AUTOMATIC CREATION OF REDUCED-ORDER MODELS USING THERMAL DESKTOP®

Derek W. Hengeveld and Jacob A. Moulton
LoadPath, Albuquerque, NM 87106

ABSTRACT

Computer simulations are often complex and computationally expensive. When properly developed, reduced-order models (ROMs) can overcome these challenges by providing a computationally efficient surrogate that accurately captures the effects of an underlying high-fidelity thermal model (e.g. Thermal Desktop®). ROMs can then provide thousands of simulation results in seconds which enables evaluation of large design spaces. A reduced-order modeling approach to predict spacecraft output responses for a set of input factors was developed. It is based on Latin Hypercube sampling and Gaussian Process regression modeling. This approach was successfully applied to a broad range of applications including the Orion Crew Exploration Vehicle and a nominal Hex Spacecraft Bus. Results compared favorably to the underlying Thermal Desktop® model. This approach was developed into software tools that provide analysis features such as screening studies, optimization, and response surface plotting.

INTRODUCTION

Spacecraft Thermal Control Subsystems (TCS) are commonly evaluated using high-fidelity, powerful modeling tools. Capable of simulating a near limitless range of conditions, these tools enable thermal engineers to examine a broad trade space. However, these computer experiments can be computationally expensive. Nominal thermal models, taking days to months to develop, can have run times on the order of hours. Comparing and evaluating multiple TCS design parameters amplifies these timelines. When built to evaluate several variables, these costs can become challenging. ROMs have the potential to help alleviate this burden. When properly developed, ROMs provide a computationally efficient surrogate that accurately captures the effects of an underlying high-fidelity model (e.g. Thermal Desktop®). ROMs can then provide thousands of simulation results in seconds which enables evaluation of large design spaces consisting of several variables. A ROM scheme was developed specifically for Thermal Desktop®. The following paper provides a brief overview of how ROMs are developed and provides details of how that approach is applied to the Thermal Desktop® environment. Finally, case studies are provided to demonstrate the approach.

REDUCED-ORDER MODEL DEVELOPMENT

ROMs were developed using a statistical scheme based on sampling and data fitting an underlying Thermal Desktop® model. This approach is considerably different than nodal reduction methods in that it relies on a set of high-fidelity simulations (i.e. training data) to generate the ROM. In doing this, the proposed approach is robust and can be easily applied to other problem classes, model types, and software packages.

The first step in developing a ROM is carefully selecting sampling points. Although full-factorial approaches examine all combinations of variables, they do so only at extreme values (i.e. design space boundaries). Consequently, interior points are overlooked, and ROMs can often fail far from the boundaries. Therefore, space-filling designs were utilized to efficiently identify and evaluate interior points that would provide improvements in the reduced-order model. Space-filling designs attempt to efficiently evaluate a design space for a given number of computer simulations. Design approaches include: sphere packing, Latin Hypercube Sampling (LHS), uniform design, maximum entropy, and the Gaussian-Process IMSE designs[1]. LHS approaches are the most commonly used for computer experiments[1]; consequently, it was selected as the basis for developing ROMs under the current work.

An LHS algorithm was developed based on concepts of the Maximin Method (full details are provided by Hengeveld and Biskner[2]). Through research and analysis, the Maximin Method has proven to be the best and most efficient method,[3] as it is a simple and effective design to implement and the linearity of the method results in short run times. The Maximin Method maximizes the minimum distance between all sampling points[4].Testing was performed on the LHS algorithm with Maximin optimization, with point-to-point distance being used as a figure of merit to compare algorithms. As optimizing the space becomes computationally difficult for higher dimensions, the Euclidean distance between points can be used as an effective measure to calculate point-to-point distance[3].

$$D_{i,j} = \sqrt{\sum_{n=1}^{N} \left(F(x_n)_i - F(x_n)_j \right)^2} \tag{1}$$

In order to test the LHS algorithm, an example design space was created and filled by seven sampling algorithms (including the developed LHS algorithm). Sampling points were generated for a 64 x 6 matrix, with the six columns representing variables. These six variables and their range of values were chosen as they effectively represent a typical ROM's design space. This design space was tested against JMP, a statistical software package, using the following seven sampling algorithms: LoadPath's LHS algorithm, nominal LHS algorithm, sphere packing, uniform sampling algorithm, maximum entropy algorithm, Gaussian Process IMSE Optimal sampling algorithm, and Fast Flexible Filling sampling algorithm. Resulting sampling points for each algorithm were evaluated by calculating average distance between points for the sampling algorithm (Table 1). The developed LHS algorithm did not provide the best results (higher scores are better) but did compare favorably to many commercially available algorithms. Future work will examine alternative algorithms (e.g. sphere packing approaches) to improve the sampling methods.

Table 1. Sampling Algorithm Comparison Results

Sampling Algorithm	Average distance between points
LoadPath's Latin Hypercube Sampling algorithm	87.762
nominal LHS	90.290
sampling with sphere packing	123.39
uniform sampling	88.379
sampling with maximum entropy	91.968
Gaussian Process sampling IMSE Optimal	61.285
Fast Flexible Filling sampling	95.842

Data fitting was achieved using Gaussian process (GP) regression methods. Introduced for computer experiments by Sacks, Welch, Mitchell, and Wynn[4], this approach is desirable in computer experiments since they provide an exact fit to the training data and require only *k+1* parameters, where k is the number of input factors. GPs do not impose a specific model structure on the underlying function, $f(x)$, being modeled[5]. Instead, a Gaussian prior is placed on the range of possible functions that could represent the mapping of input factors x to output responses y. The Gaussian prior incorporates knowledge about the underlying function in the data, where available, and is specified using the GP covariance function which provides a relationship between training data. Although several approaches can be utilized for this correlation structure, the approach used the squared exponential (SE) covariance function, one of the most common[1]. As such, GP modeling is a non-parametric modeling technique, where the training data are used to discover the model properties in a supervised manner. Details of the implemented GP method can be found from previous work of the authors[2].

