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Elaboration of a MATLAB Script to Optimize the Choosing Process of Earth Construction as a Function of Soil, Climate and Average Costs

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Abstract

Earth constructions are accessible, ecological, require less energy, and use a large part of the material found in the region, about 1 to 2% when compared to ordinary masonry constructions, which also generate high amounts of solid, liquid and gaseous waste. They are also widely used today, approximately 1/3 of the population lives in this type of residence. Because of the importance of earth constructions, this article will present a script, written in MATLAB software, to optimize the user's choice of the construction types to be used, in addition to offering the amount of material and average costs.

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Therefore, with information on the soil type and perimeter of the house, the user will be able to know how much clay, sand, lime, among other materials, are necessary depending on the construction system analyzed. The calculation follows the one proposed by the bibliographies, from the thickness of the internal and external wall, the proportion of the soil granulometry, among other pertinent points. The constructions incorporated into the script were: rammed earth, superadobe, straw bales, poured earth, COB, and adobe. As a result, this research contributed to the creation of a simple tool to systematize the average costs and materials for earth construction.

Key words: Earth Construction, Superadobe, Adobe, MATLAB, Script.

INTRODUCTION

Earth constructions began to be used hundreds of years ago by large societies such as Egypt, Iran, and Morocco [1]. According to [2], the International Construction Council (*Conselho Internacional da Construção – CIB*) points to the construction industry as the sector of human activities that most consumes natural resources and uses energy intensively, generating considerable environmental impacts. In addition to the impacts related to the consumption of matter and energy, there are those associated with the generation of solid, liquid, and gaseous waste. It is estimated that more than 50% of the solid waste generated by all human activities comes from construction. Based on this analysis of the current phase in which civil construction is, it is understood that the search for sustainable buildings, with low energy use and recyclables, is fundamental. Constructions using soil are ecological, in which to prepare them, 1 to 2% of energy is needed compared to the energy spent for construction using reinforced concrete and baked bricks. In civil construction, there are several types of constructions using the earth, in addition to variations of existing methods. Therefore, the choice of which systems will incorporate the script was made to cover the most relevant ones in different countries and the technological environment.

MATERIAL AND METHODS

Next, the calculation method and the input data used in the MATLAB software will be presented.

1.1. Adobe

Adobe is a type of construction made with sand-clay bricks. The definition of the dimensions to be used in the script are described in Table 1.

Based on the studies by [3], based on the dimensions presented by [4], [5], [6], [7] and [8], the result was that the best size is 230x110x55 mm due to its high resistance. The thickness of the joints was defined based on the proposed by [9], which indicates the minimum value of 33 cm in thickness to have good characteristics of thermoacoustic insulation. Considering the plaster thickness of 2 cm the 230x110x55 mm block does not reach the minimum thickness value [10]. As it is not interesting internal walls with very thick thickness, therefore, for this research the dimensions of 230x110x55 mm were adopted for the internal walls.

In addition to the minimum thickness, another determining factor for the choice of dimensions for the external wall was the weight of the brick, as it is a necessary factor for the calculation of material [11]. It was then chosen the dimension 290x450x120 mm presented by [10], for providing both the weight of the brick – 21.53 kg – and its width, which, adding the 2 cm of plaster, reaches the desired 33 cm of the total thickness.

Table 1 – Brick dimensions

References	Dimensions (mm)
[4]	290 x 90 x 90 ou 300 x 150 x 150
[5]	400 x 200 x 100 ou 250 x 120 x 80
[6]	380 x 380 x 80 ou 390 x 180 x 180 ou 400 x 200 x 150
[7]	300 x 150 x 150
[8]	230 x 110 x 70 ou 230 x 110 x 100
[10]	290 x 450 x 120
[12]	300 x 225 x 150 ou 450 x 225 x 150
[13]	450 x 300 x 150
[14]	200 x 200 x 400
[15]	300 x 300 x 100
[16]	100 x 190 x 400

