DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF. NLR-TP-2003-369		SECURITY CLASS. Unclassified

ORGINATOR
National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE
Approximation models for multi-disciplinary system design
Application in a design study of power optimised aircraft

PRESENTED AT
The Eurogen 2003 Conference, CIMNE, Barcelona, Spain, 15-17 September 2003

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DESCRIPTORS

Aeronautic system design	Response surface methods
Data fitting	Virtual Iron Bird
CFD	Cabin air flow

ABSTRACT
In aeronautic system design, numerical simulation and optimisation of design objectives are commonly used. Aeronautic systems can be quite complex and are usually part of one or more "higher level" systems. To analyse the behaviour of the integrated system, the system model may be composed of subsystem or component models from suppliers. To enable such a composition, usually integration requirements are agreed such as language requirements, model format requirements, visibility requirements, hardware requirements, and computational requirements. For the various cases in which models satisfying all integration requirements are not available, approximate representations based on system data sets can be used as effective and efficient alternatives. In the present study several methods are investigated and evaluated for approximate representation of steady-state system behaviour that is given in the form of data sets. Approximation methods based on polynomial functions, splines, kriging models and neural networks are considered. A software tool for easy application and quality assessment of the different approximation models has been developed and will be briefly presented. As an example, the application of the approximation methodology in a simplified aircraft cabin system model is presented. In this simplified system model the cabin airflow is included as an approximate representation based on CFD simulations. It is shown that in this way multi-disciplinary design evaluations of integrated system models can be efficiently performed.

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NLR-TP-2003-369

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This report is based on a presentation to be held at the Eurogen 2003 Conference, CIMNE, Barcelona (Spain), 15-17 September 2003.

Customer:	National Aerospace Laboratory NLR
Working Plan number:	I.1.A.1
Owner:	National Aerospace Laboratory NLR
Division:	Information and Communication Technology
Distribution:	Unlimited
Classification title:	Unclassified
	July 2003

Approved by author:	Approved by project manager:	Approved by project managing department:
4/8/03	4/8/03	4-8-2003

Summary

In aeronautic system design, numerical simulation and optimisation of design objectives are commonly used. Aeronautic systems can be quite complex and are usually part of one or more "higher level" systems. To analyse the behaviour of the integrated system, the system model may be composed of subsystem or component models from suppliers. To enable such a composition, usually integration requirements are agreed such as language requirements, model format requirements, visibility requirements, hardware requirements, and computational requirements. For the various cases in which models satisfying all integration requirements are not available, approximate representations based on system data sets can be used as effective and efficient alternatives. In the present study several methods are investigated and evaluated for approximate representation of steady-state system behaviour that is given in the form of data sets. Approximation methods based on polynomial functions, splines, kriging models and neural networks are considered. A software tool for easy application and quality assessment of the different approximation models has been developed and will be briefly presented. As an example, the application of the approximation methodology in a simplified aircraft cabin system model is presented. In this simplified system model the cabin airflow is included as an approximate representation based on CFD simulations. It is shown that in this way multi-disciplinary design evaluations of integrated system models can be efficiently performed.

List of acronyms

ANN	Artificial neural network
CFD	Computational fluid dynamics
ECS	Environment Control System
EU	European Union
GUI	Graphical user interface
ICT	Information and communication technology
IFE	In-flight Entertainment
POA	Power Optimised Aircraft
RMSE	Root Mean Square Error
VIB	Virtual Iron Bird

Contents

(14 pages in total)

1 Introduction

In aeronautic system design, numerical simulation and optimisation of design objectives are commonly used. Aeronautic systems can be quite complex and are usually part of one or more "higher level" systems. For example, an Environment Control System (ECS) aboard an aircraft consists of a complex set of air treatment and heat exchange systems, sensors and controllers, and is part of the aircraft's electric, pneumatic, and possibly hydraulic systems. The ECS behaviour also depends on the airflow and heat exchange in the aircraft cabin. Consequently, a system like an ECS is difficult to simulate accurately due to its complexity. Moreover, in order to design a system like an ECS for an aircraft it can not be properly investigated when isolated from its aircraft environment, and hence should be incorporated in an integrated model that includes its neighbouring systems, such as the electric and pneumatic distribution systems, generators and engines. Eventually, a completely integrated aircraft level system model would allow for the evaluation of the aircraft systems under realistic conditions and enable validation and optimisation of new system architectures. In such an integrated system model, however, it may be far too complex to include all functional details of the integrated sub-systems and components. In such cases approximate representations of (some of) these systems and components can be very efficient and effective[i,ii].

