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Development, Testing and Benchmarking of an Automated Thermal Model Correlation Tool

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An essential part in the development of a spacecraft is the establishment of a thermal model for the thermal design and the temperature predictions during the operation phase. Targeting for most accurate predicted temperatures, all thermal models of spacecraft are correlated with measurements from thermal tests or flight data. A tool for the automated correlation of thermal models has been developed and is named TAUMEL. The tool makes use of a very fast steady-state solving algorithm based on simplified governing equations. The principle method of the correlation is the variation of thermal conductors in the thermal model, whilst thermal capacitances and boundary conditions are excluded from modification. A beta version showed very promising results, focusing on the feasibility of such a tool and the method of the automated correlation (ICES-2015-61). This paper presents the further development, testing, benchmarking and validation of TAUMEL. With the implementation and user friendliness in focus, the tool has been tested on several thermal models. The performance of TAUMEL has been further improved. The obtained results have been benchmarked against common correlation methods on thermal models with available test data. Furthermore, the results obtained by TAUMEL have been validated on the thermal models of a one- and twenty-Newton hot gas thruster, using measurement data of steady-state hot run tests. The implementation and user-friendliness, the obtained results and the performance of TAUMEL are presented in this paper.

Nomenclature

Symbol	Unit	Description
GUI		Graphical User Interface
MAD		Mean absolute deviation of temperatures
TAUMEL		Tool for Automated Model correlation using Equation Linearization
TMM		Thermal Mathematical Model
TBT		Thermal Balance Tests
$\mathbf{A}$, $\mathbf{L}$,…	-	Matrices of real numbers $\mathbf{A} = (A_{ij})$
B, Q,…	-	Vectors of real numbers $B = (B_i)$
dim(B)	-	Dimension of vector B
diagC	-	Diagonal matrix of the vector C
$n,b,d,i,j,r,\ldots$	-	Natural numbers
Ti	K	Temperature of node i
$\dot{T}_i$	K/s	Temperature temporal change of node i: $\dot{T}_i = dT_i/dt$
t_r	s	Time-step r

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C_i	J/K	Thermal capacitance of node *i*
$\dot{Q}_i$	W	Heat input into node *i*
$\dot{Q}_{B,i}$	W	Boundary heat input into node *i*
GL_{ij}	W/K	Linear conductor value between nodes *i* and *j*
GR_{ik}	m^2	Radiative conductor value between nodes *i* and *k*
σ	$W/m^2/K^4$	Stefan-Boltzmann constant
$\mathbb{R}^+$	-	Space of positive real numbers

I. Introduction

IN space, the thermal environment is very demanding with often extreme cold temperatures on one side and extreme solar heat fluxes on the other side at the same time. Hence, thermal control is essential for a spacecraft, in order to keep all its devices within their design limit temperatures. During the design of a spacecraft, thermal mathematical models (TMM) are used to predict the thermal behavior during the mission. The predicted temperatures have to be as accurate as possible. To improve their accuracy, the thermal models are correlated to test and/or flight data during the development. This is achieved by the modification of selected model parameters.

Current methods and tools, however, are using the full thermal mathematical model for the correlation. Moreover, the correlation is an iterative process in order to find the best modification of the chosen model parameters for correlation. Consequently, these methods are in general very time-consuming, since the full thermal mathematical model needs to be calculated for each iteration of the correlation. With increasing computer power and possibilities provided by the modeling software, the complexity and size of thermal models increases. Hence, the number of possible parameter combinations and settings for the correlation increase at the same time. This means that for a correlation more and more iterations are necessary, leading to increasing calculation effort and time.

A new method suited for automated thermal model correlation has been developed. The method has been implemented into a MATLAB®-based tool called TAUMEL. The method and implementation in MATLAB® have been described in the previous paper (cf. [1]).

The tool TAUMEL has now been extended with functionalities to support the user-input and the output. It has been tested successfully on a selected thermal model. A first benchmarking by comparison to a conventional correlation has been performed. The testing and the achieved results are presented in this paper.

II. Mathematical Principle of TAUMEL and the Used Correlation Method

A. Thermal Model Governing Equation

The mathematical principle of the correlation in TAUMEL is described in detail in a previous paper (cf. [1]) . For convenience, the main idea and terms are repeated in this section of this paper.

Let a thermal mathematical model (TMM) of a spacecraft consist of d diffusion nodes. The temperatures of the nodes in the TMM are then fully described by the discrete governing equation (1) (cf. [1]):

$$C_i \dot{T}_i^r = \sum_{i \neq j} GL_{ij}(T_j^r - T_i^r) + \sigma \sum_{i \neq k} GR_{ik}((T_k^r)^4 - (T_i^r)^4) + \dot{Q}_{B,i}^r \qquad \forall i, r \tag{1}$$

Here, T_i^r are the temperatures of the diffusion nodes $i = 1, \dots, d$. $\dot{T}_i^r$ is the temporal derivative of T_i at the time t_r and C_i is the thermal capacity of the node i . $\dot{Q}_{B,i}^r$ designates the (signed) heat flows to the node i through all connected boundary conductors. The GL_{ij} and GR_{ik} are the linear and radiative conductors to the neighboring nodes T_j and T_k, respectively. σ designates the Stefan-Boltzmann constant. The upper indices r indicates the discrete time step t_r.

The thermal model can now be correlated to test data. Test data for thermal model correlation is recorded in thermal tests, usually Thermal Balance Tests (TBT).

B. Correlation between TMM and Test Temperature Measurements

Let $\mathrm{T} = (T_1, \dots, T_d)$ be the set of all temperatures of the diffusion nodes in the TMM described by equation (1). For selected diffusion nodes $\widetilde{\mathrm{T}} \subset \mathrm{T}$, temperature measurement data shall be available from a test. Let $T_i \in \widetilde{\mathrm{T}}$. Let $T_{i,Test}^r \epsilon \, \widetilde{\mathrm{T}}_{Test}$ be the temperature measurement at the time t_r at the location of the node i. The measurement information may come e.g. from a thermocouple mounted to a location at the physical model that corresponds to the node i in the TMM. The temperatures $T_i \in \widetilde{\mathrm{T}} \subset \mathrm{T}$ calculated by the TMM (1) can now be compared to the test temperatures using any convenient measure s:

$$s := |\tilde{T}^r - \tilde{T}^r_{Test}| = \mathit{difference\ between\ model\ and\ test\ temperatures\ at\ time}\ t_r \qquad (2)$$

A model correlation between the test and the TMM aims on the minimization of this difference (2) between the model and the test temperatures.

