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Sensitivity Analysis of Conformal CCs for Injection Molds: 3D Transient Heat Transfer Analysis

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Abstract

Fabricating conformal cooling channels (CCCs) has become easier and more cost-effective because to recent advances in additive manufacturing. CCCs provide better cooling performance in the injection molding process than regular (straight drilled) channels. The main reason for this is that CCCs can follow the molded geometry's paths, but regular machining methods cannot. Thermal stresses and warpage can be reduced by using CCCs, which also improve cycle time and provide a more uniform temperature distribution. Traditional channels, on the other hand, have a more involved design technique than CCC. Computer-aided engineering (CAE) simulations are essential for establishing an effective and cost-effective design. The sensitivity analysis of design variables is the emphasis of this research, with the goal of establishing a design optimization approach in the future. The ultimate goal is to optimize the location of Cooling Channels (CCs) in order to reduce ejection time and increase temperature uniformity. It can be concluded that the parametrization performed in ANSYS Parametric Design Language (APDL), as well as the design variables used, can be applied in practice and could be relevant in future optimization approaches.

1. Introduction

Injection molding, compression molding, blow molding, and hot stamping are essential industrial production methods that are utilized to create the majority of today's plastic products. CCCs serve a crucial role in enhancing cooling performance in these processes, which necessitate molds. Cooling channels were first developed for injection molding [1-3], to reduce warpage and residual stresses in injection molded parts with variable thickness, large dimensions, and/or complex shapes, as well as flat parts with partial thick volume [4], complex large automotive parts [5, 6, 7], and (local) thin-walled parts [8, 9]. CCCS have also shown potential for high-precision products with tight dimensional tolerances, such as screw caps [10], contact lenses [11], and large diameter aspherical plastic lenses [12]. CCCs outperform the standard (straight drilled) channels used in injection molding in terms of cooling performance. The major reason for this is that CCCs can follow the trajectories of the molded geometry, whereas typical channels created using traditional machining processes cannot. Cooling time, total injection time, uniform temperature distribution, thermal stress, and distortion thickness are some of the metrics that can be considerably improved by employing CCC. CCC, on the other hand, has a more complicated design procedure than traditional channels. Despite the fact that the channels in transfer molds are utilized for heating rather than cooling the cavity, as opposed to the channels in injection molds, conformal channels are advised in transfer molding to ensure more consistent and efficient heating. Although conformal heating channels are used instead of CCCs in transfer molding, the design and arrangement of conformal heating channels (as well as the physics of the process) are identical to CCCs in injection molds [13].

In the subject of the design and simulation of CCCs in injection molds, some research has been done [14-28]. Mold and channel designs have been analyzed using a variety of simulation software. Dimla et al. [14] used Moldflow analysis in I-DEASTM in 2005 to determine the best channel position. ABM Saifullah and SH Masood investigated the "cooling time of the part" [15] using ANSYS modules for thermal analysis. In 2009, the same group of researchers used MPI simulation modules to evaluate the results for conventional and quadratic CCCCS profiles, determining that conformal channels cool 38 percent faster than conventional channels [16]. Using ABS polymer as the molten material and a cooling water inflow, Gloinn et al. [17], from Ireland developed a finite element model (FEM) to calculate the mold temperature. Another study [18] conducted in 2007 used Moldflow Plastic Insight 3.1 to explore the thermal effects of CCCS design on the injection molding process.

The authors proposed a new approach to constructing a standard CC. Wang et al. [19] investigated the benefits of a cooling cycle using the same simulation modules; the authors simulated the molding temperature. Khan et al. [20] studied the impacts of conventional, serial, parallel, and additive-parallel CCs on cooling time, total cycle time, volumetric shrinkage, and temperature variance in 2017. With the goal of creating an intelligent and optimal design of CCCs systems, researchers have created a number of approaches and algorithms for the creation of Conformal CCs (CCC'S) [21-23]. Spiral [24], zigzag [25], profiled [26], and vascularized [27] are some of the CCCS patterns that have been proposed for this purpose. Nonetheless, preliminary information from the literature has been obtained, which will serve as a foundation for further research on this topic. For example, Mayer [28] has a simple link between four parameters for the design of CCCs using additive manufacturing. Using cross-sections other than circular for channels could improve cooling efficiency, according to earlier study. In the work [29], the authors investigated the use of CCs with variable spacing in tooling applications. The authors conducted a study in which they developed a complete solution for the creation of conformal channels in order to rework an existing model that had been designed with straight channels into one that used CCCs. The duct's diameter, distance between ducts, and distance between the wall and the duct were all taken into consideration. This work uses ANSYS Mechanical APDL software to parameterize the cooling ducts and compute the temperatures for the 3D heat transfer problem using design variables for use in optimization approaches by combining MATLAB and ANSYS Mechanical APDL. Under comparable settings, both ANSYS Mechanical APDL and Workbench [29] produced similar results for 2D analysis. A sensitivity analysis for the same geometric (design) factors was already performed in 2D analysis under the identical conditions [30]. This study adapts the prior 2D study and turns it into a 3D simulation, making simulations closer to real-world applications. The current effort seeks to analyze the validity of the stated design variables for usage in optimization methods by integrating MATALB with ANSYS Mechanical APDL.

3. Procedure

3.1 Geometry and sets

The geometry of the analyzed 3D model is presented in Figure 1. All the dimensions were scaled to half of the original mold [29-31], due to the need of reducing the computation power required to solve the numerical analyses.

The components of the geometry are explained in Table 1:

Table 1 –Components of the geometry used in the simulations

Component ID	Quantity	Description
1	1	Part
2	8	Channels
3	1	Mold

Water in the liquid phase was used for the cooling channels, which are numbered from (1) to (8) in Fig. 2. The injected component is polypropylene (PP), while the mold cavity is considered to be made of p20 steel.

To perform the sensitivity analysis, 16 variables/geometric parameters were defined in the ANSYS Mechanical APDL 2020 R2 project. Eight of these variables are horizontal and eight are vertical, as shown in Fig. 3

Table 2 shows the lower and upper limits of the design variables set by ANSYS considering the defined output variables.

