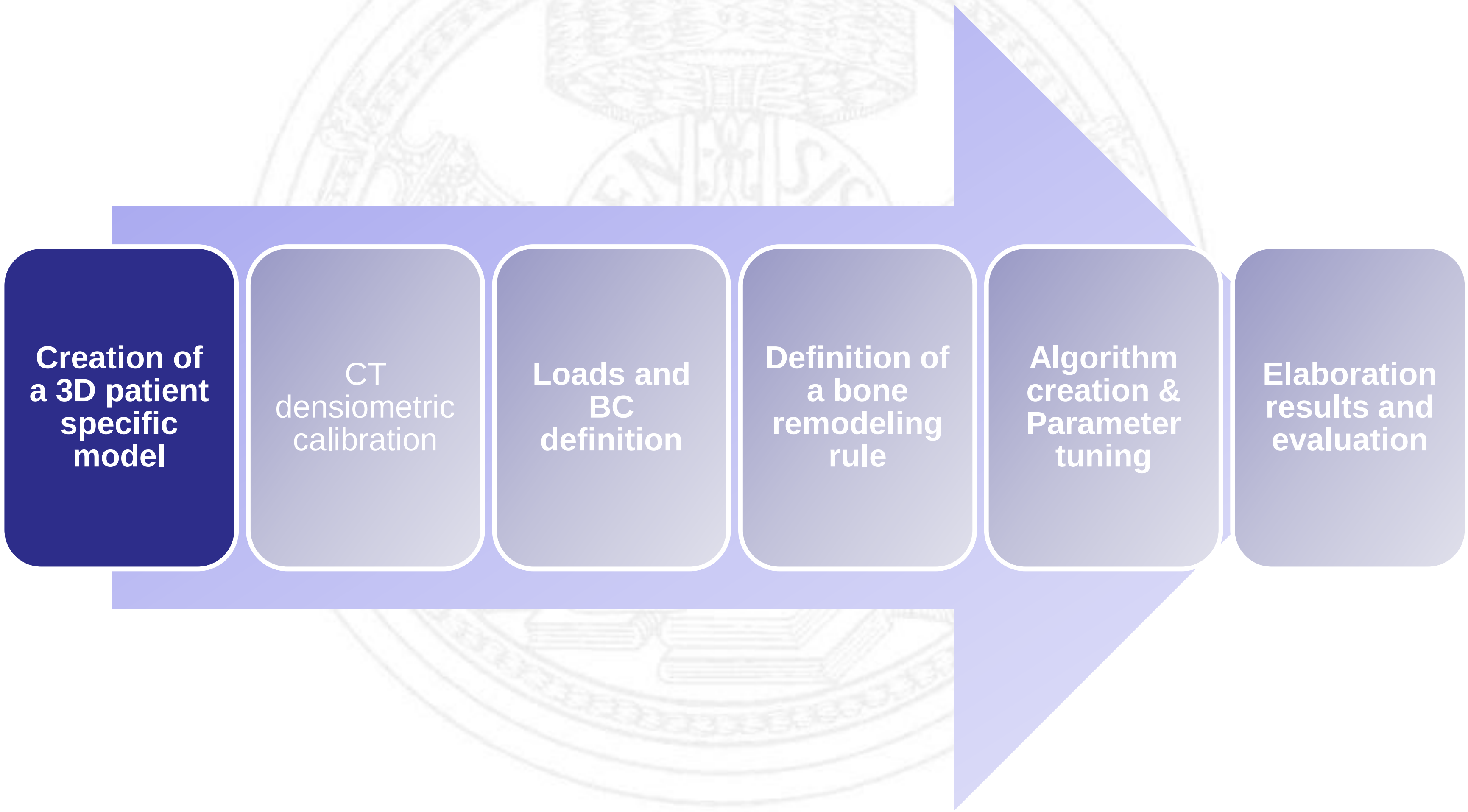
- This work differentiates from literature for the following reasons:

1. Use of **3D**, **high detailed**, **patient specific** models derived **from** in vivo **medical images**
2. Use of **realistic** and **patient specific material maps**, with **graded material properties**
3. Development of an **accurate bone remodeling prediction**, tested and confirmed by physicians experience
4. Development of a **quick predictive tool**, requiring less than one day to produce ready-to-use results
5. Implementation of all possible density variations focusing the attention **not only on bone resorption**, but **also** on **apposition**

Main steps of this work

1. Creation of a 3D patient specific model
2. CT densiometric calibration
3. Loads and BC definition
4. Definition of a bone remodeling rule
5. Algorithm creation & Parameter tuning
6. Elaboration results and evaluation

Creation of a 3D patient specific model



Creation of a 3D patient specific model

- **Two CT** exams of patients with THA were available:
  - **73 years old male**:
    - Poor image quality → an incomplete model
    - The first medical images available
    - Used for the first trials
  - **78 years old female**:
    - Good image quality
    - X-ray exposure of fractured bone after THA failure included
    - Available when the methodology was almost completely developed
    - Used as the final trial

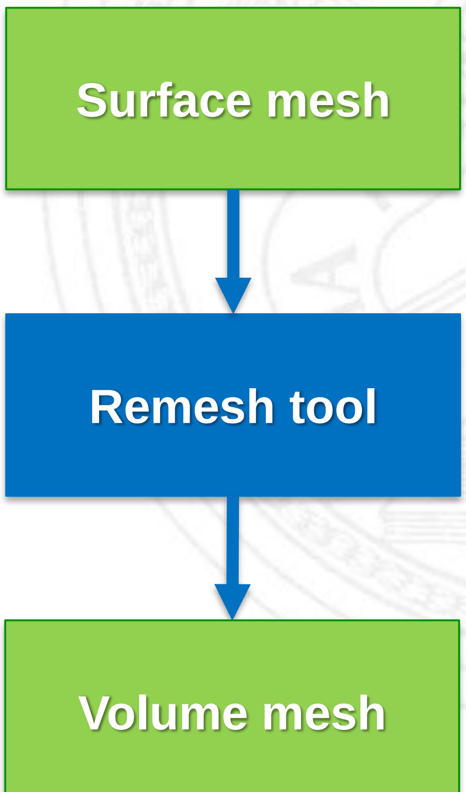
Courtesy of: Prof. Benazzo’s medical equipe
(Ortopedia Traumatologia, IRCCS San Matteo)

Creation of a 3D patient specific model

- Image **segmentation** was performed via **ITK-SNAP**
- An **.STL** file was **extracted**:
  - This file is a **surface mesh**
  - Composed only by external triangles of the model
- **Volume mesh** is required for our purpose

Creation of a 3D patient specific model

- A 3D **volume mesh mush be created**
- To do so, a remesh tool is used



Creation of a 3D patient specific model

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Surface mesh

↓

Remesh tool

↓

Volume mesh

Creation of a 3D patient specific model

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Surface mesh

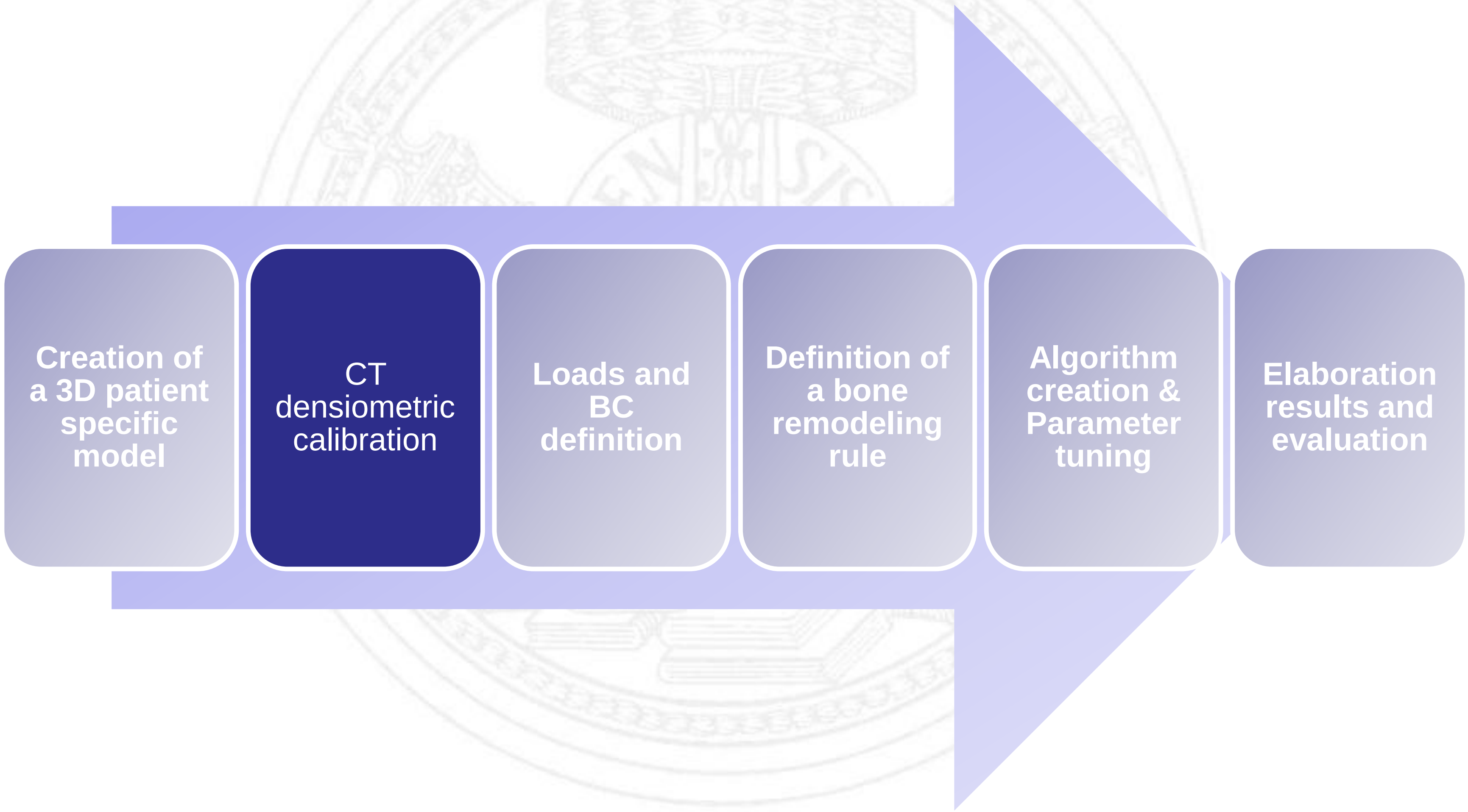
↓

Remesh tool

↓

Volume mesh

CT densiometric calibration



MATLAB

CT densiometric calibration

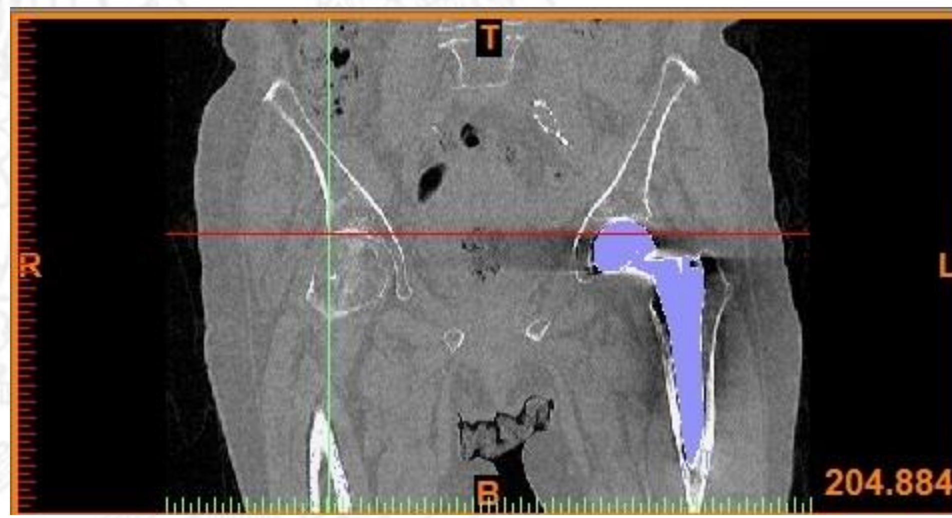
- Patient specific densities ρ and elastic moduli E must be added to the model
- A correlation between HU values, ρ and E must be found
- QCT calibration phantoms were NOT available
- These information were retrieved in literature:

1. HU/ρ relation is always linear
2. ρ /E relation can be linear or exponential
3. Typical ρ values for femur tissues and prosthesis
4. Typical E values for femur tissues and prosthesis

CT densiometric calibration

- **This procedure in mainly divided into 5 steps:**

1. **Grey masks isolation**
2. **HU values extraction & cleaning**
3. **Creation of density & E vectors**
4. **Curve fitting for** $\rho = a + b \cdot HU$
5. **Curve fitting for** $E = a_1 + b_1 \cdot \rho^{C_1}$



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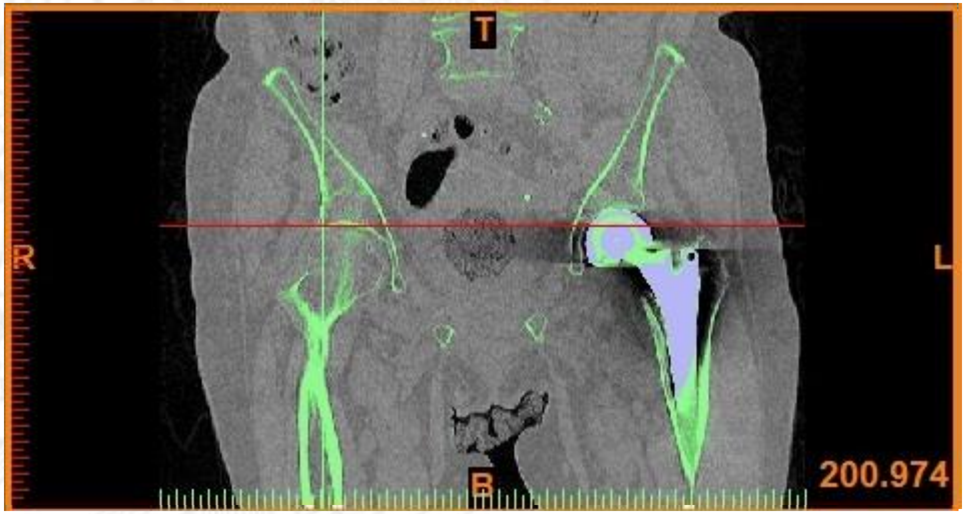

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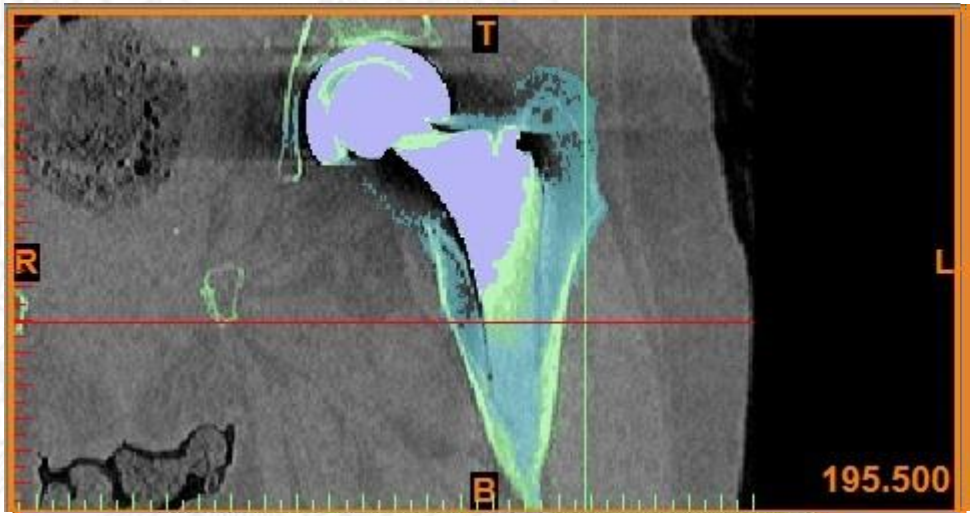

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HU values Prosthesis	HU values Cortical	HU values Cancellous
+2129	+793	+156
+2006	+711	-21
+2850	+1252	-95
+3026	+1778	+201
+2915	+1192	+203
+2999	+1354	-52
+3071	+1566	+307
+3071	+1407	+81
+3033	+1153	-85
+3055	+1153	+48
….	….	….

CT densiometric calibration

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- **Mean**, **mode**, **maximum** and **minimun** evaluated for each material
- **Outliers** removed

CT densiometric calibration

- **This procedure in mainly divided into 5 steps:**

Grey masks isolation

HU values extraction & cleaning

Creation of density & E vectors

Curve fitting for $\boldsymbol{\rho = a + b \cdot HU}$

Curve fitting for $\boldsymbol{E = a_1 + b_1 \cdot \rho^{C_1}}$

- For each HU value of a material:
  1. $\%HU$ is evaluated as:

     $$\%HU = \frac{HU - HU_{min}}{HU_{max} - HU_{min}}$$

  2. $\%HU = \%\rho$
  3. $\rho = \%\rho \cdot (\rho_{max} - \rho_{min}) - \rho_{min}$

- Now density vectors are created for each material

CT densiometric calibration

- **This procedure in mainly divided into 5 steps:**

1. **Grey masks isolation**
2. **HU values extraction & cleaning**
3. **Creation of density & E vectors**
4. **Curve fitting for $\rho = a + b \cdot HU$**
5. **Curve fitting for $E = a_1 + b_1 \cdot \rho^{C_1}$**

- For each ρ value of a material:

  1. $\%\rho = \%E$
  2. $E = \%E \cdot (E_{max} - E_{min}) - E_{min}$

- Now Young modules vectors for each material are created

MATLAB

CT densiometric calibration

- **This procedure in mainly divided into 5 steps:**

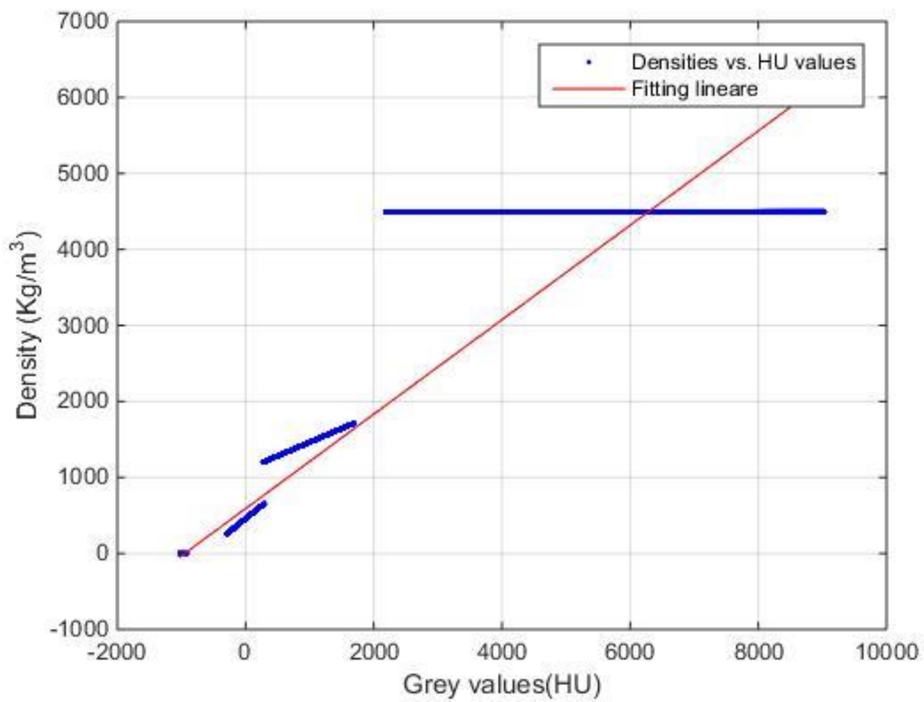
Grey masks isolation

HU values extraction & cleaning

Creation of density & E vectors

Curve fitting for $\rho = a + b \cdot HU$

Curve fitting for $E = a_1 + b_1 \cdot \rho^{C_1}$



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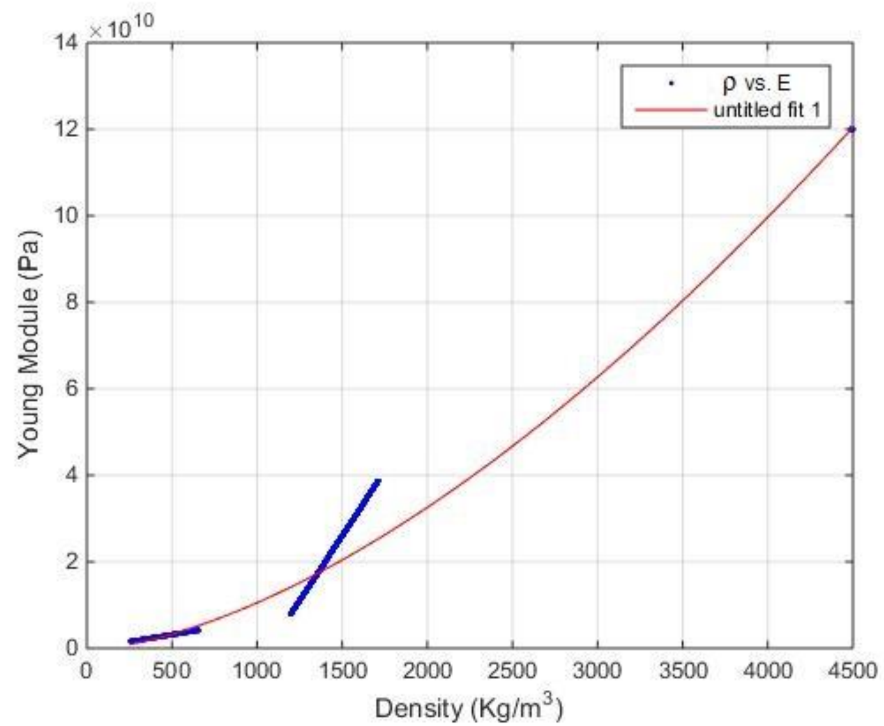
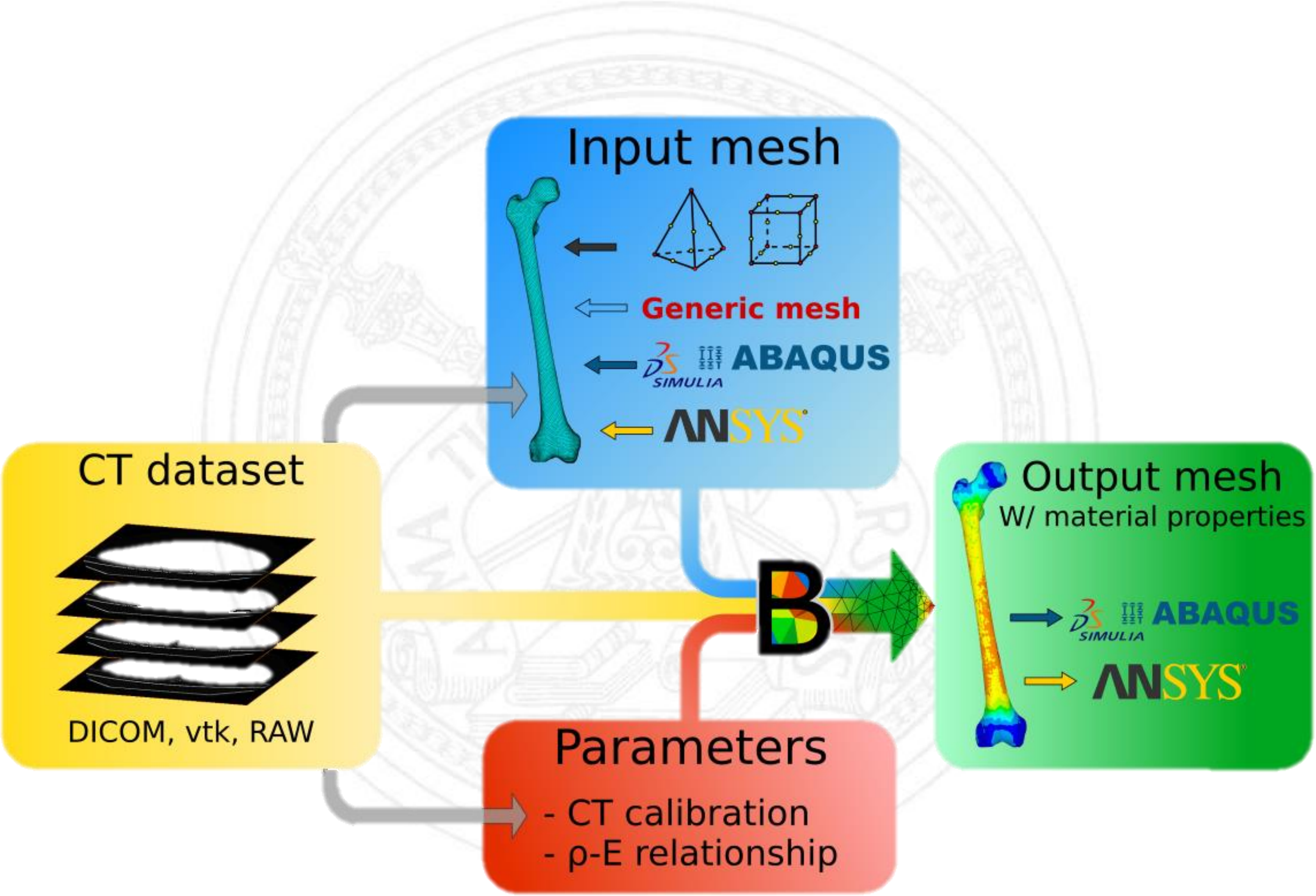
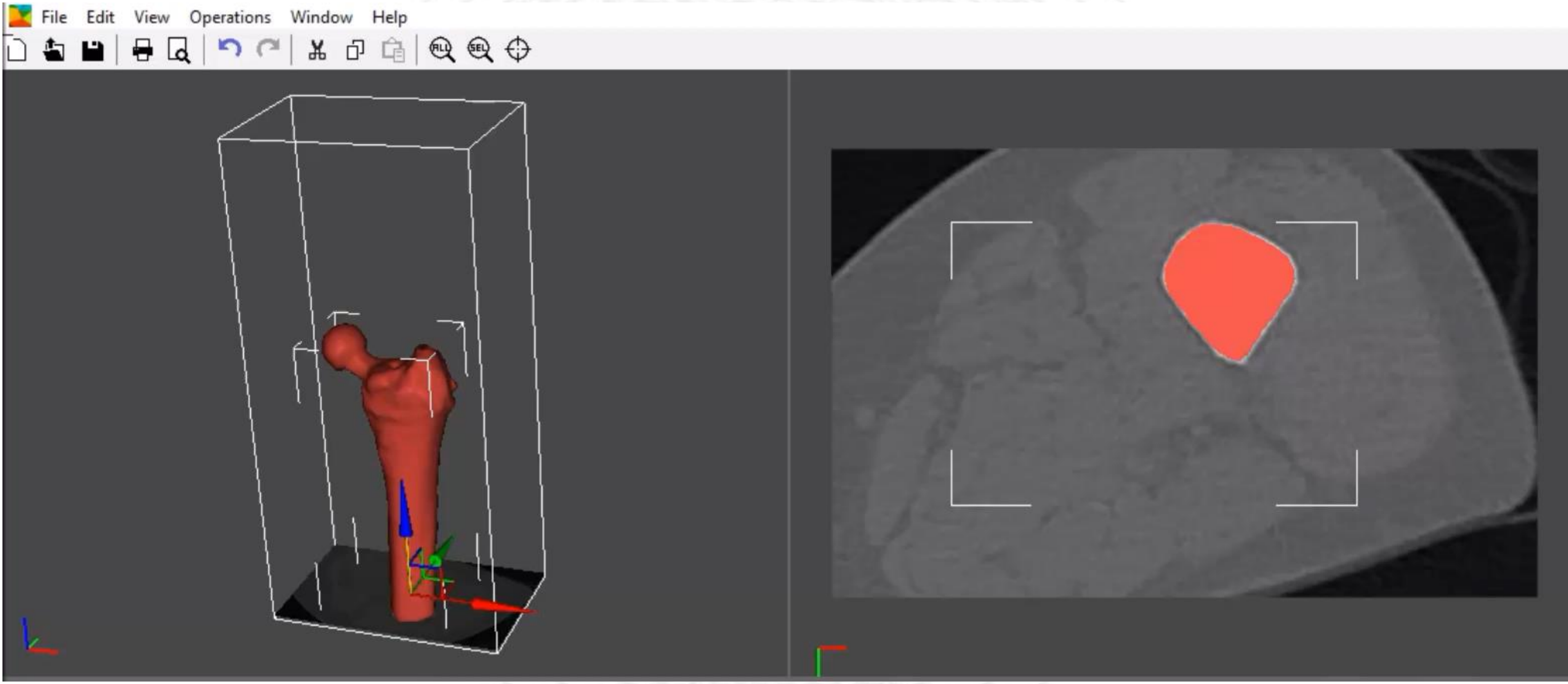


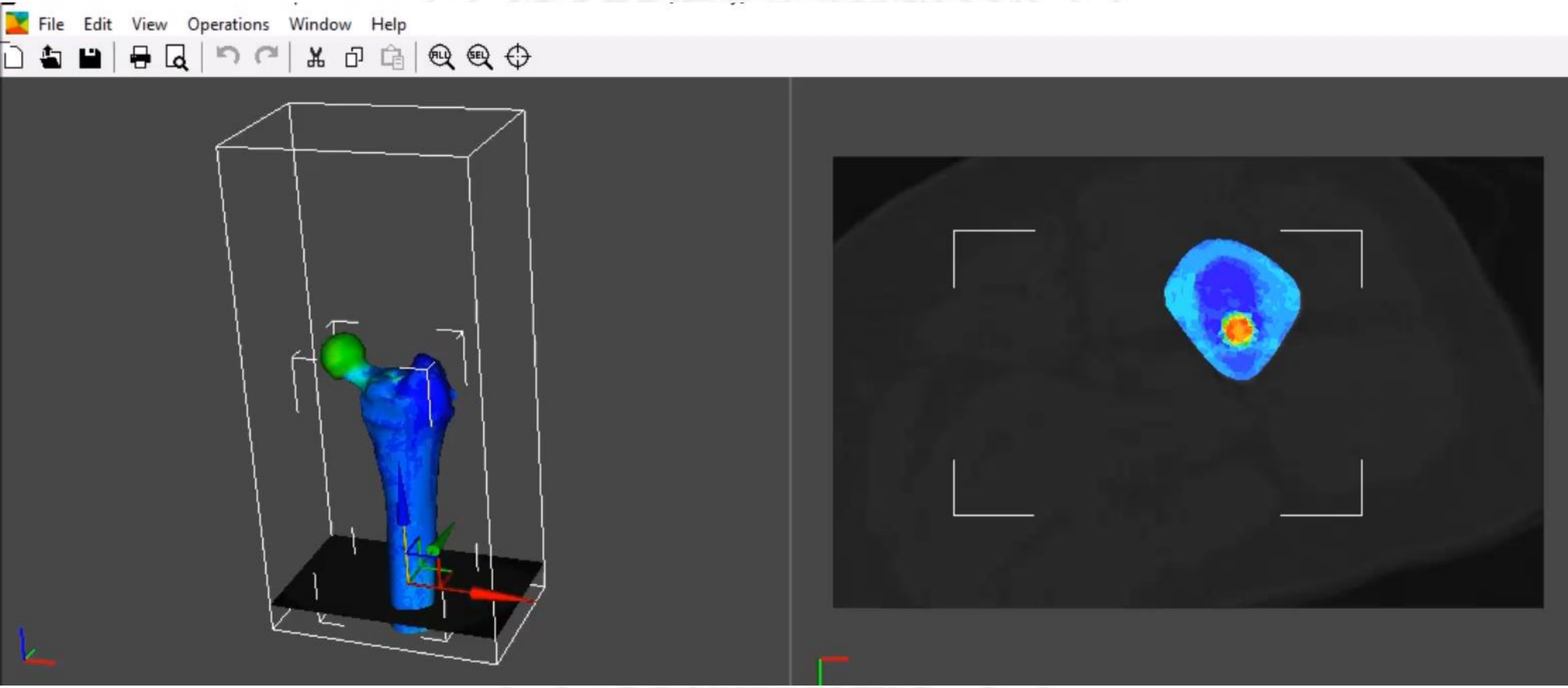
Material assignment



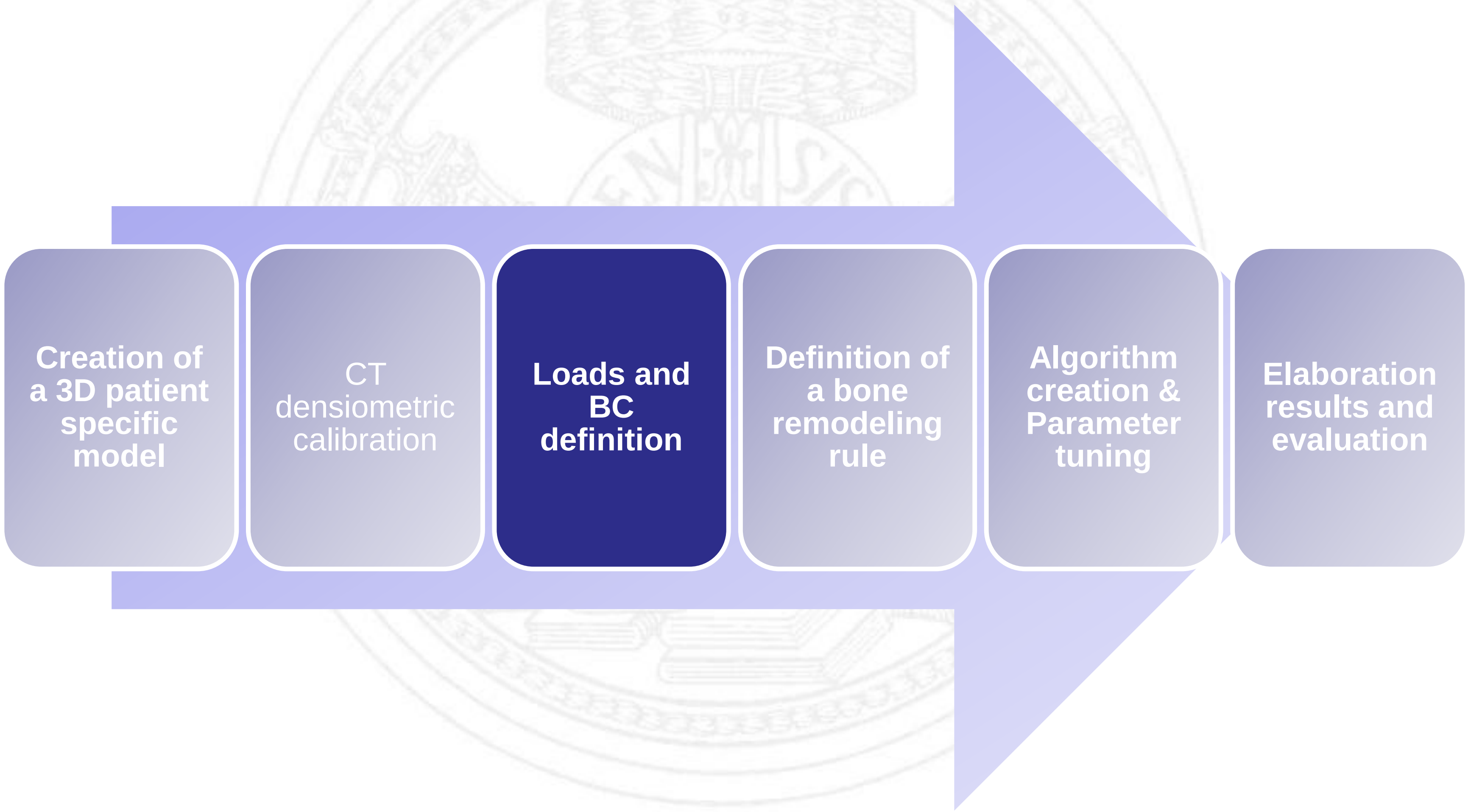
Material assignment



Material assignment



Loads and BC’s defintion



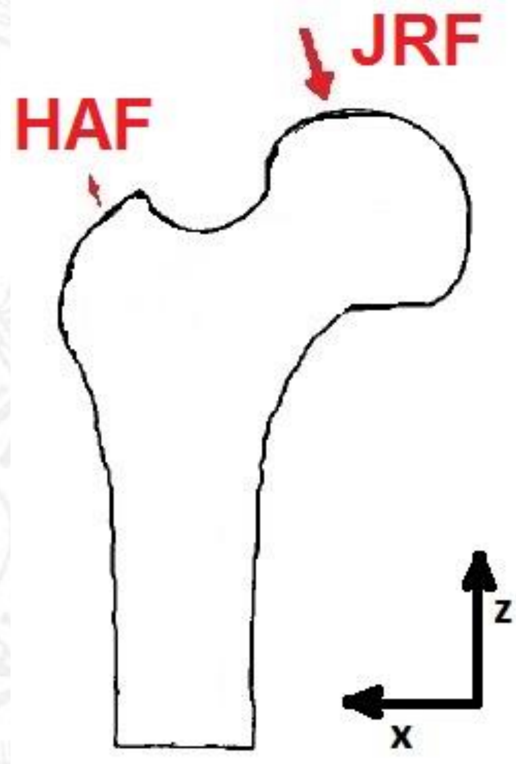
Loads and BC's defintion

- Three loading conditions and BCs were applied
- Defined as:
  - «Typical Loading condition of daily activities» (D.R. Carter , "Relationships between loading hystory and femoral cancellous bone architecture")
- Two main forces are considered:
  - Joint Reaction Force (JRF)
  - Hip Abductor Force (HAF)
- All lower nodes are fully clamped

Loading condition 1	JRF	HAF
Module	2317[N]	702[N]
Direction(from Z-axis)	27°	28°

Loads and BC’s defintion

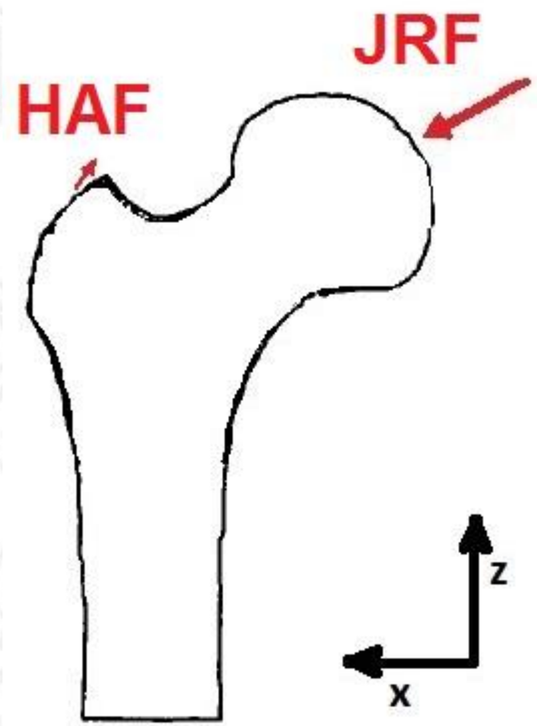
- Three loading conditions and BCs were applied
- Defined as:
  - «Typical Loading condition of daily activities» (D.R. Carter , "Relationships between loading hystory and femoral cancellous bone architecture“)
- Two main forces are considered:
  - Joint Reaction Force (JRF)
  - Hip Abductor Force (HAF)
- All lower nodes are fully clamped



Loading condition 2	JRF	HAF
Module	1158[N]	351[N]
Direction(from Z-axis)	-15°	-8°