A known measure for the correlation is e.g. the mean absolute deviation (MAD), deignated by s_{MAD}:

$$s_{MAD} := \frac{1}{dim\tilde{T}} \sum_{i=1}^{dim\tilde{T}} \left|\tilde{T}^r_{i,TMM} - \tilde{T}^r_{i,Test}\right| \qquad (3)$$

Another possible measure s_{ECSS} is motivated by the method for correlation propagated by the ECSS [2]

$$s_{ECSS} := Average\left(\left|\frac{1}{dim\tilde{T}} \sum_{i=1}^{dim\tilde{T}} \tilde{T}^r_{i,TMM} - \tilde{T}^r_{i,Test}\right|, std\right) \qquad (4)$$

Here, std designates the standard deviation of the individual differences $\tilde{T}^r_{i,TMM} - \tilde{T}^r_{i,Test}$ for each node $i \in \tilde{T}$.

For a given thermal mathematical model, all information from the equation (1) as well as the information necessary to define a measure s, is made available by the software used for thermal modelling, such as ESATAN-TMS® (cf. [3]) or Thermica®. This information is used by the developed tool TAUMEL to automatically correlate a TMM to a given set of measurements. The correlation process and the necessary user-inputs are described in the following section.

C. Correlation Method used in TAUMEL

The correlation method implemented into the tool TAUMEL is the modification of the conductors GL_{ij} and GR_{ik} in the TMM by multiplication of a parameter PL_{ij} and PR_{ik} (cf. [1]) at a selected time step t_r:

$$C_i\dot{T}_i^r = \sum_{i\neq j} PL_{ij}GL_{ij}(T_j^r - T_i^r) + \sigma\sum_{i\neq k} PR_{ik}GR_{ik}((T_k^r)^4 - (T_i^r)^4) + \dot{Q}^r_{B,i} \qquad \forall i \qquad (5)$$

The selection of the time step t_r for the correlation is a user-input to the method. Another important user input to the method is the selection and allocation of the parameters PL_{ij} and PR_{ik} and the variation ranges I_{ij} and I_{ik}, respectively. These ranges define the applied variation for a conductor. As an example, a variation of $I_{ij} = [0.8, 1.2]$ corresponds to a variation of ±20 % of the conductor GL_{ij}.

For a total of v parameters PL_{ij} and w parameters PR_{ij}, the set of all I_{ij} spans the so-called parameter space Ω:

$$\Omega := \prod I_{ij} \subset \mathbb{R}^{v+w} \qquad (6)$$

The task for the correlation method implemented in TAUMEL is now to find the best value for each parameter, such that the selected difference s becomes minimal.

The PL_{ij} and PR_{ik} are varied within the predefined variation ranges I_{ij} and I_{ik}, following a simulated annealing process to find the parameters that minimize the selected difference s. User inputs to this simulated annealing are the number of cycles and the number n_{max} of iterations per cycle (cf. [1] for more details).

The process of cycles and iterations during the simulated annealing process within Ω is indicted in Figure 1.

The tool TAUMEL hereby calculates the node temperatures T_i that correspond to the modified TMM (5) by solving the linear equation system (7). The equation (7) approximates the linear equation system (1) [1]:

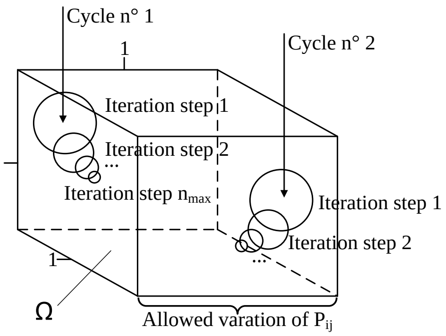


Figure 1. Indicative process of simulated annealing in the parameter space Ω

$$0 = \sum_{i\neq j} PL_{ij}GL_{ij}(T_j^r - T_i^r) + \sigma\sum_{i\neq k} PR_{ik}\widetilde{GR}_{ik}(T_k^r - T_i^r) + \dot{Q}^r_{B,i} - C_i\dot{T}^r_{i,TMM} + \dot{Q}^r_{R,i} \quad \forall i \qquad (7)$$

Here, $\dot{Q}^{r}_{R,i}$ designates a corrective term to account for the linearized radiative term. The subscript TMM in the term $C_i\dot{T}^{r}_{i,TMM}$ indicates that the temperature of node i is taken from the TMM that solved equation (1). The $\widetilde{GR}_{ik}$ are linearized radiative conductors.

It has to be noted that, depending on the thermal model, the coverage of the nodes by corresponding measurements and the number of parameters, there might be several points in the parameter space Ω where the differences s become very small. This is indicated in Figure 2. The location for the start of the cycles of iterations within Ω is randomly chosen by the simulated annealing process. Consequently, the solution found by the method might not be unique and might differ between two runs of the tool on the same problem.

However, this applies, for a given TMM and test, to every correlation method.

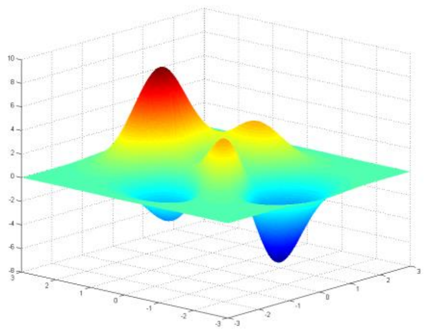


Figure 2. Indicative values of the measure *s* over the parameter space Ω

In order to minimize the effects of the linearization of the radiation-term, the equation (7) is solved twice for each set of parameters. A correction-term for the linearization of the equation is introduced for the second solution. The influence of the correction-term has been investigated, showing that after the second solution, the approximation cannot be further improved (cf. section E)

As a summary, the correlation in TAUMEL corresponds to a minimization-automatism for the difference s between the model temperatures and the corresponding test temperatures.

Please note that the model-temperatures calculated by TAUMEL are approximate figures due to the linearization of the governing equation and the neglect of temperature-dependent conductivities and temperature-dependent boundary-conditions (cf. [1] for a detailed description of the simplifications in the tool).

III. Implementation of the Method in the Tool TAUMEL

The method described before has been implemented into MATLAB® and has been named TAUMEL as described in the precedent paper (cf. [1]). In its latest development, the graphical user interface (GUI) has been further developed and the method has been further optimized for calculation performance and accuracy of the approximated results.

The process of using the tool TAUMEL is visualized in Figure 3.

