

## COLLABORATIVE ENGINEERING TECHNOLOGIES ENABLING MULTI-PARTNER THERMAL ANALYSIS IN EARLY DESIGN STAGES OF AIRCRAFT

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**Abstract.** *The TOICA EU FP7 project focuses on developing capabilities that support aircraft manufacturers and their supply chain in jointly performing thermal analyses of aircraft architectures. Collaboration capabilities and related multi-disciplinary modelling and simulation technologies are key pillars for joint thermal analyses. The paper describes two such capabilities: surrogate modelling and smooth cross-organisation workflow execution. These capabilities have been further developed based on TOICA needs. The integrated application of the capabilities is illustrated in the context of an aircraft wing fuel tank thermal analysis conducted in TOICA.*

## 1 INTRODUCTION

Aeronautics research and technology development programs generally involve collaboration among different organisations, in order to include all required skills from the supply chain, to share risks and costs and to timely and efficiently develop innovative products. To achieve the challenging objectives of contemporary and future aeronautics, and to maintain global industrial leadership [1], a high level of integrated system design of the aircraft and its subsystems is needed. This requires a continuously increased level of collaborative engineering through modelling and simulation along the supply chain in order to improve cost and time efficiency and to reduce the integration risk in later phases. Teams of engineers from various disciplines and organisations are supposed to collaborate across organisational and geographical boundaries. The size and complexity of aircraft programs, the market demands, and the competition in the market require the collaboration to be effective and efficient, while obeying security constraints and preserving the intellectual property of the supply chain members.

To achieve a step change in the way multi-disciplinary teams in an extended enterprise carry out modelling and simulation processes, several capabilities that support collaboration and multi-disciplinary modelling and simulation were developed in the context of the TOICA EU FP7 project. TOICA develops these capabilities for application in the thermal analysis of aircraft architectures and validates them on realistic thermal use cases. The need for thermal analysis of aircraft architectures has emerged from the increased application in aircraft of technologies that strongly impact the thermal behaviour of the aircraft.

Collaborative engineering through modelling and simulation along the supply chain has to deal with two opposite goals. Firstly, the supply members want to protect their intellectual property rights (IPR) amongst each other, whereas more integrated simulation may ask for more and agile exchange of data among the supply chain. Secondly, security policies at the supply chain members limit access to simulation resources, whereas increased collaboration asks for well-established simulation workflows across the supply chain that support reproducibility and traceability of simulation data and processes.

In the TOICA project, the Netherlands Aerospace Centre NLR developed and applied two innovative technologies that enable collaborative engineering through modelling and simulation, while respecting IPR and security policies among the supply chain: the Brics capability and surrogate modelling. Brics enables multi-disciplinary and multi-partner engineering teams achieving cross-organisational simulation workflows while dealing with security constraints and measures of the involved organisations. Surrogate modelling is an effective method for reducing a complex simulation model to a 'light' version, which may respect IPR policies and can be exchanged easily among the supply chain. A surrogate model is specifically useful for extensive trade-off studies at aircraft level during conceptual design (as in TOICA), since a surrogate model requires low computational efforts.

The two innovative technologies are illustrated on the realistic use case of fuel tank thermal modelling, which was set up in the abovementioned TOICA project. This use case is driven by the needs to investigate the potential of fuel as heat sink and to support certification of a wing fuel tank that is made from non-aluminium materials. The potential of fuel as heat sink is limited by thermal constraints due to certification requirements. In case of novel materials for the fuel tank extensive testing and/or detailed thermal analysis is necessary to determine the bulk fuel tank thermal behaviour for different flight cases.

Section 2 will introduce the TOICA project, the fuel tank thermal modelling use case, and the problems and challenges that have led to the development of the Brics and surrogate modelling technologies. Sections 3 and 4 describe the backgrounds, details, and realistic example

applications of Brics and surrogate modelling, respectively. Section 5 describes the integrated application of the two technologies to the fuel tank thermal modelling use case. Section 6 presents conclusions.

## 2 OUTLINING THE CONTEXT

This section describes the context and rationale of the study of which the results are presented in this paper. Subsection 2.1 introduces the TOICA project. Subsection 2.2 introduces the fuel tank thermal modelling use case. Subsection 2.3 describes the problems and challenges that have led to the development of the two innovative capabilities addressed in this paper.

### 2.1 Introduction to TOICA

Thermal behaviour has become a crucial topic in the development of modern aircraft. This is due to the increasing number of complex systems required by modern, more electric commercial aircraft, the introduction of hotter engines with higher by-pass ratios, the increased use of composite material in aircraft structures, and the confinement of highly dissipative equipment and systems in smaller areas, to save space for passengers and cargo. New advanced techniques to manage the aircraft thermal behaviour at the early stages of development are essential to take the right configuration decisions while meeting market demands.

The ‘Thermal Overall Integrated Conception of Aircraft’ (TOICA) EU FP7 project intends to change the way thermal studies are performed within the aircraft design processes [2]. The project focuses on the creation and management of new aircraft architectures, including thermal analysis and trade-off studies of such architectures, via a so-called “Architect’s Cockpit” as depicted in Figure 1. The thermal analyses require collaborative effort from the supply chain involved in the development of modern aircraft. The TOICA project develops advanced capabilities to support the collaborative analyses.

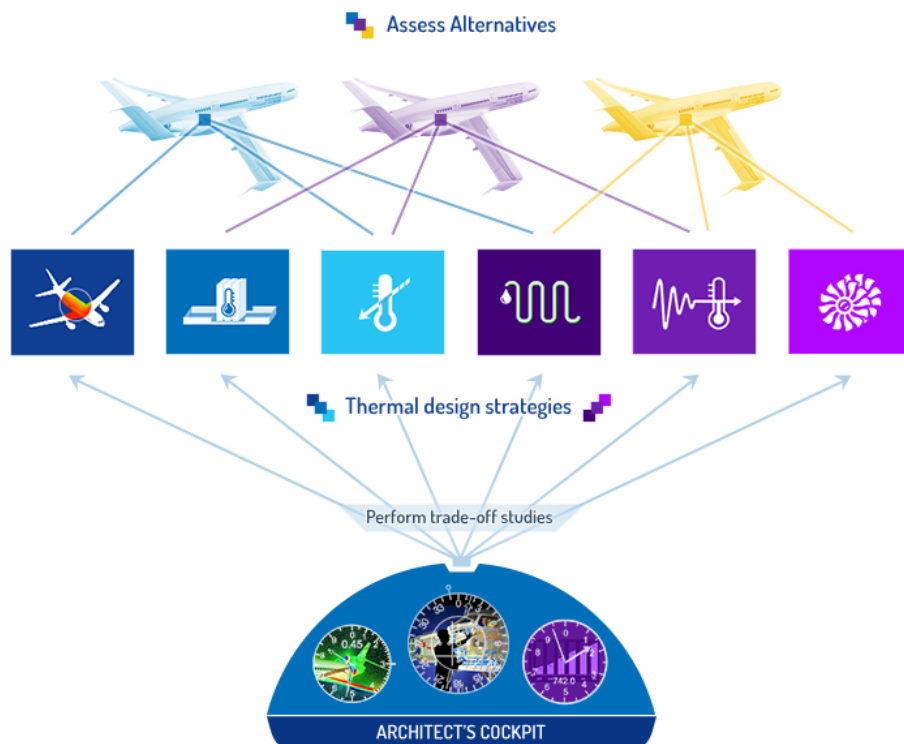


Figure 1: Depiction of the TOICA Thermal Architect's Cockpit that enables collaborative thermal trade-off studies (source: [2])

## 2.2 The fuel tank leading edge case

The use case addressed in this paper is related to one of the use cases of the TOICA project: using fuel as a heat sink for waste heat from other systems. This may raise certification issues with regards to the fuel tank, especially if innovative, non-aluminium materials are involved. Therefore, part of the TOICA use case is dedicated to the integrated analysis of the thermal behaviour of a wing fuel tank. The applicable wing fuel tank thermal model is part of the Ale-nia Thermal Aircraft Model lead by Finmeccanica's Aircraft Division. To comply with certification standards of a wing fuel tank that is made from non-aluminium materials, extensive testing and/or detailed thermal analysis is necessary to determine the bulk fuel tank thermal behaviour for different flight cases. The methodology for the fuel tank thermal characteristics evaluation shall indicate - during the aircraft preliminary design phase - whether or not a flammability reduction means (FRM) is needed.