Following the proposal by [9], the joints must be between 1.5 cm and 2 cm thick to avoid cracks, so the value of 1.5 cm was defined for the script. For the blocks and mortar quantity, what was proposed by [17] was followed, so the formulas below were used to quantify these materials:

$$n = \frac{1}{(b_1 + e_h) \times (b_2 + e_v)} \tag{1}$$

$$v = [1 - n \times (b_1 \times b_2)] \times b_3 \tag{2}$$

Where:

n = number of bricks per m².
v = volume of mortar.
b_1 = brick length.
b_2 = brick height.
b_3 = brick width.
e_h = horizontal mortar thickness.
e_v = vertical mortar thickness.

If the soil has a high concentration of clay, it will be necessary to stabilize it with sand. Cement stabilization will not be used in the script, as it has lower strength results, in addition to being an expensive stabilization method [3, 9]. Therefore, the stabilization with sand will be done with an increase of 50% for clay soils as it is an average value among those presented in Table 2. Such correction is not necessary for sandy-clay soils because they are in a similar proportion to that presented in Table 2.

Table 2 – Recommended soil granulometry

References	Sand	Clay	Silt
[15]	1:2:2 (sand:clay:tierra blanca mix)		
[18]	40%	20%	
[19]	More than 40%	Less than 20%	
[20]	50%	20%	30%
[21]	30% - 75%	10% - 40%	10% - 30%
[22]	55% - 65%	35% - 45%	
[23]	50%	50%	
[24]	1 volume of clay soil for 2 volumes of sandy soil		
[25]	1:1 (sand:clay) 2:1 (sand:clay)		

1.2. Rammed Earth

Rammed earth walls are built by hitting the moist soil between the wooden forms [26]. Therefore, wall density must be determined to calculate the amount of soil to be used. Based on the authors described in Table 3, the value of 2000 kg/m³ was chosen for being an average value among those presented.

Concerning thickness, there are minimum values to be considered, which are shown in Table 4, in addition to having an evident variation in thickness, as shown in Table 5 [27]. Due to the thickness diversity, this value will be a data provided by the user.

At the end of the compacting, the walls have a good finish and do not need plastering, so their consideration in the script will not be made [28]. Cement stabilization will also not be used as it increases the cost of materials [29]. Therefore, stabilization by granulometric correction with the addition of 50% sand for clay-sandy soils will be used [30]. Such correction is not necessary for sandy-clay soils as they are in a similar proportion to that shown in Table 6.

Table 3 – Rammed earth wall density

References	Density (kg/m³)
[27], from the data of [31], [32] and [33]	1,700 – 2,200
[29]	1.840 – 2.240
[34]	Usually above 2,000 and always above 1,700
[35]	1.800 – 2,000
[36]	1.800 – 2,200
[37]	1.650 – 2,150

Table 4 – Minimum wall thicknesses

References	Thickness range
[30]	600 – 1000mm
[36]	300 – 600mm
[38]	400 – 800mm
[39]	456 – 610mm

Table 5 – Thickness range

Referência	Internal wall (mm)	External wall (mm)
[32]	125	200
[40]	305	457
[41]	250	250
[42]	300	300

Table 6 – Recommended soil granulometry

References	Sand	Clay	Silt
[33]	45% - 75%	0% - 20%	10% - 30%
[42]	70% - 80%	20% - 30%	-
[43]	50% - 70%	5% - 15%	15% - 30%
[44]	10% - 20%	25% - 30%	50% - 80%
[45]	65% - 70%	30% - 35%	-
[46]	45% - 75%	10% - 25%	15% - 30%
[47]	65% - 70%	30% - 35%	-

1.3. Straw Bale

The original method of construction using straw bales is called Nebraska. This is the simplest method, in addition to requiring little prior knowledge of construction and being quite accessible [57, 58]. Next, the construction components are determined, which were divided as follows for better organization in the script, according to [57], [59], [60], and [61].