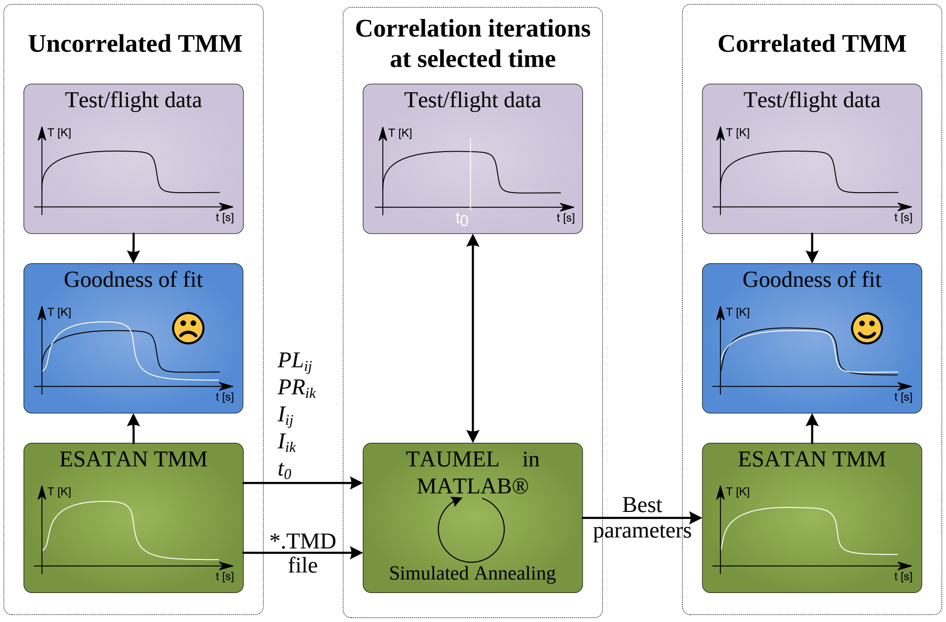


Figure 3. TAUMEL process - user inputs to optimized conductors

A. User-Defined Input

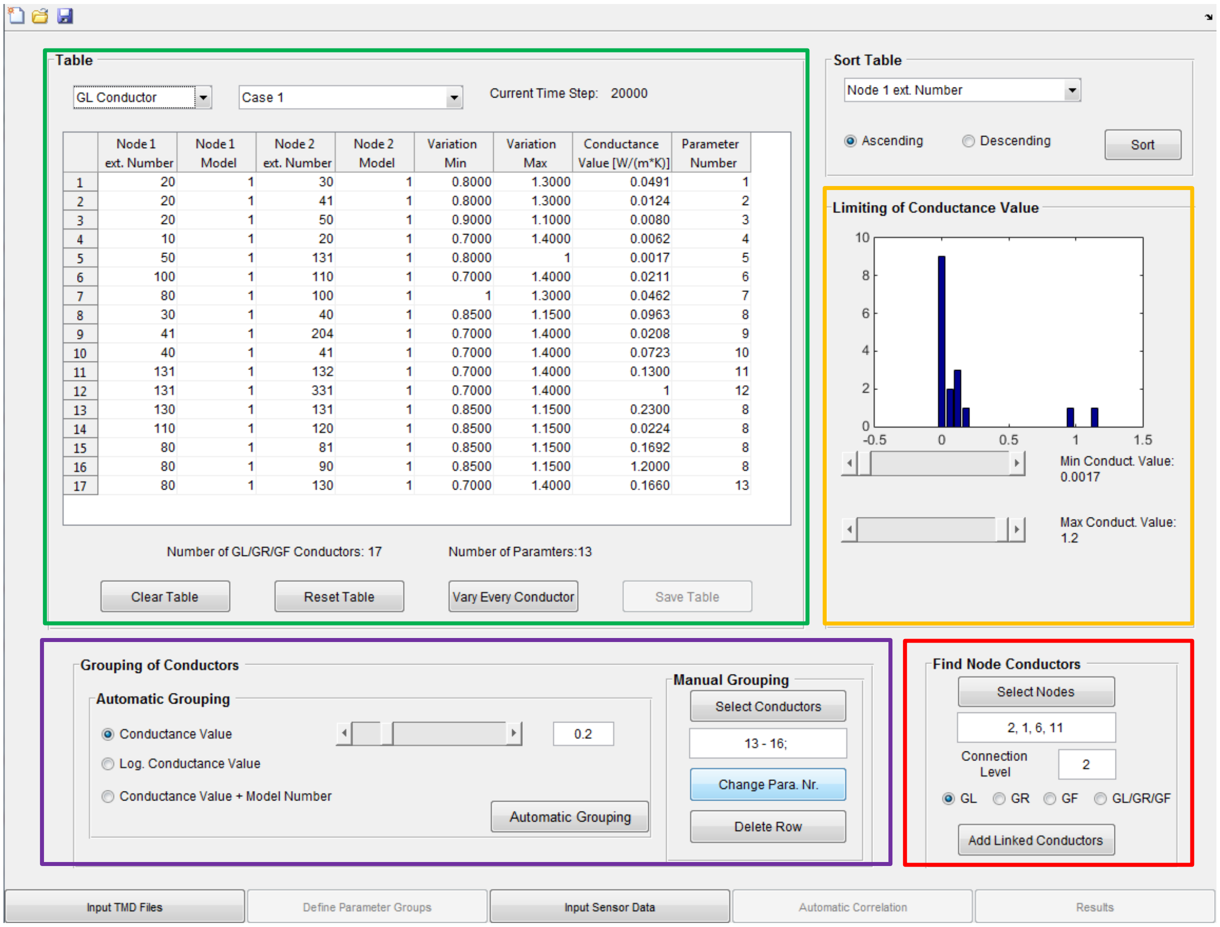
The information necessary to set up the equation (7) is brought into TAUMEL via the GUI. The input consists of two main components:

1) The information of the $C_i\dot{T}^r_{i,TMM}$, $\dot{Q}^r_{B,i}$, GL_{ij} and GR_{ik} is read automatically from selected ESATAN-TMS® binary output files (*.TMD-files) for a selected time-step t_0, defined via a dedicated GUI.
2) The parameter information PL_{ij} and PR_{ik} and the variation intervals I_{ij} and I_{ik} are user-inputs via a dedicated GUI.

Note that the user can select multiple *.TMD-files for correlation. In this case, TAUMEL will average the results of the minimization criteria s of all selected cases.

The selection of the conductors to be varied by the multiplicative parameters is the most crucial part of the correlation with TAUMEL. In order to allow for a most convenient input of the parameters, the tool provides a dedicated GUI, shown in Figure 4. With the help of this GUI, the user can

a) Allocate parameters manually and individually to conductors in the table (green framed area in Figure 4)
b) Group conductors to assign them with one parameter, meaning that he can choose several PL_{ij} or PR_{ik} to be varied identically by the tool (support functions indicated in purple framed area in Figure 4)
c) Assign individual parameters exclusively to conductors that are connected to a sensor-node (red framed area in Figure 4)
d) Exclude condoctors from variation outside selected thresholds for the conductor value (yellow frame in Figure 4)



Table

GL Conductor

Case 1

Current Time Step: 20000

	Node 1 ext. Number	Node 1 Model	Node 2 ext. Number	Node 2 Model	Variation Min	Variation Max	Conductance Value [W/(m*K)]	Parameter Number
1	20	1	30	1	0.8000	1.3000	0.0491	1
2	20	1	41	1	0.8000	1.3000	0.0124	2
3	20	1	50	1	0.9000	1.1000	0.0080	3
4	10	1	20	1	0.7000	1.4000	0.0062	4
5	50	1	131	1	0.8000	1	0.0017	5
6	100	1	110	1	0.7000	1.4000	0.0211	6
7	80	1	100	1	1	1.3000	0.0462	7
8	30	1	40	1	0.8500	1.1500	0.0963	8
9	41	1	204	1	0.7000	1.4000	0.0208	9
10	40	1	41	1	0.7000	1.4000	0.0723	10
11	131	1	132	1	0.7000	1.4000	0.1300	11
12	131	1	331	1	0.7000	1.4000	1	12
13	130	1	131	1	0.8500	1.1500	0.2300	8
14	110	1	120	1	0.8500	1.1500	0.0224	8
15	80	1	81	1	0.8500	1.1500	0.1692	8
16	80	1	90	1	0.8500	1.1500	1.2000	8
17	80	1	130	1	0.7000	1.4000	0.1660	13