Figure 2 depicts a 3D schematic view of a wing fuel tank and leading edge. The tank is filled with fuel up to a certain level. Consequently, there remains a part of the tank that is not filled with fuel, but which may contain fuel vapour. This part is called the 'ullage'. The tank compartment is separated from the leading edge compartment by a spar. Within the leading edge compartment a bleed pipe resides that transports hot air from the engine. The bleed pipe causes the fuel and the ullage to heat up when the engine is switched on. Furthermore, other heat sources such as solar radiation on the wing may cause the fuel and the ullage to heat up. All such heat sources need to be taken into account into the integrated thermal analysis of the wing fuel tank.

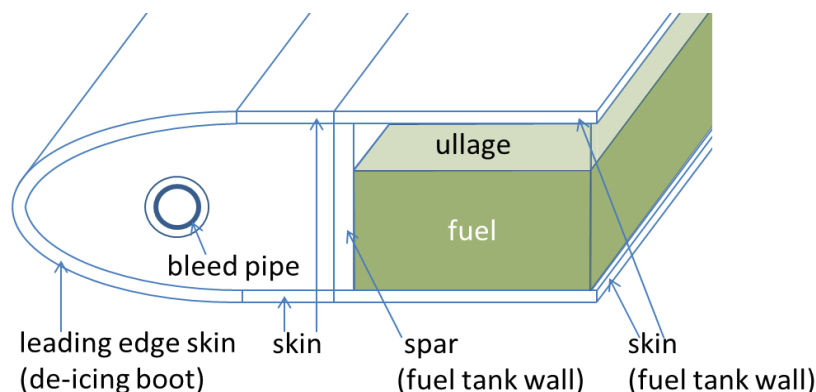


Figure 2: Schematic of the wing fuel tank. The bleed pipe is located in front of the wing fuel tank. The bleed pipe causes the fuel and ullage, i.e., the unfilled part of the tank, inside the tank to heat up.

The thermal analyses are performed at two levels:

- Detailed thermal analysis by calculating the three-dimensional temperature profiles via structural Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD).
- Quick thermal analysis and prediction of the bulk temperature via a nodal model, applying a thermal network approach. The nodal model must be validated by the detailed thermal analysis. An efficient and sufficiently accurate model is needed for applying the analysis during the aircraft predesign phase.

Both analysis levels rely on accurate boundary condition estimations for the fuel tank structure. Therefore, the effect of heat sources that are located close to the tank (e.g. the bleed pipe) is modelled to identify hot spots on the boundary of the fuel tank due to external heat sources.

On the detailed level this estimation is supported by a model of the wing leading edge. This model is described in further detail in subsection 5.1. On the quick analysis level the estimation is performed by a surrogate model of the wing leading edge. The derivation of the surrogate model is described in subsection 5.2.

Figure 3 provides a scheme of simulation models that are involved in the fuel tank thermal analysis together with their interrelations and thermal coupling. The different simulation models depicted in Figure 3 have been developed by different partners with different tooling: University of Padova using StarCCM+ for the fuel tank CFD model, Siemens Industry Software using LMS Imagine.Lab Amesim<sup>TM</sup> for the fuel tank nodal model, and NLR using Abaqus for the fuel tank structure FEA model and for the leading edge FEA/CFD model. The latter model is addressed in this paper. In the ideal situation these models run all at one physical location: at the aircraft manufacturer. However, if this is not the case, collaborative engineering technologies can facilitate an efficient integration workflow/process. Various reasons for such collaborative multi-partner approach will be explained for the general case in the next section.

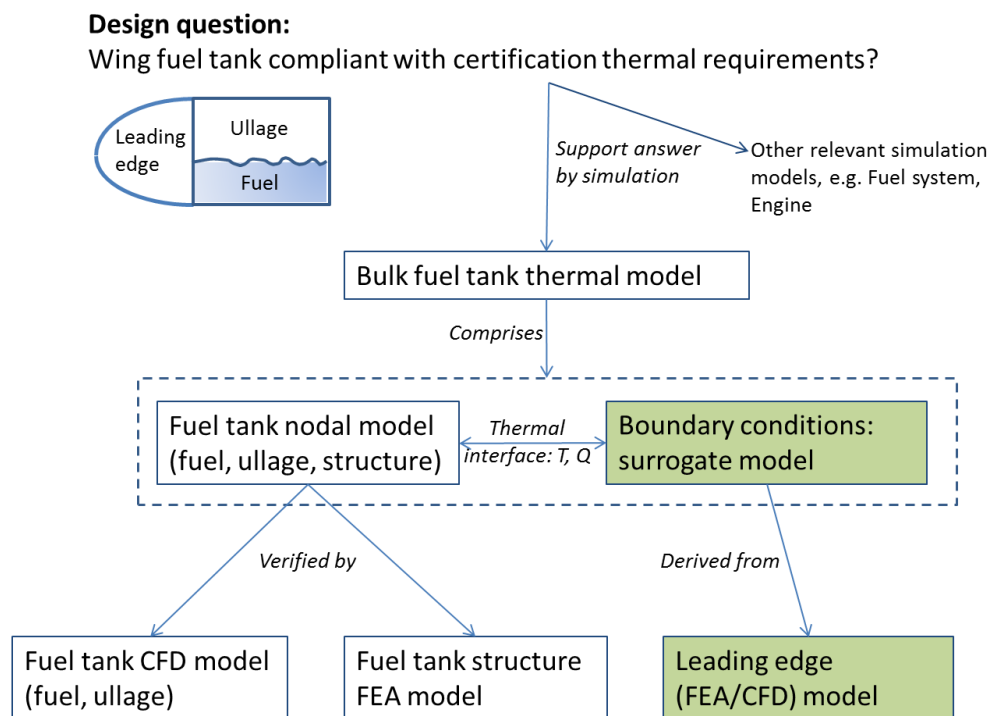


Figure 3: Model coupling and relation scheme of the fuel tank thermal analysis. The models in the green blocks will be further detailed in this paper (see section 5).

## 2.3 Problem description and challenge

Collaborative modelling and simulation in aeronautical industry with a multi-disciplinary, multi-organisational and multi-site engineering team are commonly hampered by security constraints, protection of intellectual property, and dependency on simulation tools and complex simulation models that are expensive to run. Several research projects in the EU framework programmes, such as VIVACE, CESAR, and CRESCENDO have been dedicated to development of innovative concepts and technologies that support collaborative engineering processes in the aerospace context. In the context of TOICA, NLR addressed two particular aspects: distributed collaboration technologies and cost and time efficient simulation technologies.

With respect to distributed collaboration, NLR investigated the limitations of cross-organisation collaborative engineering resulting from the fact that organisations are protective with respect to access to their own assets. Due to a variety of security constraints imposed by the connected organisations, running a simulation workflow that comprises tools at the different organisations is not obvious. Organisational rules and fire wall settings seem to make participation of a partner in a cross-organisation simulation workflow difficult or even impossible. NLR's challenge in this respect is to facilitate and smoothen the execution of cross-organisation workflows while dealing and complying with the policy and rules of the involved organisations. The approach is outlined in section 3.