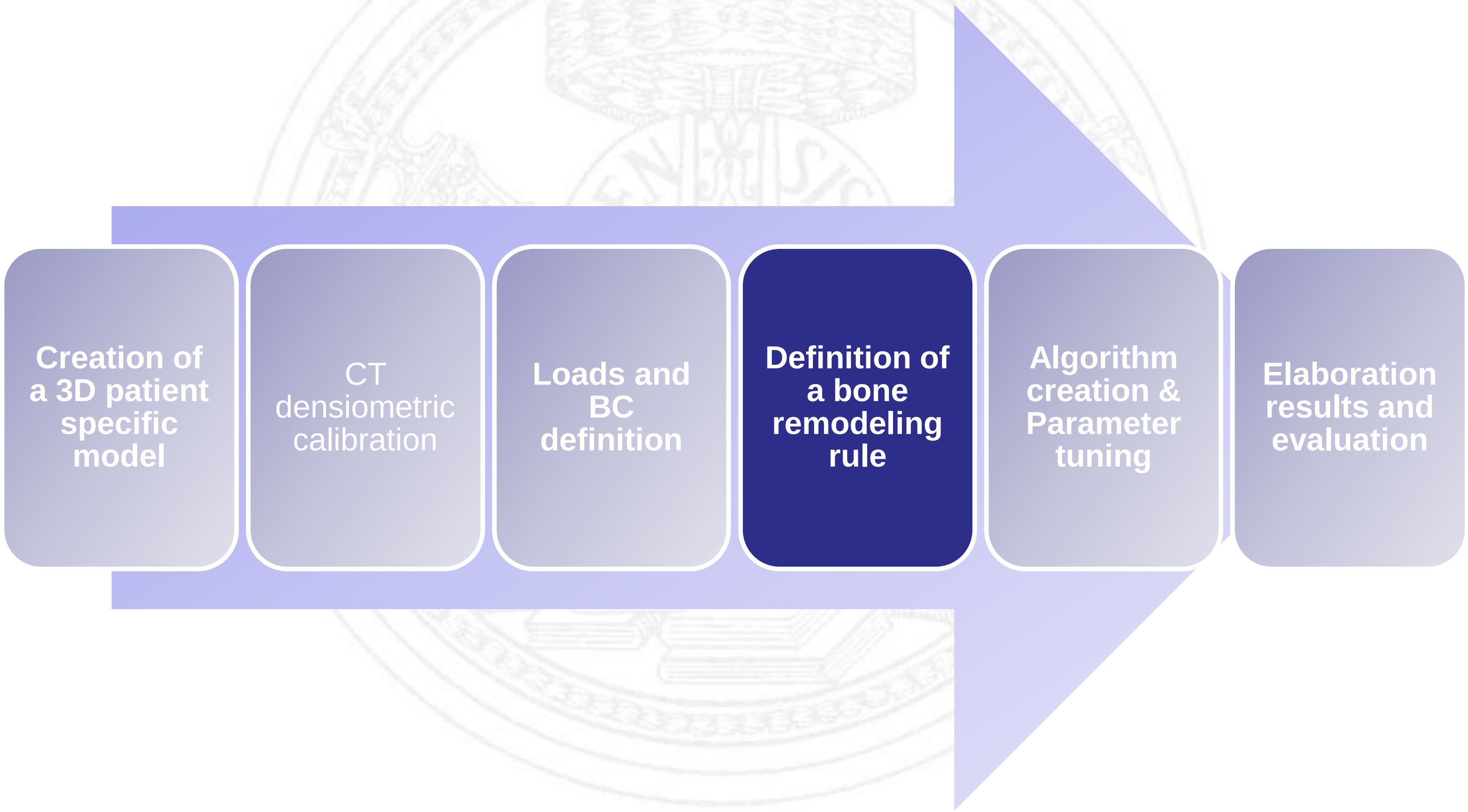
Loads and BC's defintion

- Three loading conditions and BCs were applied
- Defined as:
  - «Typical Loading condition of daily activities» (D.R. Carter , "Relationships between loading hystory and femoral cancellous bone architecture")
- Two main forces are considered:
  - Joint Reaction Force (JRF)
  - Hip Abductor Force (HAF)
- All lower nodes are fully clamped



Loading condition 3	JRF	HAF
Module	1548[N]	468.5[N]
Direction(from Z-axis)	56°	35°

Definition of a bone remodeling rule



Definition of a bone remodeling rule

- According to Wolff's law, density variation in time unit is:

$$\frac{\Delta\rho}{\Delta t} = B \cdot \Delta S \qquad where \qquad \Delta S = S - (1 \pm C_S)S_{ref}$$

- S function is used for measuring solicitations in bone tissues

- This function will be evaluated for each element of the model

- S function is defined as $S = \frac{U}{\rho}$, where:
  - U is the strain energy density of an element
  - ρ is the density of an element

- S_{ref} will be referred to the pre-operative condition

- S will be referred to the post-operative condition

Definition of a bone remodeling rule

- The comparison of S and S_{ref} for each element of the two models can lead to three possible scenarios:

  - $S < S_{ref}$ → the element is underloaded in the post operative configuration → bone resorption will occur

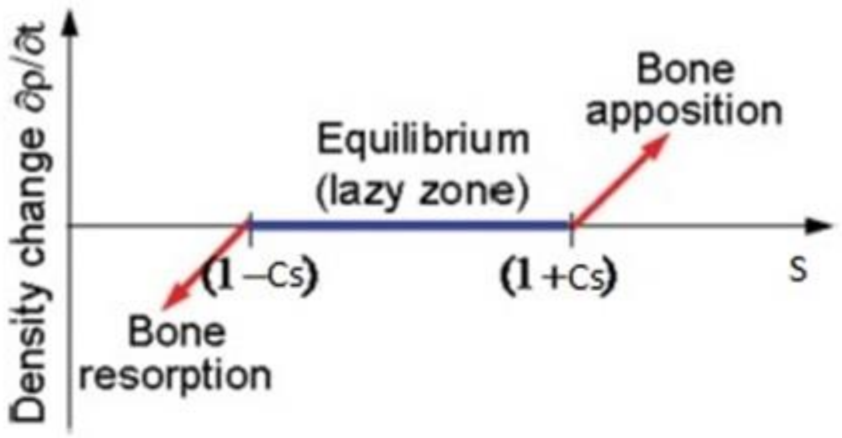
  - $S = S_{ref}$ → the element is stable → no modifications will be considered

  - $S > S_{ref}$ → the element is overloaded in the post operative configuration → bone apposition will occur

Definition of a bone remodeling rule

- The difference between S and S_{ref} must be significative to trigger a remodeling stimulus

- Lazy zone parameter C_S is introduced to mimic this biological behavior



- *B*, bone remodeling rate, retrieved from literature

Algorithm creation & Parameter tuning

1. Creation of a 3D patient specific model
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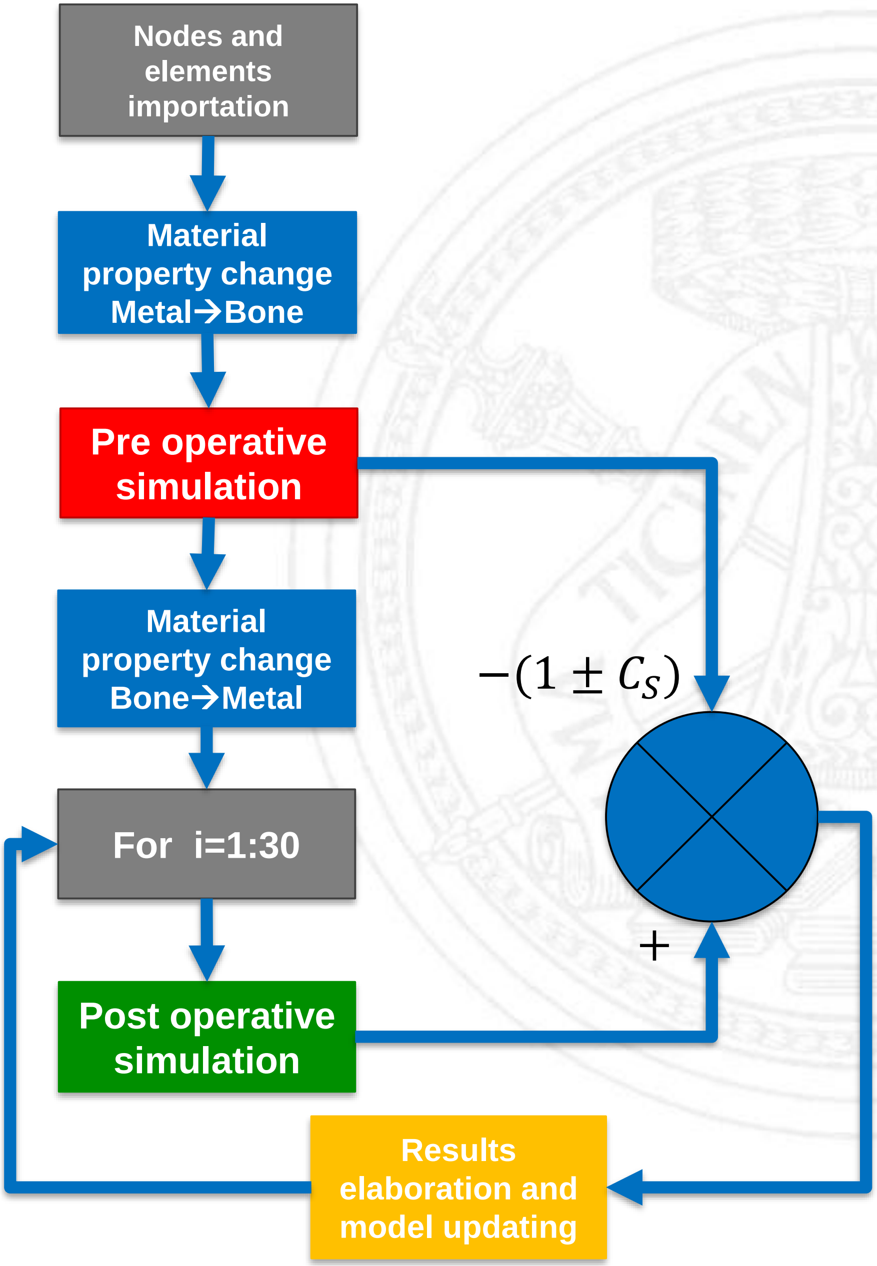
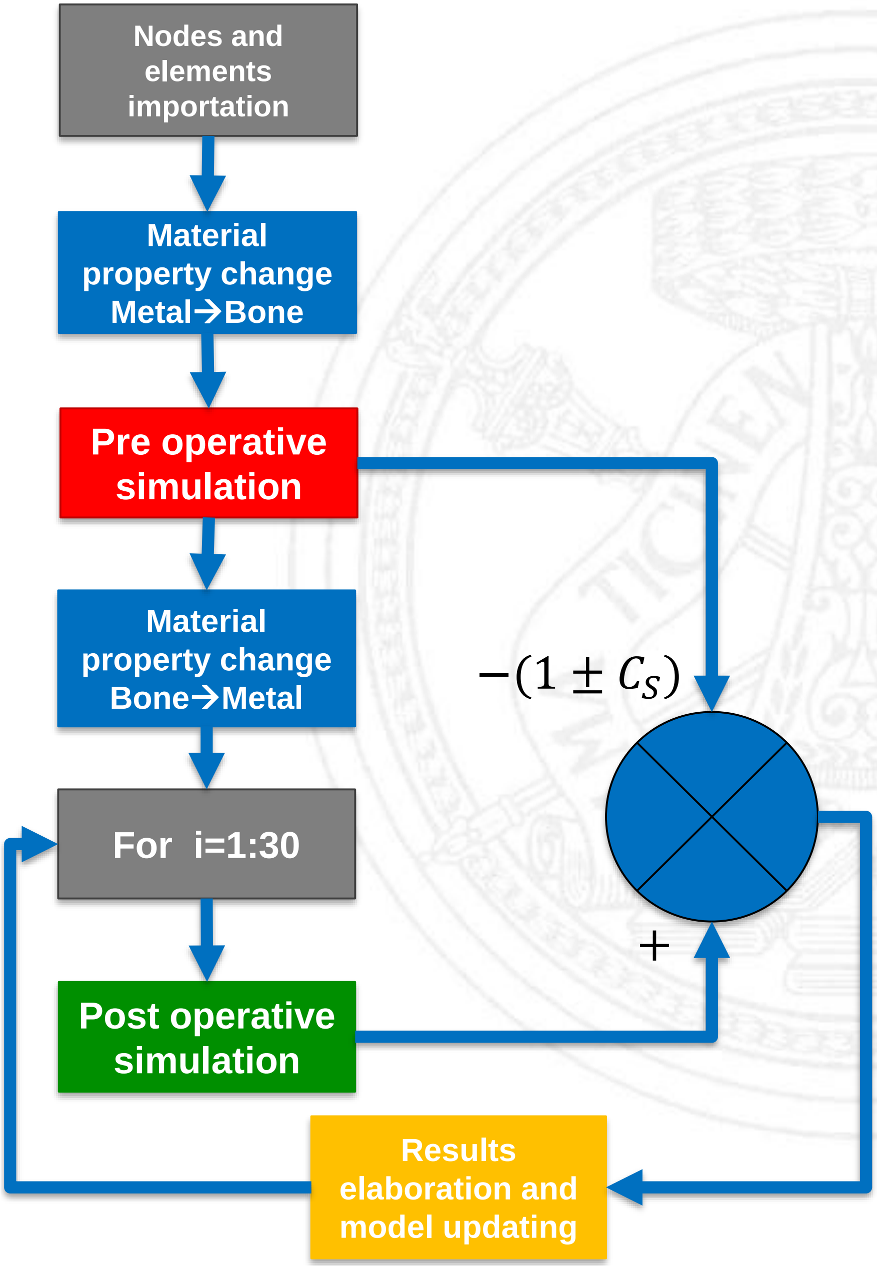
Algorithm creation & Parameter tuning



Nodes & elements importation:

1. Nodes are imported
2. Elements are created
3. Material sections are created

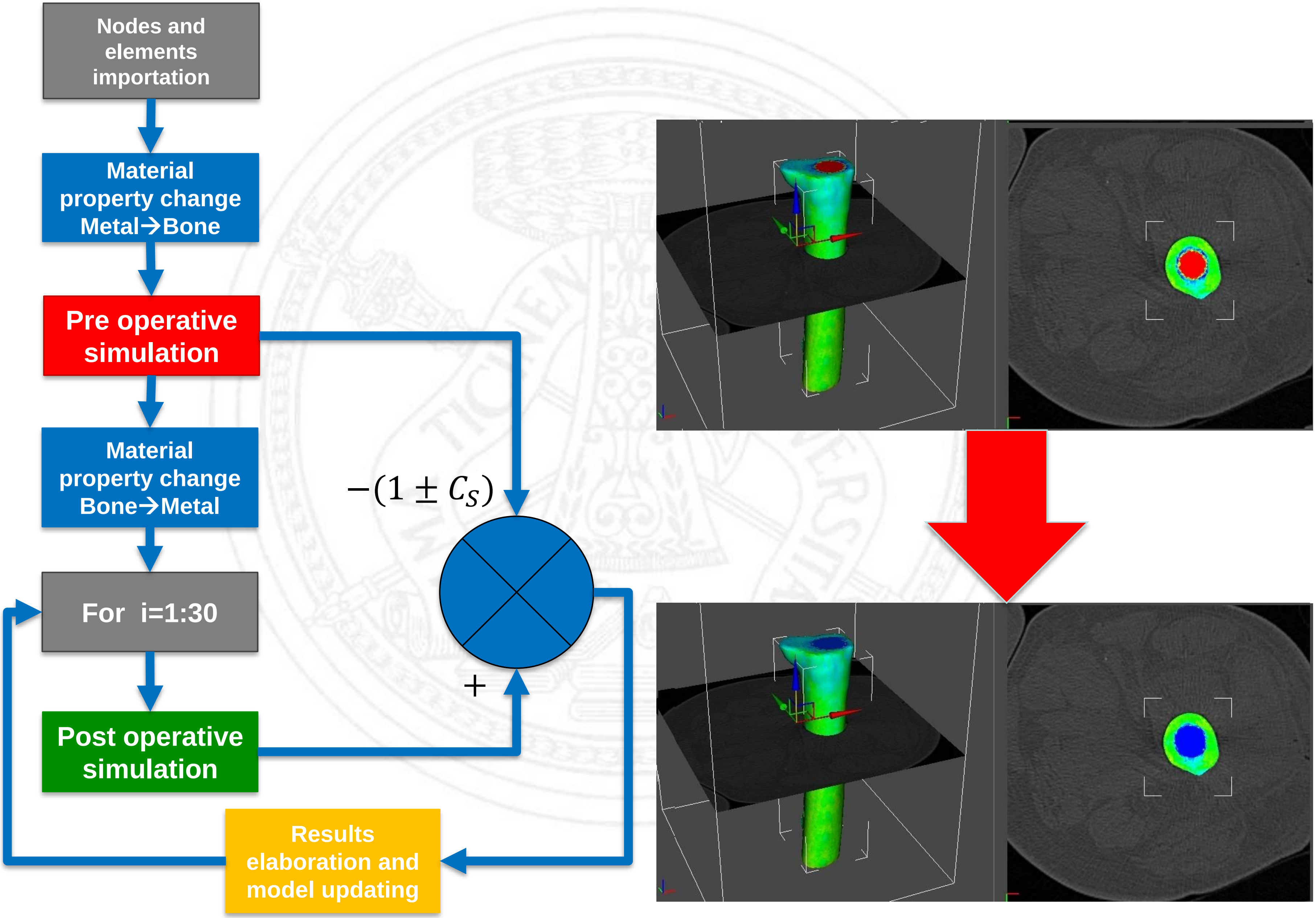
Algorithm creation & Parameter tuning



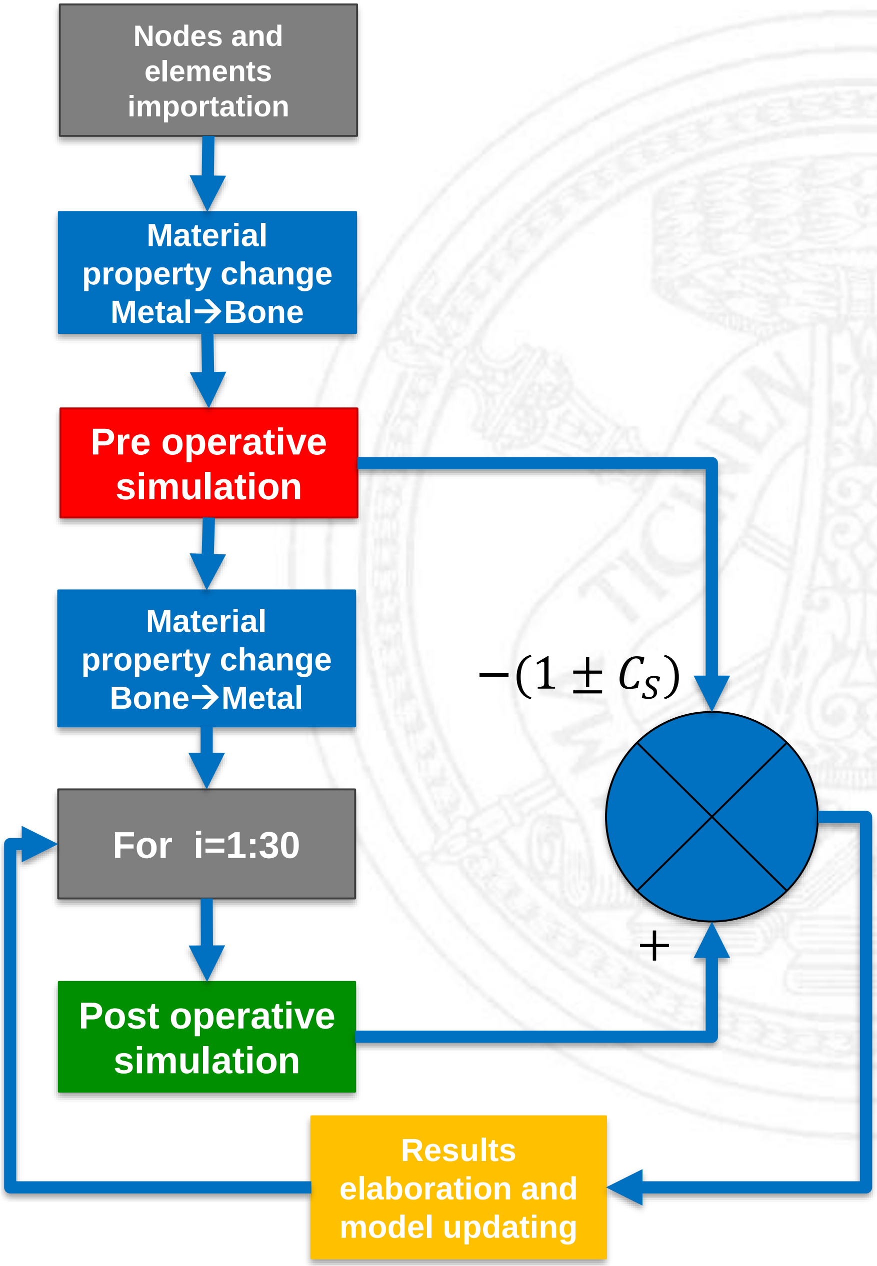
Material property change:

- **Pre-operative situation is not available**
- **Prosthesis replaced by cancellous bone tissue**
- **Assumption justified by:**
  1. Implants are placed in cancellous bone regions
  2. Bone remodeling is caused only by mechanical properties alteration and not by geometrical alterations

Algorithm creation & Parameter tuning



Algorithm creation & Parameter tuning



Pre-operative simulation is performed:

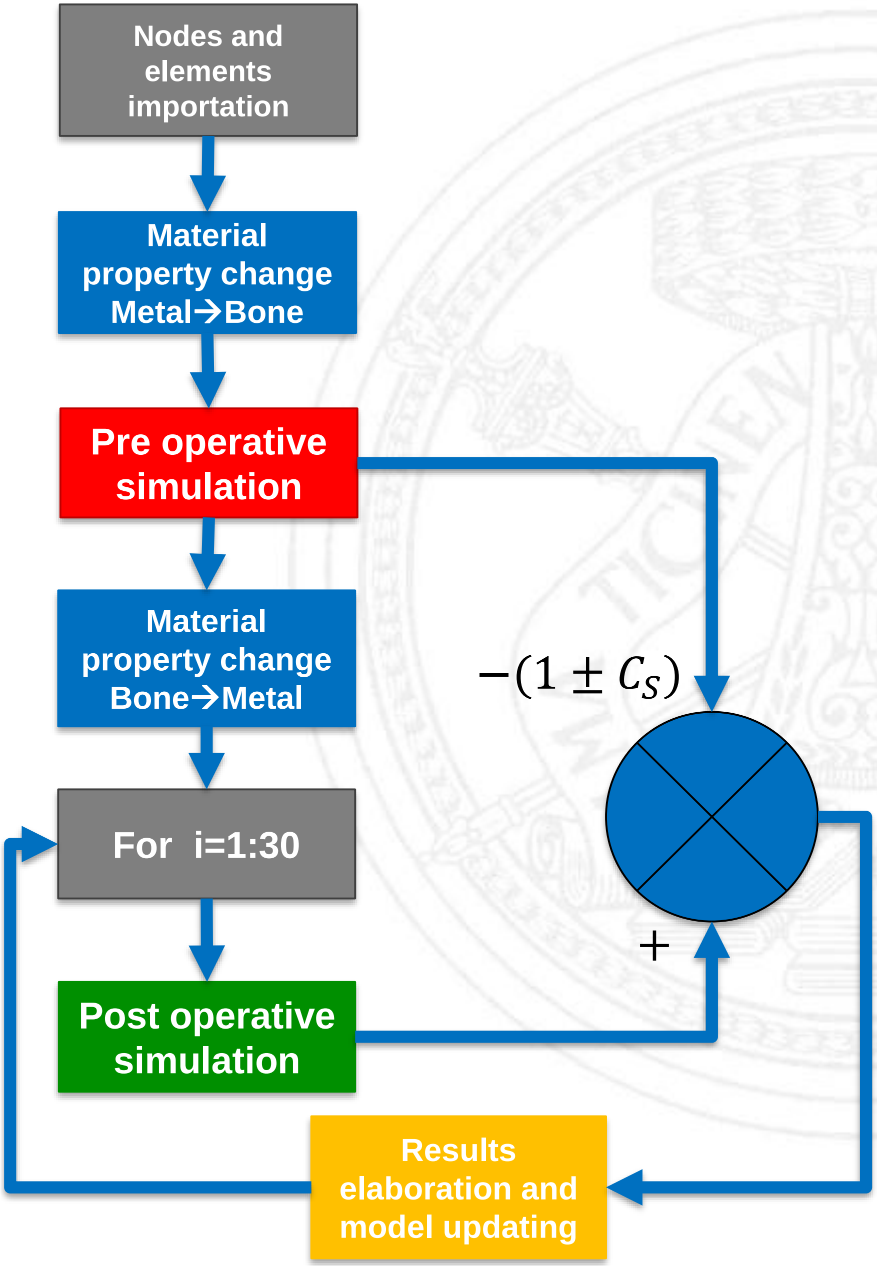
- S_{ref} **function evaluated for each element for the 3 loading conditions:**

$$(S_{ref1}, S_{ref2}, S_{ref3})$$

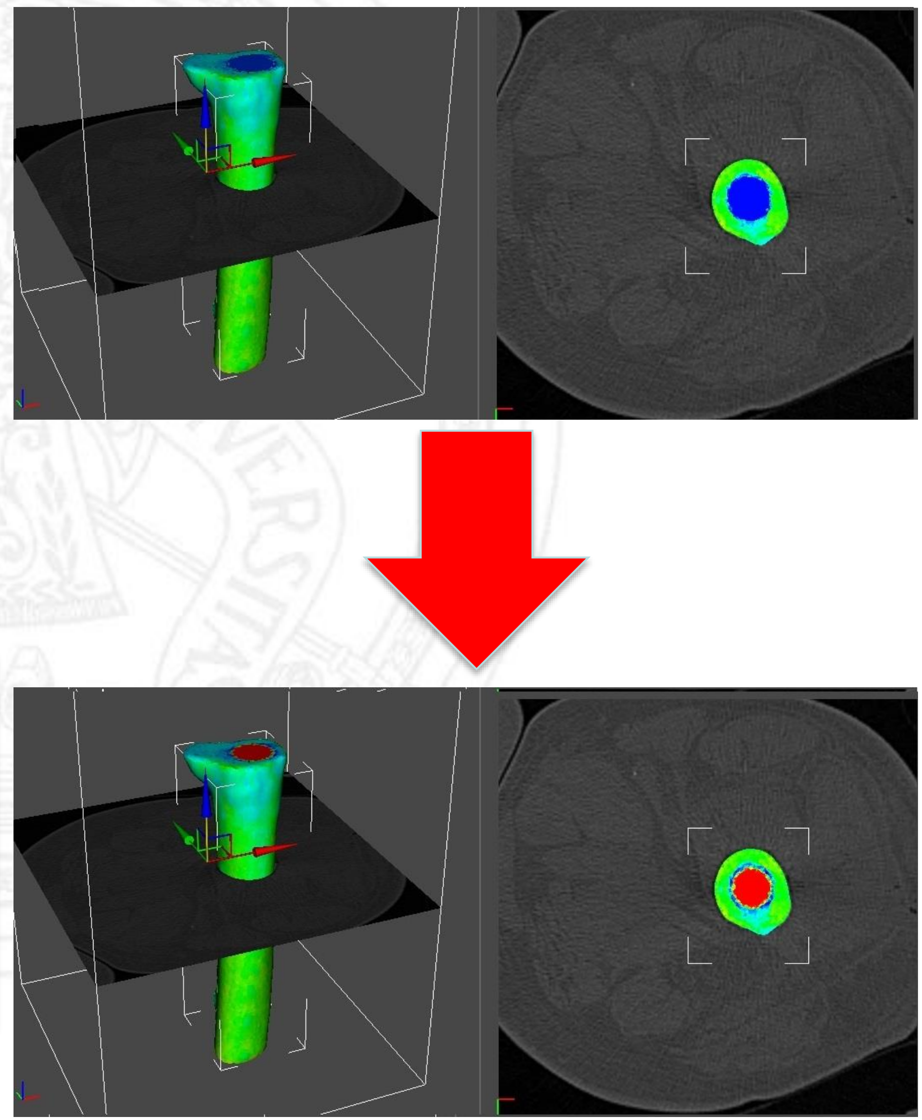
- **A mean value is obtained for each element:**

$$S_{ref} = \frac{S_{ref1} + S_{ref2} + S_{ref3}}{3}$$

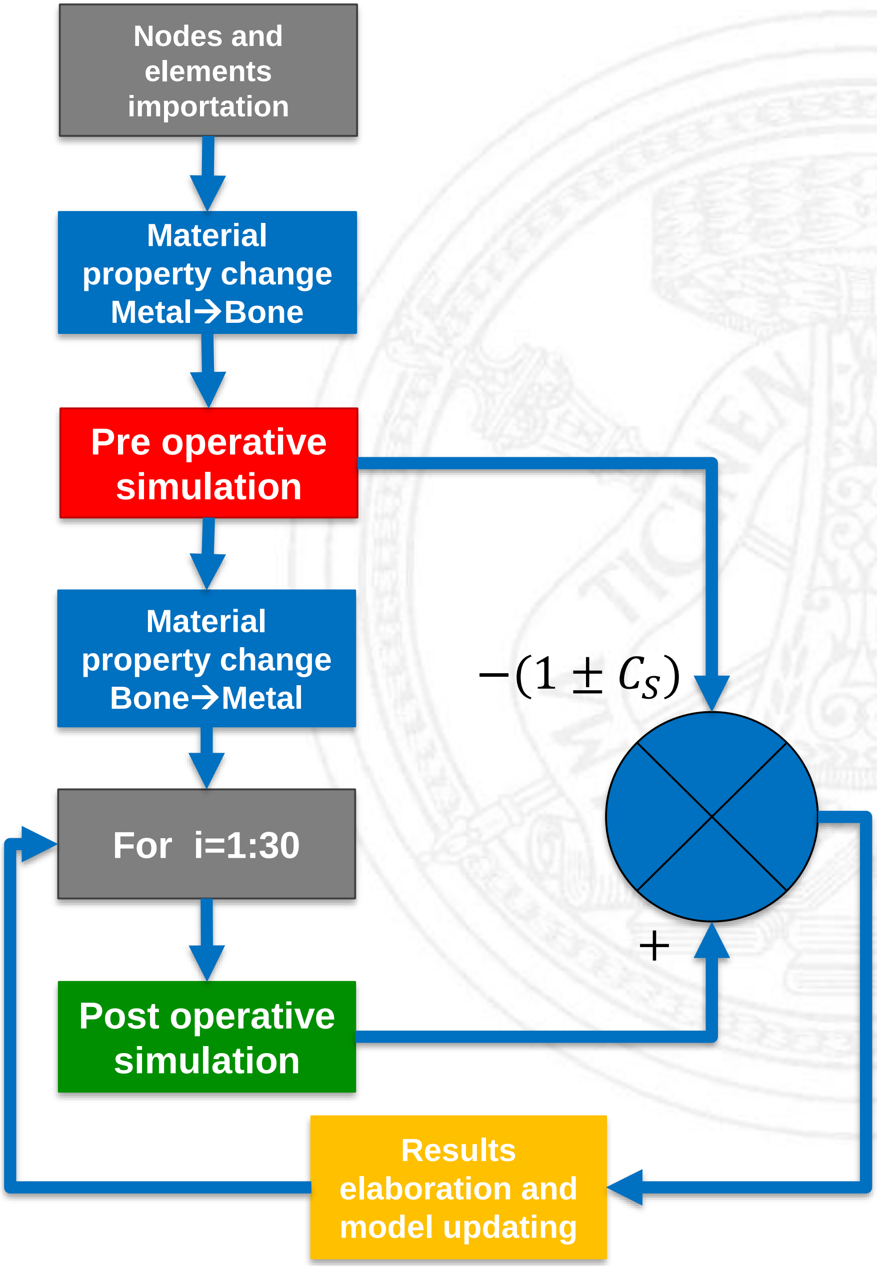
Algorithm creation & Parameter tuning



Material property change:



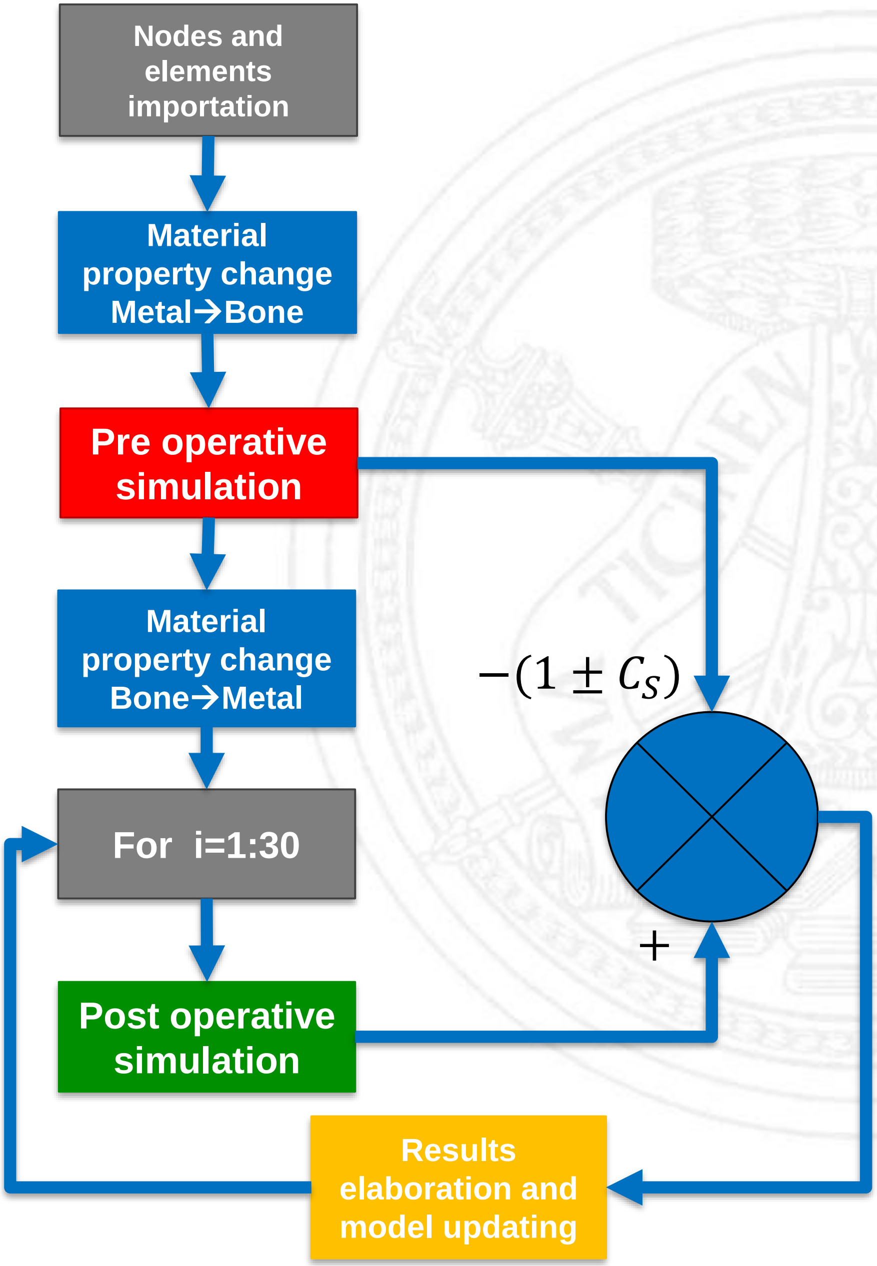
Algorithm creation & Parameter tuning



For cicle:

- **Two simulations performed:**
  1. **30 days simulation:**
     - 1 step=1 day
  2. **6 months simulation:**
     - 1 step=1 week

Algorithm creation & Parameter tuning

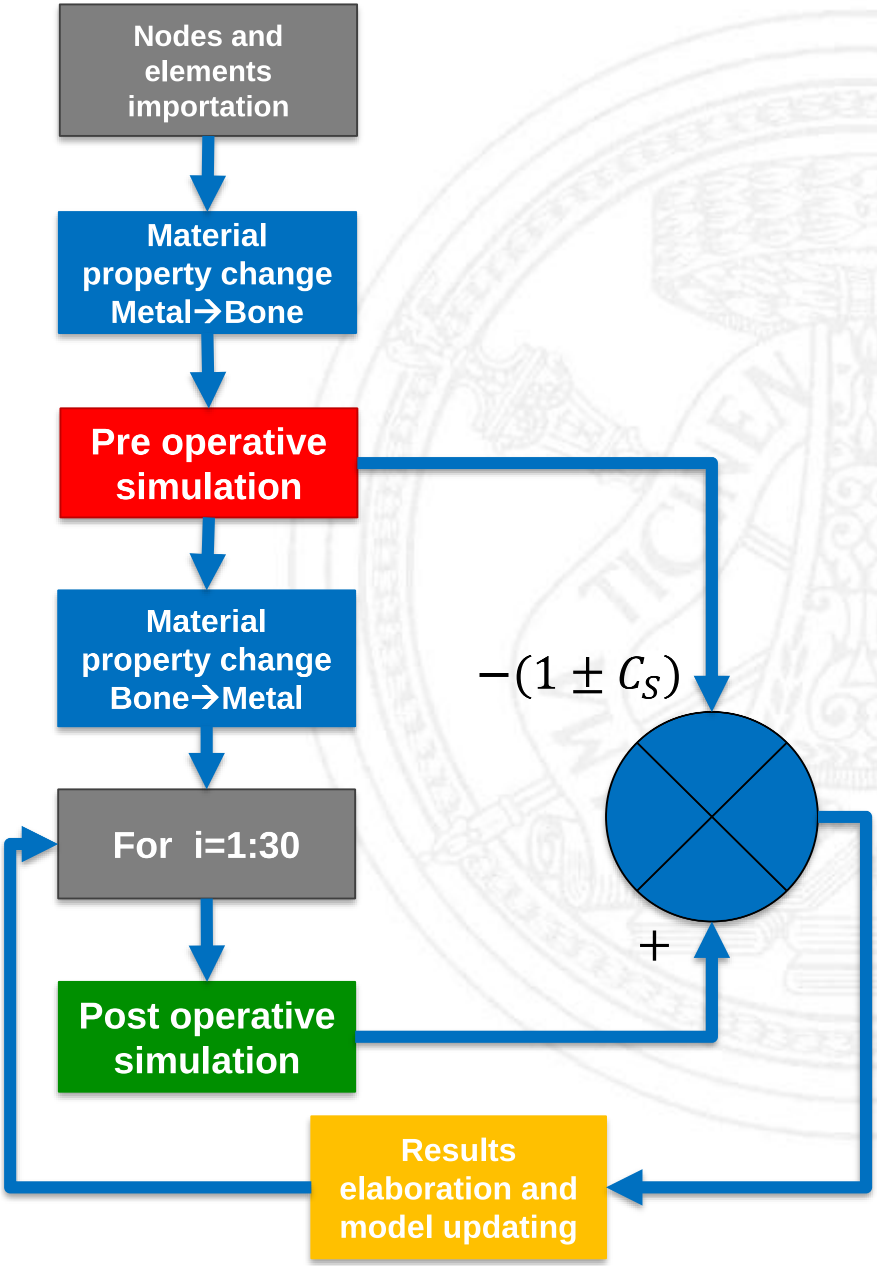


Post-operative simulation:

- Same as pre-operative simulation
- A mean S value for each element is obtained as:

$$S = \frac{S_1 + S_2 + S_3}{3}$$

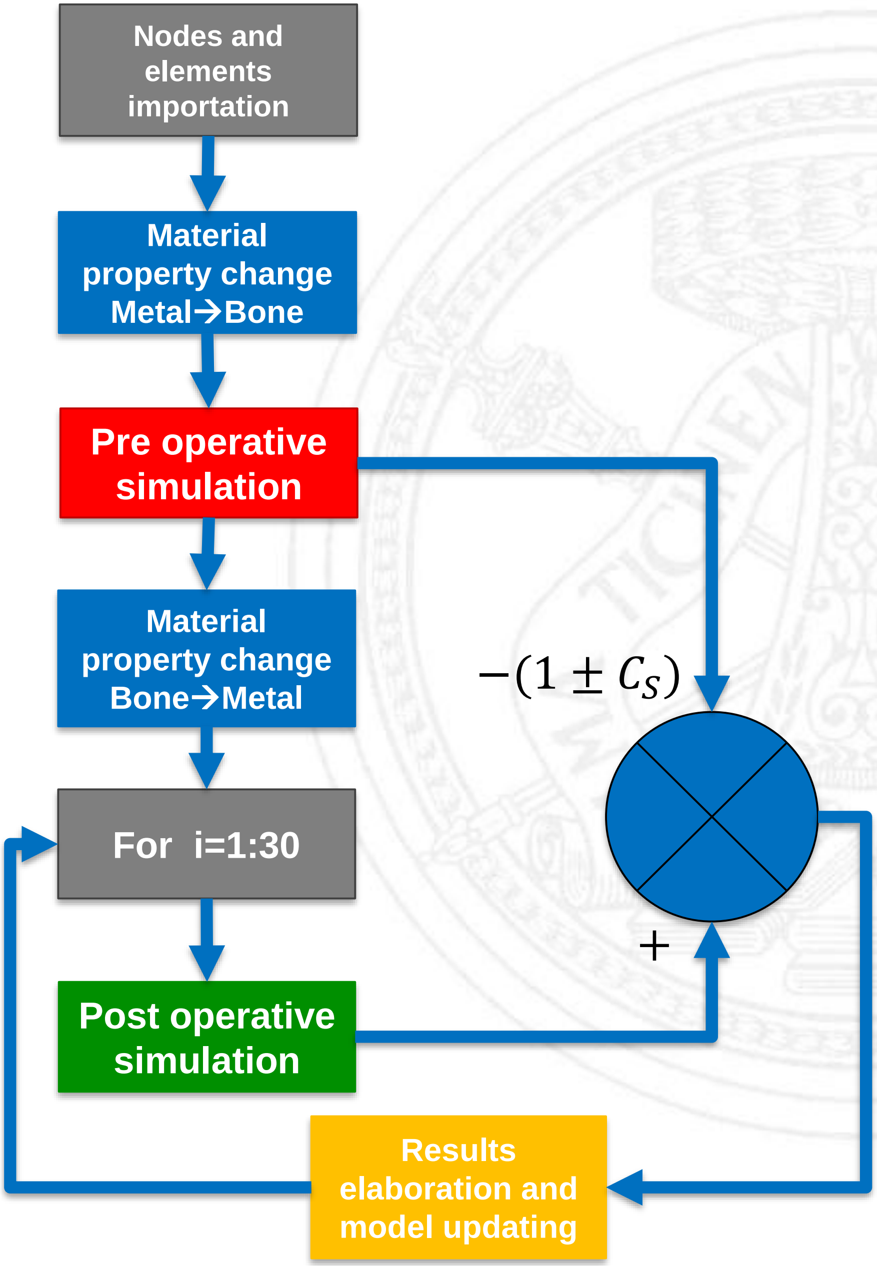
Algorithm creation & Parameter tuning



Pre/Post confrontation:

- $S < S_{ref}$ → bone resorption
- $S = S_{ref}$ → no modifications
- $S > S_{ref}$ → bone apposition

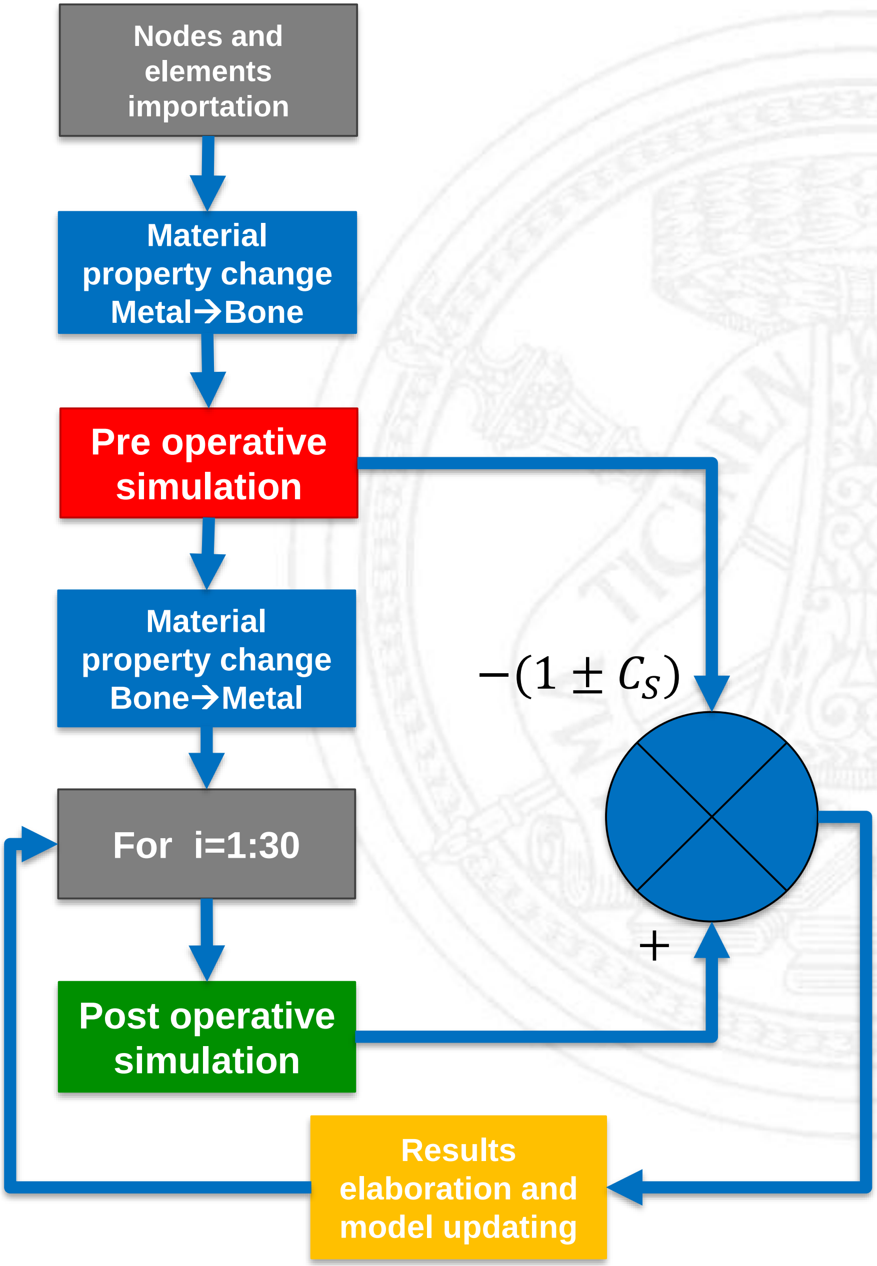
Algorithm creation & Parameter tuning



Model updating:

- If an element is subjected to **bone remodeling,** its density and E will change as:
  - $\Delta\rho = B \cdot \Delta S \cdot \Delta t$
  - $\rho_{new} = \rho + \Delta\rho$
  - $E_{new} = a_1 + b_1 \cdot \rho_{new}^{C_1}$

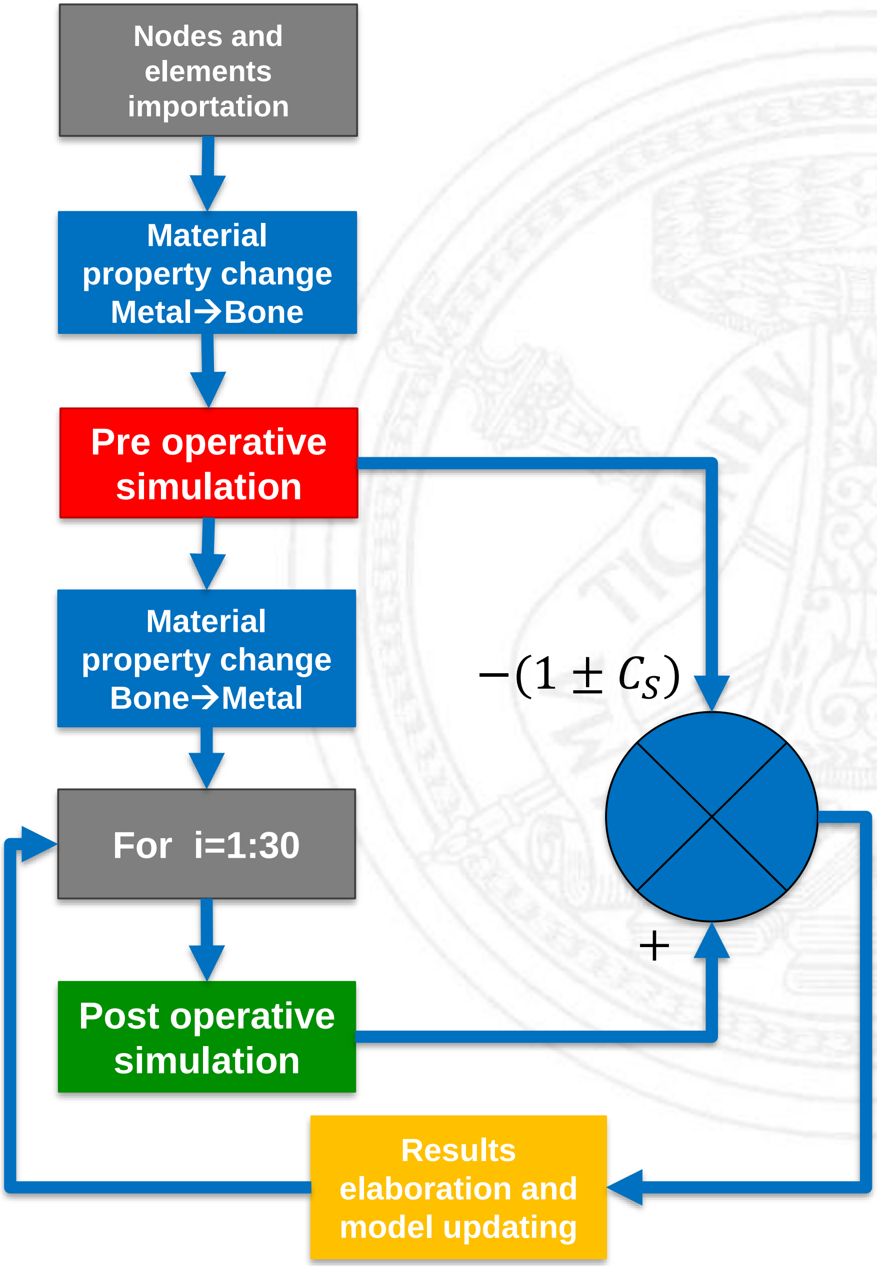
Algorithm creation & Parameter tuning



Results elaboration:

- A list of the elements subjected to remodeling is extracted
- Density changes between each step are saved
- A 3D map of density changes between of the i-th step regarding the initial condition is saved

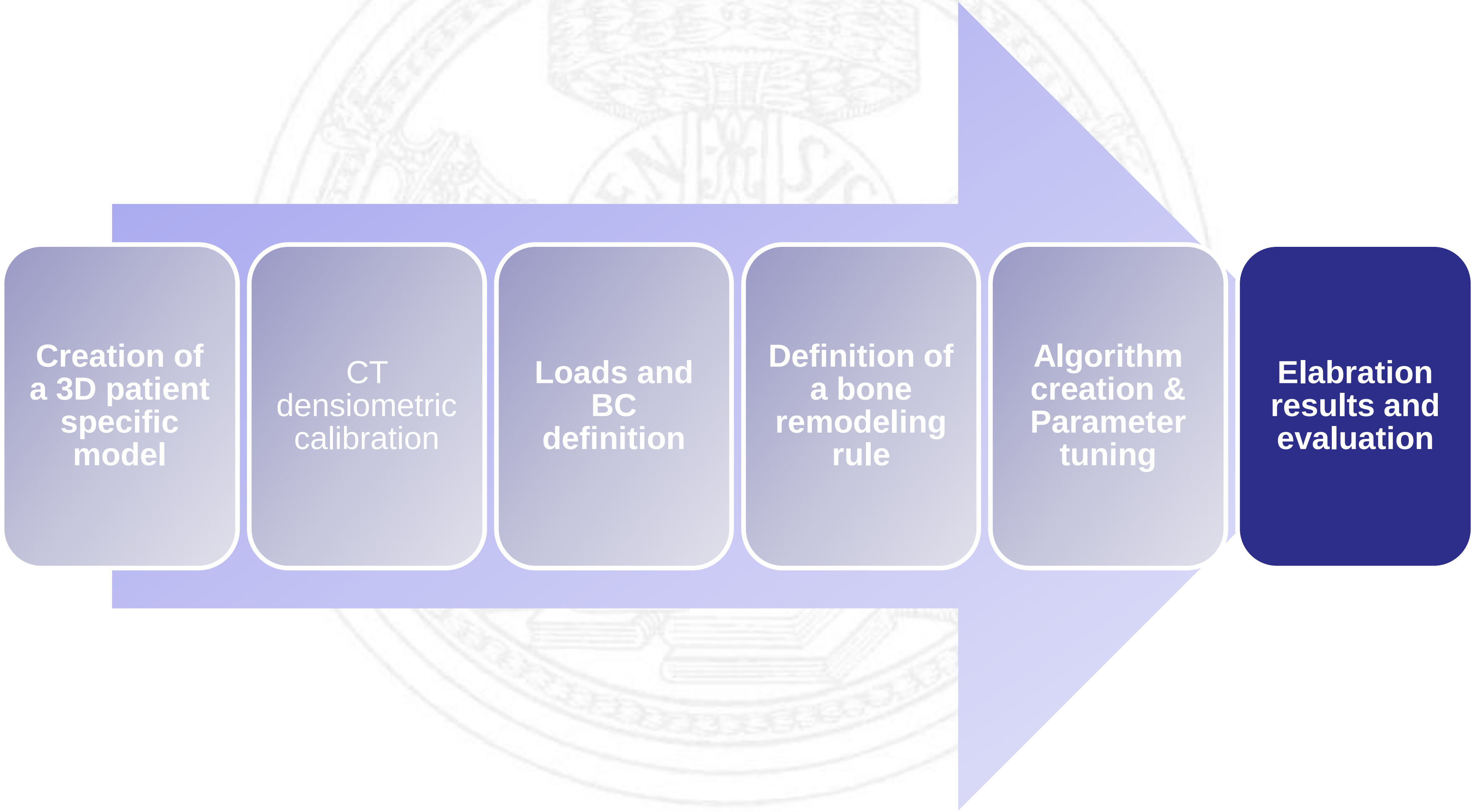
Algorithm creation & Parameter tuning

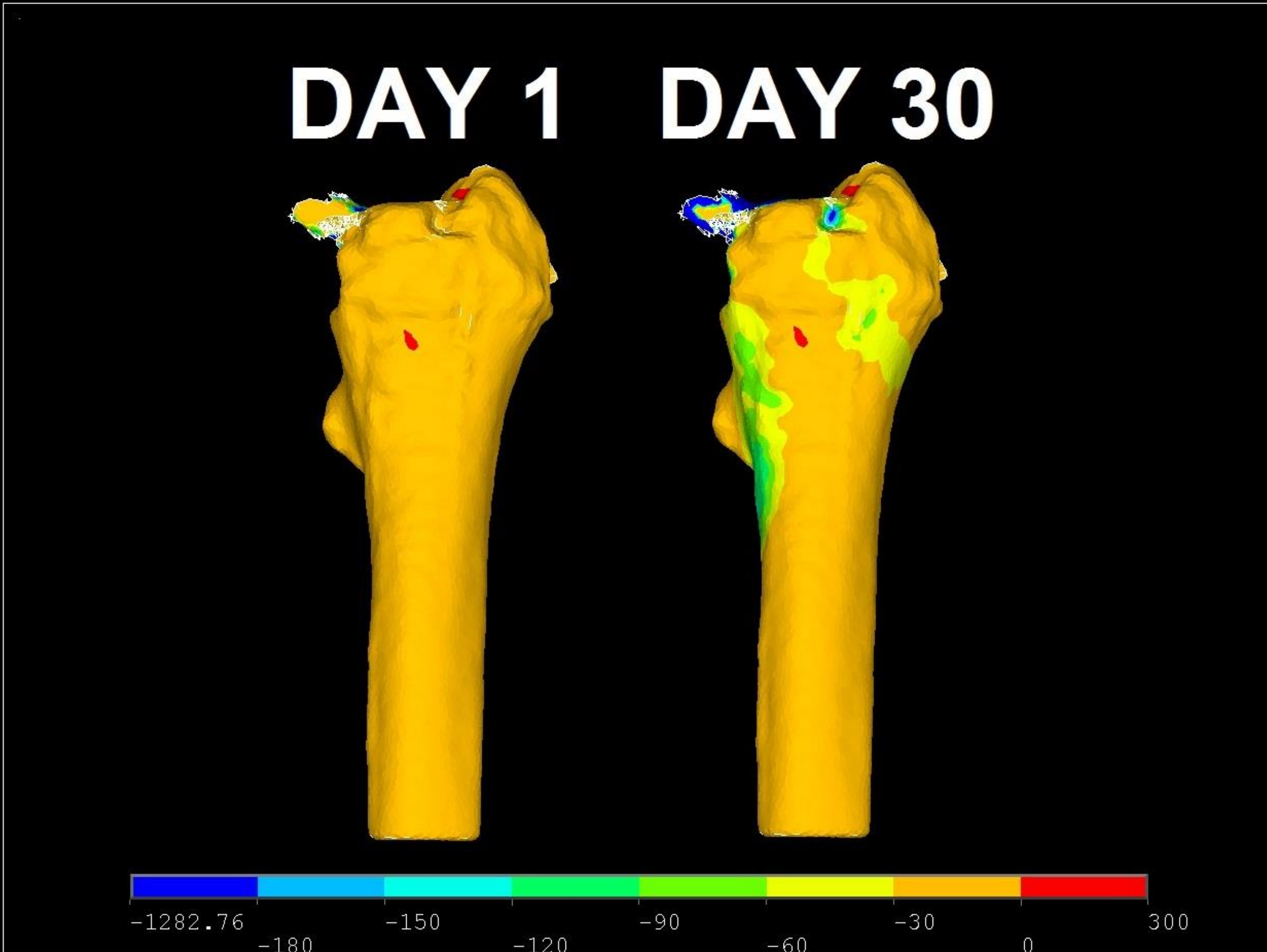


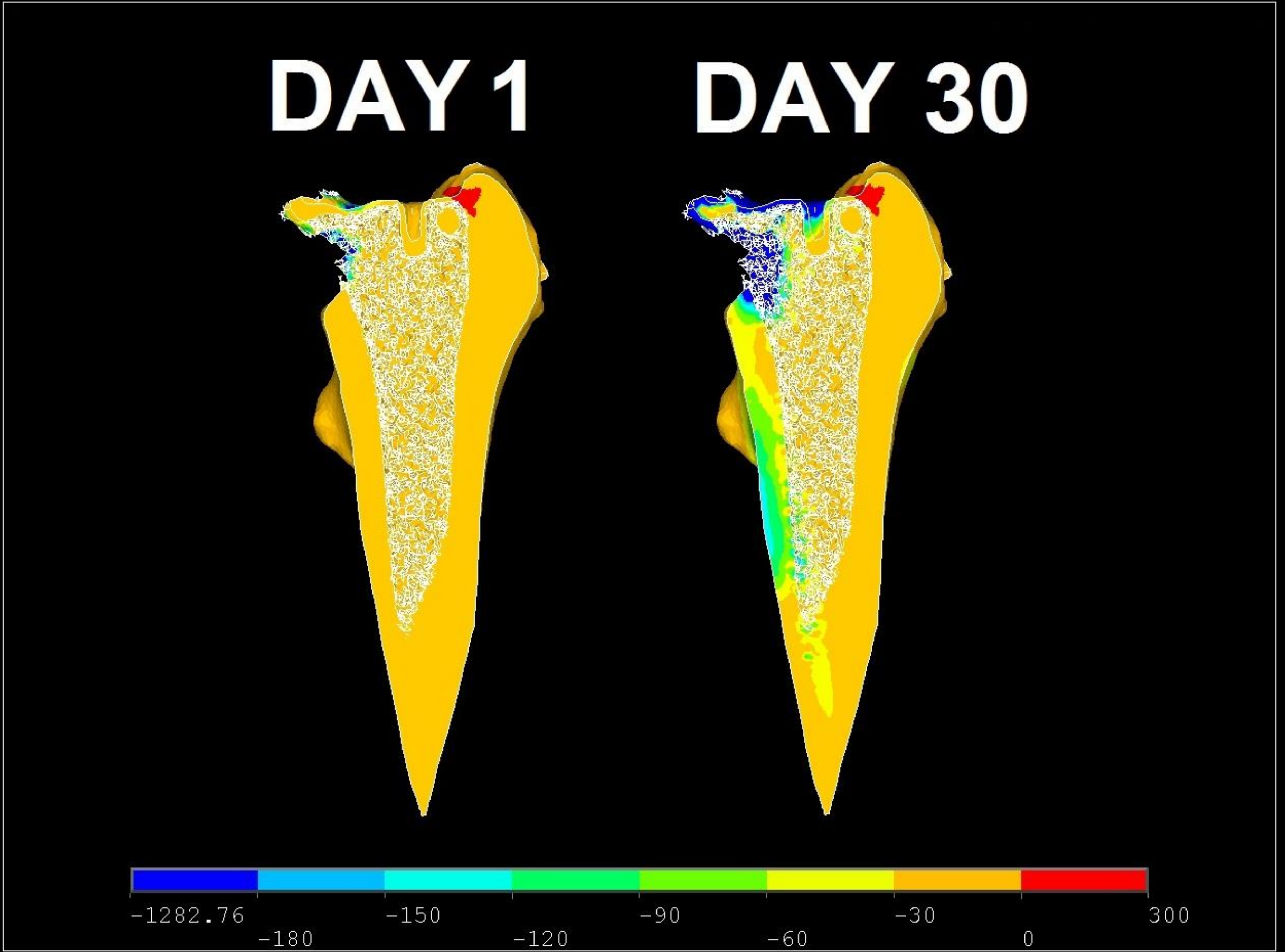
For cicle:

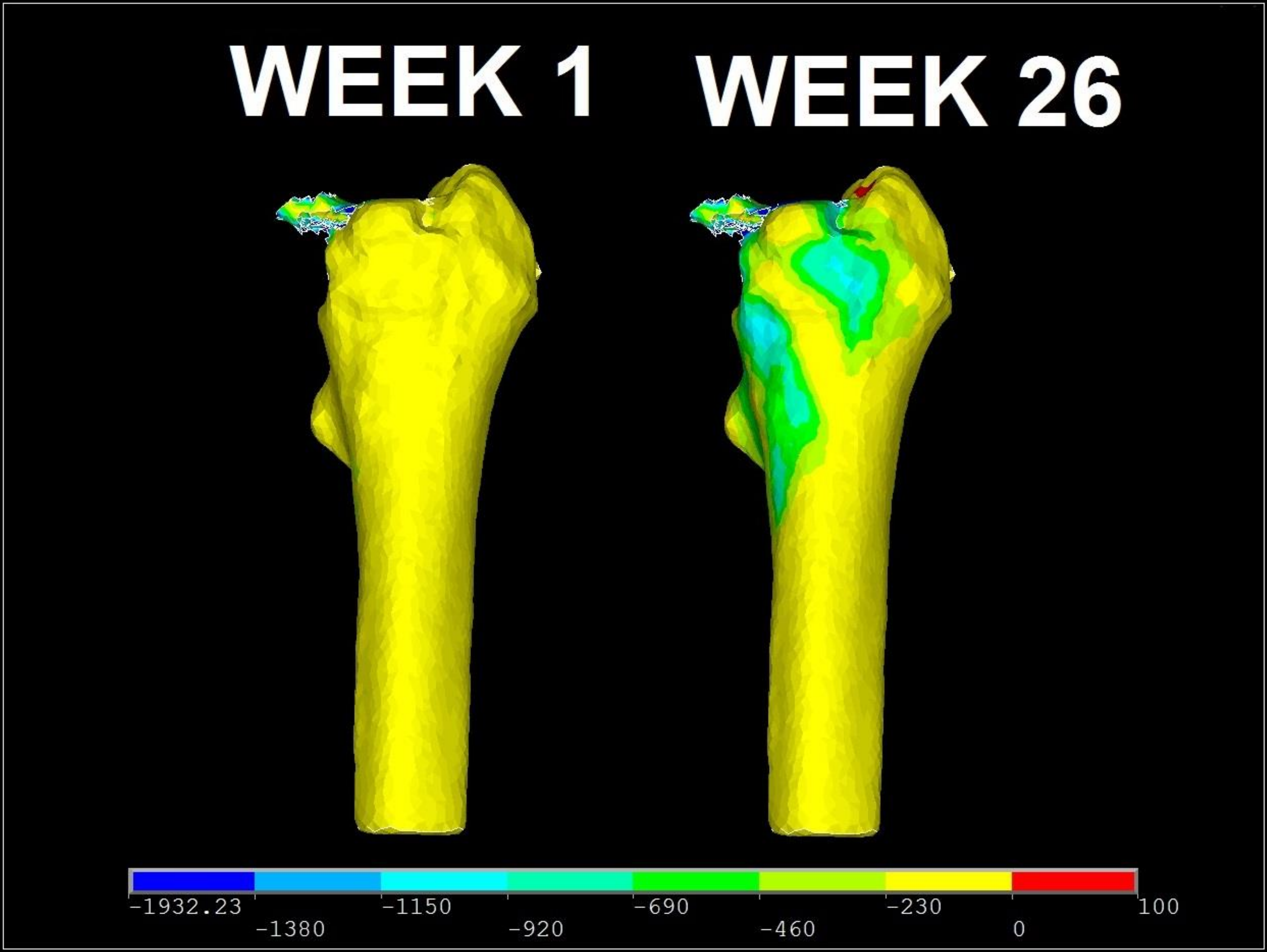
- The output model is the new post-operative model
- An iterative bone density changes map is thus obtained

Results elaboration and commentary

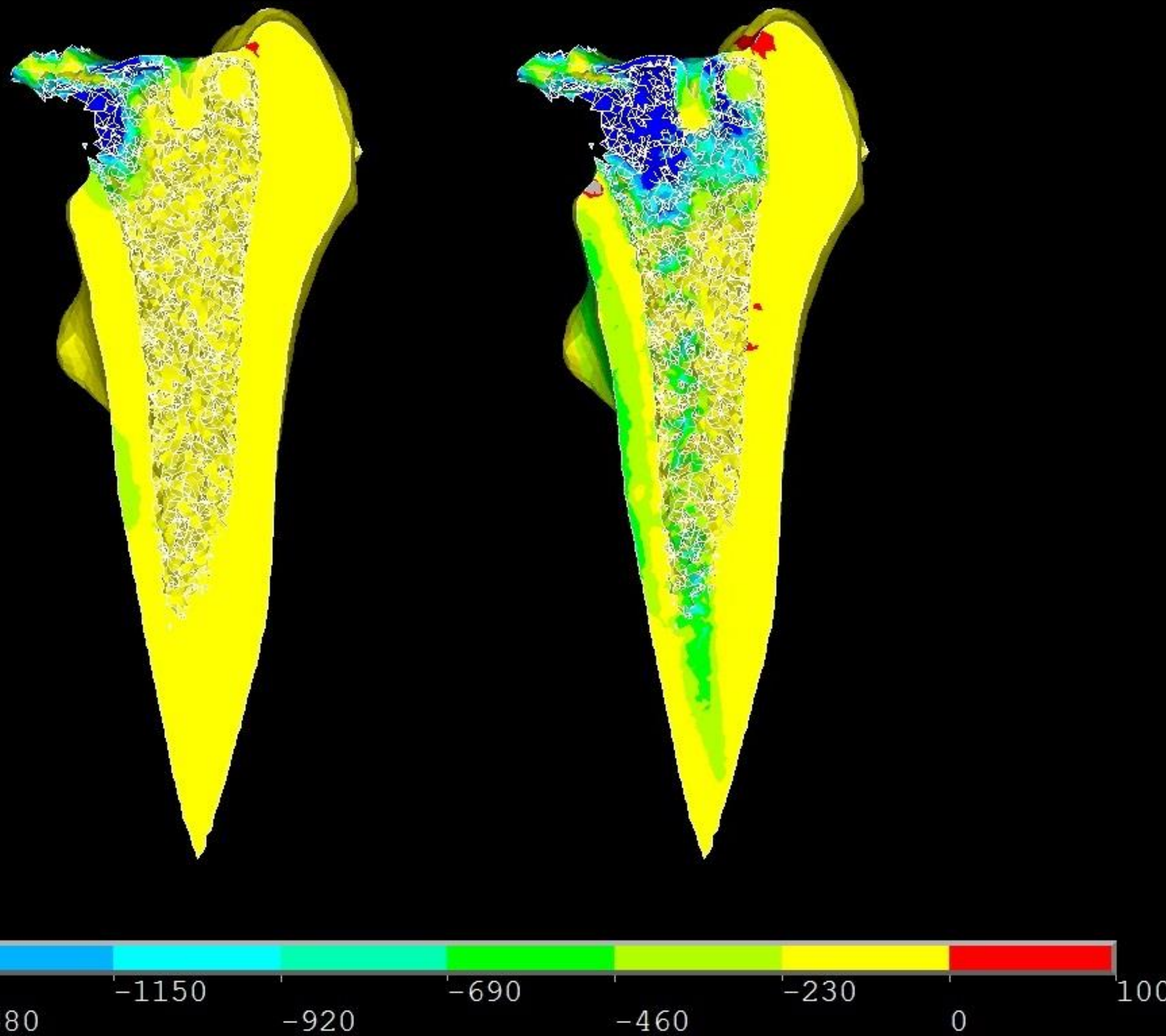



DAY 1
DAY 30
-1282.76
-180
-150
-120
-90
-60
-30
0
300


DAY 1
DAY 30
-1282.76
-180
-150
-120
-90
-60
-30
0
300


WEEK 1
WEEK 26
-1932.23
-1380
-1150
-920
-690
-460
-230
0
100

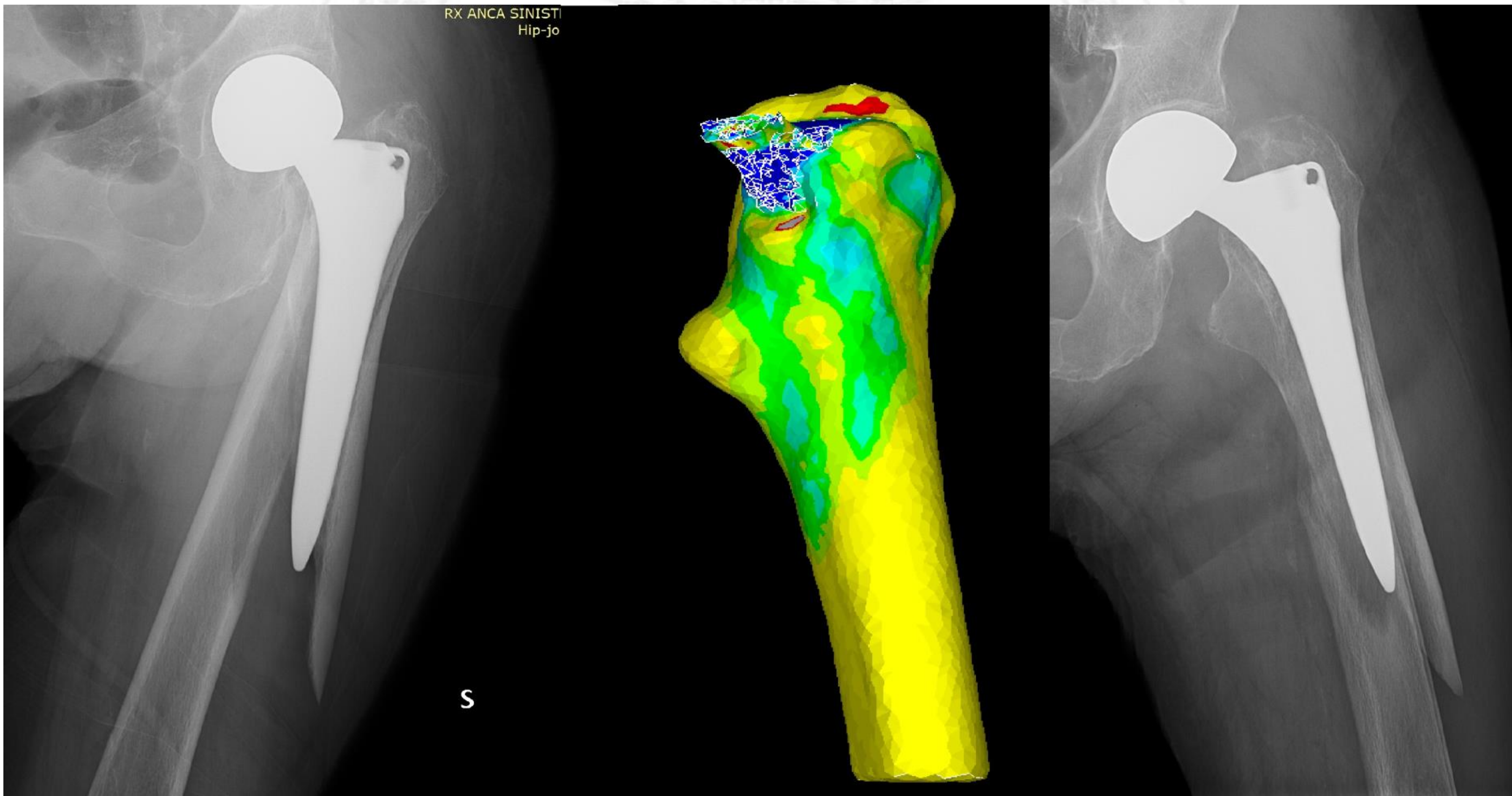
WEEK 1 WEEK 26



Results elaboration and commentary

- **«The model predicted correctly the risk zones»**

  Prof. Benazzo’s medical equipe (Ortopedia Traumatologia, IRCCS San Matteo)



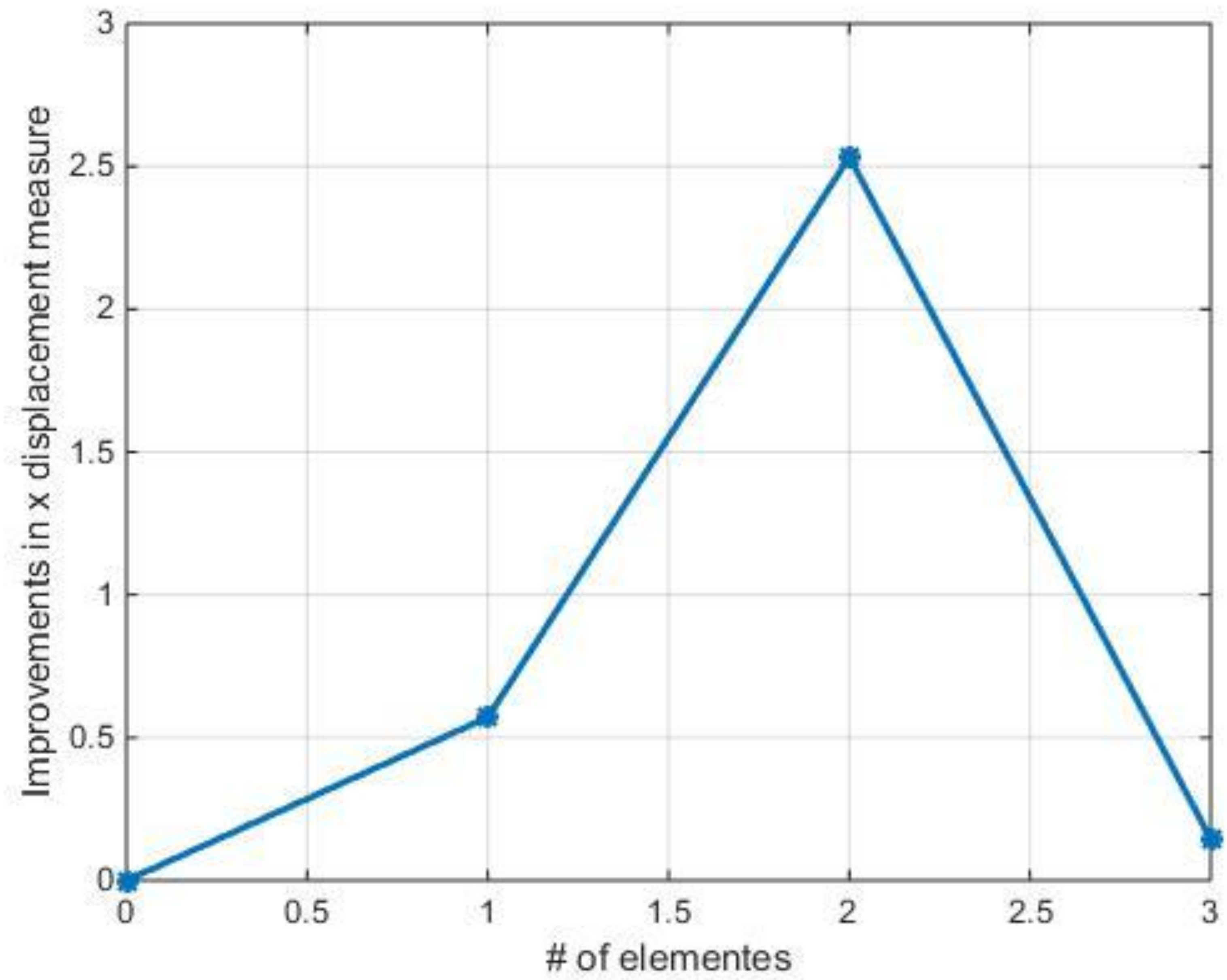
Future improvements

- **Ready to use:**
  - Experimental protocol, performing CT scans before and after THA:
    - Use of calibration phantoms
  - More available studies could help out finding the correct parameter's calibration
  - Introduction of a failure criterion to predict bone failure

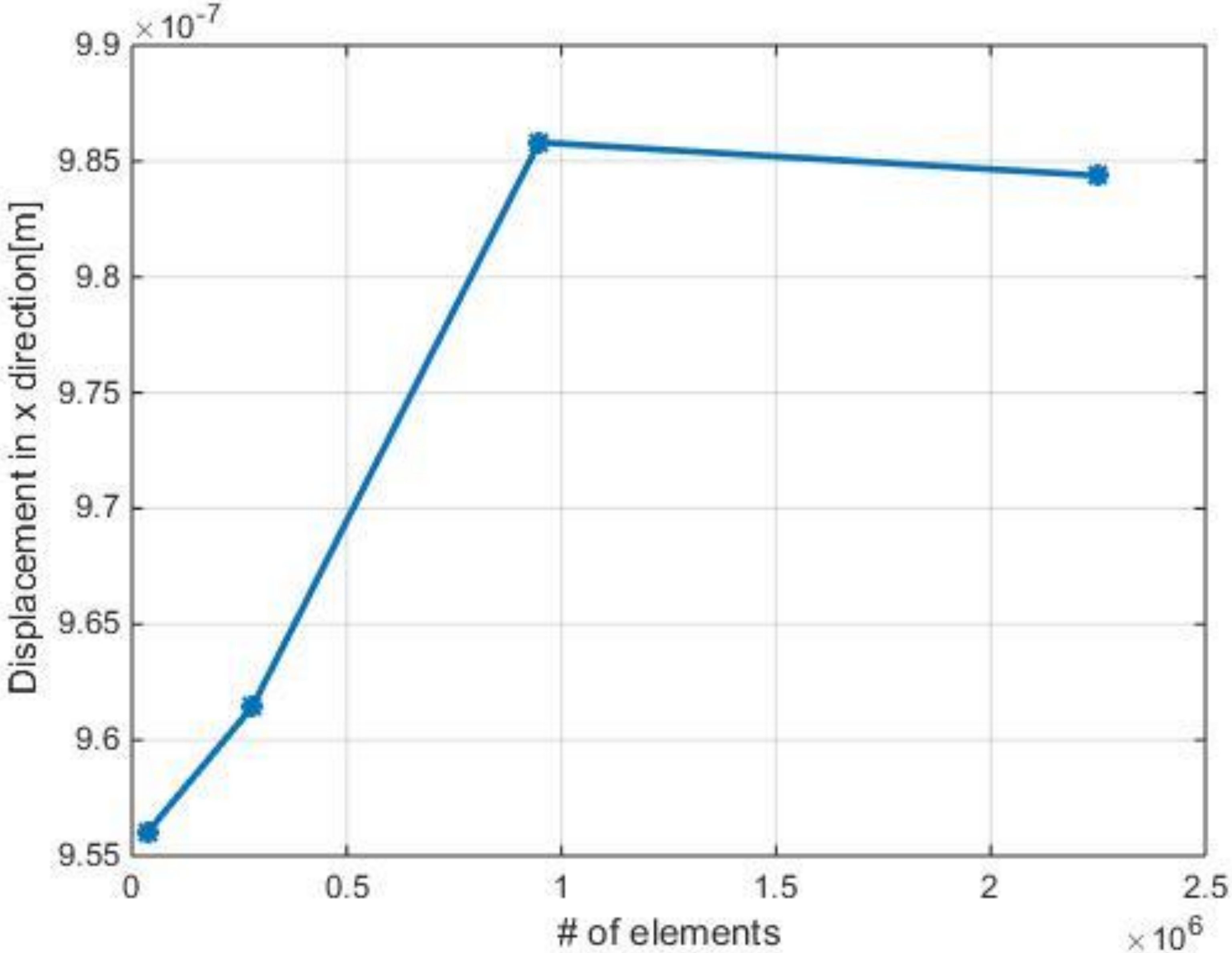
- **Long term:**
  - Pre operative surgery planning
  - A deep study about patient's lifestyle in the first days after THA
  - The use of patient specific loading conditions:
    - Motion capture techniques
  - Implementation of additional loading conditions to simulate a physiotherapy maneuver applied with regularity