Number of GL/GR/GF Conductors: 17

Number of Paramters:13

Sort Table

Node 1 ext. Number

● Ascending ○ Descending

Limiting of Conductance Value

Min Conduct. Value: 0.0017

Max Conduct. Value: 1.2

Grouping of Conductors

Automatic Grouping

● Conductance Value

○ Log. Conductance Value

○ Conductance Value + Model Number

0.2

Manual Grouping

13 - 16;

Find Node Conductors

2, 1, 6, 11

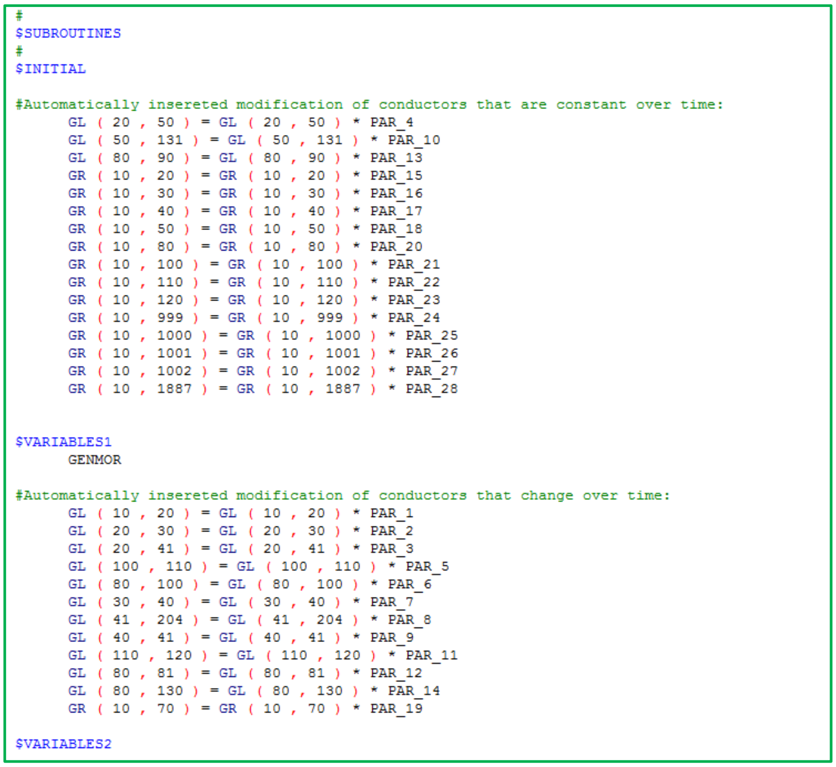
Connection Level 2

● GL ○ GR ○ GF ○ GL/GR/GF

Figure 4. GUI for the parameter definition

For the moment, TAUMEL is designed to export its results to TMM files in ESATAN-TMS®. The user can select the main *.d-file of the thermal model and TAUMEL automatically inserts the modification of the conductors in either the $INITIAL or $VARIABLES block depending on whether the conductors are temperatur-dependent or not as shown in Figure 5.

After the adaptation of the *.d-file, the user can launch the TMM in ESATAN-TMS® from TAUMEL in the so-called batch-mode. The TMM model is executed in ESATAN-TMS® and the results are imported into TAUMEL.



```
#
$SUBROUTINES
#
$INITIAL

#Automatically insereted modification of conductors that are constant over time:
      GL ( 20 , 50 ) = GL ( 20 , 50 ) * PAR_4
      GL ( 50 , 131 ) = GL ( 50 , 131 ) * PAR_10
      GL ( 80 , 90 ) = GL ( 80 , 90 ) * PAR_13
      GR ( 10 , 20 ) = GR ( 10 , 20 ) * PAR_15
      GR ( 10 , 30 ) = GR ( 10 , 30 ) * PAR_16
      GR ( 10 , 40 ) = GR ( 10 , 40 ) * PAR_17
      GR ( 10 , 50 ) = GR ( 10 , 50 ) * PAR_18
      GR ( 10 , 80 ) = GR ( 10 , 80 ) * PAR_20
      GR ( 10 , 100 ) = GR ( 10 , 100 ) * PAR_21
      GR ( 10 , 110 ) = GR ( 10 , 110 ) * PAR_22
      GR ( 10 , 120 ) = GR ( 10 , 120 ) * PAR_23
      GR ( 10 , 999 ) = GR ( 10 , 999 ) * PAR_24
      GR ( 10 , 1000 ) = GR ( 10 , 1000 ) * PAR_25
      GR ( 10 , 1001 ) = GR ( 10 , 1001 ) * PAR_26
      GR ( 10 , 1002 ) = GR ( 10 , 1002 ) * PAR_27
      GR ( 10 , 1887 ) = GR ( 10 , 1887 ) * PAR_28


$VARIABLES1
      GENMOR

#Automatically insereted modification of conductors that change over time:
      GL ( 10 , 20 ) = GL ( 10 , 20 ) * PAR_1
      GL ( 20 , 30 ) = GL ( 20 , 30 ) * PAR_2
      GL ( 20 , 41 ) = GL ( 20 , 41 ) * PAR_3
      GL ( 100 , 110 ) = GL ( 100 , 110 ) * PAR_5
      GL ( 80 , 100 ) = GL ( 80 , 100 ) * PAR_6
      GL ( 30 , 40 ) = GL ( 30 , 40 ) * PAR_7
      GL ( 41 , 204 ) = GL ( 41 , 204 ) * PAR_8
      GL ( 40 , 41 ) = GL ( 40 , 41 ) * PAR_9
      GL ( 110 , 120 ) = GL ( 110 , 120 ) * PAR_11
      GL ( 80 , 81 ) = GL ( 80 , 81 ) * PAR_12
      GL ( 80 , 130 ) = GL ( 80 , 130 ) * PAR_14
      GR ( 10 , 70 ) = GR ( 10 , 70 ) * PAR_19

$VARIABLES2
```