Table 2-Sets of geometric variables studied. The dimensions regarding Var1 to Var16 are expressed in mm.

Designation	Lower limit		Initial Value		Upper limit
Var ID	1	2	3	4	5
Var1	5	7,5	10	12,5	15
Var2	5	7,5	10	12,5	15
Var3	5	7,5	10	12,5	15
Var4	5	7,5	10	12,5	15
Var5	5	7,5	10	12,5	15
Var6	5	7,5	10	12,5	15
Var7	5	7,5	10	12,5	15
Var8	5	7,5	10	12,5	15
Var9	2.5	3.75	5	6.25	7.5
Var10	2.5	3.75	5	6.25	7.5
Var11	2.5	3.75	5	6.25	7.5
Var12	2.5	3.75	5	6.25	7.5
Var13	3	4	5	6	7
Var14	3	4	5	6	7
Var15	3	4	5	6	7
Var16	3	4	5	6	7

3.2 Materials

In the simulations, performed in ANSYS Mechanical APDL 2020 R2, water was used for the cooling channels and PP was used for the injected component. P20 steel was utilized for the mold. Only water is considered as a fluid; PP and steel, on the other hand, are regarded to be solid. The properties of the materials used are listed in Table 3.

Table 3 - Properties of water, PP and P20 steel [27,28].

Material	Water in liquid state	Polypropylene, with 10% mineral	P20 steel
Density [(kg/m^3)]	998.2	1050	7861 [11]
Specific heat [J / (kg.K)]	4182	1800, Considered constant	502,48 [12]
Thermal conductivity [W/(mK)]	0.6	0.2 Considered constant	41,5

3.3 ANSYS Mechanical APDL

The sensitivity analysis was carried out with the help of ANSYS Mechanical APDL, in which transient thermal analyses were carried out in a 3D geometry. The methodology used in this work to obtain results in shown in Fig. 4.

The ANSYS input file were parametrized with the variables. The outputs were programmed in APDL (ANSYS Parametric Design Language), as well. The boundary conditions implemented in ANSYS Mechanical APDL 2020 r2 are listed in Table 4.

Table 4 – Thermal conditions applied [32-34]

Condition	Value [C]	Application
Tini	210	Part, 1 volume, component (9)
Tini	40	Cooling channels, 8 volumes, components (1) to (8)
T	40	Mold, 1 volume, represented by (10)
T	23	Boundary, outer areas of (10) (Total of 6 areas)

The temperature of 210 [C] is an approximation of the processing temperature of PP. It is assumed that the water in the cooling channels is at a constant temperature of 40 [C]. The results were queried in nodes around the model, as in the black lines shown in Fig. 5 . The results were queried in a total of 285 nodes

4. Results And Discussion

4.1 Temperatures

In order to study the sensitivity of the model to the variation of the design variables selected, 5 values of each geometric variable were studied, keeping all others as constant. The values of each variable ID, from 1 to 5 are specified in Table 2.

Figs. 6-8 show the Maximum, Average, Minimum temperatures in the injection molded part, respectively. Value ID 3 is used as a reference, and the very same model was used in all calculations.

In Fig. 6, it can be seen that the values of the temperature vary significantly for different variables and for the same Value ID. The values range up to 2 degrees. The maximum temperature is slightly higher than 52.5 ºC and the minimum is slightly higher than 50.5 ºC. It is not clear which variable the system is more sensitive to the variations of Temperature. In fact, the lowest and highest temperatures, in terms of maximum temperature, obtained for each variable ID are obtained for different variables.

In Fig. 7, it can be seen that the values of the temperature vary significantly for different variables and for the same Value ID. The values range up to slightly more than 1 degrees, for Value ID 5. The maximum temperature is slightly higher than 41.25 ºC and the minimum is slightly higher than 40 ºC. It is not clear which variable the system is more sensitive to the variations of Temperature. In fact, the lowest and highest temperatures, obtained for each variable ID are obtained for different variables. There is a significantly narrower amplitude of temperature compared to the results of the maximum temperature (Fig. 6)

In Fig. 8, it can be seen that the values of the temperature vary with a high amplitude for different variables and for the same Value ID. The values range up to close to 9 degrees, for Value ID 5. The highest temperature is slightly higher than 41.25 ºC and the lowest is slightly higher than 33.5 ºC. It is not clear which variable the system is more sensitive to the variations of Temperature. In fact, the several variables do not present ordered temperature values for each Value ID. There is a significantly wider amplitude of temperature compared to the results of the maximum temperature (Fig. 6) and average temperature (Fig. 7). Fig. 9 shows the temperature amplitude.

In Fig. 9, the values of the Tmax-Tmin (maximum temperature minus minimum temperature) range from close to 18 [°C] for Var16 and for a value ID of 5, to close to 27.5 [°C] for Var1 and for a value ID of 1.

4.2. Analysis of the sensitivity

Although the results of Figs. 6-9 allow us to know that all the variables are relevant for design optimization, so far, it is not possible to have accurate measures regarding the sensitivity of the variables. Therefore, the expressions (1.1) and (1.2) were developed. For the results shown in Figs. 10 and 11, the Var ID 3, of Table 2, was considered as the reference point. Then, the Tmax (Fig. 6) and Tavg (Fig. 7) results for the other Var IDs were compared with the reference model, using Eq. 1.1 and 1.2. In the last step, the sensitivities are normalized, by dividing by the range of the interval $Varv_h$ minus Varv. This ensures that the range of the variables (Table 2), does not have influence the results.

$$vaTM[\%] = \frac{Maximum\left(\frac{TM_x - TM_{ref}}{TM_{ref}}\right)*100}{Varv_l - Varv_h} \quad (1.1)$$

Where $Varv_h$ and $Varv_l$ are the highest and lowest value of each variable, respectively, as shown in Table 2.

$$vaTA[\%] = \frac{Maximum\left(\frac{TA_x - TA_{ref}}{TA_{ref}}\right)*100}{Varv_l - Varv_h} \quad (1.2)$$

For x=1,2,4 and 5.