1.3.1. Straw Bales

Due to the diversity of dimensions that a bale of straw can have, as can be seen in Table 8, the dimensions will be user input. In relation to the headroom of the work, walls of a single floor or ground floor are generally six or seven bales in height and may be higher [62], however, it is important that the height to be provided by the user is a multiple of the chosen bale height, as it must not be cut – the baling is done in such a way that the straw is tied to have a good density, resulting in high strength.

Table 8 – Common dimensions of straw bales

References	Straw bale dimensions
[57]	450 mm x 350 mm x 900 mm –1,125 mm
[58]	18” wide by 14” and 24” wide by 16” or 18” high – the length can vary from 32” to 40 ”
[59]	350 mm x 450 mm x 900 mm
[63]	450 mm x 350 mm x 900 mm
[64]	450 mm x 500 mm x 1.000 mm
[65]	5.5: 1 height to thickness ratios and 15.5: 1 length to thickness ratios (per Austin City Code [66], Pina County Code [67] and Californian Residential Code 68])
[69]	375 mm x 500 mm x 990 mm
[70]	350 a 400 mm x 450 mm x 900 mm

1.3.1. Wood pins

The connection of consecutive rows of straw bales is carried out by wood pins with a diameter of 38 to 50 mm to provide an improvement in the stability and integrity of the wall [57, 71]. Both the diameter and the height of the pins will be input from the user. Such stakes were divided into two groups for the script:

- Internal pins: from the third row of bales, two pins are placed per bale, with a maximum height of 2 and a half bales [71].
- Base pins: pins driven into the upper and lower wooden base, also with an interval of two stakes per bale and an average height of a bale [57].

1.3.2. Top and bottom boxing

The main role of the top and bottom boxing is to apply tension to the bales of straw, compressing them. Regarding the top boxing, in addition to the role of transferring the load as uniformly as possible on the bale wall, it also ensures that the thread that will tie the structure will not cut the straw bales [59].

The boxing is composed of three components: (i) the external plates, which can be of OSB or plywood, with a thickness between 11 to 18 mm, (ii) the noggin and (iii) the timber, which can be salvaged wood, 50 mm by 100, 150 or 225 mm [57]. Because the thickness depends on the wood available on the market, this will be user input.

1.3.3. Plaster

Two types will be calculated, the lime plaster and the soil plaster. The lime plastering is done in a 1:3 ratio (hydrated lime and sand), while the other is between 1:4 to 1:2 (clay and sand). For the calculation of necessary material, the mass trace will be used [57].

The adopted densities of lime and sand will be equal to 1,600 kg/m^3 [72]. The densities of predominantly clayey or sandy soil were taken at values close to 1,200 and 1,300 kg/m^3, respectively [39].

Regarding the thicknesses recommended in the literature (Table 9), we have a range of values from 10 to 75 mm, so the desired total plaster thickness will also be user input.

Table 9 – Recommended thicknesses

References	Thickness
Amazon Nails [57]	12 – 50 mm
Searle [58]	25 – 75 mm
Sutton, Black e Walker [69]	Around 35 mm
Cabral, Pinto e Lima [74]	10 to 20 mm first layers 2 to 5 mm to finish
NZS 4298 [78]	25 – 75

1.3.4. Polyester Strapping

Attaching the walls with polyester ties secures that any bale that does not have a good density is compressed [60]. The calculation of the number of polyester filaments and their length will be given based on the one proposed by [60]. For the script, this calculation will be divided into three components:

- Base filaments: smaller pieces of 1.5 m that will go below the wooden boxes on the floor [60].
- Upper filaments: are passed over the wall, in greater lengths.
- Connectors: to make the connection between the base and upper filaments.