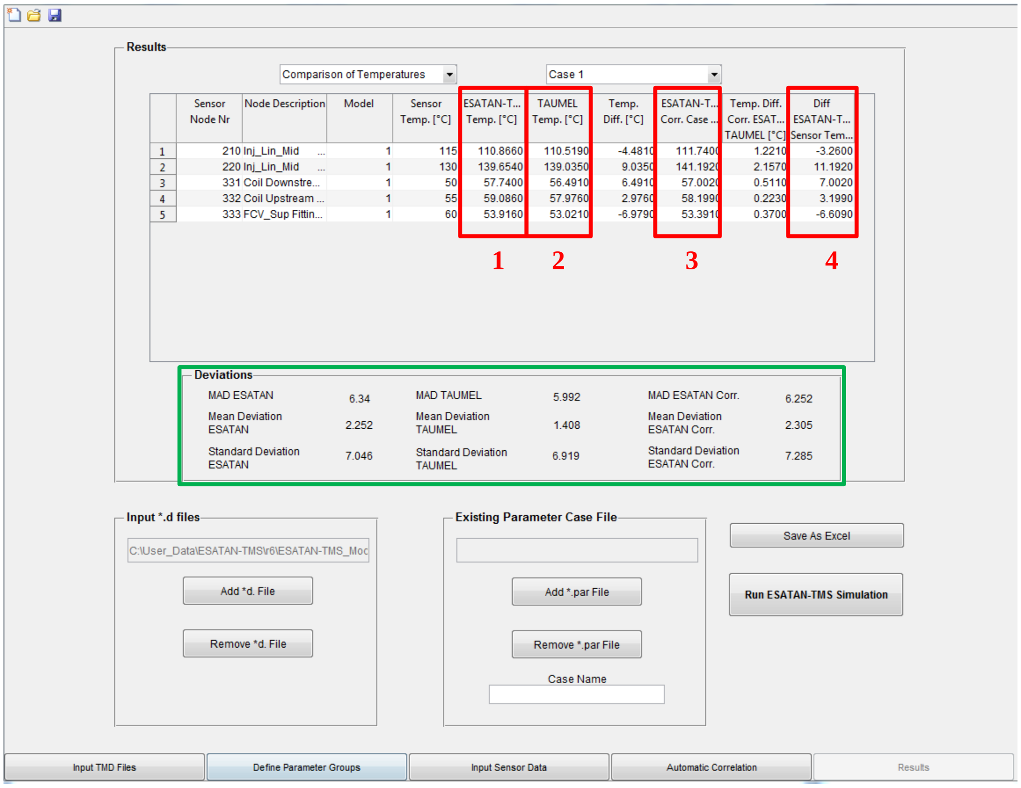
Figure 5. Automatically modified *.d-file

B. Post-processing of the Results in TAUMEL

After the correlation in TAUMEL and the automatic adaptation of the TMM in ESATAN-TMS®, the user can post-process the results in TAUMEL directly.

The GUI shows the temperature recordings (1) as well as the originally predicted temperature by the TMM before correlation (2). To evaluate the correlation performed in TAUMEL, the GUI shows the approximate temperatures of the modified TMM calculated by TAUMEL (3). After having the model file (*d.-file) automatically edited by TAUMEL, the user can re-run the ESATAN-TMS-simulation in batch-mode and re-run the simulation. The differences between ESATAN-TMS® after the modifications and the test temperatures is then shown in the GUI automatically (4). The results of the two critera s_{MAD} and s_{ECSS} are shown separately (green framed area).

Note that due to the approximation in TAUMEL, there are differences between the temperatures obtained by TAUMEL and the temperatures obtained with the TMM in ESATAN-TMS®. The differences between these results have been investigated in the testing phase, described in section E.



Comparison of Temperatures

Case 1

	Sensor Node Nr	Node Description	Model	Sensor Temp. [°C]	ESATAN-T... Temp. [°C]	TAUMEL Temp. [°C]	Temp. Diff. [°C]	ESATAN-T... Corr. Case ...	Temp. Diff. Corr. ESAT... TAUMEL [°C]	Diff ESATAN-T... Sensor Tem...
1	210	Inj_Lin_Mid ...	1	115	110.8660	110.5190	-4.4810	111.7400	1.2210	-3.2600
2	220	Inj_Lin_Mid ...	1	130	139.6540	139.0350	9.0350	141.1920	2.1570	11.1920
3	331	Coil Downstre...	1	50	57.7400	56.4910	6.4910	57.0020	0.5110	7.0020
4	332	Coil Upstream ...	1	55	59.0860	57.9760	2.9760	58.1990	0.2230	3.1990
5	333	FCV_Sup Fittin...	1	60	53.9160	53.0210	-6.9790	53.3910	0.3700	-6.6090

Deviations

MAD ESATAN	6.34	MAD TAUMEL	5.992	MAD ESATAN Corr.	6.252
Mean Deviation ESATAN	2.252	Mean Deviation TAUMEL	1.408	Mean Deviation ESATAN Corr.	2.305
Standard Deviation ESATAN	7.046	Standard Deviation TAUMEL	6.919	Standard Deviation ESATAN Corr.	7.285

C:\User_Data\ESATAN-TMS\r6\ESATAN-TMS_Moc

Figure 6. Post-processing GUI

C. TAUMEL Calculation Performance

The calculation performance of the tool TAUMEL has been measured for 6 different TMMs. These models were of different sizes in terms of total number of nodes and total number of conductors. The user-settings were set for all models to 100 cycles and 100 iterations, i.e. 10000 iterations in total[4].

The achieved process times over the total number of nodes are shown in Figure 6. The process times are shown as a function of the number of nodes. The number of nodes defines the size of the linear equation system to be solved for each iteration. The variations in the calculation time may be explained by differences in the preparation of the linear equation system, depending on the conductor matrix.

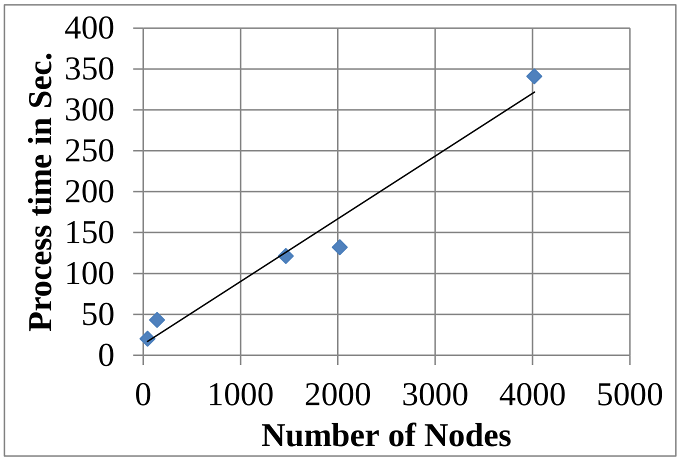


Figure 7. Process time of 10000 iterations over the total number of nodes (linear regression in Eq. 8)

The results indicate that on the used machine[4] the expected calculation time could be estimated according to the formula:

$$8.0E^{-06}\, s \cdot (n° \; of \; nodes) \cdot (n° \; of \; cycles) \cdot (n° \; of \; iterations \; per \; cycle) \; + \; 13\, s \tag{8}$$

The 13 s of fixed time correspond to the reading-process of the input files.