THERMAL DESKTOP® AND VERITREK

Using the previously described sampling and data fitting approaches, a ROM creation framework was developed for Thermal Desktop®. The *Veritrek* software suite consists of a *Creation Tool* and *Exploration Tool*. The *Creation Tool* (Figure 2) bridges the gap between detailed high-fidelity models and ROMs to more efficiently evaluate different TCS design parameters and trade-offs.

A ROM can be created using this tool by varying user-specified input parameters for selected case sets in Thermal Desktop®, fitting the ROM to the outputs requested from the Thermal Desktop® model, and then validating the ROM by comparing different combinations of inputs to the original model. The end-result is a set of files that contain the details and fitting coefficients used to define the ROM. The ROM can then be easily imported into the *Exploration Tool*, to obtain thermal analysis results in near real-time. The ROM creation process for Thermal Desktop® involves several steps.

1. The first step in the ROM creation process is to select the Thermal Desktop® model file to be used as the high-fidelity thermal model, from which the surrogate ROM is developed (Figure 1).

ROM File Summary

ROM Name demoA_buildApr3_20180404

Location C:\Users\JacobMoulton\Desktop\Veritrek\VCT

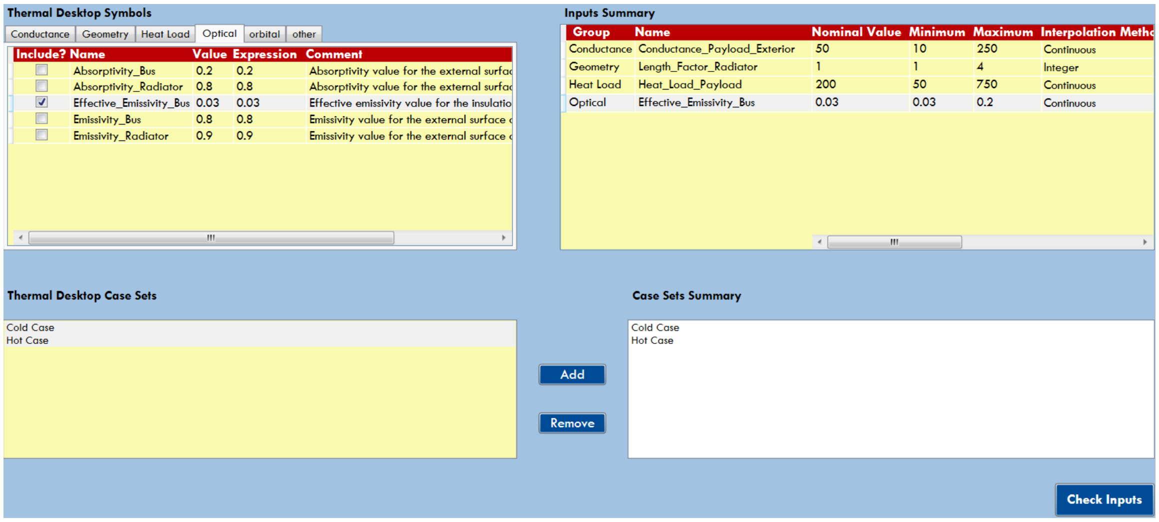
Model Name C:\Users\HP z620\Desktop\Veritrek CT\VeritrekCT_demoA_v22\VeritrekCT_demoA_v22.dwg

ROM Name: demoA_buildApr3_20180404

Thermal Desktop Model: C:\Users\HP z620\Desktop\Veritrek CT\VeritrekCT_demoA_v22\VeritrekCT_demoA_v22.dwg

Figure 1. Selection of ROM name and Thermal Desktop® model inside of *Veritrek.*

2. Next, input factors and their ranges are selected that will be included in the ROM (Figure 2). These input factors represent the variables of interest for a user's thermal analysis and include Thermal Desktop® symbols or case sets. The input factors and their range define the design space for ROM creation.



Thermal Desktop Symbols

Include?	Name	Value	Expression	Comment
☐	Absorptivity_Bus	0.2	0.2	Absorptivity value for the external surfac
☐	Absorptivity_Radiator	0.8	0.8	Absorptivity value for the external surfac
☑	Effective_Emissivity_Bus	0.03	0.03	Effective emissivity value for the insulatio
☐	Emissivity_Bus	0.8	0.8	Emissivity value for the external surface
☐	Emissivity_Radiator	0.9	0.9	Emissivity value for the external surface

Inputs Summary

Group	Name	Nominal Value	Minimum	Maximum	Interpolation Metho
Conductance	Conductance_Payload_Exterior	50	10	250	Continuous
Geometry	Length_Factor_Radiator	1	1	4	Integer
Heat Load	Heat_Load_Payload	200	50	750	Continuous
Optical	Effective_Emissivity_Bus	0.03	0.03	0.2	Continuous