In the present study we investigate and evaluate efficient methodologies for approximate representation of steady-state system behaviour that is given by data sets. Approximation methods based on polynomial functions (in this case the approximation method is commonly referred to as response surface method[iii]), splines[iv], neural networks[v] and kriging models[vi] will be considered. Some of these methods have been assessed in previous work[vii]. In this study the methods are applied to a design case of a power optimised aircraft.

In Section 2 of this paper the context of this study is given. Section 3 briefly presents the approximation methods and in Section 4 an example will be given of the approximation approach in a simplified aircraft cabin system model. Section 5 gives some conclusions.

2 Context: Power optimised aircraft

In the EU project POA (Power Optimised Aircraft)[viii] that is currently in progress, new system architectures for large civil aircraft are investigated[ix]. One of the objectives in POA is to minimise power consumption of all non-propulsive systems aboard the aircraft (Figure 1).

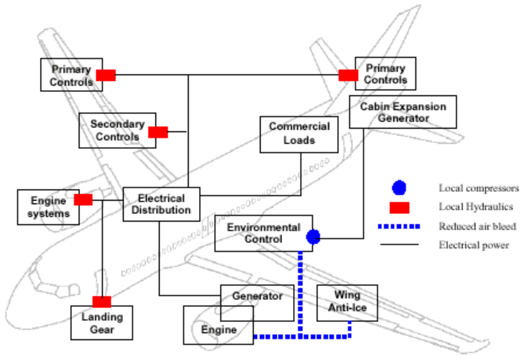

Figure 1: Overview of the aircraft systems considered in the POA project

In order to evaluate the behaviour of all systems for validation on aircraft level, it is required to apply an integrated model of all considered systems. In POA this integrated model is referred to as the "Virtual Iron Bird" (VIB). The VIB, which is currently being developed in the POA project, will be used for different analyses of the systems' behaviour. Among others will the VIB include steady-state system models for simulation of long-term behaviour, such as power consumption during full flight missions. The steady-state behaviour of a considered system may typically consist of parametric analytical functions and/or may be based on existing data sets. These data sets may arise from complex system simulations (e.g. computationally expensive CFD simulations of the cabin airflow in the case of the ECS model) or experiments, which represent the underlying system behaviour. It may be impracticable to fully evaluate the underlying behaviour of these systems, in particular if validation or optimisation of the integrated system on aircraft level is considered. In such cases, approximate representations of the behaviour of these systems can provide good possibilities for efficient evaluation at low computational cost and with adequate accuracy. The use of such approximate representations is investigated in this study.

3 Approximation methods

In the present study efficient methodologies have been investigated for approximate representation of steady-state system behaviour given by data sets. The output data to be approximated are assumed to be scalar and depend on a vector $\boldsymbol{x}$ of n independent variables. Let the real system be denoted as $y=f(\boldsymbol{x})$ and the approximation as $\hat{y}=\hat{f}(\boldsymbol{x})$, where $\boldsymbol{x} \in \Re^n$ and $y,\hat{y} \in \Re$. In general the approximation is achieved by fitting an approximation model, based on a specific approximation method, to a given data set $\{(\boldsymbol{x}_i, y_i),\ i= 1,2,\ldots,m\}$ that represents the real system. The quality of the approximation model depends on the achieved accuracy, which may be expressed in terms of the error $\varepsilon = y-\hat{y}$, and on the size m of the applied data set: the best approximation model achieves the highest predictive accuracy with the smallest data set. A brief description of the methods considered in this study is given in the following.

- Polynomials: In this study the polynomial method fits a polynomial function in $\boldsymbol{x}$ of order q, $\hat{y}=\hat{p}_q(\boldsymbol{x})$, to the data set using a standard least-squares regression technique as available in Matlab[x]. Polynomial functions of orders two to six are considered.
- Splines: Splines are defined as piecewise polynomial fits to data sets. Both interpolating and smoothing cubic splines as available from Matlab[x] have been used in this study.
- Artificial Neural Networks (ANNs): In this study feed-forward ANNs with one hidden layer, as available from the Matlab Neural Network toolbox[x], are used. The number of hidden nodes is automatically determined such that the approximation is optimised.
- Kriging models: The kriging method[vi] relies on the decomposition $\hat{y}=\hat{f}(\boldsymbol{x}) + \hat{\varepsilon}(\boldsymbol{x})$, where $\hat{f}(\boldsymbol{x})$ is a polynomial function and the model of the error, $\hat{\varepsilon}(\boldsymbol{x})$, is stochastic with non-zero covariance. For this study kriging interpolation methods have been selected with a combination of a polynomial of orders zero, one or two, and an error model function based on a Gaussian, Exponential or Cubic spline correlation function[xi].