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[4] Operating System:	(6.1, Build 7601) Service Pack 1 (7601.win7sp1_gdr.150722-0600)
Processor:	Intel(R) Xeon(R) CPU X5680 @ 3.33GHz (12 CPUs), ~3.3GHz
Memory:	24576MB RAM
Software:	Matlab 2013a

IV. Testing

After development, intensive testing has been performed on the tool. During testing several aspects have been investigated. It was intended to cover all aspects that might have an impact on the final result achieved by the correlation with the tool TAUMEL:

1) Investigation of the influence of the user-defined inputs for the tool on the final results
    a) Investigation of different methods for the selection of the conductors in the TMM to be modified by TAUMEL
    b) Investigation of the influence of the interval for the variation of the parameters PL_{ij} and PR_{ik}.
    c) The influence of the number of modified conductors to the final result

2) Investigation of the influence of the mathematical simplifications made by TAUMEL
    d) Investigation of the influence of the correction-term to the results

3) Investigation of the influence of other correlation-aspects
    e) Investigation of the influence of the quality of the steady state
    f) Investigation of the influence of the coverage of nodes with thermo-couples

The results of this intensive testing are presented hereafter in the following subsections.

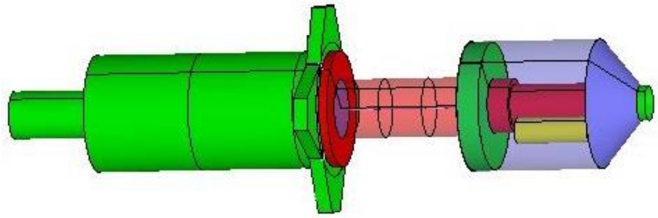

Figure 8. GMM of the 1N-thruster

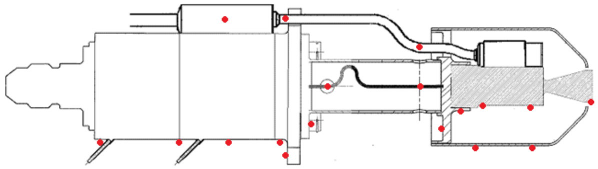

Figure 9. Indicative locations of thermo-couples

A. Testing – Selection of the Thermal Model and Test Case

The testing of TAUMEL was performed on a thermal model for a 1N-thruster, used for the attitude control of a small spacecraft.

The selection of the model was based on the following rational:

1) A relatively high number of measurements has been done on the thruster with a coverage of 66% of the nodes of the thermal model
2) A correlation using conventional methods of the model already exists
3) The model is relatively small with a total number of 45 diffusion nodes and 234 conductors

A geometrical representation of the thermal model of the 1N-thruster is shown in Figure 8. The allocation of the thermocouples placed on the test-item is shown in Figure 9.

As test case a TBT of the thruster was selected. The main parameters of the test case were as follows:

1) Test-chamber pressure $<10^{-7}$ mbar (no convective boundary conditions considered)
2) Test case duration: 20000 s
3) Steady-state heating of all installed heaters and shroud temperatures

This test-setup guaranteed a good quality of the steady state and a good representation of the boundary conditions (no convection present).

Table 1 shows the measured temperatures T_{Test} used in the correlations conducted for the following investigations as well as the temperatures predicted by ESATAN-TMS. This TMM was already correlated using a conventional correlation method. The MAD for this TMM showed a MAD of 3.42 °C.

The model used for the testing in TAUMEL was this conventionally correlated TMM.

The results from most of the following investigations can be evaluated regarding the improvement by comparing the MADs with the MAD of this initial setup.

Table 1: Predicted and measured temperatures of TMM nodes used for correlation

TMM node n°	Thermo Couple	T_{Test} [°C]	T_{Pred} [°C]	ΔT [°C]
10	TC_NOZ	179,0	182,0	3,0
20	TC_CB3	189,9	192,2	2,3
30	TC_CB1	165,3	165,3	0,0
40	TC_FP/ TC_TCAFL	150,0	151,5	1,5
70	TC_COV1/ TC_COV2	118,0	119,2	1,2
80	TC_HBFL1/ TC_HBFL2	55,5	53,7	-1,8
90	TC_FL	50,9	53,0	2,1
100	TC_HB1	69,6	68,4	-1,2
120	TC_HB2	137,7	133,1	-4,6
130	TC_FCV4	54,1	54,4	0,3
131	TC_FCV3	56,5	57,7	1,2
132	TC_FCV2	57,8	59,6	1,8
133	TC_TB1	51,9	51,9	0,0
200	TC_CT2	77,2	78,6	1,4
220	TC_CT1	108,6	134,2	25,6
		MAD:	**3,42 °C**	

B. Investigation of different methods for the selection of the conductors in the TMM to be modified by TAUMEL

One crucial part of the correlation process is the selection of conductors being correlated. TAUMEL offers a tool to select and group conductors that shall be varied during the process. But considering the number of potential conductors existing in a thermal model, a thorough thought process for the selection is necessary. During testing the following 2 methods were examined that might help with this problem:

1) choosing conductors connected to nodes whose predicted temperature and measured temperature differ substantially ($\Delta T = T_{TMM} - T_{Test} > 1.5\ °C$)
2) selecting conductors randomly

The correlation was conducted 4 times for both methods and in each process 80 conductors were being changed. Each run consisted of 100 cycles and 100 iterations (10000 different parameter combinations were tested). For the first method the conductors being changed stayed the same. For the second method each run another configuration of conductors was being correlated. To compare the two strategies the MADs of each run are used.

Table 2: Results for method 1)

Experiment Nr	Mean Absolute Deviation [°C]	
	TAUMEL	ESATAN-TMS (corr.)
1	2,452	2,553
2	2,568	2,600
3	2,542	2,531
4	2,671	2,847

Table 3: Results for method 2)

Experiment Nr	Mean Absolute Deviation [°C]	
	TAUMEL	ESATAN-TMS (corr.)
1	2,705	2,938
2	2,707	2,748
3	2,600	2,677
4	2,553	2,600

The results show that selecting conductors connected to nodes whose ΔT is bigger than a selected threshold (in this case 1.5°C) is the best of the two examined selection strategies. This method was also used in the final correlation (cf. section IV-H) and later benchmark tests.

C. Investigation of the influence of the interval for the variation of the parameters PL_{ij} and PR_{ik}

Another important part of selecting the conductors being correlated is limiting the variation range. The algorithm looks for parameters only in between these variation limits, hence the variation limits directly affect the number of possible parameter configurations and thus increases the required time to test each configuration. The goal of the next investigation was finding sufficient variation limits provide good results in a reasonable amount of time. The tested variation limits can be seen in Table 4. For each variation limit, four runs were conducted with an increasing number of iterations. The number of cycles was 100 in every run. For each run, the chosen conductors 30 GL and 30 GR conductors randomly selected stayed the same.