NLR also focussed on cost and time efficient simulation technologies. These are often a challenge within aeronautic design. Models that describe the behaviour of an aircraft component in detail are usually expensive to run. They may be dependent on specific simulation tools and difficult to interface with other models. This makes it difficult to apply them in trade-off studies on aircraft level. Furthermore, they may not be shared with partners in order to protect the company's knowledge that lies behind the model. Surrogate modelling can provide a solution to these challenges. In order to achieve cost and time efficient simulation technologies NLR's objective is to develop surrogate models in such way that:

- the generated models have an appropriate accuracy (fit for purpose),
- the generated models are efficient (computationally cheap),
- intellectual property of the detailed model owner is protected,
- integration and model derivation effort is minimal, and
- both transient and steady-state thermal behaviour can be simulated.

This capability is presented in section 4.

Both capabilities will be illustrated by separate application examples in the frame of TOICA. Furthermore, their integrated application in the context of the fuel tank leading edge use case is described in subsection 5.3.

### **3 SMOOTH EXECUTION OF CROSS-ORGANISATION WORKFLOWS**

This section introduces Brics as capability for the support of smooth execution of cross-organisation workflows. A quick, high-level introduction to Brics, describing its rationale and a global overview is given in subsection 3.1. A more detailed description of Brics is given in subsection 3.2. Implementation aspects of Brics are described in subsection 3.3. A first realistic example application of Brics in the context of a distributed MDO study is briefly presented in subsection 3.4. The application of Brics in the context of fuel tank thermal modelling is described in subsection 5.3.

#### **3.1 Cross-organisation collaboration challenges**

Collaborative engineering activities and simulation workflows are largely supported by information and communication technology and software tools. But making cross-organisation collaborative engineering efficient and effective in practice requires a step change. For example, collaborative workflows typically span the networks of the collaborating organisations. The workflows would ideally run seamlessly across the networks of these organisations. However, with the current complexity of design, analysis and simulation tools and workflows it is difficult to be compatible with the varying security settings and the variety thereof. Engineers are facing unintended security restrictions due to security rules, fire walls and proxy servers. These restrictions help organisations protecting their assets and intellectual properties and obeying legislation and regulations. In practice, aircraft collaborative design teams end up in using standard facilities, such as e-mail and FTP servers, and in dealing with IT depart-

ments and security officers that seem unwilling to cooperate. From an aircraft program technical point of view, effective and efficient collaboration in the jungle of security rules, measures and technologies is a big challenge. This challenge has been the point of departure for the development of Brics.

NLR has long history of experiences in supporting the realisation of cross-organisation workflows. The knowledge, expertise and reusable solutions have been collected in, and are being deployed through Brics. In a nutshell, Brics targets to achieve smooth and secure execution of cross-organisational multi-partner collaborative workflows. It enables all engineering partners to participate, even if they are “network access restricted” because of security measures [3]. At the same time, Brics complies with the security constraints of the organisations involved. Brics also aims to allow each partner to have full control over its own resources, including computing resources, on-line data, and software tools. This means that organisations do not have to put their resources under management of Brics, any cross-organisation workflow nor any umbrella authority. The resources may be deployed on behalf of cross-organisation workflows only under full control of the organisation’s own employees. Brics caters for a “man-in-the-loop”, as is shown in Figure 4.

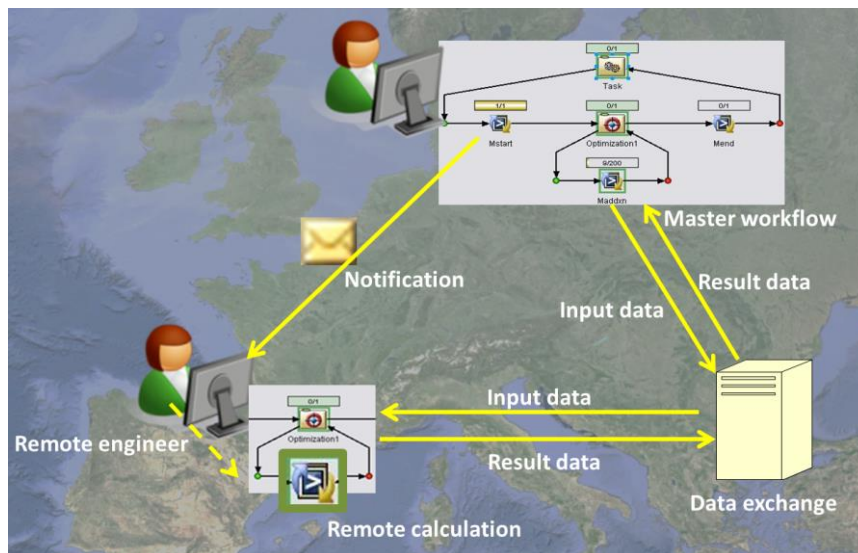


Figure 4: Schematic overview of the basic idea behind Brics: performing a remote calculation from within a “master” workflow by sending a notification to a remote engineer, who may decide on whether or not perform an action or a series of similar actions. Brics in addition facilitates the orchestration of the remote job and the data exchanges involved.

The “evolution” of Brics started more than ten years ago, in research projects aimed at establishing virtual or extended enterprises in the support of collaborative engineering activities (VIVACE[4], CESAR[5], CRESCENDO[6]). Cross-organisation collaboration used to be mainly based on the exchange of data files via e-mail, FTP servers, websites for information exchange and collaboration (e.g., SharePoint), product lifecycle management and support systems, telecon and videoconference systems. In some cases it involved the shared use of tools, workflows and data on centralised systems. Commercial workflow management tools are available to support cross-organisation workflows but generally put heavy demands on the interconnectivity of the systems and organisation networks involved. They usually enforce the collaborating partners to install and use the same tool.

Brics has evolved and still is evolving “on the job”. This means that it is being developed in projects that target or apply collaborative engineering activities and workflows. Its devel-



opment is fed by needs and requirements that come from projects, use cases, and engineering teams that involve more and more cross-organisation collaborative engineering while facing ever increasing security constraints. Through the years, the security rules and mechanisms have become and still are becoming stricter. At the same time, partners in collaborations want to persist using their own processes, methods and tools, even while fulfilling their role in collaborations and collaborative workflows. This will enable them to fully exploit their own expertise and to pursue their own way of working, but on the other hand leads to more and more heterogeneous environments to be dealt with in collaborations. The two growing barriers of security and heterogeneity have fed and still feed the ongoing evolution of Brics.

### **3.2 Brics technology to support cross-organisation collaborative workflows**

Brics comprises protocols and supporting middleware that facilitate remote execution of tools and workflows. The remote execution involves sending of notifications to remote engineers, exchange of data, and synchronisation of distributed activities. Brics is based on default and standard network protocols, tools and facilities. Application of Brics has minimum “connectivity” requirements: being able to send and receive e-mail messages and to upload and download files to a file or data server that is accessible to at least one other partner. To avoid misunderstandings, Brics does not “penetrate” fire walls nor rely on known bugs in networking software or in other security means. The communication related to Brics-enabled cross-organisation workflows is fully transparent and can be explained easily to the involved IT departments and security officers upon request. Brics respects the security rules of the collaborating partners. It supports the application of secure communication technologies, it involves remote engineers explicitly and it enables the collaboration partners to have full control over their own resources. Brics can be used complementary to existing engineering tools and workflows, and does not require changes of tools, methods, and processes in organisations. These properties contribute to the possible deployment of Brics with minimum impact on the business of the connected organisations.

Brics is based on a simple protocol that arranges the execution and data flow between an orchestrating (or “master”) workflow in one organisation and a remote engineer in another organisation who is assigned to execute a tool or a part of the workflow. The protocol comprises the uploading of data files that are input for a remote process, sending a notification to a remote engineer requesting the execution of a task, the synchronisation with the remote task, and the downloading of the data files that are output of the remote task; cf. Figure 5. The ‘single-task’ protocol is suitable for the execution of a single remote task. If the same protocol were applied in a loop, the remote engineer would repeatedly be notified to execute the same task again with slightly different input data. The handling of a consecutive series of similar notifications is cumbersome, time consuming and error prone. Brics has an extended protocol for gracefully dealing with such multi-task jobs. The ‘multi-task’ protocol centralises the triggering of the remote engineering into a single notification, requesting the remote engineer to execute a series of equal tasks. The protocol furthermore deals with handling the series of equal tasks and the graceful termination thereof. The protocols are described in detail in [7].