Grazie per l'attenzione

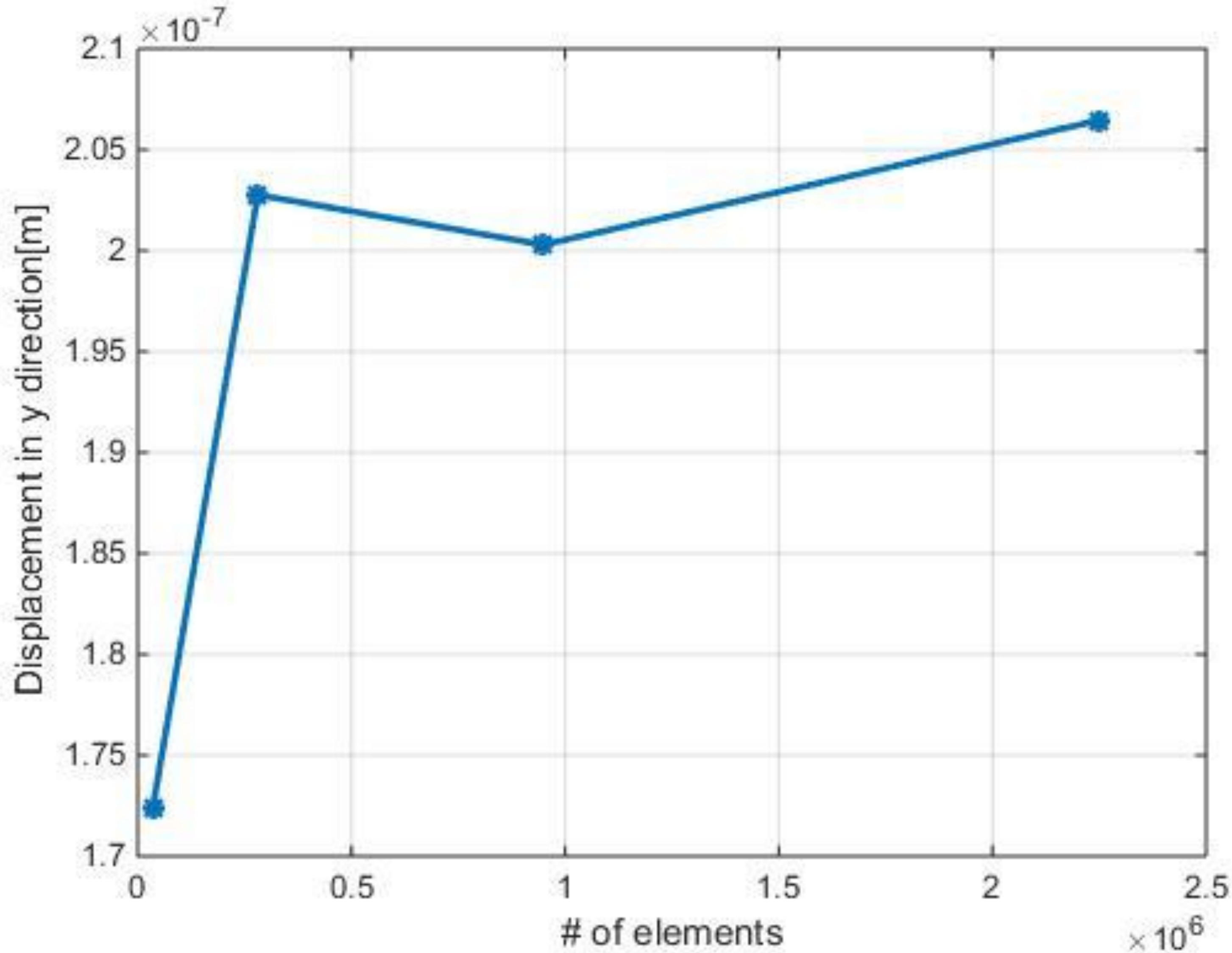
Convergence analysis



Convergence analysis



Convergence analysis



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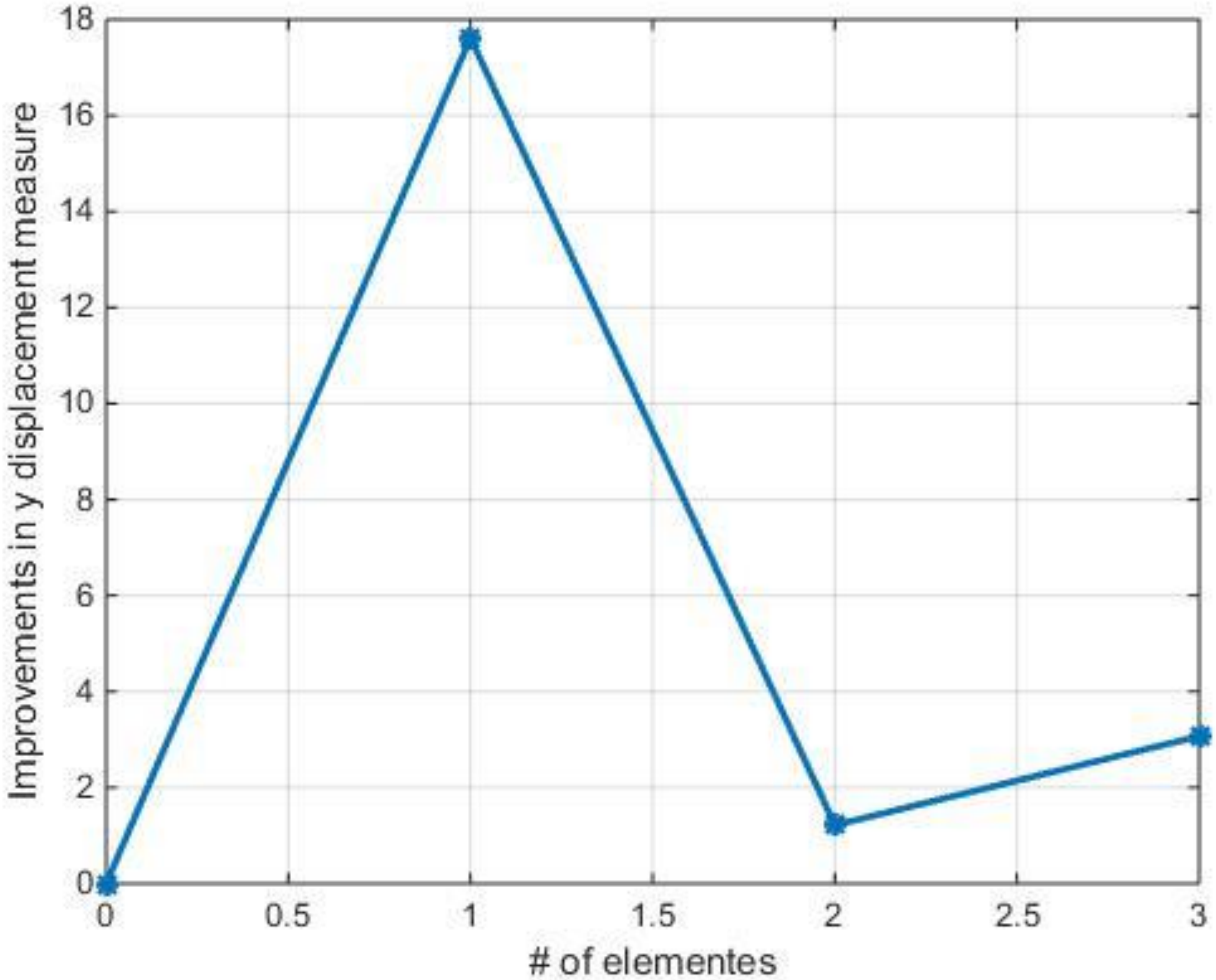

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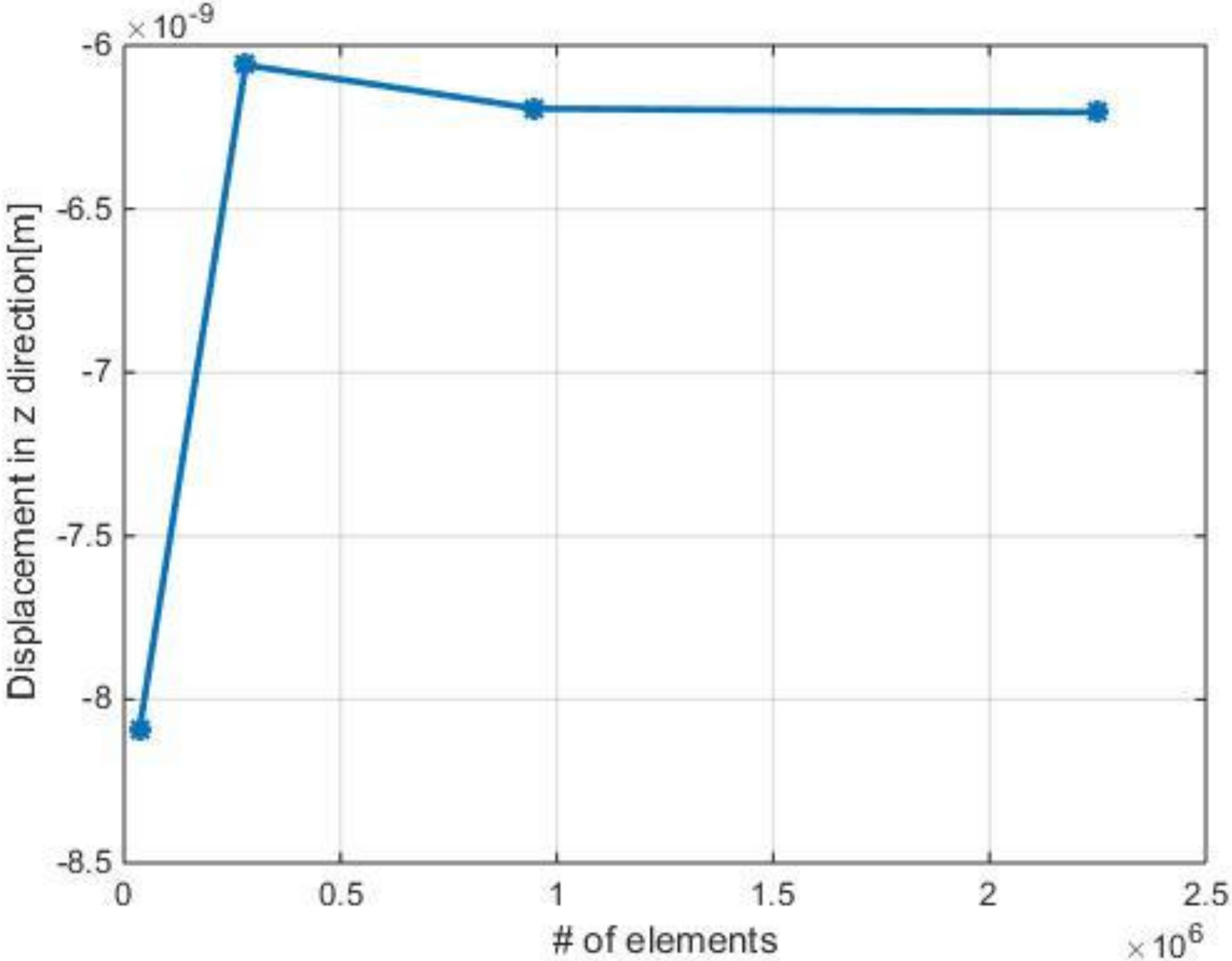

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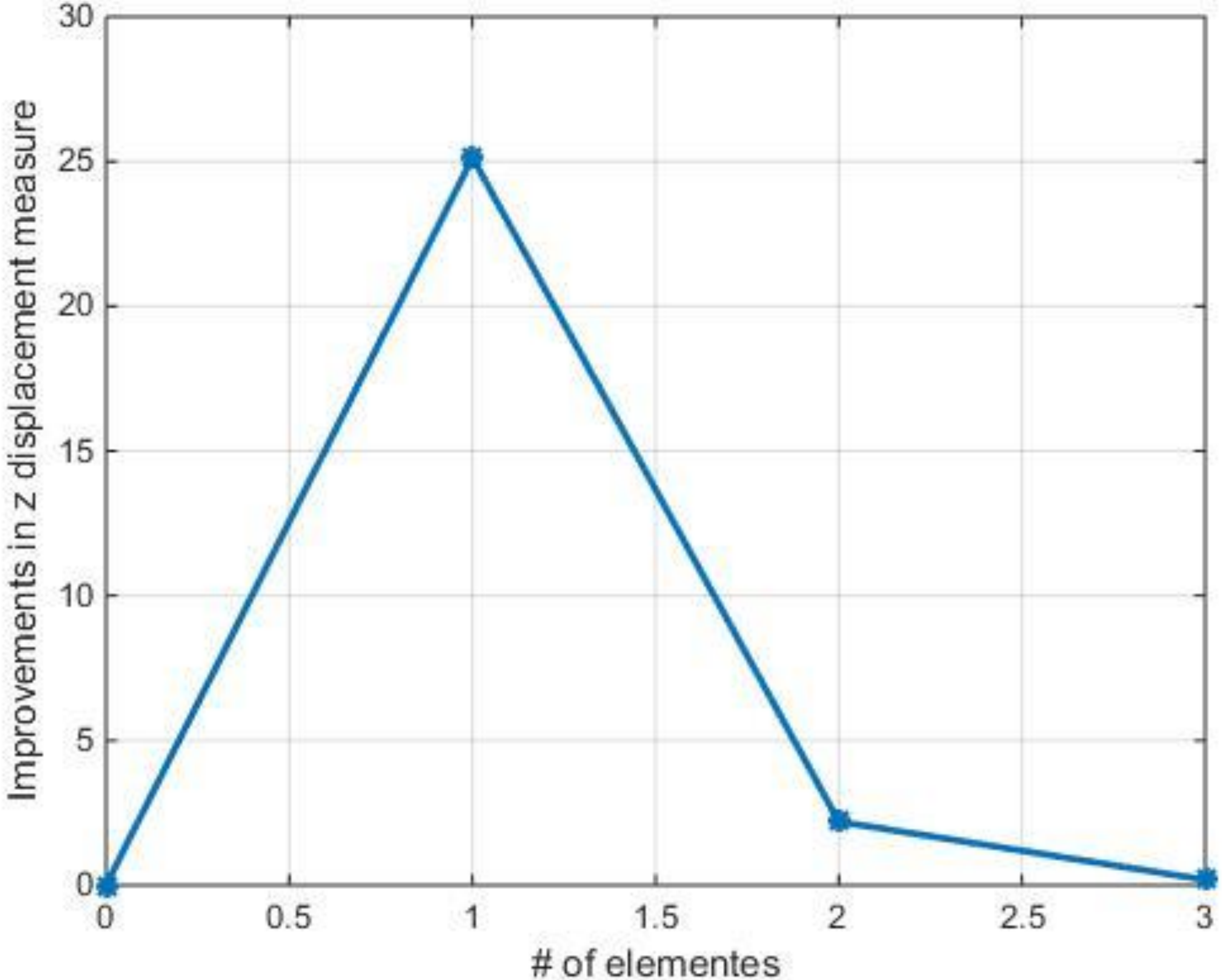

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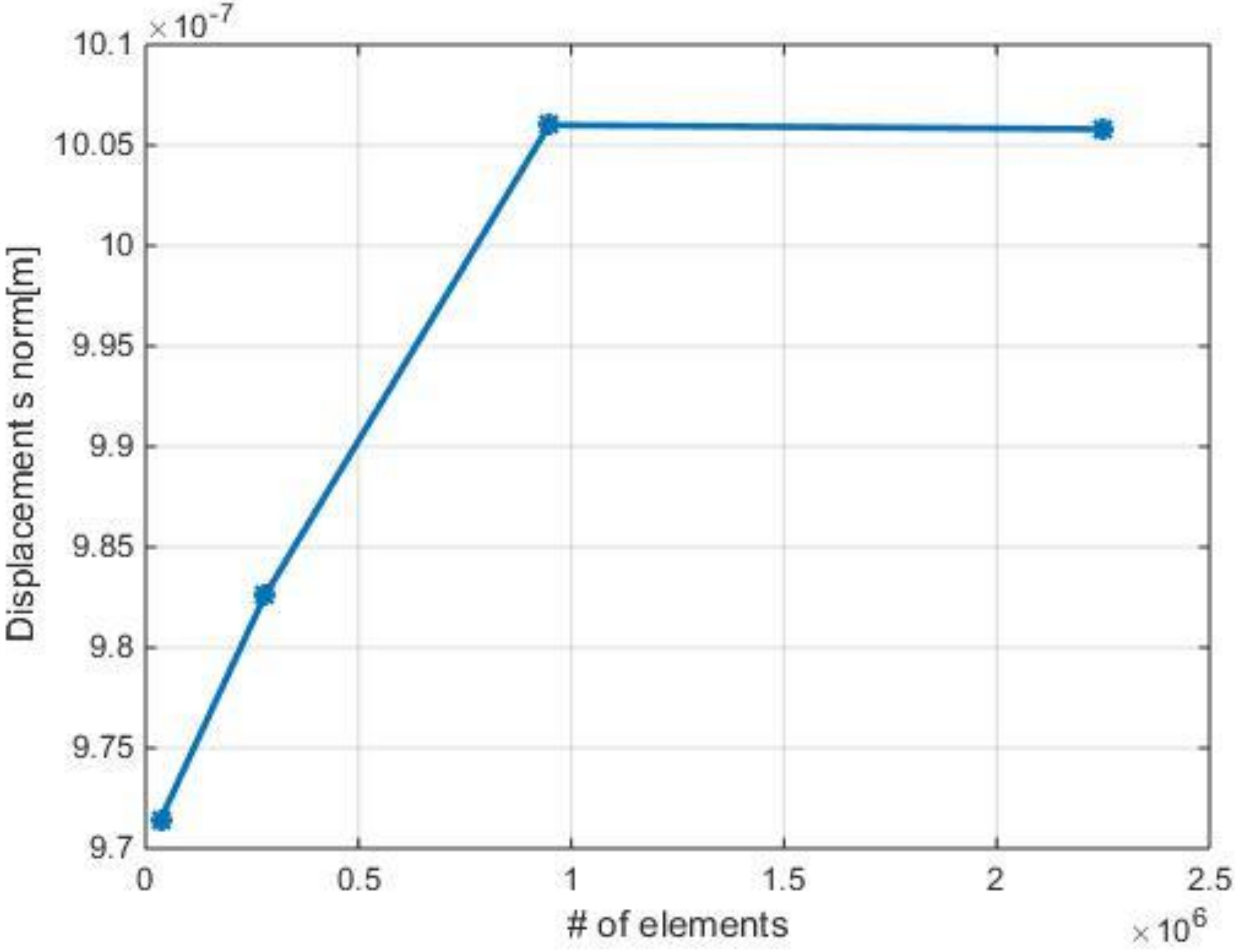