Table 4: Parameter interval settings and results

Experiment Nr	Min. Variation	Max. Variation	Iterations	Mean Absolute Deviation [°C]	
				TAUMEL	ESATAN-TMS (corr.)
1	0,95	1,06	100	0,896	0,899
			200	0,867	0,846
			300	0,846	0,820
			400	0,854	0,842
2	0,9	1,11	100	0,734	0,695
			200	0,728	0,711
			300	0,671	0,645
			400	0,663	0,658
3	0,8	1,25	100	0,740	0,681
			200	0,723	0,716
			300	0,647	0,631
			400	0,647	0,660
4	0,7	1,43	100	0,778	1,007
			200	0,774	1,078
			300	0,720	0,980
			400	0,659	0,651
5	0,6	1,67	100	0,928	1,594
			200	0,738	1,343
			300	0,831	1,226
			400	0,818	1,142

The results show that the MADs get better with increasing range of variation until the point where the range of variation is too large and thus the number of possible parameter combinations is too big. As the range of variation gets bigger more cycles and iterations are needed to get sufficient results. With a range of variation 0,8 - 1,25 the best results were achieved. It provided enough room for parameters to be found that reduced the temperature difference between measured and predicted temperatures significantly, but was not too big keeping the probability to find good parameters high enough regarding the number of cycles and iterations used.

D. The influence of the number of modified conductors to the final result

The goal of the next investigation was examining the influence of the number of conductors being changed during correlation to the final result. Nine tests were conducted with 2 runs each time. The number of modified conductors was increased for each test (Table 5). The conductors were selected randomly. Every run consisted of 100 cycles and 100 iterations with parameter varying between the variation limits: min. 0,7 and max 1.4.

Table 5: Summary – coverage of the varied conductors

Exp. Nr	# varied GL	# varied GR	# total	Coverage of varied conductors	Mean Absolute Deviation [°C]		
					TAUMEL	ESATAN-TMS (corr.)	ΔT [°C]
1	5	5	10	4,3%	3,254	3,242	-0,012
2	10	10	20	8,5%	2,938	2,922	-0,016
3	20	20	40	17,1%	2,662	2,735	0,073
4	30	30	60	25,6%	2,507	2,502	-0,005
5	35	40	75	32,1%	2,558	2,653	0,095
6	35	60	95	40,6%	2,669	2,609	-0,060
7	35	80	115	49,1%	2,605	2,797	0,192
8	35	100	135	57,7%	2,503	2,626	0,123
9	35	140	175	74,8%	2,135	2,562	0,427

It appears that at first the MAD improves with an increasing number of modified conductors until it fluctuates around a MAD of 2,5 after 60 modified conductors are included in the correlation. At this stage the difference between the results in TAUMEL and the results in ESATAN-TMS after reintroduction with modified conductors is small. This difference gets bigger with more conductors being correlated, which makes sense considering that

- the temperature dependency of the GL conductors is not included in TAUMEL due to simplification.
- the linearization of the GR conductors in TAUMEL leads to differences between TAUMEL and ESATAN

All these small deviations accumulate resulting in a significant difference between the results in TAUMEL and ESATAN-TMS.

E. Investigation of the influence of the correction-term to the results

TAUMEL uses a linearized radiative term to solve the equation system. Due to the linearization, a part of the radiative term is neglected resulting in a deviation of the results. This deviation is quite small when the temperatures of nodes before and after the correlation are similar. As this temperature difference increases the resulting error increases as well. In order to reduce this error, a correction term was introduced in TAUMEL. After solving the equation system using the linearized radiative term, the new temperatures are used to calculate the temperature difference ΔT. The equation system is solved again this time with the full radiative term using this ΔT providing a more exact approximation. The effect of this implementation was tested by comparing the difference between temperatures calculated in TAUMEL and in ESATAN-TMS with the correction term and without. To assure the comparability of both results, the same conductors were modified with the same parameter. In the experiment, all GL conductors were multiplied by 10 to receive temperatures before and after the modification that differ significantly. The results are the following:

Without correction term
Sum of absolute temperature deviations between TAUMEL and ESATAN of all 45 diffusion nodes: 170,9 °C

With correction term
Sum of absolute temperature deviations between TAUMEL and ESATAN of all 45 diffusion nodes: 144,5 °C

The comparison show that the correction term reduces the overall temperature difference of nodes between TAUMEL and ESATAN-TMS and thus provides more accurate temperatures. The additional time needed for solving the equation system a second time is marginal and acceptable considering the improvement.

F. Investigation of the influence of the quality of the steady state

The mathematics behind TAUMEL are based on the assumption that the correlation is conducted at a time when the thermal system is in a steady state. Because most thermal systems seldomly reach a perfectly balanced steady state it is interesting to analyze how the deviation from a steady state will affect the results.

The impact can be seen in the difference of MAD between TAUMEL and ESATAN-TMS after correlation. In this experiment four different times were selected for correlation. For each time, two runs were conducted to prevent outliers – remember that the optimization algorithm used in TAUMEL is a stochastic algorithm, and results can therefore be different between to runs with the same user-defined settings. The degree in which the system deviates from a steady state at each time was determined as follows:

$$\sum_{i=1}^{d} C_i \cdot \frac{dT_i}{dt} \tag{9}$$

d: Number of all diffusion nodes

The temperature profile of a sample node for the test can be seen in Figure 10.

Table 6: Mean absolute deviation at the selected times

Experiment Nr	Time [s]	$\sum C_i \frac{dT_i}{dt}$	Mean Absolute Deviation [°C]	
			TAUMEL	ESATAN-TMS (corr.)
1	20000	1	2,710	2,696
2	9000	38.2	2,759	2,726
3	7000	136.8	2,620	2,852
4	5000	486.1	2,657	2,669

As it can be seen in Table 6, the deviation between TAUMEL and ESATAN-TMS gets bigger with an increasing $C_i \frac{dT_i}{dt}$. In order to minimize the error of approximation and to receive sufficiently good results, the time of correlation needs to be as close to the steady state as possible.

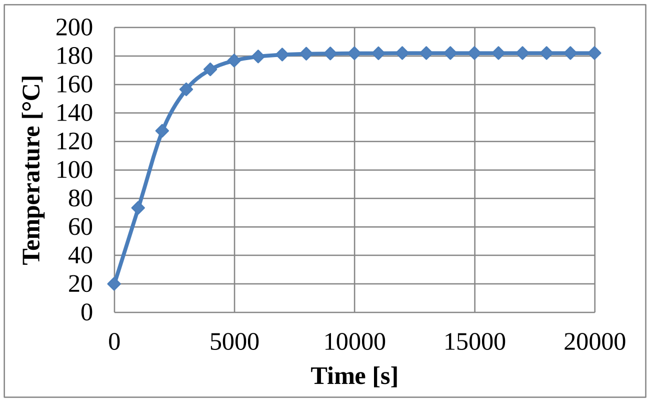

Figure 10. 1N thruster nozzle temperature (Thermo-couple TC_NOZ = Node n° 10)

G. Investigation of the influence of the coverage of nodes with thermo-couples

The goal of the following investigation was to analyze how the coverage of nodes with thermocouples influences the MAD. For this test the number of sensor temperatures included in the correlation process is reduced each time. For each run the number of cycles and iterations as well as the chosen conductors stayed the same.