Some of the required functionality for these approximation methods is provided directly by Matlab[x] and by freely available toolboxes and some has been created with in-house developed programs. A coherent software tool, named MultiFit, that integrates all the considered approximation methods and provides easy access to these methods by a graphical user interface (GUI), has been developed in Matlab. An illustration of an approximation procedure with MultiFit is given below (Figure 2).

In the upper-left panel an example of a 3-D data set ($y=f(\boldsymbol{x})$; $n=2$, $m=121$) is shown. This data set resulted from the case study that is described in the next section. The upper-right panel shows the MultiFit GUI in which this data set has been loaded and the projection of the data points onto a selected plane in the "data set space" is plotted. In this GUI the user can select an approximation method to fit the data, or the method that best fits the data can be automatically determined. Once the approximation model has been generated, it can be directly exported to

Modelica[xii] source code, which is interpreted by the Dymola[xiii] modelling environment, as is shown in the lower-left panel. As such, the approximation model can be directly used in the POA-VIB, which is defined in the Dymola environment, and of which a strongly simplified example is shown in the lower-right panel.

As an illustration of the assessment of the approximation methods, the errors (RMSE) of the fits on the data set shown above, determined in an additional validation data set (*y=f(**x**); n=2, m=16*), are given in the following table. The interpolating spline method gave the best fit for this particular data set.