1.4. COB

COB is a process best described as plaster of mud – soil (clay and sand) and straw [48]. The amount of soil will be calculated from the density of 1,700 kg/m^3 as it is an average of the data found in the literature, which are described in Table 7. The amount of straw will be 25 kg/m^3 by the average presented by [49], which is 20 to 30 kg/m^3 of fresh COB. The amount of clay and sand will be within the range of 50% to 85% sand and 50% to 15% clay – cement stabilization is not suitable for this construction [49, 50].

Table 7 – Characteristic densities of COB walls

References	Density (kg/m^3)
[48]	1,700 a 1,900
[51]	1,475
[52]	1,909
[53]	1.909 (moist) e 1.544 (dry)
[54]	1,200 a 1,700
[55]	1,600

For [50], it is ideal to use a plaster based on soil, which is mixed with the ingredients in the same proportions as COB (clay, sand, and straw). According to [55], the plaster thickness of the COB walls should be approximately 2 cm. As the values of finished wall thickness are varied (200 to 300 mm for [51] and [54], 300 to 450 mm for [52], 600 to 900 mm for [56] and 500 to 600 mm for [49]), this data will be entered via the user's MATLAB.

1.5. Poured Earth

Poured earth is a technique cataloged within monolithic walls, capable of supporting efforts to allow the use of this as load-bearing walls [75]. [76] define poured earth as a plastic fluid containing aggregates like sand and clay. The wall is made by filling shapes in a plastic state and must not be compacted [77].

The material cost calculation will be done according to the recommended by [78], which determines the use of cement to stabilize 10% in the mixture to decrease shrinkage and increase the resistance and durability of the walls. The soil to be used must have a low clay content [78].

According to [79], the poured earth technique, in general, is not well known and there are few studies and theoretical characterizations developed, therefore, the quantification of the material will be made from the estimates, such as 1,200 and 1,500 kg/m^3 for clayey and sandy soils, respectively [80]. Both for sandy and clay soils with granulometric correction, the value of 10% cement for stabilization will be taken [78].

1.5. Superadobe

The amount of material and budget items presented by [11] will serve as a basis for defining the elements considered in the calculation of the MATLAB software. This study describes the detailed methodology for calculating the number of bags, the amount of wire, soil, among others.

RESULTS

The scripts were divided into primary, secondary, and the main one. The primary script is those that include calculations of material quantity and budget. The secondary auxiliary scripts 1 and 2 aim to optimize the main algorithm. The main script has the function of gathering all the other functions and compiling them as a whole. Figure 1 and Figure 2 show some interactions between the user and the algorithm, and how the user's preferences are entered.

```
Command Window
Please make sure the data below is correct:

The region's soil is PREDOMINANT CLAY
The region's climate is VARIABLE

Is the above information correct?
If so, good! Type 1.
If not, can we fix it? Type 2.
fx
```

Figure 1 – User soil specifications

```
Command Window
The earth constructions indicated for the climate of your region are:

SUPERADOBE
ADOBE
RAMMED EARTH
POURED EARTH

Do you already have the plant information and would you like to make a budget?
Just select the construction systems you want! Below is the list of all available construction systems and their
respective numbers.
NOTE: Remember which ones are recommended for your region's
climate.

1 - SUPERADOBE
2 - COB
3 - ADOBE
4 - RAMMED EARTH
5 - POURED EARTH
6 - STRAW BALE

How many earth constructions do you want to budget?
fx  >> |
```

Figure 2 – Choice of earth constructions to execute the budget and the quantity of material

3.1. Adobe

For the dimensioning of this system, the input values are requested to the user according to Figure 3 and the output values according to Figure 4.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3
   Internal perimeter (in meters) = 100
   External perimeter (in meters) = 50
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1
```

Figure 3 – Input data for adobe

```
ABOUT ADOBE:

   Material quantity:
   > 8747 units of brick for the internal walls.
   > 4779 units of brick for the external walls.
   > 4.329 m3 of mortar for the internal walls.
   > 12.161 m3 of mortar for the external walls.
   > 18.000 m3 of plaster.
   > 62008 kg of soil for making bricks.
   > 62008 kg of sand for making bricks.
   > 20694 kg of soil for making plaster and mortar.
   > 27593 kg of sand for making plaster and mortar.