The middleware provide software methods to support the protocols. The methods can be plugged in easily as commands in scripts and tools in workflows and hence enable the use of the protocols from within scripts and workflows. The middleware supports the use of various existing mechanisms for notifications and data exchanges. It includes mechanisms to deal with proxy servers and to use permitted communication channels with the required level of security. It also includes mechanisms for relaying data files and notifications, to cater for situations in which partners have no access to particular data, file or e-mail services. The middle-



ware furthermore supports engineers in providing specific parametric calculations “as a service”, for use by (possibly remote) engineers and workflows [8].

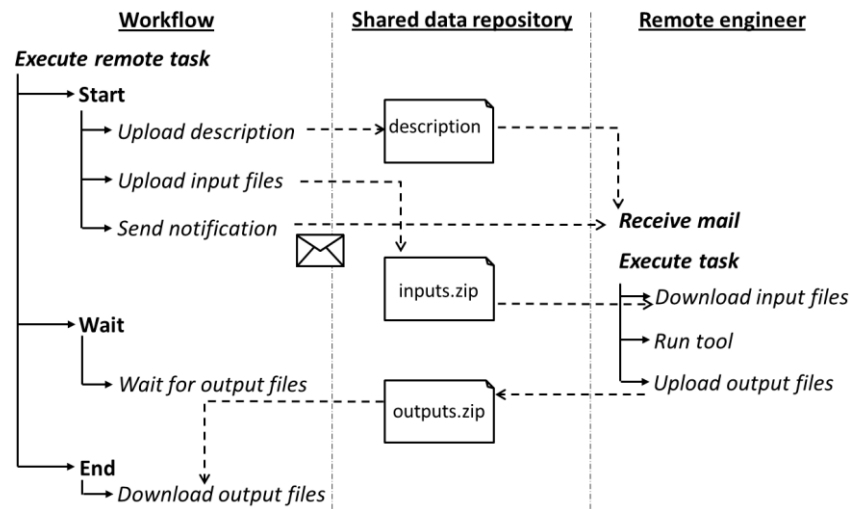


Figure 5: Simplified sequence diagram of the Brics single-task protocol.

### 3.3 Implementation

The Brics middleware comprises a set of Java packages with a small number of ‘main’ programs and interfaces. As such, Brics is operational on a variety of operating systems, including Windows, Linux, and UNIX. The Java packages enable easy integration of the middleware in Java applications and existing products. Brics has been successfully integrated in COTS and open-source workflow management and optimisation tools such as Boss Quattro, Isight/FIPER, RCE, and Optimus. The main programs include simple command interpreters that cater for interactive use of Brics as well as use of Brics from within script languages such as UNIX and Linux command scripts, Windows BAT scripts, Python, and Matlab.

To support data exchange, Brics is capable of interacting with a variety of data and file servers. Examples are FTP, MS SharePoint, Share-A-space, and shared file systems. Interfaces to other, including new and organisation-specific data exchange services, such as Airbus’ FTS+ service, can be added easily at the Brics developer’s level. Brics’ default mechanism for notifications is e-mail. Brics has also provisions for dealing with product-specific notification mechanisms.

As might be clear from the above, Brics includes many interfaces. The middleware is also capable of communicating through a variety of – secure as well as insecure – internet communication channels. Use of Brics requires some configuration, which includes the specification of what data server and e-mail interfaces to use, web addresses and authentication information for the services, and proxy servers to deal with. The configuration information can be provided as parameters at the Java level as well as via environment variables and configuration files for the main programs and interfaces. The light-weight configuration means makes Brics an agile tool in the various collaboration settings.

### 3.4 Example application in a distributed MDO process

Brics has been installed in industry, research institutes, software vendors, and SMEs. It has been, and still is being applied for the implementation of cross-organisation distributed workflows in several EU and national research projects (VIVACE, CRESCENDO, CESAR, TOICA). In these projects, Brics has proven to be a valuable tool through which partners can

experience collaborative working in a flexible and easily accessible way, even in an early stage of the development of multi-partner scenarios and workflows.

Brics facilitates the transformation and integration of local workflows into cross-organisation collaborative engineering workflows, by supporting the replacement of a tool by a ‘stub’ that handles the remote execution of the tool as if it runs locally. Section 5.3 describes the application of Brics in thermal analysis of an aircraft wing fuel tank. A realistic example application was set up and demonstrated live in the context of TOICA [9]. In this use case, Brics has been used for the realisation of an automated multi-partner and cross-organisation distributed multidisciplinary design optimisation (MDO) workflow; see Figure 6.

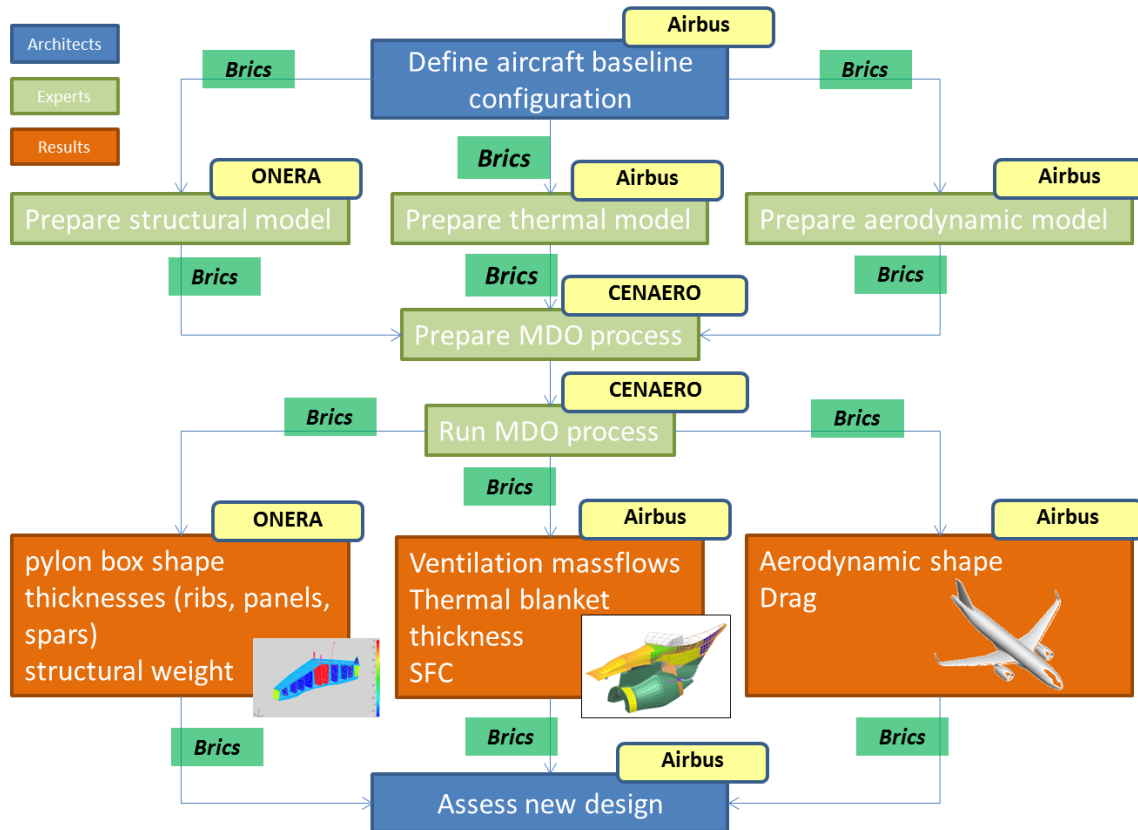


Figure 6: Overall process of preliminary design of power plant structures under thermal constraints. The process includes a distributed cross-organisation MDO workflow. The yellow boxes indicate the different partners. Note that different departments from Airbus were involved. The small green boxes indicate the role of Brics for orchestration and data exchange.