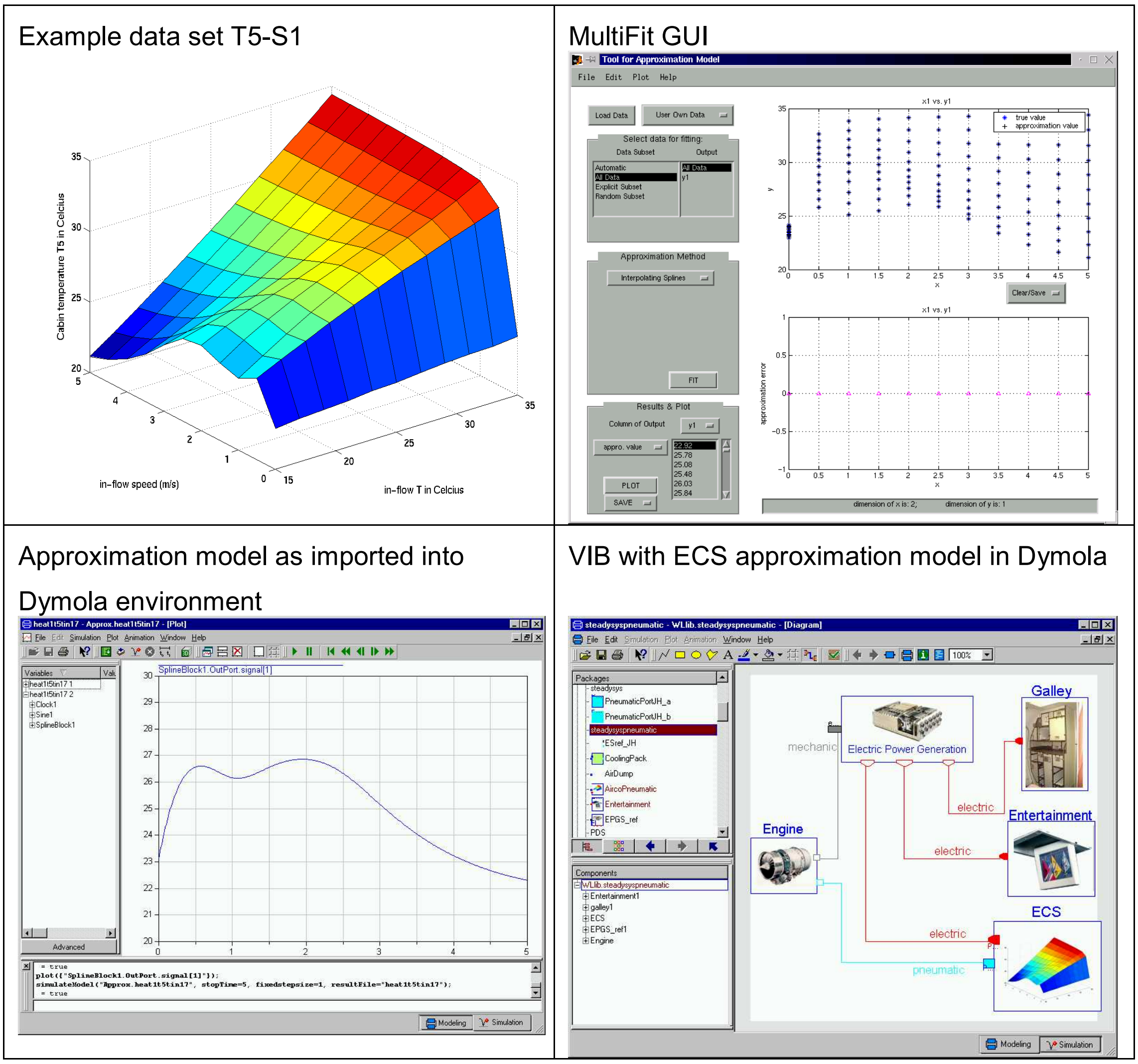

Figure 2: Illustration of the approximation procedure and application in a simplified VIB

Table 1: RMSE values for all considered methods for the validation set of the T5-S1 example data set.

Method	**RMSE (abs/rel)**	**Method**	**RMSE (abs/rel)**
2nd order polynomial	1.1479 / 0.0405	Kriging (const.regr., Gauss corr.)	0.6251/ 0.0223
3rd order polynomial	1.1927 / 0.0425	Kriging (const.regr., Exp. corr.)	1.0670 / 0.0376
4th order polynomial	1.1291 / 0.0401	Kriging (const.regr., Spline corr.)	0.8485 / 0.0301
5th order polynomial	0.8966 / 0.0320	Kriging (lin.regr., Gauss corr.)	0.6333/ 0.0225
6th order polynomial	0.6515 / 0.0236	Kriging (lin.regr., Exp. corr.)	1.0690 / 0.0369
Interpolating spline	0.5288 / 0.0190	Kriging (lin.regr., Spline corr.)	0.8090 / 0.0286
Smoothing spline	1.0344 / 0.0365	Kriging (quadr.regr., Gauss corr.)	0.6005 / 0.0214
ANN	2.5926 / 0.0918	Kriging (quadr.regr., Exp. corr.)	1.0478 / 0.0376
		Kriging (quadr.regr., Spline corr.)	0.7503 / 0.0266

4 Case study

As an illustration of the use of the POA-VIB, an example is given here of the evaluation of aircraft power consumption by a strongly simplified VIB that represents an aircraft cabin system consisting of steady state models for the ECS, the galley and the in-flight entertainment (IFE) system (also see Figure 2Figure 3). In this approach, the ECS behaviour model was included as an approximation model based on data that was generated by parameter studies of the ECS settings using a simplified 2-D CFD model of the cabin airflow.
In POA, typically the power consumption as a function of flight mission time is to be simulated in order to assess the appropriate behaviour of all systems and their possible interactions. For the sake of illustration, very simple representations of the galley and IFE are used in this study, i.e. prescribed steady state values for power demand as a function of the flight mission time. The ECS however, taking care of the air-conditioning of the aircraft cabin, depends for its power consumption on the thermodynamic "loads" in the aircraft cabin. It can be assumed that, for example, the phase of the flight mission and the related on-board services and activated systems contribute to these loads. The simulation of the ECS requires therefore that the cabin airflow and its dependency on the flight phase are properly simulated. Although CFD simulation is well suited for this purpose, the computational cost of such simulations is too high for the intended computational efficiency of the VIB. Therefore we have investigated in this study how the relevant phenomena in the cabin airflow can be adequately described by an approximation model in order to efficiently predict the ECS settings in the VIB simulation of a flight mission.
The figure below (Figure 3) presents an overview of the geometry, grid and some of the key boundary conditions and results of the CFD simulations of the cabin airflow in the different flight phases that have been performed. The upper-left panel illustrates the standard situation (only the right half of the symmetric cabin), with velocity and temperature boundary conditions

for the ECS inflow, the location of the ECS outflow and the temperature boundary conditions for the passengers' heads. The lower-left panel illustrates the additional optional rigid bodies in the flow field, representing the food trolley and the TV, with their temperature boundary conditions. The numbered stars in both these panels represent the positions of the seven points where flow velocity and temperature are measured in the simulations, which can be used to control the ECS and the passengers' comfort. In each of the four considered cabin flow situations (i.e., with and without trolley and/or TV; S1-S4, Figure 3), a parameter study of 11x11 CFD simulations, each with different settings of the ECS inflow temperature and velocity, with respective ranges of [15, 35]°C and [0, 5] m/s, has been performed. This resulted in the training data sets for the ECS approximation model.