In Fig. 10, It can be seen that the sensitivity of the maximum temperature for all variables is very low. The most sensitive variable is Var 16, with a sensitivity of 0.72 %. The variable with lowest sensitivity is Var 6, with a value of 0,08 %.

In Fig. 11, It can be seen that the sensitivity of the maximum temperature for all variables is very low. The most sensitive variable is also Var 16, with a sensitivity of 0.37 %. The variable with lowest sensitivity is Var 5, with a value of 0,02 %.

5. Conclusions

The following are the key conclusions of this study:

-It is shown that the variable Var16 is the one that the system is most sensitive to.

-The chosen design variables are relevant for the case analyzed, as the temperatures change when the variables' values change.

-The parameterization of the ANSYS input file has been shown to be effective in determining the effect of design variables on the temperatures in the analyzed model.

-In the future, the results of the sensitivity analysis can be used to specify the weights of the variables, to be used in optimization procedures/methodologies

Declarations

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a. Funding

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b. Conflicts of interest/Competing interests

There are no declared Conflicts of interest/Competing interests

c. Availability of data and material (data transparency)

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

d. Code availability

Not applicable

e. Ethics approval

Not applicable

f. Consent to participate

Not applicable

g. Consent for publication

Not applicable

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[34] Silva HM, Noversa T, Fernandes L, Rodrigues H, Pontes A, Design Optimization of conformal cooling channels for injection molds: 3D Transient Heat Transfer Analysis [submitted]

Figures

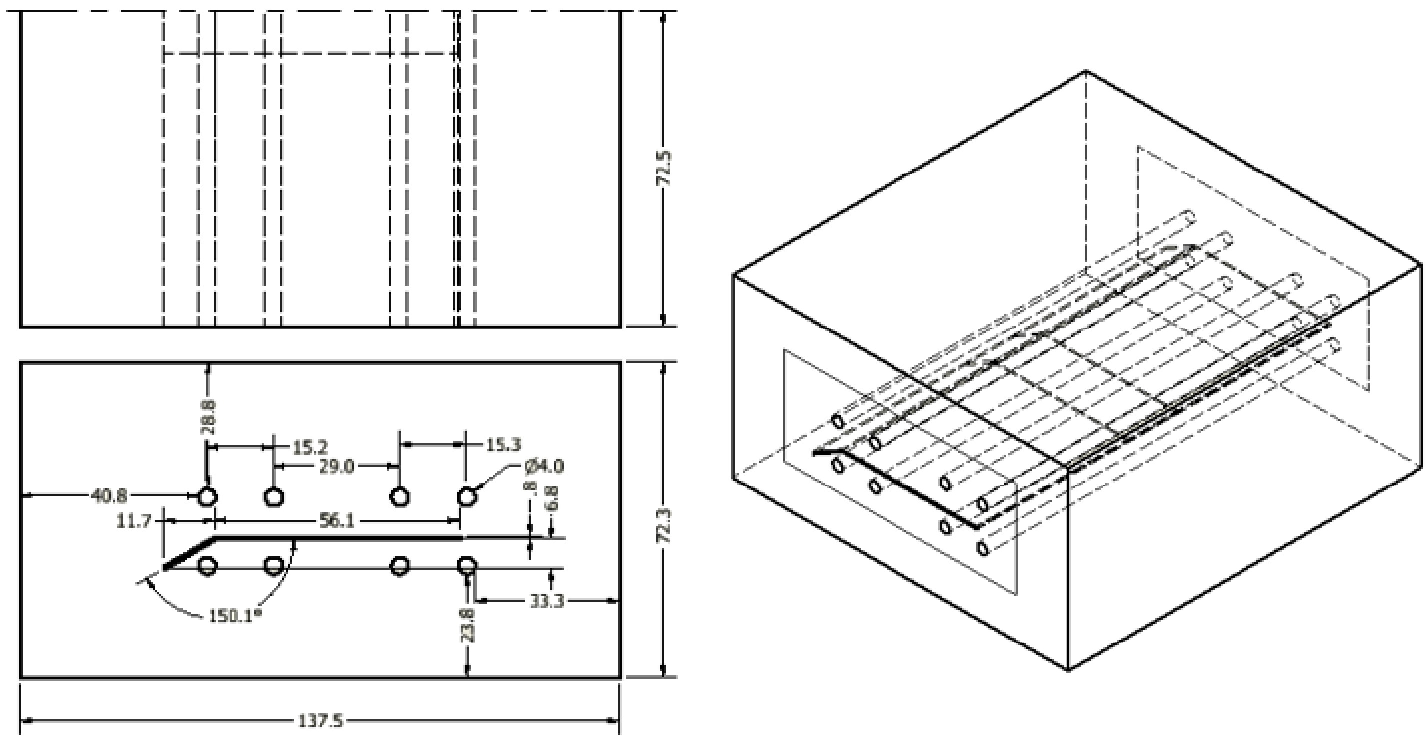

Figure 1

Set drawing: simplification of the 3D model, also presented in [32,34] The components of the geometry (Fig. 1), are shown in Fig. 2.