The MDO workflow serves to support the preliminary design of aircraft power plant structures under thermal conditions. The optimisation requires multiple disciplines and tools available from the aircraft OEM as well as the suppliers. The MDO workflow concerns the optimisation of an aircraft pylon design using structural, thermal as well as aerodynamic simulations. The so-called “master” workflow drives the MDO process and is operated from the OEM’s site by a simulation expert. The progress of the optimisation process can be monitored by the simulation expert as well as the architect. The master workflow uses Brics to initialise the optimisation and simulation processes (tools and workflows) at the different partners. The optimisation process uses Brics to orchestrate the simulations and to manage the data exchanges in between. The remote partners use Brics to respond to the series of simulation re-

quests and to manipulate the data to be exchanged. Notifications are sent by e-mail messages, and data exchanges take place via a single shared data server located at the OEM.

Subsection 5.3 describes the application of Brics in the fuel tank modelling case introduced in section 2.2. In that case, Brics has been used in combination with the surrogate modelling techniques that are discussed in the next section.

## 4 SURROGATE MODELLING

This section describes the details of NLR's surrogate modelling capability. An introduction is provided in subsection 4.1. The general surrogate modelling process is presented in subsection 4.2. Subsection 4.3 focusses on surrogate modelling of time-dependent models. A first realistic TOICA application of the surrogate modelling capability is discussed briefly in subsection 4.4. The application of the capability in the context of fuel tank thermal modelling is described in subsection 5.2.

### 4.1 Capability introduction

A surrogate model is an approximating model that replaces a more complex simulation model. The terminology "surrogate model" is used in the context of behavioural models. It is also referred to as "reduced model". Similarly to the complex simulation model the surrogate model is a representation of the behaviour of a system. The surrogate model however aims at reducing the complexity needed to compute the system behaviour. There are several possible reasons for creating a surrogate model from a complex model:

- Numerical efficiency – A surrogate model requires less computational power than the complex model. This is specifically useful in case the model needs to be used in an optimisation loop and therefore executed many times
- Protection of intellectual property (IP) – The complex model may not be distributed to other parties because of the protection of IP. A surrogate model may be an alternative for this as it can be implemented as a black-box. The contents of the original complex model are not visible anymore.
- Ease of integration – Running a complex model may require the specific tool, which it was developed with. In several cases the model needs to be integrated with other models, developed with other tools at other organisations. These tools do not necessarily interface with each other. A surrogate model – being a simplified representation of the original complex model – can usually be integrated more easily into other tools.

One can consider two broad families of surrogate/ reduced models. First, data-fitted surrogate models are data-driven models that emulate the responses of a complex simulation model (see Figure 7). This type is applicable to this paper. Second, simulation models can also be reduced in a physics-based way. This type is not treated in detail in this paper, but is considered in TOICA e.g.:

- Model reduction by means of geometry simplification of the original CAD model; see [10] and [11].
- Model reduction by means of thermal nodal modelling; see [12] for an explanation.

In aeronautic design surrogate models are usually applied as part of a design optimisation loop. In some cases the surrogate models are adapted on the fly as part of the optimisation algorithm: so-called adaptive surrogate models. Another frequent application is the creation of surrogate models as part of data analysis and statistics. A surrogate model is then directly derived from experimental data in order to predict a certain behaviour that is under investigation [13].

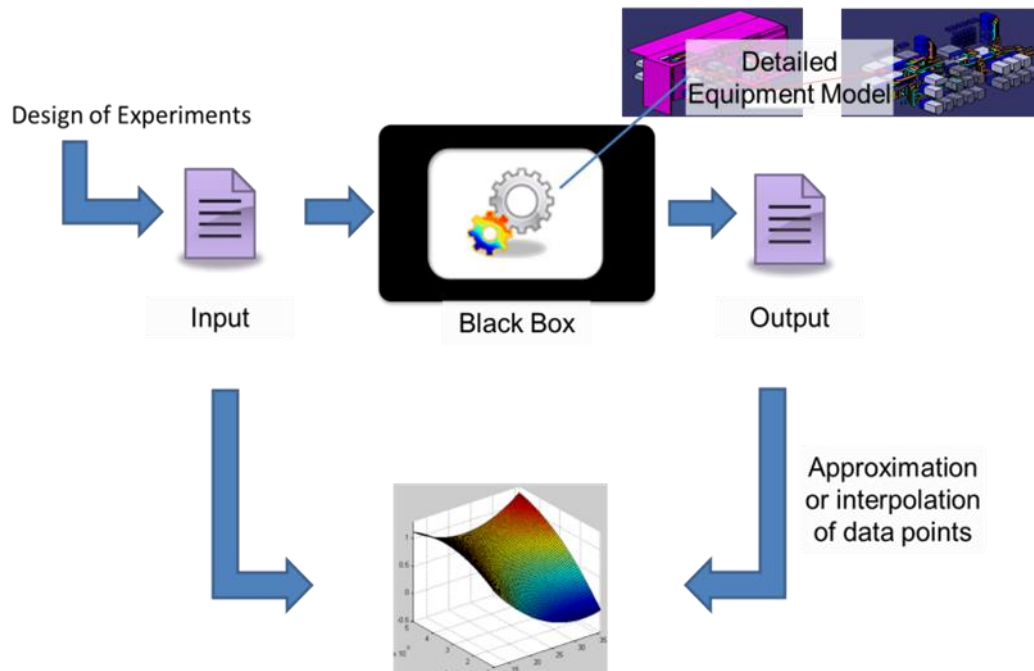


Figure 7: Illustration of data-fitted surrogate model derived from a detailed model of an equipment behaviour.

Organisations that need to create surrogate models develop their own tools for it or use commercial-off-the-shelf (COTS) software packages. Several steps in the surrogate modelling process can indeed be performed automatically (see also subsection 4.2), but to derive a surrogate model that is fit for purpose the involvement of experts is still essential. Expert judgment is needed as the choice for the most appropriate data fitting method depends very much on the data set that is to be fitted. NLR has long experience in developing and applying surrogate models based on data fitting from various EU research projects (e.g., POA[14], ICE[13], VIVACE[15], CRESCENDO[16], MAAXIMUS[17]).

## 4.2 Workflow for surrogate model derivation

The derivation of a surrogate model comprises several steps. When a surrogate model is derived from a set of input/output data of the complex model, the sampling of the data points is based on a so called Design of Experiments (DoE). The DoE is a crucial ingredient of the surrogate generation process, especially when the function evaluations are expensive. It should provide sufficient variation in the input values to cover the desired input range because it must contain as much information as possible. Examples of DoE methods are full or fractional factorial designs, Latin Hypercube Sampling (LHS) or D-optimal methods. Based on the DoE a database is derived that contains the results (input and output data) of the sequence of simulations with the complex model.

The surrogate model itself is derived by fitting the set of input-output data. For this several fitting techniques exist. The most common is polynomial regression, also referred to as response surface method. Other methods have been developed with more complicated analytical expressions like artificial neural networks, kriging, radial basis functions, splines, etc. The methods can be divided in *interpolation* and *approximation* methods. In case of interpolation the resulting surrogate model exactly matches the data points from which it was created with estimations in between those data points. In case of approximation the surrogate model does not exactly match the data points but approximates them as well as the space in between. The feasibility of a fit method depends on the nature of the data set: high or low dimensional,

sampled in a grid or scattered, noisy or clean, sampled in a sparse or dense manner (referring to the DoE), etc.