Thermal Desktop Case Sets

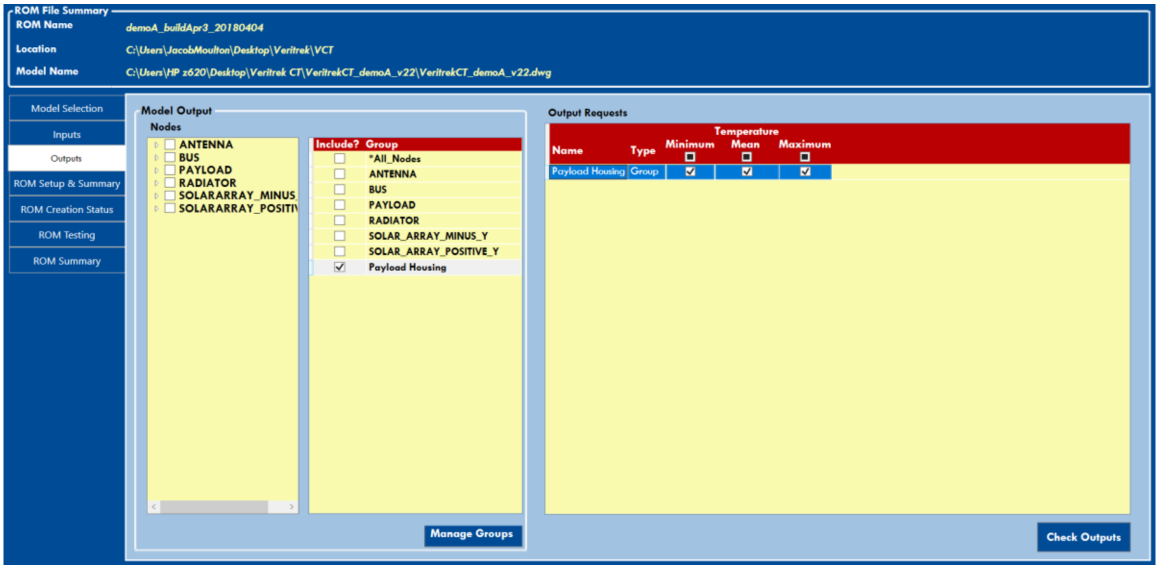
Cold Case
Hot Case

Case Sets Summary

Cold Case
Hot Case

Figure 2. Selection of input factors from a Thermal Desktop® model inside of *Veritrek*.

3. The third step in the ROM creation process is to select output responses (Figure 3). This is performed in a similar fashion to the selection of input factors. The output responses represent the outputs of interest from a user's Thermal Desktop® model and can be a node temperature or an entire submodel temperature, among many others.



ROM File Summary

ROM Name: demoA_buildApr3_20180404

Location: C:\Users\JacobMoulton\Desktop\Veritrek\VCT

Model Name: C:\Users\HP z620\Desktop\Veritrek CT\VeritrekCT_demoA_v22\VeritrekCT_demoA_v22.dwg

Model Output

Nodes

- ☐ ANTENNA
- ☐ BUS
- ☐ PAYLOAD
- ☐ RADIATOR
- ☐ SOLARARRAY_MINUS_
- ☐ SOLARARRAY_POSITI\

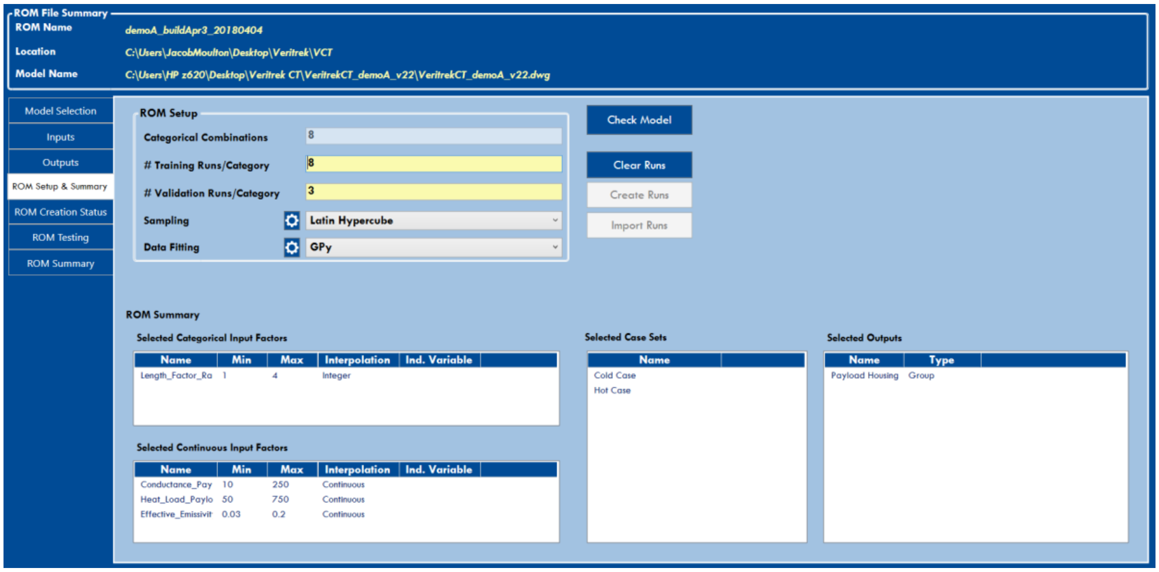
Include?	Group
☐	*All_Nodes
☐	ANTENNA
☐	BUS
☐	PAYLOAD
☐	RADIATOR
☐	SOLAR_ARRAY_MINUS_Y
☐	SOLAR_ARRAY_POSITIVE_Y
☑	Payload Housing

Output Requests

Name	Type	Temperature Minimum ■	Temperature Mean ■	Temperature Maximum ■
Payload Housing	Group	☑	☑	☑

Figure 3. Selection of output responses from a Thermal Desktop® model inside of *Veritrek*.