   Average costs:
   > $6200.79 of soil for making the bricks.
   > $6200.79 of sand for making the bricks.
   > $2069.44 of soil for making plaster and mortar.
   > $2759.26 of sand for making plaster and mortar.
```

Figure 4 – Output data for adobe

3.2. Rammed Earth

For the dimensioning of this system, the input values are requested to the user according to Figure 5 and the output values according to Figure 6.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3
   Internal perimeter (in meters) = 100
   External perimeter (in meters) = 50
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1

ABOUT RAMMED EARTH:
   Internal thickness (in millimeters) = 300
   External thickness (in millimeters) = 300
```

Figure 5 – Input data for rammed earth

```
   Material quantity:
   > 135000 kg of soil for wall construction.
   > 135000 kg of sand for wall construction.

   Average costs:
   > R$13500.00 of soil for wall construction.
   > R$13500.00 of sand for wall construction.
```

Figure 6 – Output data for rammed earth

3.3. COB

For the dimensioning of this system, the input values are requested to the user according to Figure 7 and the output values according to Figure 8.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3
   Internal perimeter (in meters) = 50
   External perimeter (in meters) = 100
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1

ABOUT COB:
   Thickness (in millimeters) = 300
   Unit price of straw ($/kg) = 0.1
```

Figure 7 – Input data for COB

```
Material quantity:
> 114750.000 kg of soil for wall construction.
> 114750.000 kg of sand for wall construction.
> 3375.000 kg of straw for wall construction.
> 5400.000 kg of soil for the plaster.
> 7200.000 kg of sand for the plaster.
> 180.000 kg of straw for the plaster.

Average costs:
> $11475.00 of soil for wall construction.
> $11475.00 of sand for wall construction.
> $1012.50 of straw for wall construction.
> $540.00 of soil for the plaster.
> $720.00 of sand for the plaster.
> $54.00 of straw for the plaster.
```

Figure 8 – Output data for COB

3.4. Straw Bale

For the dimensioning of this system, the input values are requested to the user according to Figure 9 and the output values according to Figure 10 and Figure 11.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3.15
   Internal perimeter (em metros) = 100
   External perimeter (em metros) = 40
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1

ABOUT STRAW BALE:
   Straw bale length (in millimeters) = 450
   Straw bale width (in millimeters) = 350
   Straw bale height (in millimeters) = 450
   Plaster thickness (in millimeters) = 12
   Plywood plate thickness (in millimeters) = 12
   Wood pins width (in millimeters) = 12
   Wood pins height (in millimeters) = 12
   Length of the used polyester roll (in meters) = 10
   Lime unit price ($/kg) = 0.1
   Straw bale unit price ($/unid) = 0.1
   Connector unit price ($/unid) = 0.1
   Polyester roll unit price ($/unid) = 0.1
```

Figure 9 – Input data for straw bale

```
Command Window

    Straw bale quantity:
    > 7 units of vertical straw bales.
    > 311 units of horizontal straw bales.
    > 2178 total units of straw bales.

    Internal and base pins quantity:
    > 1244 wood pins of 450.0 mm.
    > 2489 wood pins of 1125.0 mm.

    Top and bottom boxing quantities:
    > 4 plates of dimensions:
      >> 140.000 m of length.
      >> 374.0 mm of width.
      >> 12.0 mm of thickness.
    > 4 timbers of dimensions:
      >> 140.000 m of length.
      >> 12.0 mm of width.
      >> 12.0 mm of thickness.
    > 1244 noggins of dimensions:
      >> 350.000 m of length.
      >> 12.0 of width.
      >> 12.0 of thickness.

    Quantity of items for strapping:
    > 622 ties of 1.5 m of length.
    > 622 ties of 7.618 m of length.
    > 5673.422 m of polyester .
    > 1244 connector units.

    For plastering the wall:
    > Plaster Type 1 (lime and sand):
      >> 4872 kg of lime.
      >> 12991 kg of sand.
    > Plaster Type 2 (soil and sand):
      >> 6496 kg of soil.
      >> 8661 kg of sand.
fx
```