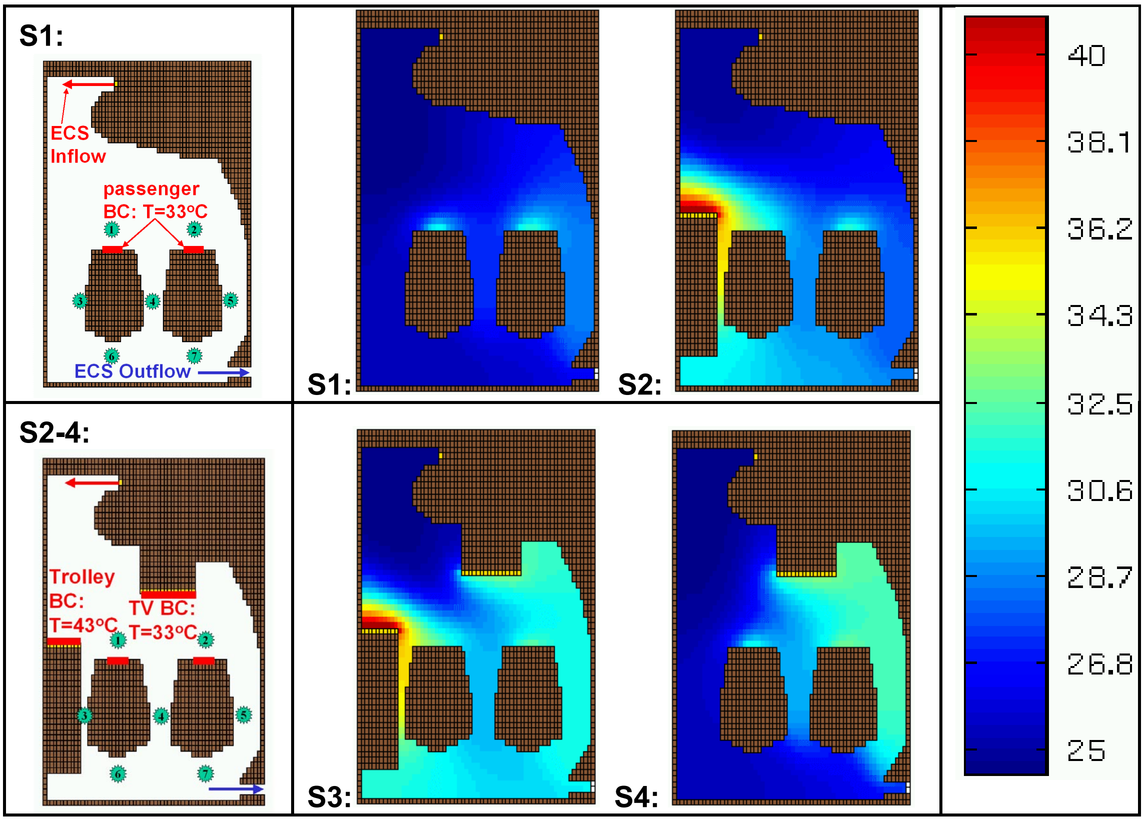

Figure 3: Overview of the geometry, grid and some of the key boundary conditions (left), and resulting steady state temperature distributions in each of the four different cabin airflow situations (middle, S1-S4)

An overview of selected results of the CFD simulations for each of the four different situations is given in the middle panels of the figure below. The upper-middle panel shows the standard situation S1 where the ECS is active and the passengers are in the seats, and S2 where the trolley with hot meals has arrived in the aisle. The lower-middle panel shows S3 where, in addition to the trolley, also the TV screen is lowered from the ceiling and activated, and S4 where the trolley has left, but the TV screen is still active. With the simplified VIB the cruise part of a reference flight mission, as specified in POA, has been simulated. Four subsequent phases during this cruise flight are distinguished:

1. Passengers in seats, ECS is active, galley switched on to prepare hot meals;
2. Galley switched off, trolley with hot has meals arrived in aisle;
3. IFE switched on, e.g. TVs are activated, and trolley is still in aisle;
4. IFE still active, trolley has been removed from aisle.