4. The fourth step in the ROM creation process is to select the sampling and data-fitting algorithm to be used (Figure 4). Parameters can be adjusted such as number of training/validation runs per category and data-fitting lengthscales, among others.



ROM File Summary

ROM Name: demoA_buildApr3_20180404

Location: C:\Users\JacobMoulton\Desktop\Veritrek\VCT

Model Name: C:\Users\HP z620\Desktop\Veritrek CT\VeritrekCT_demoA_v22\VeritrekCT_demoA_v22.dwg

ROM Setup

Categorical Combinations: 8

Training Runs/Category: 8

Validation Runs/Category: 3

Sampling: Latin Hypercube

Data Fitting: GPy

ROM Summary

Selected Categorical Input Factors

Name	Min	Max	Interpolation	Ind. Variable
Length_Factor_Ra	1	4	Integer	

Selected Continuous Input Factors

Name	Min	Max	Interpolation	Ind. Variable
Conductance_Pay	10	250	Continuous	
Heat_Load_Paylo	50	750	Continuous	
Effective_Emissivit	0.03	0.2	Continuous	

Selected Case Sets

Name
Cold Case
Hot Case

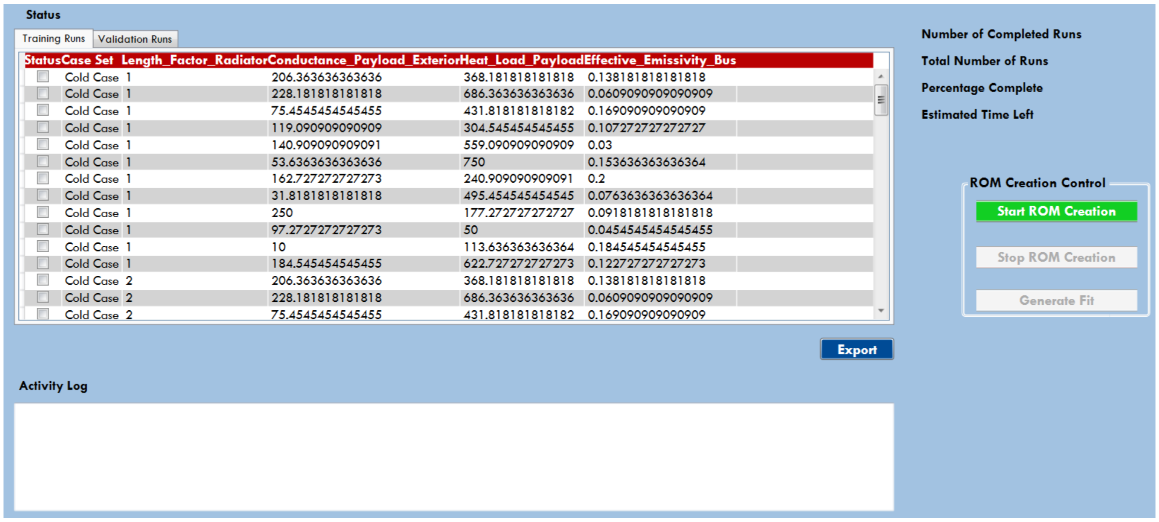
Selected Outputs

Name	Type
Payload Housing	Group

Figure 4. Selection of sampling and data fitting algorithms inside of *Veritrek*.

5. The fifth step involves the actual automated generation of the ROM. Thermal Desktop® runs are created based on the input factors, output responses, and sampling algorithm settings. The *Creation Tool* communicates with Thermal Desktop® using an Application Programming Interface (API) introduced in Thermal Desktop® 6.0. The API is provided via the Microsoft .NET framework and allows Windows applications written in the C# or VB.NET programming languages to interact with Thermal Desktop. These runs, along with their corresponding output response data, are grouped together as training data. The

final ROM creation step includes running the generated training data through the user-specified data-fitting algorithm to effectively fit the ROM (Figure 5).



Status	Case Set	Length_Factor_Radiator	Conductance_Payload_Exterior	Heat_Load_Payload	Effective_Emissivity_Bus
☐	Cold Case	1	206.363636363636	368.181818181818	0.138181818181818
☐	Cold Case	1	228.181818181818	686.363636363636	0.0609090909090909
☐	Cold Case	1	75.4545454545455	431.818181818182	0.169090909090909
☐	Cold Case	1	119.090909090909	304.545454545455	0.107272727272727
☐	Cold Case	1	140.909090909091	559.090909090909	0.03
☐	Cold Case	1	53.6363636363636	750	0.153636363636364
☐	Cold Case	1	162.727272727273	240.909090909091	0.2
☐	Cold Case	1	31.8181818181818	495.454545454545	0.0763636363636364
☐	Cold Case	1	250	177.272727272727	0.0918181818181818
☐	Cold Case	1	97.2727272727273	50	0.0454545454545455
☐	Cold Case	1	10	113.636363636364	0.184545454545455
☐	Cold Case	1	184.545454545455	622.727272727273	0.122727272727273
☐	Cold Case	2	206.363636363636	368.181818181818	0.138181818181818
☐	Cold Case	2	228.181818181818	686.363636363636	0.0609090909090909
☐	Cold Case	2	75.4545454545455	431.818181818182	0.169090909090909

Figure 5. Automated ROM creation using Thermal Desktop® runs inside Veritrek.