Figure 10 – Output data for straw bale concerning quantitative of material

```
Average costs:
> $487.17 kg of lime for plaster type 1.
> $1299.11 kg of sand for plaster type 1.
> $649.56 kg of soil for plaster type 2.
> $866.07 kg of sand for plaster type 1.
> $217.78 for 2178 straw bales.
> $124.44 for 1244 connectors.
> 568.00 units of polyester rolls.
> $56.80 for 568 rolls.
```

Figure 11 – Output data for straw bale concerning average cost

3.5. Poured Earth

For the dimensioning of this system, the input values are requested to the user according to Figure 12 and the output values according to Figure 13.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3
   Internal perimeter (in meters) = 100
   External perimeter (in meters) = 40
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1

ABOUT POURED EARTH:
   Thickness (in millimeters) = 300
   Unit price of cement ($/kg) = 0.1
```

Figure 12 – Input data for poured earth

```
Material quantity:
> 42525 kg of cement.
> 72900 kg of soil.
> 97200 kg of sand.

Average costs:
> $4252.50 of cement.
> $7290.00 of soil.
> $9720.00 of sand.
```

Figure 13 – Output data for poured earth

3.5. Superadobe

For the dimensioning of this system, the input values are requested to the user according to Figure 14 and the output values according to Figure 15.

```
Command Window
>>Now, how about giving us some information to calculate the
average costs?
   Readroom (in meters) = 3
   Internal perimeter (in meters) = 100
   External perimeter (in meters) = 50
   Unit price of soil ($/kg) = 0.1
   Unit price of sand ($/kg) = 0.1

ABOUT SUPERADOBE:
   Length of wire roll used (in meters) = 100
   Soil unit price (R$/unid) = 0.1
   Bags unit price (R$/unid) = 0.1
```

Figure 14 – Input data for superadobe

```
Material quantity:
> 24 rows of bags.
> 296 bags per row.
> 7104 bags for the total wall.
> 46 kg each bag.
> 326784 kg of soil in total.
> 4156 wire meters.
> 42 wire rolls.

Average costs:
> R$0.10 per bag unit.
> R$710.00 for 7104 bags.
> R$0.10 for 1 kilo of soil.
> R$32678.40 total for 326784 kilos of soil.
> R$0 the wire roll unit.
> R$4  total for 42 rolls of wire.
```

Figure 15 – Output data for superadobe

CONCLUSIONS

As a result, this research contributed to the creation of a simple tool to systematize the average costs and materials for earth construction. The script allows the user to obtain all proposed responses within 5 to 10 minutes. Such responses are the following:

- Adobe: bricks and mortar quantity for the external and internal wall, the average price of total soil for making the bricks, plaster, and mortar.
- Rammed earth: total amount and price of soil to be used for construction.
- COB: amount of soil and straw for the construction of the wall and plaster, and their respective values separately.
- Straw bale: quantity of vertical, horizontal and total bales, the number of pins, quantity, and dimensions for the top and bottom boxing, the quantity and dimensions of strapping, the number of connectors, quantity of lime and sand for type

1 plastering, quantity of soil for plastering type 2, and the total value of lime, soil, straw bales, connectors, polyester strapping needed for construction.
- Poured earth: cement and soil quantity and their respective costs for the construction of the wall.
- Superadobe: the total number of bags, the number of rows of bags and the number of bags per row, the amount of soil required, the number of meters of wire and the number of wire rolls, the total value for the bags, soil and wire.

All outputs include the quantity and price of sand and clay in case the granulometric correction is required, as previously presented in the materials and methods section. Therefore, it is believed that in this way there can be greater dissemination of earth constructions.

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