The fitting process is usually supported by dedicated software tools that statistically analyse and pre-process the data set, provide multiple fit methods and facilitate a fit assessment to select the best method with the appropriate settings. At NLR the MATLAB based in-house fitting tool MultiFit[15] is used. The assessment of a candidate surrogate model is performed by excluding a number of points of the data set from the fit and reserving them for validation afterwards by comparing the surrogate prediction in these points with the true values. This validation data set can be shifted across the complete data set to have a better validation range: cross-validation. Several error metrics are available to represent the validation, e.g. Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), R-squared test and quantile tests.

Figure 8 shows the identified steps that constitute the generic surrogate modelling workflow. Almost all steps are implemented using MATLAB. Only the runs with the high-fidelity model depend on its particular enabler (e.g. CFD or FEA computations). These runs can be orchestrated and linked into the surrogate modelling workflow using Brics. Such integration is detailed in subsection 5.3.

The resulting surrogate models are represented with analytical functions, calculating an output prediction in one step. As such they require very low computational effort.

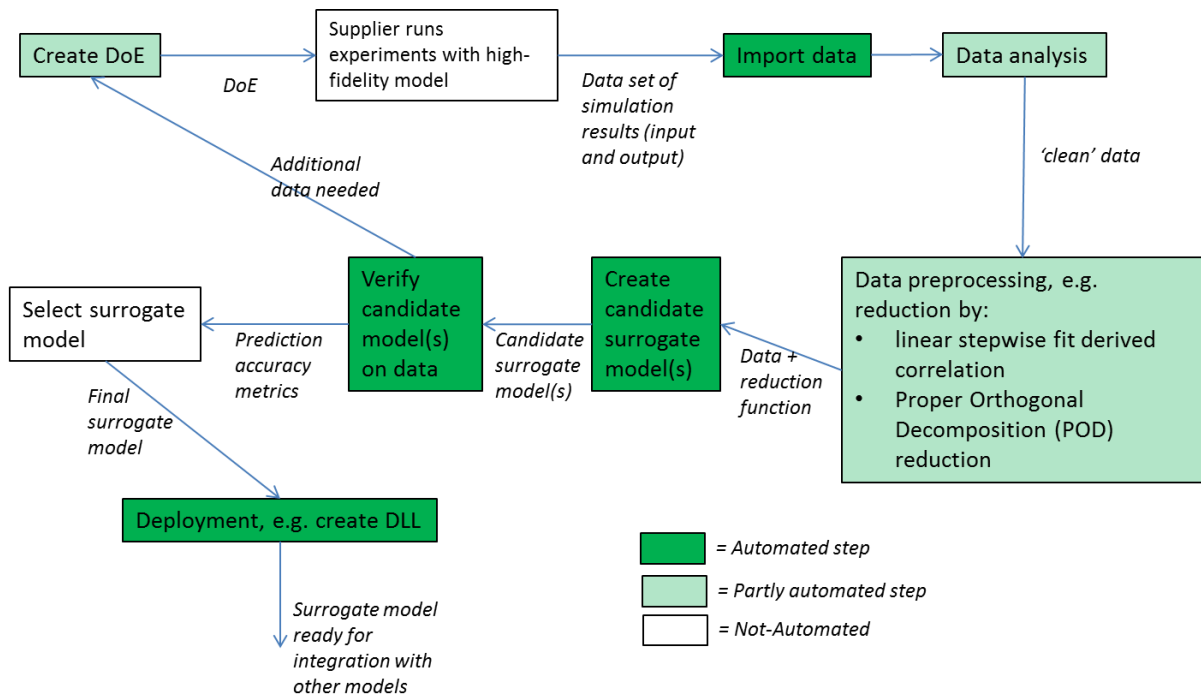


Figure 8: Generic workflow for deriving a surrogate model.

The surrogate models are by default available as MATLAB analytical functions, since they were created in the MATLAB environment. They have been exported as C type DLL or executable file using the MATLAB Coder. The export makes the model a black box and easy to integrate with other simulation tools, e.g. as Functional Mock-up Unit [18].

### 4.3 Transient surrogate modelling

In most cases data-based surrogate models are applied in the context of a steady-state analysis of system behaviour. During TOICA a method has been developed for creating transient surrogate models. This means that the surrogate model is able to capture time-dependent behaviour, specifically in short intervals of time (dynamic behaviour). The transient surrogate modelling problem is formulated as follows. Derive a function  $f$  such that

$$y(t) \approx f(y(t - \Delta t), u(t), u(t - \Delta t), \Delta t), \quad (1)$$

with  $y$  the vector of output variables,  $u$  the vector of input variables,  $t$  the simulation time and  $\Delta t$  a time step. For simplicity reasons only one time delay  $\Delta t$  of  $u$  and  $y$  is added in equation 1 but one could also consider multiple time delays here. In the context of thermal analysis  $y$  usually represents a temperature field whereas  $u$  represents boundary temperatures and/or heat flows.

The creation of a transient surrogate model gives rise to a significant increase of data, because complete time histories of the model inputs and outputs are needed to derive a surrogate model. Furthermore the dimensions of  $u$  and  $y$  may be very high, e.g. if complete temperature fields on a structure are to be predicted. In general, the more input dependencies need to be taken into account by the surrogate model, the more data points are needed. In many cases a large number of simulations is not feasible, because of the computational cost (e.g. CFD runs). In such cases it is useful to analyse whether the dimensionality of the inputs and outputs can be reduced. In the context of a thermal analysis this reduction can be applied to the temperature field  $y$ . As such a data pre-processing step is performed in which a transformation of the data is created that affects the eventual surrogate model. The transformation function will become part of the final surrogate model. The data pre-processing step has been performed using Proper Orthogonal Decomposition (POD) [19]. With this method the dimension of the data is reduced by finding the (spatial) coherence in the simulated time histories of  $y$  by performing a singular value decomposition of the snapshot matrix and retaining the singular vectors that correspond with largest singular values. These POD vectors derived from the simulation results form a reduced basis for  $y$ . Then a function  $g$  is to be fitted such that

$$c(t) \approx g(c(t - \Delta t), u(t), u(t - \Delta t), \Delta t), \quad (2)$$

with  $c$  the predictions of the POD coefficients (i.e., the representation of  $y$  in the new basis),  $u$  the vector of input variables,  $t$  the simulation time and  $\Delta t$  a time step. Typically  $c$  has a dimension that is orders of magnitude smaller than  $y$ .

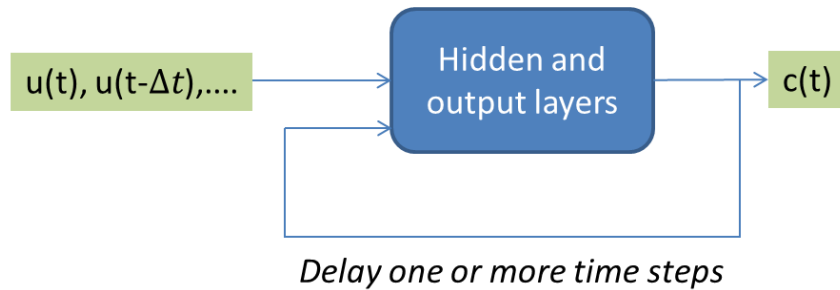


Figure 9: Top-level view of a recurrent artificial neural network that fits the POD coefficients  $c(t)$ .

A suitable method for deriving the function  $g$  is a recurrent artificial neural network (ANN). This method supports fitting of time series [20]. The recurrent ANN fits the values  $c(t)$  of the POD coefficient matrix as a function of the inputs  $u(t)$  -including a number of time delays of

$u(t)$  - and it feeds the predictions of  $c(t)$  back into the network with one or multiple time delays. This is illustrated in Figure 9. A recurrent ANN is applied as surrogate modelling method in the fuel tank use case described in subsection 5.2.