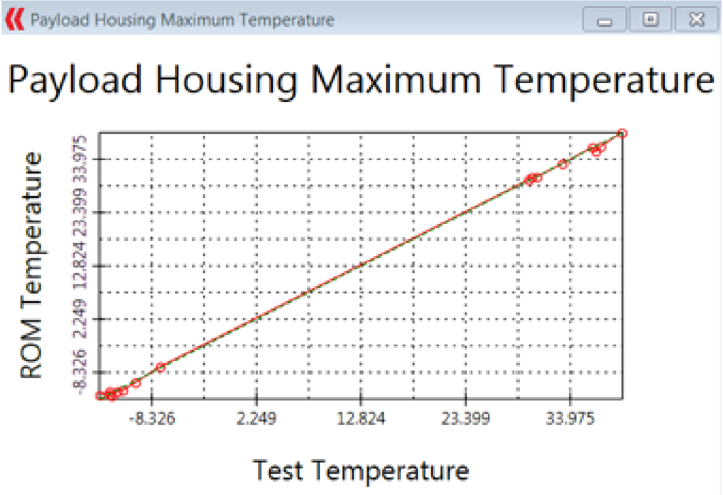
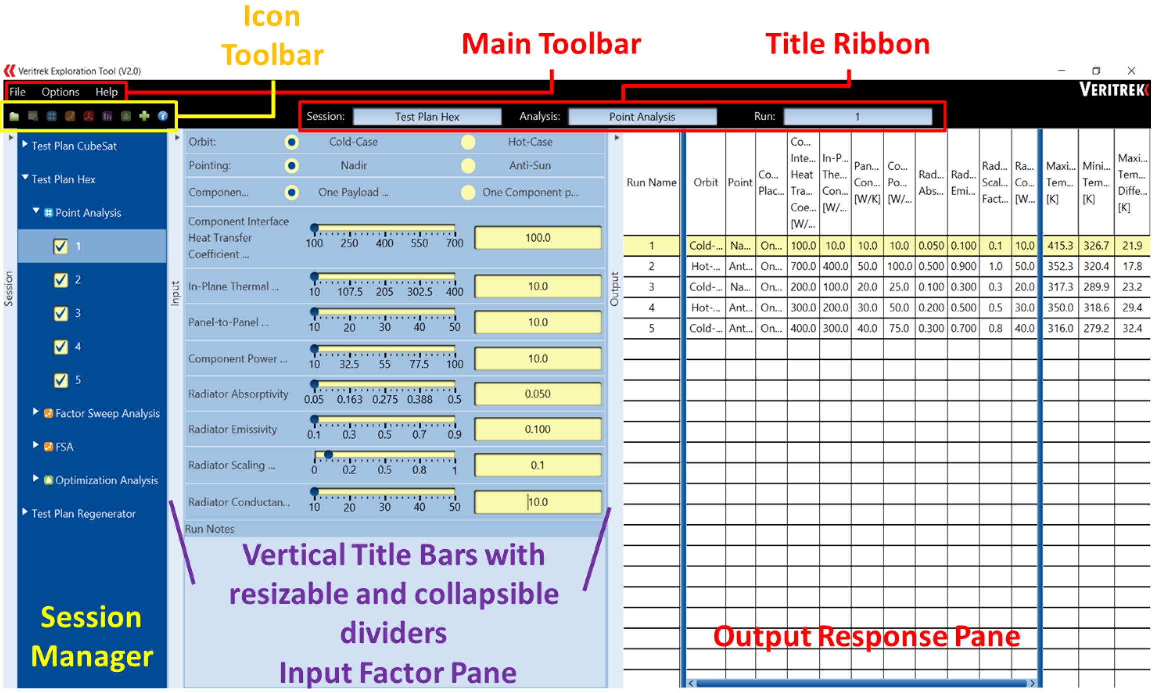


Figure 6. Testing comparing ROM and Thermal Desktop® results.

6. The final step in creating a ROM is testing. In this step, the performance of the ROM is compared to that of the original high-fidelity Thermal Desktop® model. This involves solving several additional Thermal Desktop® runs, computing the estimated results from the ROM using the same inputs, and comparing the outputs of both. Comparison plots include ROM versus Thermal Desktop® results (Figure 6). In addition to these comparison plots, ROM verification and validation is also shown through performance metrics. Metrics include the ROM's mean of residual and standard deviation of the residual compared to Thermal Desktop® outputs.

7. The *Exploration Tool* (Figure 7) provides a framework for visualizing and analyzing developed ROMs. In addition to typical toolbars, this software provides a session manager, input factor pane, and output response pane. The Session Manager is used as an organizational tool, as each group of analyses is stored into Session-trees, which are recorded for quick and easy access within the Session Manager. The input factor pane allows for the selection of different variable and variable values when performing an analysis, and the output response pane displays graphical or numerical results.