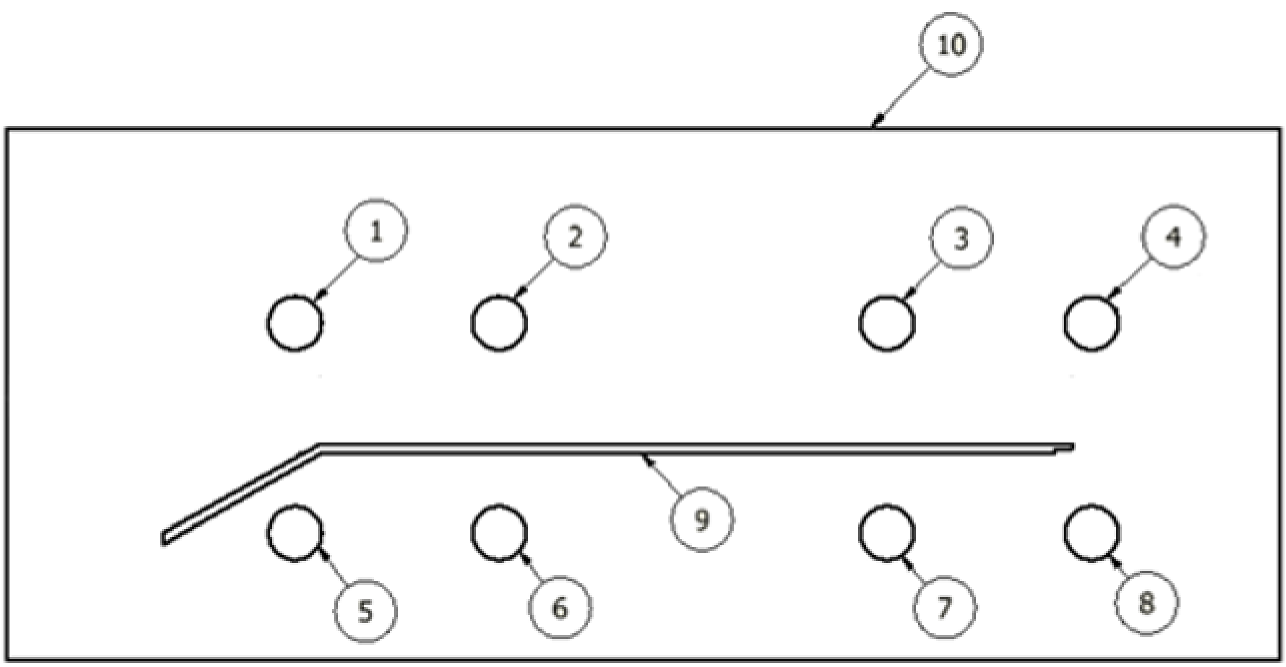

Figure 2

Components of the assembly, represented by numbers from 1 to 10

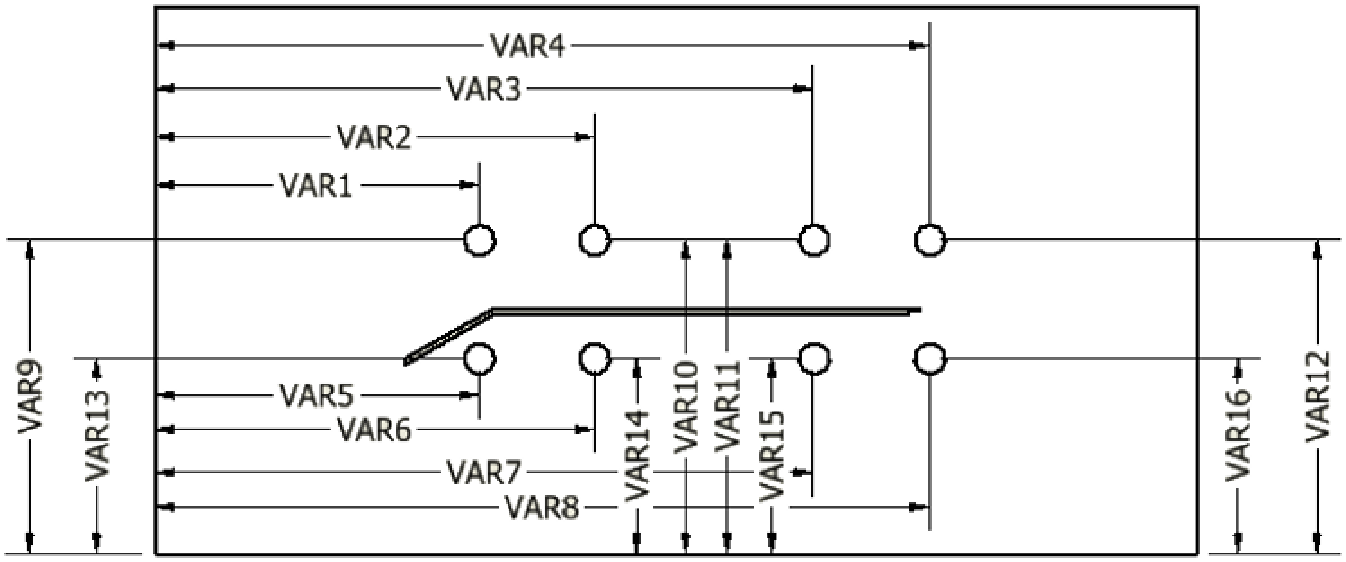

Figure 3

Variables under study

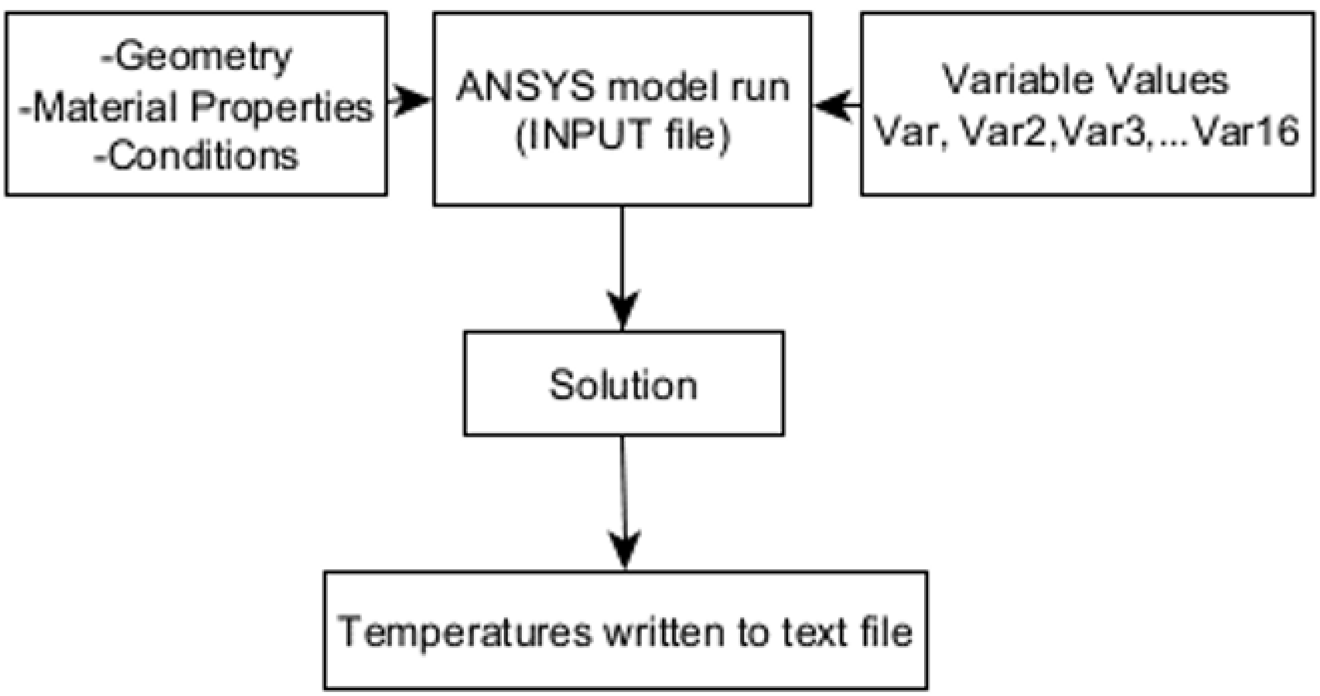