With a recurrent ANN the time step  $\Delta t$  is assumed to be fixed. In some cases the data set may contain time series with different time step values, e.g. when the data set is assembled from other data sets. In those cases a feed-forward ANN can be used instead, in which the histories of  $c(t)$  and the time step  $\Delta t$  are to be treated as inputs as well. Such ANN is illustrated in Figure 10, and has been applied in the example described in subsection 4.4.

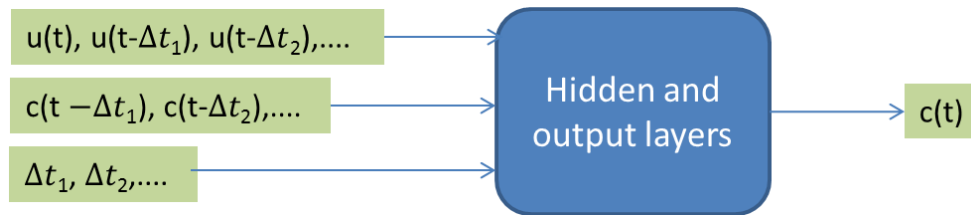


Figure 10: Top-level view of a feed-forward artificial neural network that fits the POD coefficients  $c(t)$ , for time histories with variable time steps

The steps for creating transient surrogate models have been automated as much as possible using the generic workflow depicted in Figure 8.

#### 4.4 Example application in equipment thermal integration

The application of the transient surrogate modelling method to the fuel tank analysis use case is detailed in subsection 5.2. Earlier during TOICA, the method has been applied in the context of equipment thermal integration. That realistic application is summarised in this subsection.

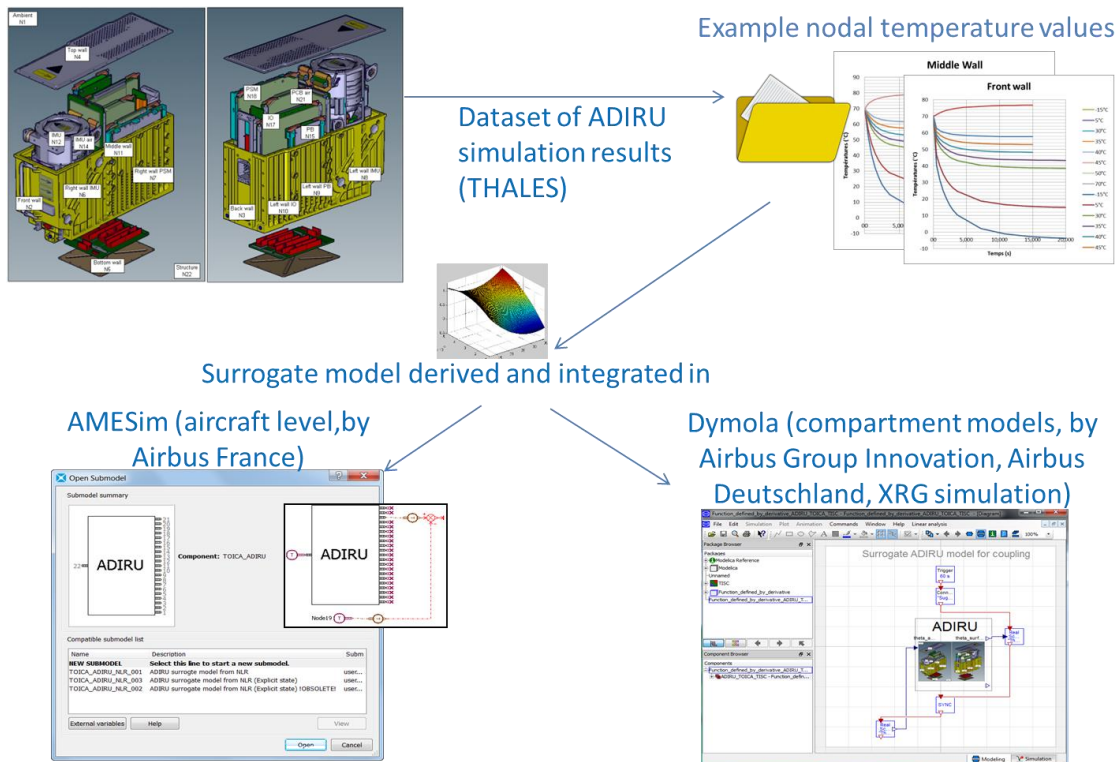


Figure 11: Illustration of surrogate modelling in the context of equipment thermal integration.



A data set has been provided of the transient thermal behaviour of the Air Data Inertial Reference Unit (ADIRU), by Thales (see Figure 11). The data set contains a number of time histories of 21 nodal temperatures on the equipment with varied initial conditions and a varied ambient temperature. The nodal temperatures represent the vector of output variables  $y$  to be predicted and the ambient temperature represents the input variable  $u$  (see equation 1). The data set consists of 5448 records in total. The dimensions of the data set have been reduced using POD. Five singular vectors have been retained. The POD coefficients have been predicted by a feed-forward ANN, taking the time history of the POD coefficients at the previous time step, the ambient temperature and the time step as input (see also Figure 10). The ANN consists of 2 hidden layers of size 12 and 8 respectively. Training has been performed using Bayesian regularisation. The resulting surrogate model has a temperature prediction error of order 1-2 °C (measured on the full data set used for fitting).

The surrogate model has been exported as a C type DLL which has been integrated with the system simulation tools (representing equipment thermal integration, see Figure 11):

- Amesim, used for integration of the surrogate ADIRU model on aircraft level.
- Dymola, used for integration of the surrogate ADIRU model on avionics compartment level.

## 5 THERMAL SIMULATION OF A FUEL TANK LEADING EDGE

This section details the case of thermal simulation of a fuel tank leading edge, which is related to one of the use cases of the TOICA project: using fuel as a heat sink for waste heat from other systems. Part of the TOICA use case is dedicated to the integrated analysis of the thermal behaviour of a wing fuel tank. The applicable wing fuel tank model is part of the Ale-nia Thermal Aircraft Model lead by Finmeccanica's Aircraft Division.

In subsection 5.1 the thermal model of a hot spot close to the fuel tank is described. The model is used to simulate the thermal effect of a bleed pipe on the tank wall. Furthermore, in subsection 5.2 a surrogate model is created from the results obtained in subsection 5.1. This surrogate model is then shown to produce comparable results of thermal history as the original model of subsection 5.1. Finally, in subsection 5.3, the simulation and surrogate creation steps are integrated into the collaborative engineering chain. All simulations have been performed by NLR.

### 5.1 Thermal modelling

Thermal analysis of an aircraft wing fuel tank consists of an internal and external temperature simulation. External temperature analysis covers the wing structure and structural heat sources, e.g. bleed pipe. Internal temperature covers the fluid and ullage (cf. Figure 2).

To identify the effect of heat sources external to the wing tank, a thermal model is necessary that is able to capture convection, conduction and radiation effects of these heat sources. Such heat sources are typically components that are running through the wing where the fuel tank is located. These components may not be directly in contact with the wing fuel tank. However, their supports are typically connected to the wing spar that is part of the fuel tank structure, causing the wing spar to locally heat up. Furthermore, the air inside the bay where the heat source is located is heated up. Therefore, a fluid-structure model is created that models the effect of heat sources and e.g. cooling effects of vents that are present in front of the fuel tank wall. The present case consists of a hot spot in the form of a bleed pipe located in the wing leading edge in front of the fuel tank; see Figure 2.

The thermal model for fuel tank external heat sources consists of two individual models that are coupled. The first model is a structural thermal model using a Finite Element ap-

proach and simulates the structural thermal loading. The second model consists of a fluid thermal model using a Finite Volume approach and models thermal behaviour of the air inside the leading edge. The two models are coupled to exchange temperature and heat flux values. These models are simulated in Abaqus standard (Finite Element) and Abaqus CFD (Finite Volume), and are coupled through Abaqus co-simulation engine [21].