Session: Test Plan Hex
Analysis: Point Analysis
Run: 1

Orbit: ● Cold-Case ○ Hot-Case
Pointing: ● Nadir ○ Anti-Sun
Componen... ● One Payload ... ○ One Component p...
Component Interface Heat Transfer Coefficient ... (100 – 700): 100.0
In-Plane Thermal ... (10 – 400): 10.0
Panel-to-Panel ... (10 – 50): 10.0
Component Power ... (10 – 100): 10.0
Radiator Absorptivity (0.05 – 0.5): 0.050
Radiator Emissivity (0.1 – 0.9): 0.100
Radiator Scaling ... (0 – 1): 0.1
Radiator Conductan... (10 – 50): 10.0

Run Name	Orbit	Point	Co... Plac...	Co... Inte... Heat Tra... Coe... [W/...	In-P... The... Con... [W/...	Pan... Con... [W/K]	Co... Po... [W/...	Rad... Abs...	Rad... Emi...	Rad... Scal... Fact...	Ra... Co... [W...	Maxi... Tem... [K]	Mini... Tem... [K]	Maxi... Tem... Diffe... [K]
1	Cold-...	Na...	On...	100.0	10.0	10.0	10.0	0.050	0.100	0.1	10.0	415.3	326.7	21.9
2	Hot-...	Ant...	On...	700.0	400.0	50.0	100.0	0.500	0.900	1.0	50.0	352.3	320.4	17.8
3	Cold-...	Na...	On...	200.0	100.0	20.0	25.0	0.100	0.300	0.3	20.0	317.3	289.9	23.2
4	Hot-...	Ant...	On...	300.0	200.0	30.0	50.0	0.200	0.500	0.5	30.0	350.0	318.6	29.4
5	Cold-...	Ant...	On...	400.0	300.0	40.0	75.0	0.300	0.700	0.8	40.0	316.0	279.2	32.4

Figure 7. Typical screen inside the Veritrek Exploration Tool.

Five analysis features are available in the *Veritrek Exploration Tool* and include: point analysis, factor sweep analysis, surface plot analysis, screening analysis, and optimization analysis. The following section provides two case studies and examples of several of these analysis features.

EXAMPLES AND APPLICATIONS

Orion Crew Exploration Vehicle (CEV)

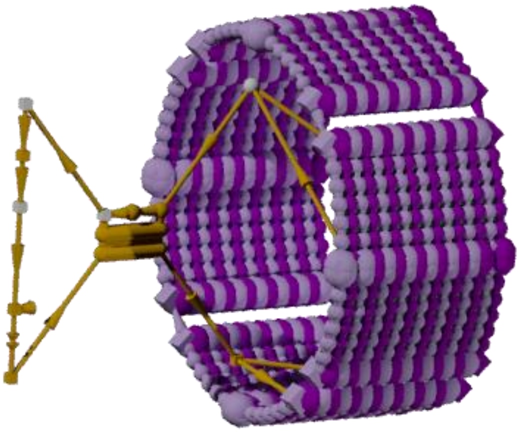


Figure 8. Illustration of Simplified Orion CEV Thermal Desktop® Model.

A simplified Orion Crew Exploration Vehicle (CEV) thermal model, developed in Thermal Desktop®, was converted into a ROM. The CEV thermal model consists of an external fluid loop and detailed heat rejection system (i.e. radiators) (Figure 8). Simulating internal heat development of the crew module is done through a single heat source (i.e. symbol QLOAD). The fluid loop setpoint (i.e. temperature of FLOW.487) is controlled via a PID to control the flow (via a bypass loop) through a regenerative heat exchanger. Heat dissipation is rejected to a constant temperature environment. The Orion CEV thermal model consists of several thermal submodels (e.g. radiator submodel) and one fluid submodel (i.e. FLOW). Based on discussion with NASA personnel, evaluation of the thermal model, and results of a factor screening effort, the following input factors and corresponding ranges were selected for use in subsequent ROM efforts (Table 2). Also included are nominal values (i.e. values that were utilized in the supplied thermal model).

Table 2. Summary of Input Factors

No.	Input Factor	Symbol Name	Range
1	Working Fluid	Not Applicable	Dynalene HC 50, Galden HT 170, HFE 7000
2	Regenerator Area per Node	Aheat_HFC	0.5 to 2.0 m^2
3	Space Temperature	TEMP_SPACE	0 K to 300 K
4	Radiator Emissivity	Opt_Epsilon	0.7 to 1.0
5	Radiator Fin Efficiency	rad_fin_eff	0.7 to 1.0
6	Tube Inside Diameter	RadTubD	0.003175 m (0.125”) to 0.005080 m (0.200”)
7	Fin-to-Tube Conductance	TContact	50 to 1000
8	Regenerator Thermal Mass per Node	HX_THERMAL_MASS	500 to 4,000 J/K
9	Heatload	QLOAD	0 to 4,000 W

Based on discussion with NASA personnel and evaluation of the thermal model, the following primary output responses were selected for use in subsequent reduced-order modeling efforts (Table 3).

Table 3. Summary of Primary Output Responses

No.	Output Response	Symbol Name	Description
1	Set-point Temperature	FLOW.487	Temperature of FLOW.487 at end of simulation.
2	Fluid Hydraulic Power	Varies	Calculated fluid hydraulic power based.
3	Pressure	FLOW.365	Pressure at FLOW.365
4	Pressure	FLOW.2262	Pressure at FLOW.2262
5	Pressure	FLOW.2272	Pressure at FLOW.2272
6	Flow Rate	---	System flow rate
7	Average Radiator ΔT	Varies	Average ΔT as a result of TContact of 7 radiators

Based on the LHS algorithm and the developed high-resolution thermal model, training data was obtained. This data provided the foundation upon which the ROM was developed using GP methods. For the HFE 7000 working fluid, the ROM predicted temperatures (i.e. set-point and average radiator ΔT) with a maximum residual mean of 0.6 K and standard deviation of 3.7 K. The model predicted fluid hydraulic power with a maximum residual mean of 0.02 W and standard deviation of 0.09 W. Finally, it predicted pressures with a maximum residual mean of 0.08 kPa and standard deviation of 0.6 kPa with a maximum percent difference standard deviation of 0.6%. The ROM did not perform well in capturing time to steady-state and percent bypass as indicated by high residuals and % difference values. In fact, maximum and minimum percent bypass values were unrealistic (i.e. greater than 100% and less than 0%, respectively).