The results in Table 7 show that the difference between ESATAN-TMS and TAUMEL MADs after correlation is quite similar even as the number of sensors decreases. Although the deviation is the biggest with only 3 sensors in use the differences is quite small. One thing that is noticeable is that the MAD gets smaller as the number of sensors decreases. The reason behind this is that with less sensors there are more possible parameter combinations to achieve matching temperatures and thus it's easier for the algorithm to find good parameters while the temperatures of nodes without an associated sensor may differ significantly.

Table 7: Mean absolute deviation and difference results

Experiment Nr	# Temperature sensors	Mean Absolute Deviation [°C]			ΔT [°C]
		ESATAN-TMS (uncorr.)	TAUMEL	ESATAN-TMS (corr.)	ESATAN-TMS (corr.) - TAUMEL
1	13	1,390	0,994	0,996	0,002
2	10	1,455	1,040	1,023	-0,017
3	7	1,313	0,890	0,890	0,000
4	5	1,233	0,360	0,360	0,000
5	3	1,442	0,173	0,200	0,027

H. Final Test-Run and first Benchmarking on 1N-Thruster

The above performed test were performed on the model of the 1N-Thruster, described in section IV-A.

The model was correlated to the test data with a conventional method, the resulting mean absolute deviation was 3.42 °C (cf. Table 1). This conventionally correlated TMM of the 1N-Thruster severd as the model for the testing described in the sections IV-A to IV-G.

The original TMM of the 1N-Thruster shows a mean absolute deviation to the test data of 13,92 °C (cf.Table 8).

For a final test-run, the original TMM of the 1N thruster has been correlated in TAUMEL.

Table 8: Original version of the 1N-Thruster TMM

TMM node n°	**Thermo Couple**	**T_{Test} [°C]**	**T_{Pred} [°C] (Original)**	ΔT [°C]
10	TC_NOZ	179,0	215,1	36,1
20	TC_CB3	189,9	224,9	35,0
30	TC_CB1	165,3	198,9	33,6
40	TC_FP/ TC_TCAFL	150,0	137,1	-12,9
70	TC_COV1/ TC_COV2	118,0	107,3	-10,7
80	TC_HBFL1/ TC_HBFL2	55,5	46,7	-8,8
90	TC_FL	50,9	46,3	-4,6
100	TC_HB1	69,6	89,2	19,6
120	TC_HB2	137,7	135,5	-2,2
130	TC_FCV4	54,1	47,5	-6,6
131	TC_FCV3	56,5	53,6	-2,9
132	TC_FCV2	57,8	57,4	-0,4
133	TC_TB1	51,9	53,7	1,8
200	TC_CT2	77,2	65,2	-12,0
220	TC_CT1	108,6	130,2	21,6
		MAD:	**13,92 °C**	

For this final test run, the objective was to start from the original TMM, perform a correlation in TAUMEL and then check for

- The final result compared to the result achieved with the already performed conventional correation
- The time needed to perform this correlation in TAUMEL

Table 9: Results from final test run with original TMM

Run	**Description of strategy**	**# GL**	**# GR**	**Interval**	**Mean Absolute Deviation [°C]**
0	Initial state				13,926
1	GL connected to nodes 10, 30, 100, 220 and their neighbouring nodes	18	0	0,7 - 1,4	8,6157
2	Adding GRs conected to nodes 10, 30, 100, 220	18	47	0,7 - 1,4 (new cond.) +-0,5 (cond. from run 1)	8,192
3	observed large ΔT for nodes 40 and 70. Adding of GLs connected to 40 and 70	18	68	0,7 - 1.4	7,4223
4	observed large ΔT for nodes 40 and 200 Adding of GLs connected to neighbours of 40 and 200 up to neighbours of 5th grade	27	68	0,7 - 1,4	6,642
5	Adding of all other GLs	36	68	0,7 - 1,4	6,539
6	Repetition wth all parameters starting with results from run 5	36	68	(+-) 0,2	4,489
7	Repetition wth all parameters starting with results from run 6	36	68	(+-) 0,3	2,484
8	Repetition wth all parameters starting with results from run 7	36	68	(+-) 0,2	1,679
	Final ESATAN-TMS run				**1,801**

The gathered information from the testing was used for the correlation strategy. The correlation was achieved by subsequent runs of TAUMEL. Each run used the parameters found in the previous run as starting point. After 8 subsequent runs of TAUMEL in approximately 25 minutes, a MAD of 1,679 °C was achieved. The changes were implemented into the ESATAN TMM using the automatic routine and lead to a final MAD of 1.801 °C.

The applied strategy for the 8 subsequent runs is described in Table 9.

The conventional correlation lead to a mean absolute deviation of 3.42 °C (cf. Table 1) and took considerably longer than 25 minutes.

These results from the final test run are the first benchmark of the tool.

V. Conclusion

A method for automated correlation between thermal models and temperature measurements has been developed. The method itself relies on the variation of thermal conductors in the thermal model. The variation is made by multiplication of “correlation parameters” to the conductors. The best conductors can then be determined by minimization of the difference between the measurements and the model.

This method has been implemented in a MATLAB®-based tool called TAUMEL. The tool uses a simulated annealing algorithm to determine the best parameters. It has to be mentioned that, independent from TAUMEL, the adapted TMM is seldom unique.

The tool is very fast in finding the best TMM-settings: e.g. for a user-defined 10 cycles with 1000 iterations, the tool is taking approximately 5 min. to find the best parameters for a 4000-nodes TMM. The computer in this case was an off-the shelf workstation.

The intensive testing of the tool showed that

- A good strategy to use the tool is to start with the correlation of selected areas with the biggest differences and subsequently, in an iterative manner, extend the modification to other areas in the TMM.
- The results are sensitive to the variation range allowed for the conductors. With a range of variation 0,8 - 1,25 the best results were achieved.
- The results are sensitive to the coverage of the varied conductors, with respect to the impact of the mathematical simplifications in the tool: The more conductors are varied, the larger is the impact of the linearization and constant conductivities. Here, further improvement is in progress showing good results especially with respect to the linearization. The correction term mentioned can be further improved and will be implemented in the near future.
- The results are sensitive to the quality of the steady state of the TMM. The better the steady state, the better are the results.
- The tool is fast and, in a first benchmark, achieved better correlation compared to a correlation using conventional methods.

The tool will be further improved with respect to the functionalities to support the user in the selection and the grouping of the conductors to be varied. The linearization effect will be minimized by the current improvement of the correction term implemented in the mathematical equation.

The tool is therefore ready for formal verification, giving way to the implementation into industrial processes.

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