Each of these four phases correspond to one of the four cabin airflow situations (S1-S4) for which the approximation models have been created from the data sets of the CFD simulations. As such the effect of the galley (via the hot trolley) and the IFE on the cabin airflow can be assessed and the required adaptation of the ECS settings can be predicted. For example, in the case where the temperature in measurement point 1 (Figure 3) (T_1) is to remain below 24 ^oC and the ECS inflow velocity is fixed at 4 m/s (the ECS inflow is usually fixed for a certain number of passengers because of air quality requirements), the required ECS inflow temperature (T_{in}) for each of the four cabin situations can be predicted with the approximation model, as indicated in Figure 4. These decreased inflow temperatures will require an increased electric power demand by the ECS, while the ECS pneumatic power demand will not change (Figure 4). The effect of the ECS settings on ECS power demands would actually also require a rather complex model of the ECS thermodynamic conversion, but is simplified here to a linear relation in the inflow temperature: $\Delta P_{el} = k\, \Delta T_{in} = -1\ (T_{in} - T_{in\text{-}S1})$, [kW].

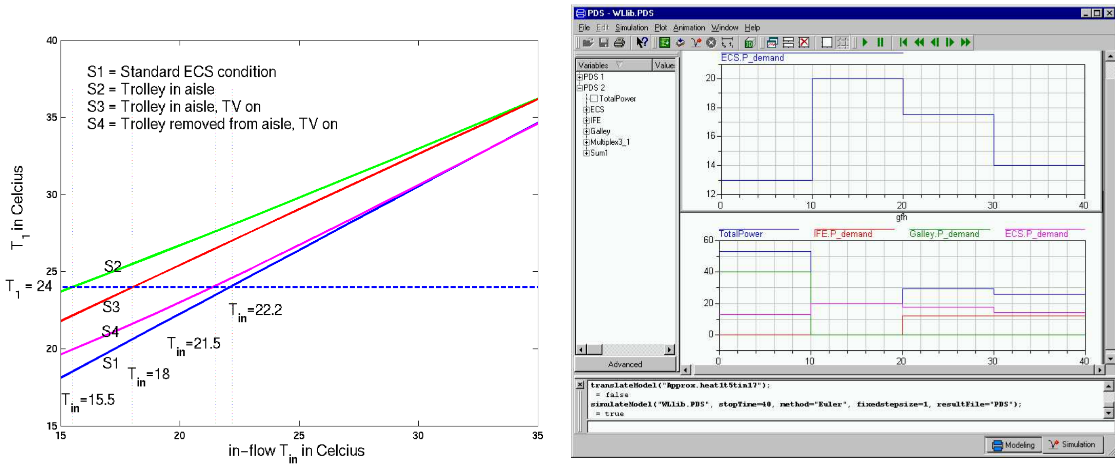

Figure 4: Illustration of the VIB flight mission evaluation. Left: T_1 as a function of T_{in} for each of the four cabin airflow situations S1-S4. Right: the different power demand values as simulated by the simplified VIB (right).

5 Concluding remarks

An illustration of the application of approximation methodology in multi-disciplinary system design has been given. Although the design case was strongly simplified, the considered aircraft system model contained some key features for integrated multi-disciplinary system design as envisaged for the POA-VIB, i.e., component models from different physical domains, model integration, component interaction and generic modelling by approximation methods. The ECS power demand (Figure 4) was derived from the CFD based ECS approximation model. It should be noted that this power appeared to decrease, unexpectedly, after the IFE (TV) was activated (and more heat was generated in the cabin). This illustrates the effect on the ECS setting of the local measurement in point 1, which was captured by the CFD results and consequently included in the ECS approximation model.

The approximation methodology applied considered both standard and state of the art methods, and was shown to be relatively easily applicable in combination with the Modelica multi-physical modelling approach as employed in the VIB.

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Acknowledgements: The presented work has partially been performed within the framework of the POA project, under contract G4RD-CT-2001-00601. Furthermore the support of Mr. R. Maas, of NLR, and Ms. C. Shen, of the University of Amsterdam, in the work on the approximation modelling, and of Dr. H. van der Ven, of NLR, and Prof. A. Veldman, of the University of Groningen, in the work on de cabin airflow simulations, are gratefully acknowledged.