Results indicated that the ROMs provide a useful surrogate for smooth functions. Non-smooth functions (e.g. Time to Steady State) challenge ROM predictive capabilities. However, these might be overcome by providing higher sampling densities around these discontinuities.

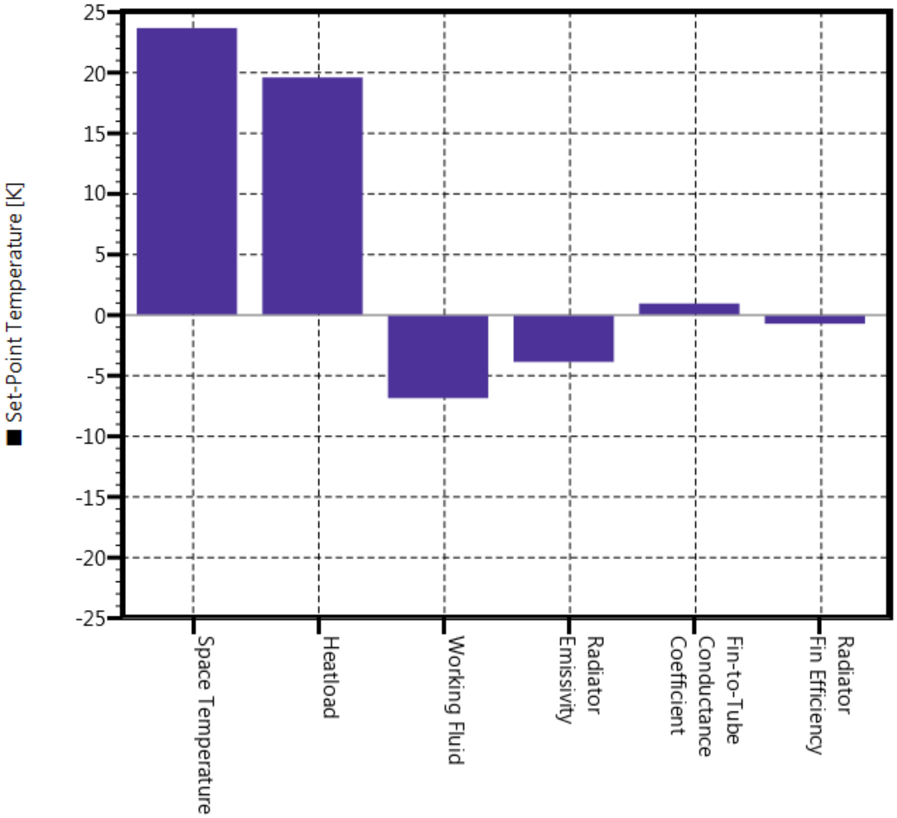


Figure 9. Screening Analysis results using the Orion CEV ROM.

The Orion CEV ROM that was developed could be used to perform many different TCS design trade-offs. Using the *Exploration Tool*, a screening analysis study was performed to determine which input factor has the most significant impact on the set-point temperature of the CEV. Results from a screening analysis were obtained within seconds. Example results can be seen in Figure 9. From these instantaneous results, it can be determined that Space Temperature and Heatload have the most significant impact on the Set-point Temperature, while Working Fluid, and Radiator Emissivity also impact the Set-point Temperature.

In addition to the screening analysis study, a factor sweep study was performed to observe in detail how changes in a single input factor impact output results for a certain design case. This factor sweep analysis was performed using the *Exploration Tool*, by setting all input factors to a certain value and observing how changes to a single input factor impact an output response. For example, a certain design revision of the Orion CEV may call for a specific Tube Inside Diameter and Radiator Fin Efficiency, while another design revision may involve a different Tube Inside Diameter and Radiator Fin Efficiency; however, the emissivity of the radiator may not be known in either of these revisions. In this case, a factor sweep analysis can be used to observe how changes to radiator emissivity impacts fluid hydraulic power for each of these design revisions. A table of example input factor settings for each of these design revisions (REVA and REVB) can be seen in Table 4. Results from this example of a factor sweep analysis are shown in Figure 10.

Table 4. Summary of Input Factor Setting for Orion CEV Factor Sweep Analysis

	Working Fluid	Regenerator Area per Node $[m^2]$	Radiator Fin Efficiency [---]	Tube Inside Diameter [m]	Fin-to-Tube Conductance Coefficient [---]	Heat load [W]
REVA	DYN HC 50	0.5	0.9	0.004	50.0	1000.0
REVB	DYN HC 50	0.5	0.8	0.005	50.0	1000.0

From these results, it can be seen that REVA always yields higher Fluid Hydraulic Power compared to REVB, but that both design revisions experience a maximum Fluid Hydraulic Power at a radiator emissivity value of about 0.9. This result may help a thermal engineer decide which optical coating to use for the radiator. This analysis could be easily expanded to include: other working fluids, additional tube inside diameters, and a range of heat loads, to name a few.