Figure 4

Flowchart of the methodology

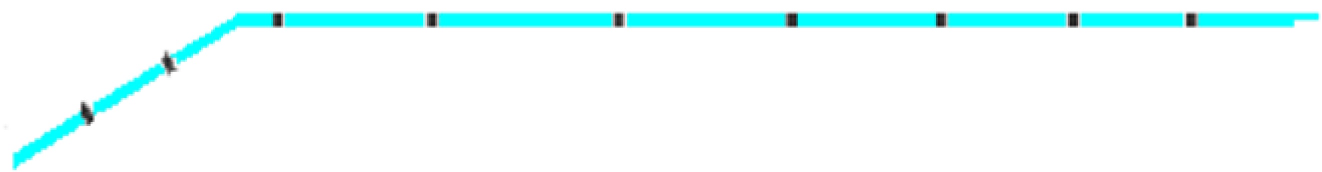

Figure 5

Places were the results were queried

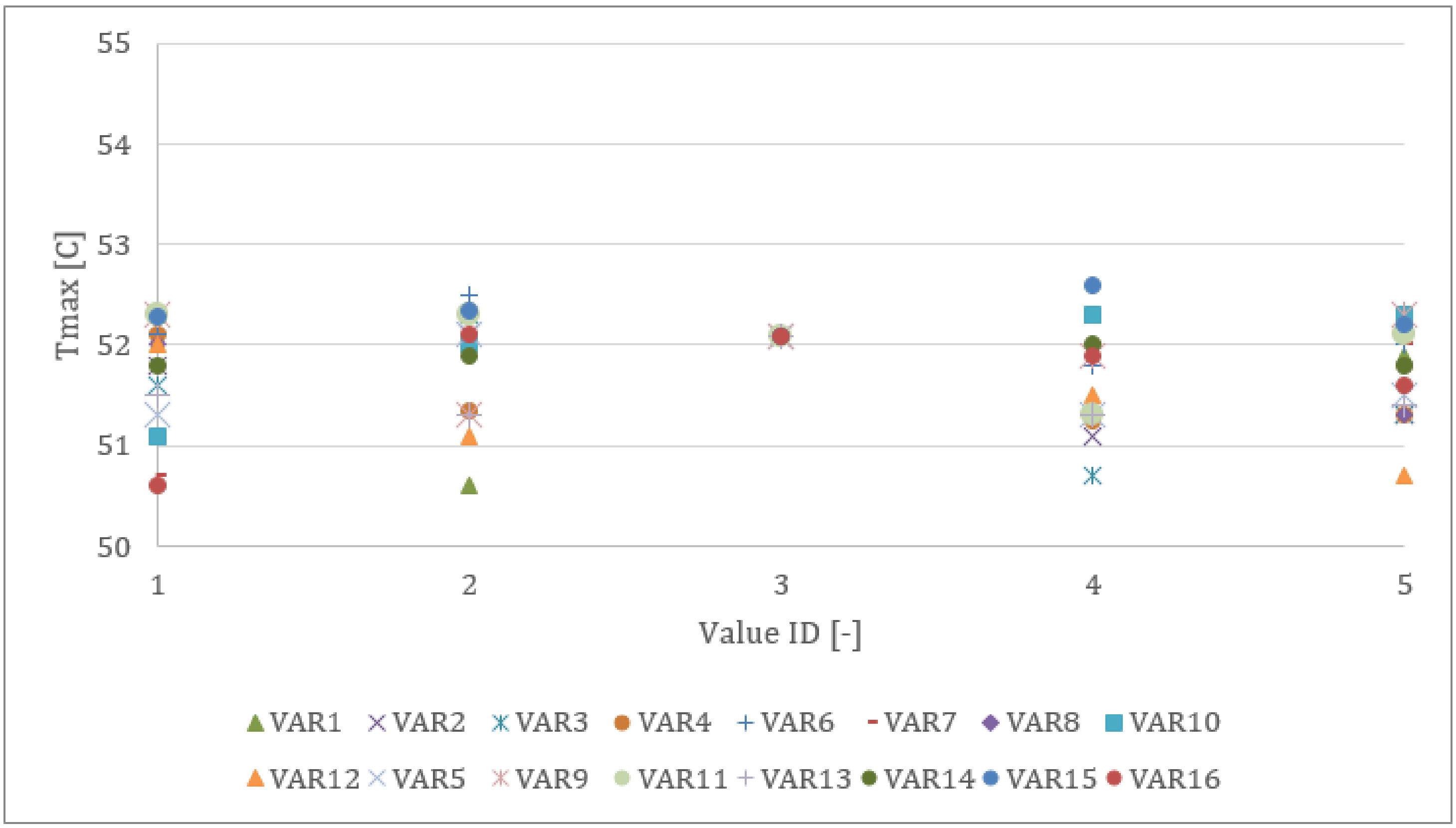

Figure 6

Maximum temperature for 5 points and for all the variables.