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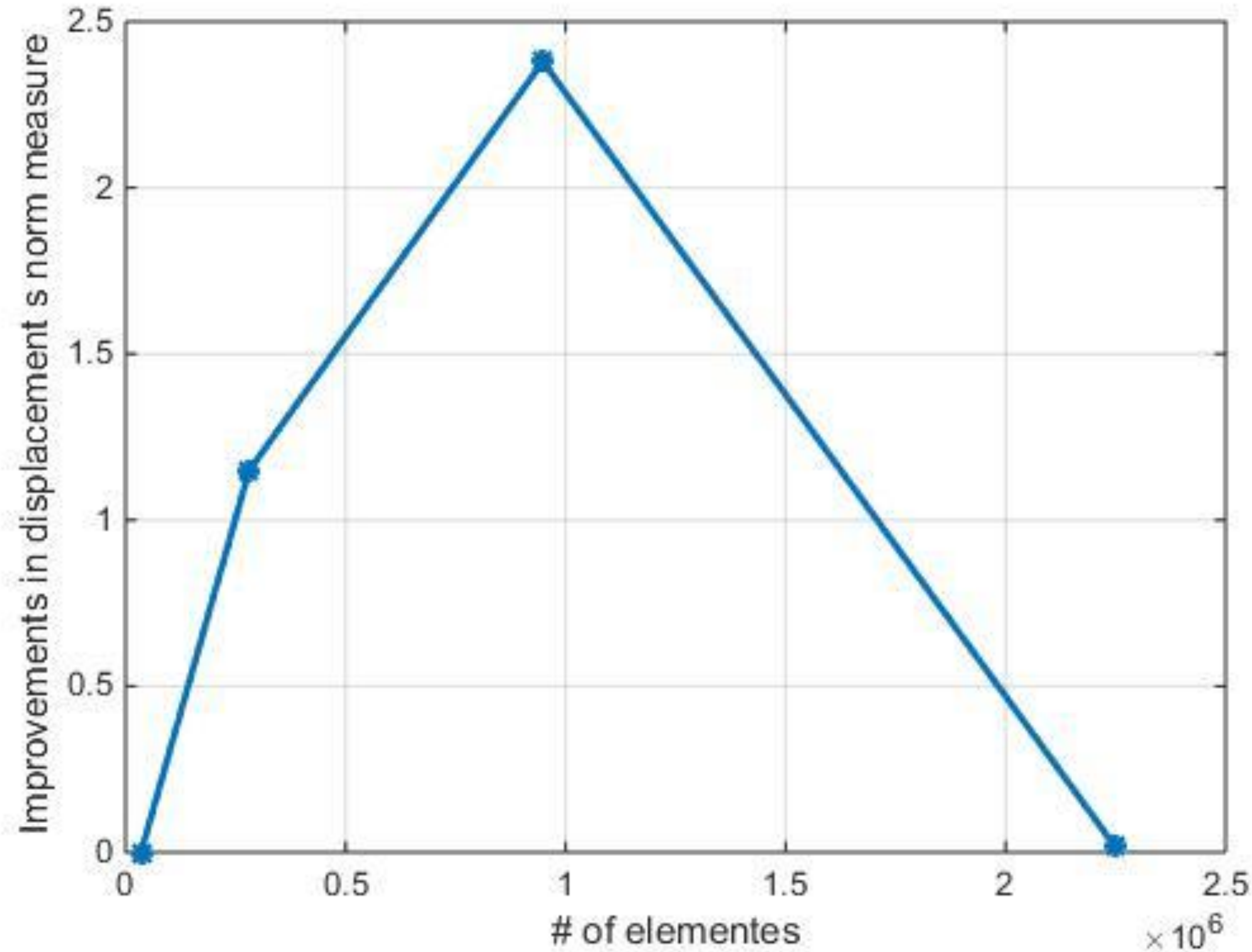
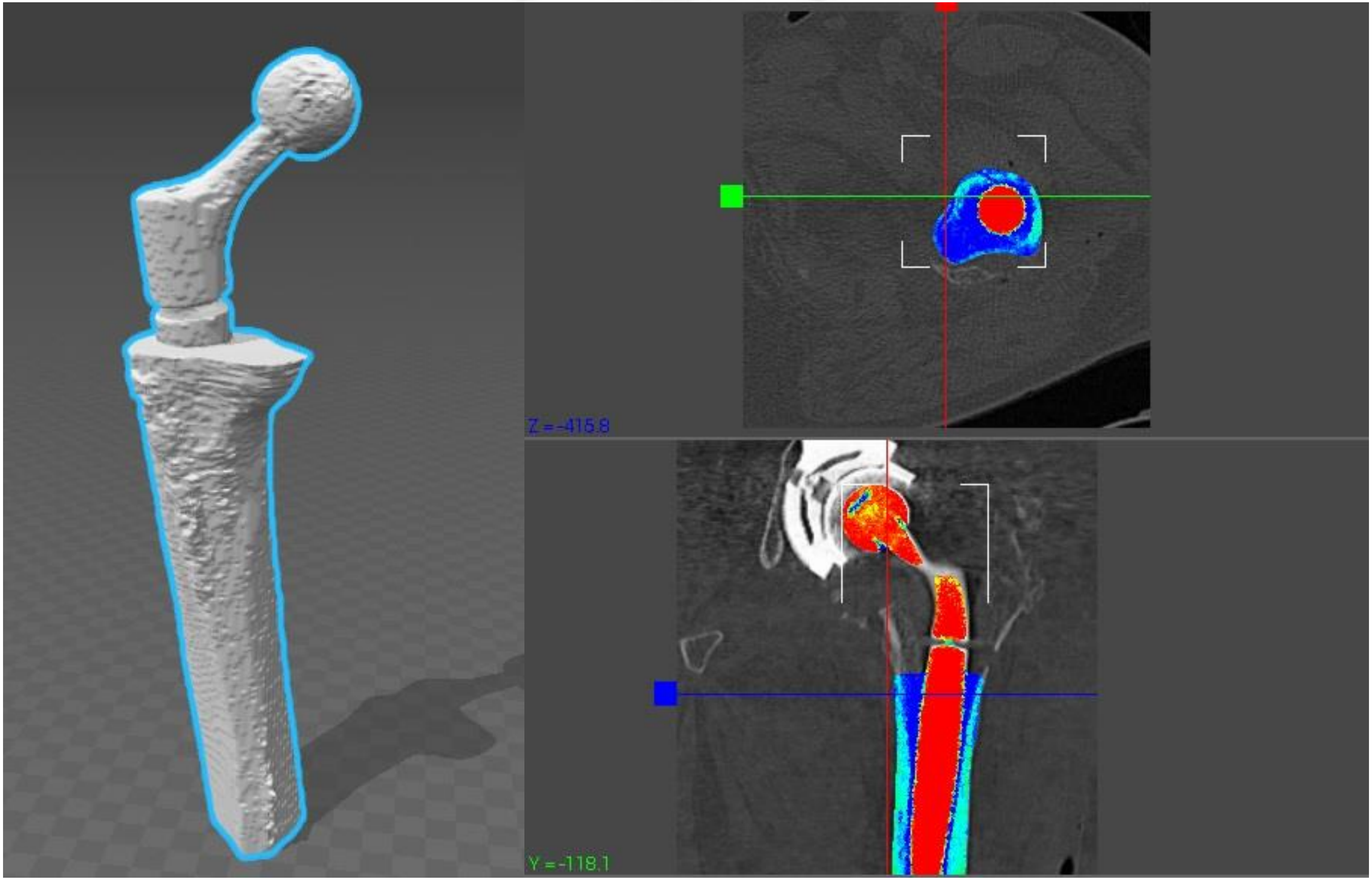
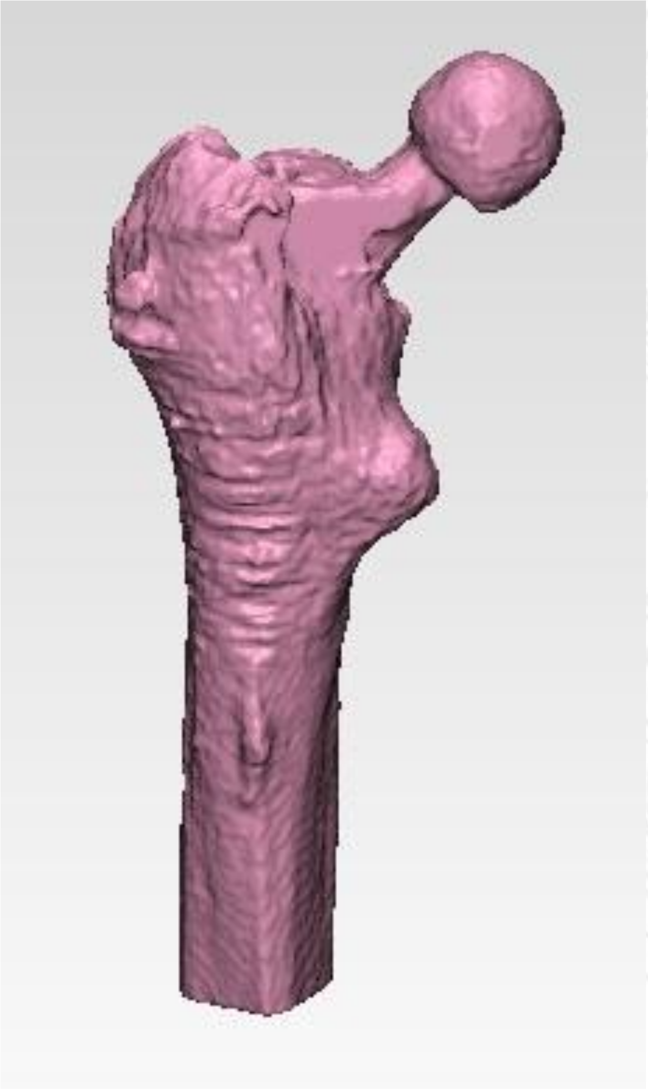
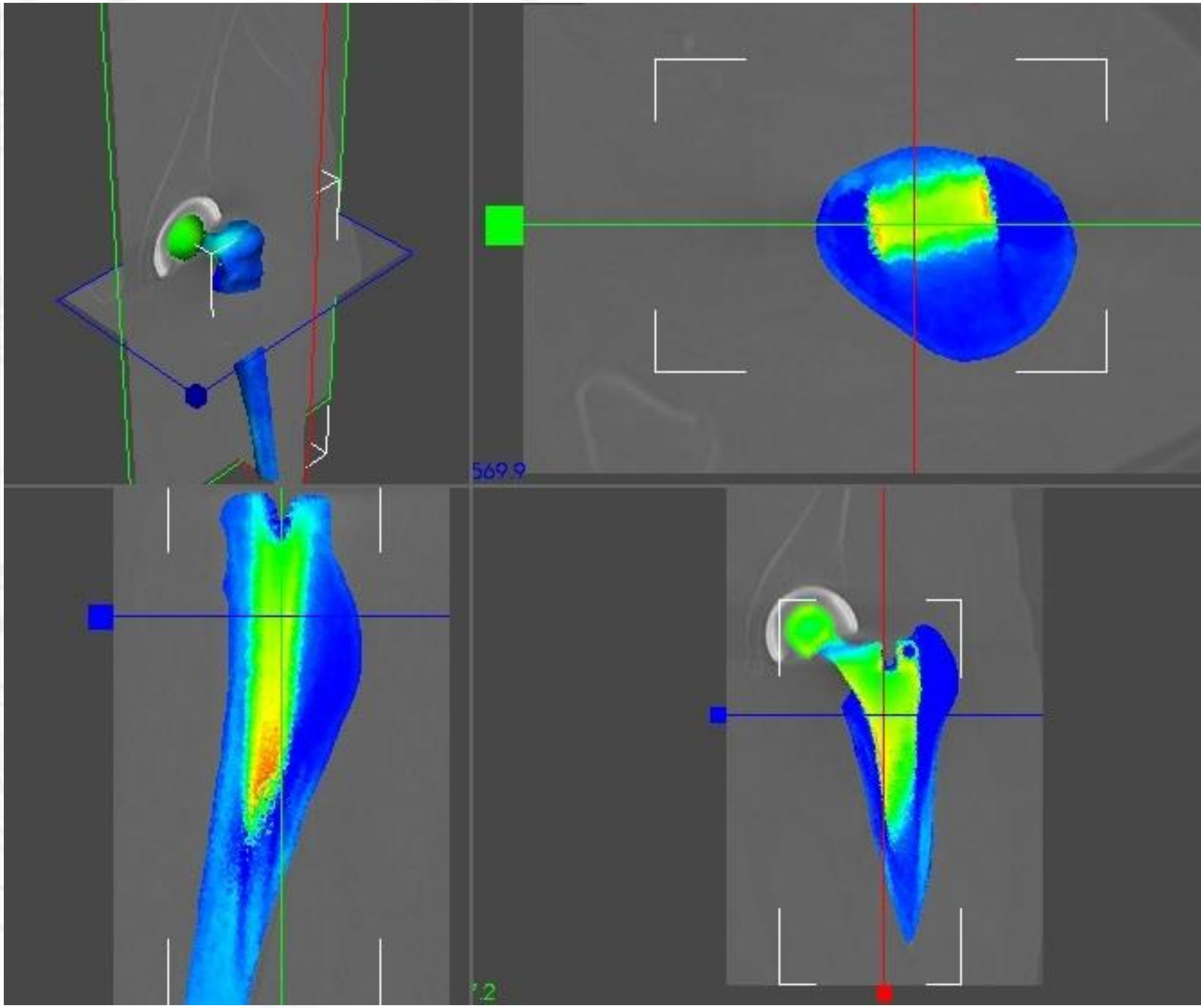


The two models

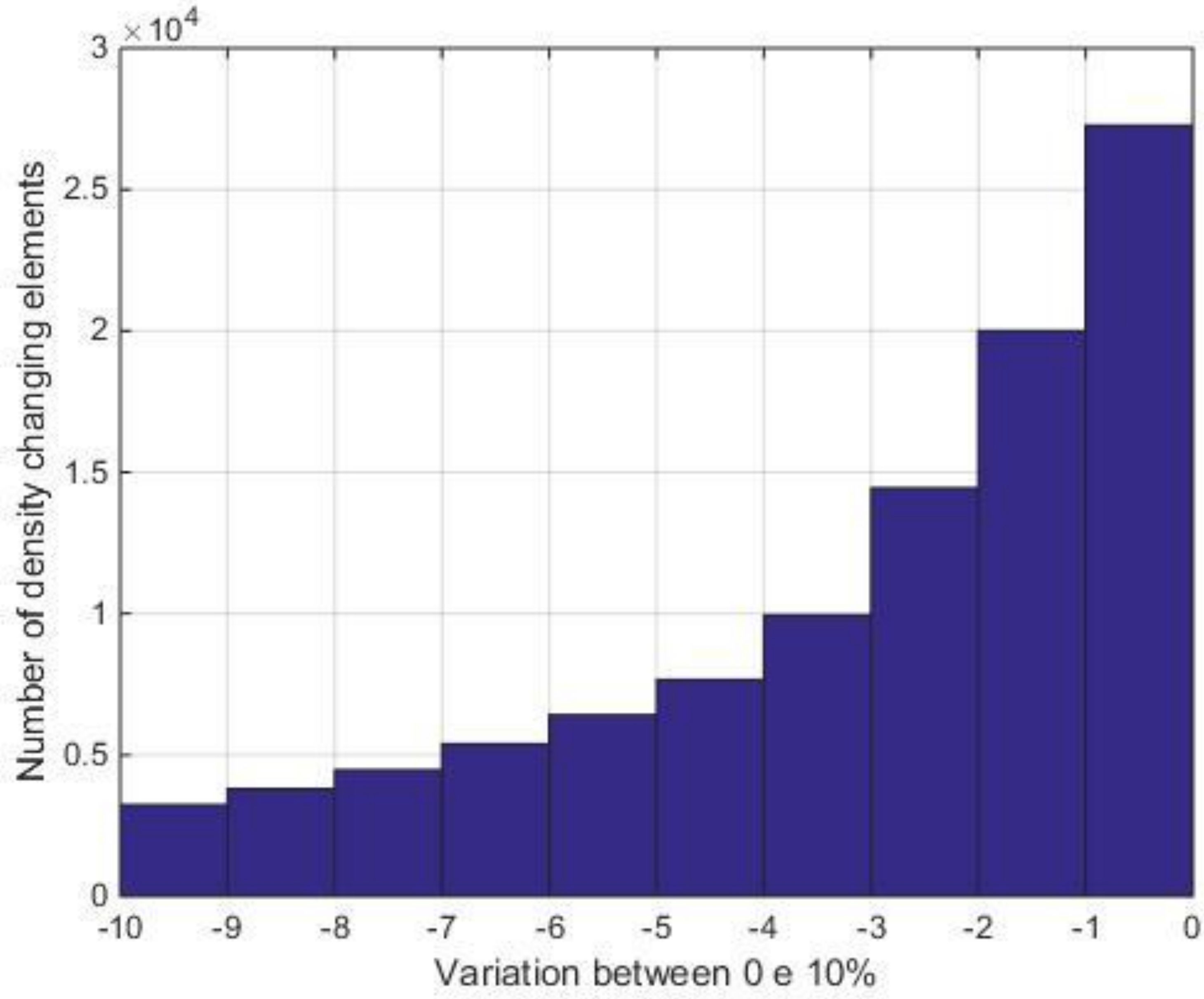


The two models



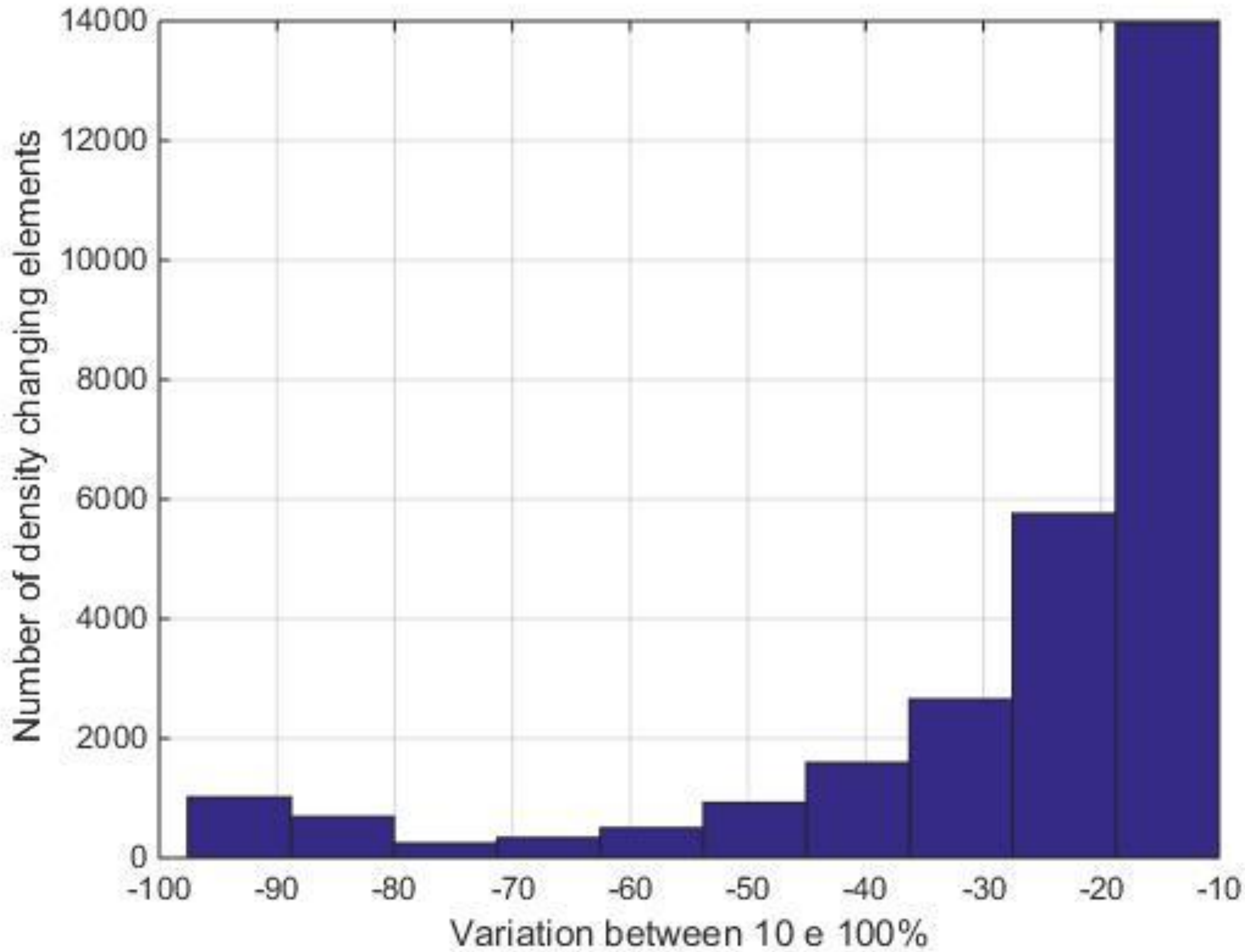


Histograms



$\times 10^4$
3
2.5
2
1.5
1
0.5
0
Number of density changing elements
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Variation between 0 e 10%

Histograms



Number of density changing elements
Variation between 10 e 100%
14000
12000
10000
8000
6000
4000
2000
0
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10