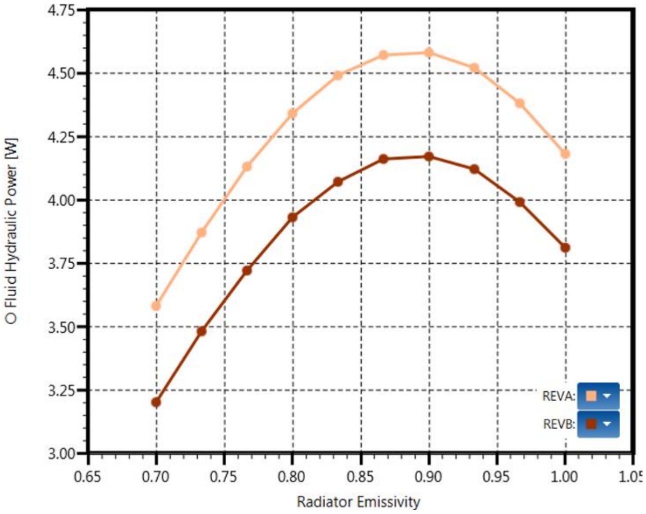


Figure 10. Factor Sweep Analysis results using the Orion CEV ROM.

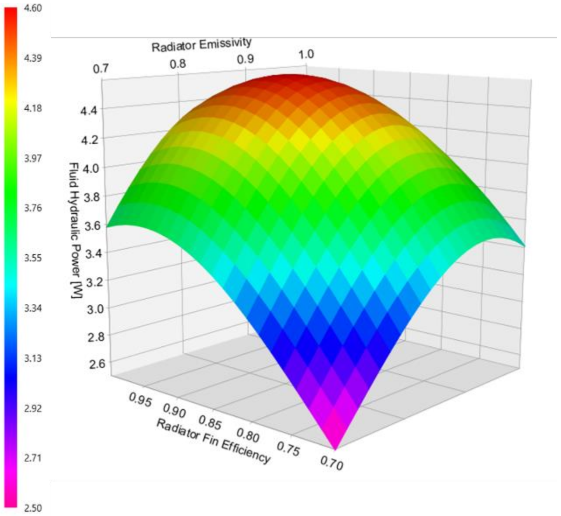


Figure 11. Surface Plot Analysis results using the Orion CEV ROM.

This analysis can be taken a step further, and a Surface Plot Analysis could be used to try and determine an overall radiator design that will maximize the Fluid Hydraulic Power of the Orion CEV. From within the *Veritrek Exploration Tool,* a Surface Plot Analysis can be used to observe the impact that two input factors have on a single output response. In this case, both Radiator Emissivity and Radiator Fin Efficiency can be analyzed with Fluid Hydraulic Power as the output response. A Surface Plot Analysis performs two individual factor sweeps and plots them together as a 3D plot, which can be seen in Figure 11. Results again show that a maximum Fluid Hydraulic Power occurs at a radiator emissivity value of about 0.9, but that this can also be coupled with a Radiator Fin Efficiency of about 0.92 to achieve an overall radiator design that maximizes Fluid Hydraulic Power. Again, this analysis could be expanded to include different working fluids, heat loads, etc. The screening analysis, factor sweep analysis, and surface plot analysis are just three examples of effective thermal design studies that can be performed instantaneously with a reduced-order model.

CONCLUSIONS

When properly developed, reduced-order models (ROMs) can overcome challenges by providing a computationally efficient surrogate that accurately captures the effects of an underlying high-fidelity model (e.g. Thermal Desktop®). ROMs can then provide thousands of simulation results in seconds which enables evaluation of large design spaces. A ROM scheme was developed in combination with Thermal Desktop®. The approach utilizes a statistical sampling scheme (as opposed to nodal minimization) that relies on Latin Hypercube Sampling (LHS). Test results showed that the developed LHS compared favorably to many commercially available algorithms; however, improvements could be made. Following sampling, a statistical data-fitting scheme that relies on Gaussian Process (GP) techniques was utilized to generate the ROM.

A ROM creation framework was developed for Thermal Desktop® and includes the Veritrek Creation and Exploration Tools. Together, this software suite enables end-users to develop and use ROMs from Thermal Desktop® models. The tools provide a semi-automated method for generating ROMs and provide users with five analysis features including: point analysis, factor sweeps, surface plots, screening, and optimization studies. This approach was successfully applied to two applications: the Orion Crew Exploration Vehicle and a nominal Hex Spacecraft Bus. Results compared favorably to the underlying Thermal Desktop® model and several analysis approaches were developed and implemented. In the future, additional features and capabilities will be explored and added based on the foundation of this work. Examples might include: additional sampling and data fitting schemes, implementation of uncertainty quantification methods, ROM/test correlation capabilities, and/or ROMs for controller designs.

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CONTACT

Derek Hengeveld, PhD, PE | Senior Engineer | LoadPath, LLC | 2309 Renard Place SE, Ste. 101 | Albuquerque, NM 87106 | dhengeveld@loadpath.com | 605.690.1612 | www.loadpath.com

Jacob Moulton | Staff Engineer | LoadPath, LLC | 3333 South Bannock St., Ste. 430 | Englewood, CO 80110 | jmoulton@loadpath.com | 505.401.4853 | www.loadpath.com

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

D	Euclidean distance between points
k	number of input factors
N	number of points
GP	Gaussian Process
IMSE	Integrated Mean-Square Error
LHS	Latin Hypercube Sampling
ROM	Reduced-Order Model
TCS	thermal control subsystem

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