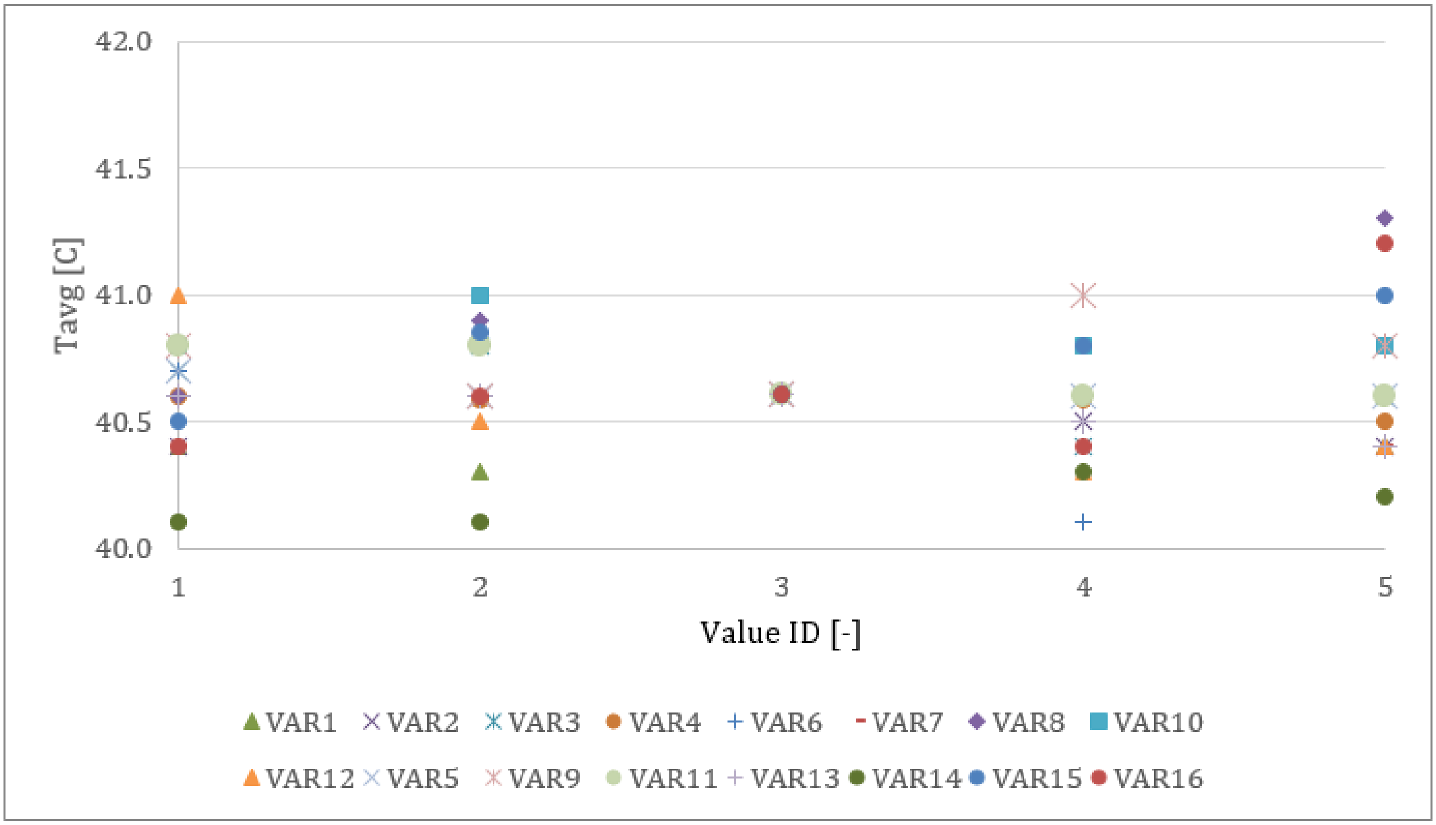

Figure 7

Average temperature for 5 points and for all the variables.

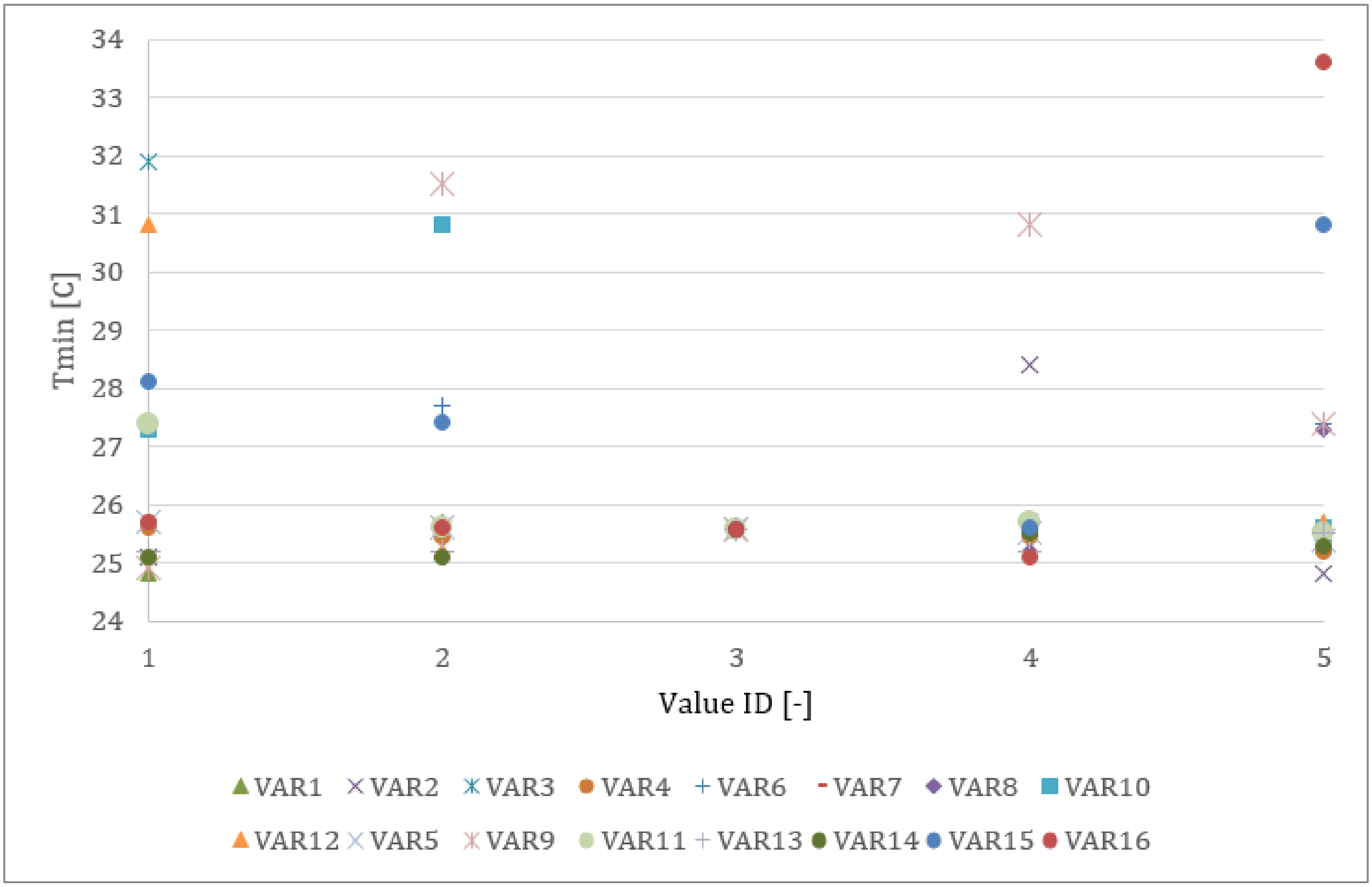

Figure 8

Minimum temperature, for 5 values of Value ID and for all the variables.

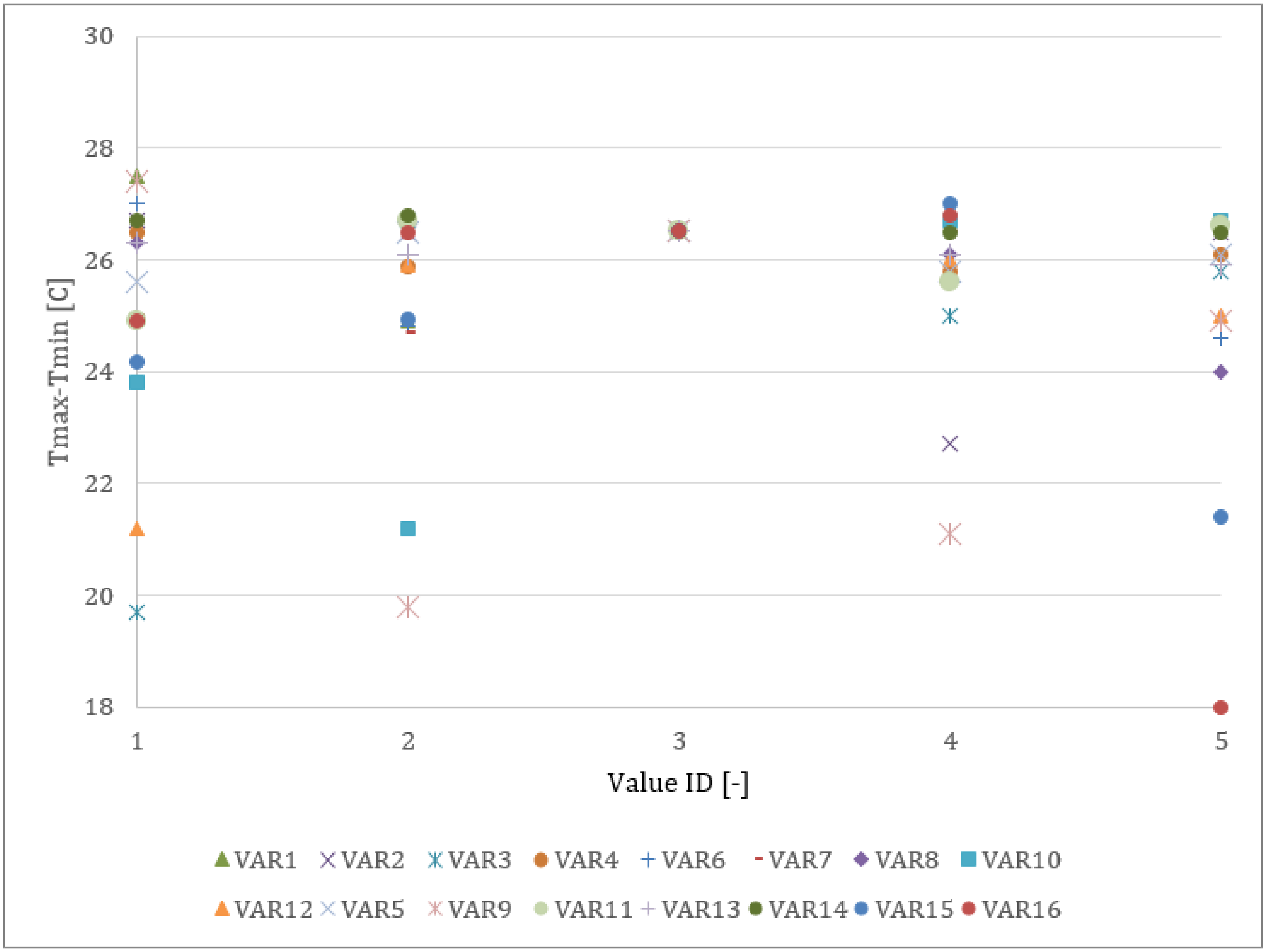

Figure 9

Temperature amplitude, for 5 values of Value ID and for all the 16 variables.

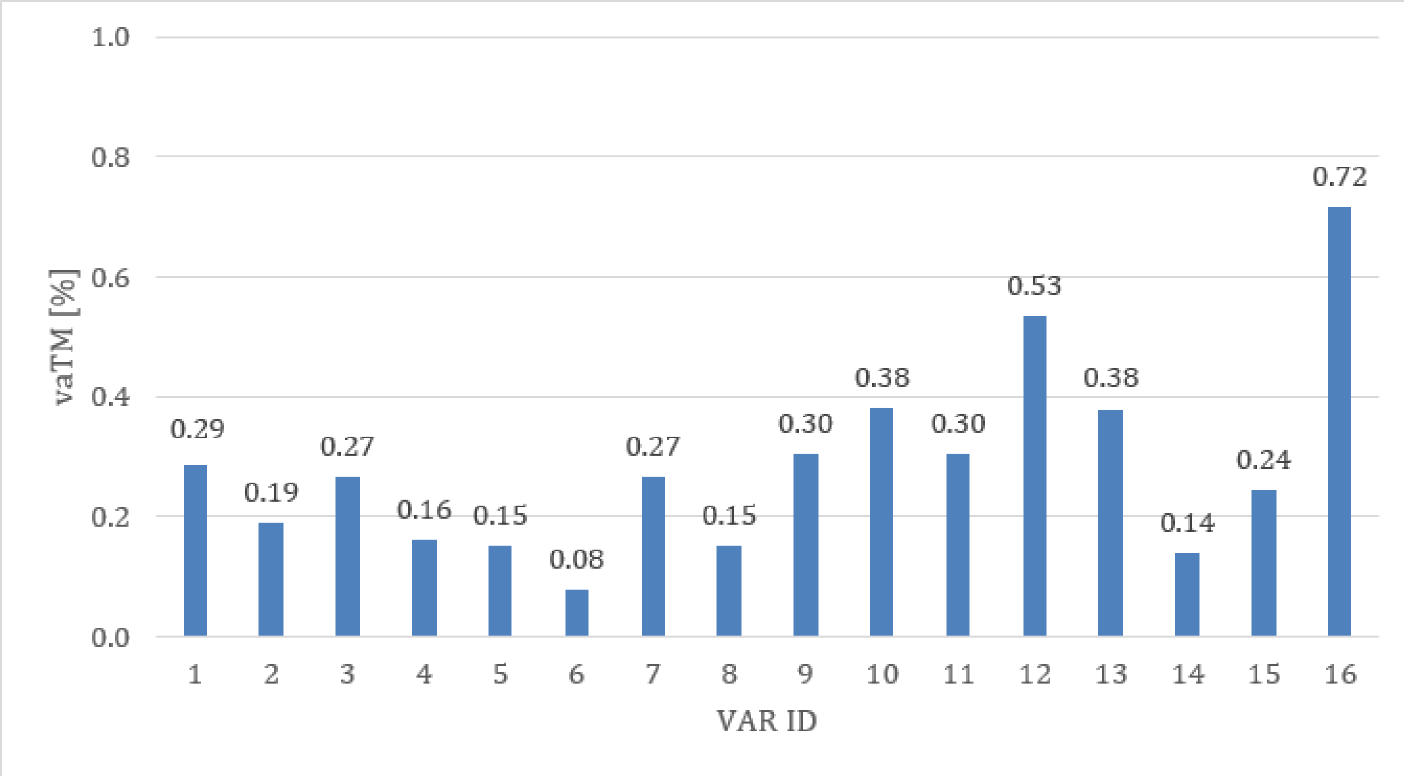

Figure 10

Maximum value for Tmax, for all the variables, according to the methodology described.

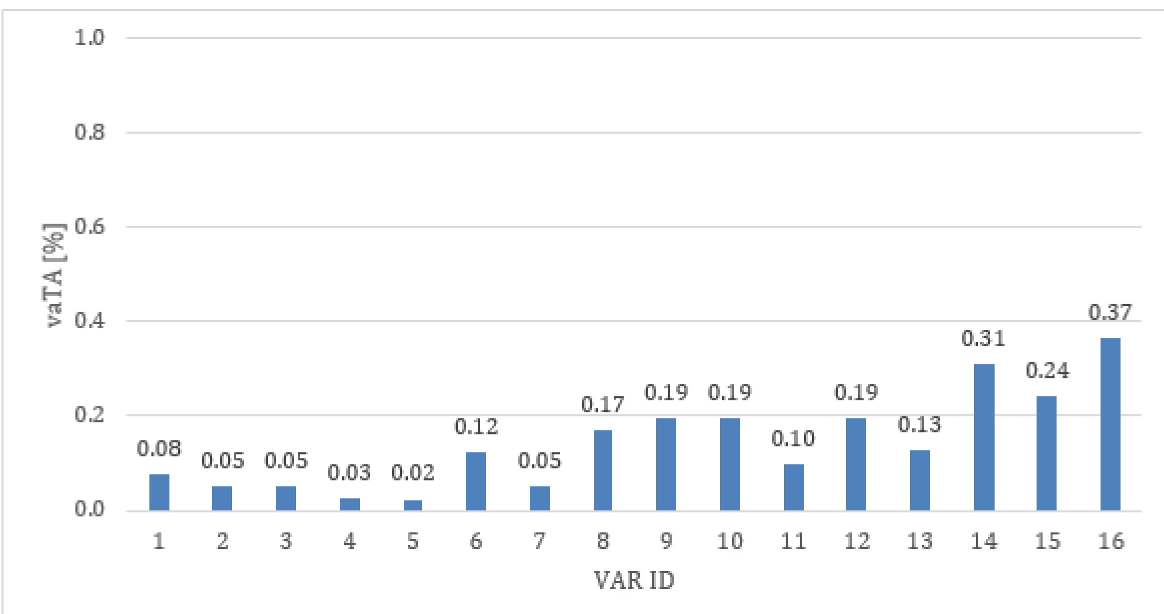

Figure 11

Maximum value for Tavg, for all the variables, according to the methodology described.