In Figure 2, an overview is given of the wing structure consisting of skin, spar, and bleed pipe. The fluid model consists of the air inside the wing leading edge bounded by skin, spar and bleed pipe. Hence, the hot air inside the bleed pipe is not part of the CFD model but modelled as boundary conditions for the structural FE model. Furthermore, the front spar is the boundary of the structure model. The fuel and ullage section is not modelled in this fluid-structure model and is taken into account via a boundary condition. Modelling of the fuel and ullage are carried out by another TOICA partner, the University of Padova, using a CFD program.

### Structural model

The upper and lower skins as well as the wing spar are made of composite material with different thermal properties in plane  $6.7 \text{ W/mK}$  and out of plane  $0.7 \text{ W/mK}$ , a density of  $1.60 \text{ g/cm}^3$  and specific heat of  $1.4 \text{ J/gK}$ . The curved part of the leading edge consists of a de-icing boot. Inside the leading edge is a bleed pipe made of aluminium. The structure model is shown in Figure 12.

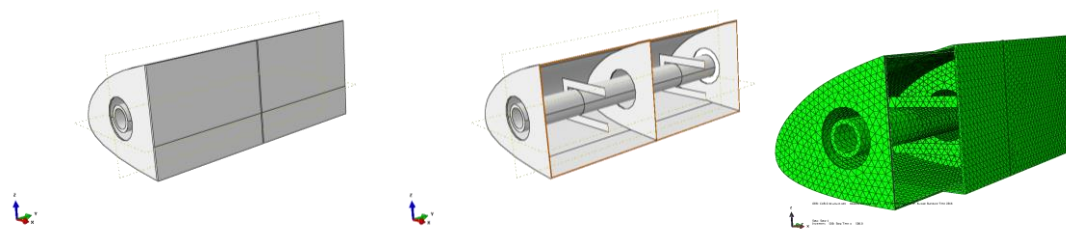


Figure 12: Wing structure part for which an FEA model is created. Left: the closed wing leading edge. Middle: a cut-out to show the internal structure showing the ribs, bleed pipe and bleed pipe supports. Right: the finite element mesh of the leading edge structure, bleed pipe and supports. Via a cut-out the internals are shown.

Hot air coming from the engine is running through the bleed pipe. This bleed pipe is then heated up and releases its heat via radiation to the surrounding walls. Additionally, via convection with the air inside the leading edge and finally via conduction with the bleed pipe supports, the walls are heated up. Air is running through the wing leading edge via ventilation holes. As can be seen in Figure 12 the bleed pipe radius is smaller than the hole in the rib section. Through this open area air is entering the wing leading edge in the model. On the opposite side air is leaving the wing leading edge via the space between the rib and the bleed pipe.

For meshing the structural model, linear tetrahedron elements are used and mesh seeding is chosen such that it more or less corresponds to the mesh seed that is used for the fluid domain. Boundary conditions are fixed temperatures on the wing top and bottom skin (including the de-icing boot). Thermal interaction of the front wing spar with the fuel is modelled via a heat transfer coefficient that was obtained from a CFD analysis conducted by the University of Padova for the fuel tank internals, i.e. ullage and fuel. The interaction with the air inside the leading edge is modelled via a fluid-structure interaction. Calculated wall temperatures on the FEA nodes are transmitted to the fluid calculations and the fluid calculations return heat trans-

fer coefficients on the CFD nodes. Interpolation of the calculated values is used to map results of the FEA onto the CFD and vice versa.

### Fluid (air) model

To model the thermal interaction via convection of the wing leading edge structure and the air inside the leading edge, a fluid (air) model is created of the leading edge internals. In Figure 13 the geometry is shown. To summarise, all the empty space inside the leading edge is used for the volume mesh.

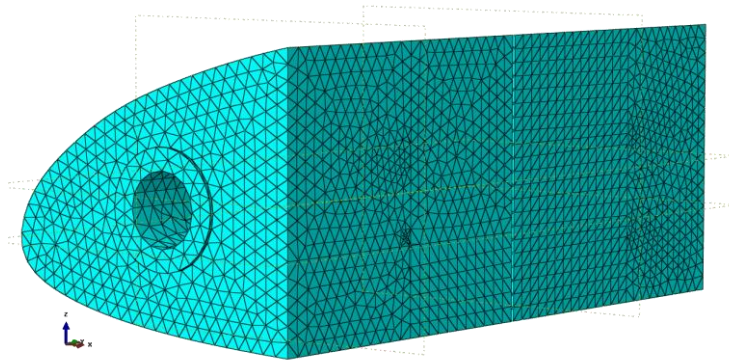


Figure 13: Wing leading edge air model showing the mesh of the air inside the wing leading edge that is modelled via a finite volume approach.

The fluid model is meshed using fluid linear tetrahedron elements. The mesh seed is chosen such that it more or less corresponds to the mesh seed that is used for the structure domain. The Spalart-Allmaras turbulence model is applied that uses wall functions to avoid very fine meshes near the walls. Boundary conditions are no slip conditions where the air touches the structure. Furthermore, a constant fluid flow is prescribed on one side of the leading edge.

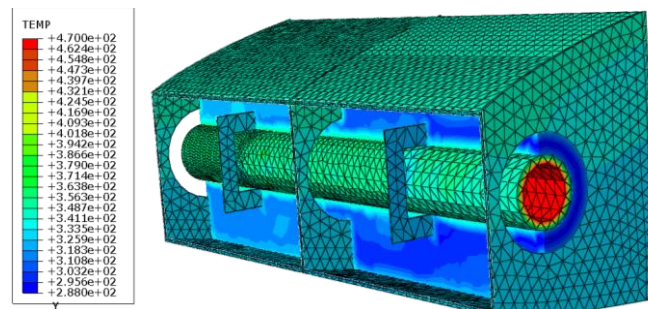


Figure 14: Temperature plot in degrees Kelvin of a cut-out of the Finite Element model for the structure filled up with a cut-out of the Finite Volume model for the fluid (air) in the leading edge.

The air intake is located on the front side of the leading edge shown in Figure 14. The ventilation is taken into account in the model using a constant 1kg/s airflow running from left to right through the ribs. There is an opening in the rib that is larger than the size of the bleed pipe. On the back side of the leading edge the rib has an opening and here a constant pressure of 1 bar is applied. The result is a flow of air that cools the leading edge and prevents the leading edge internal from heating up too much by the bleed pipe.

### Co-simulation approach

A transient analysis is carried out with an initial time step of 1 for both FEA and CFD. For the CFD model an automatic time stepping scheme is used called Courant-Friedrichs-Lewy

(CFL) time increment method and the time integration method is Galerkin. The numerical procedure to solve the pressure equation is using Bi-Conjugate Gradient, stabilised with a preconditioner algebraic multigrid. Furthermore, the inflow of air is smoothly introduced over a period of ten seconds.

The FEA model uses a fixed time increment, a direct solver and Full Newton. The maximum allowable temperature change per increment is 10 degrees and the maximum allowable emissivity change per increment is 0.1.

The Co-simulation agent uses a Gauss-Seidel coupling algorithm (FEA and CFD are solved sequentially). The target time step for both analyses is the FEA time step. The FEA uses so-called fixed time stepping, i.e. lockstep, and the CFD uses so-called subcycling, i.e. multiple time stepping within a targeted time step.

## Main results

The heat flow in the leading edge is simulated for a situation where the aircraft is on ground with engine on. Several ambient temperatures are chosen as starting condition. Furthermore, cooling of the leading edge is accomplished via a constant mass flow of ambient air into the leading edge. The top part of the leading edge is heated up by a constant solar radiation that leads to a 344K temperature of upper skin. The bottom part of the leading edge is heated via reflection of solar radiation from the ground leading to a 327K temperature of lower skin. Hot air (473K) is heating up the bleed pipe which is modelled via sink temperature and convection coefficient. The right tank compartment is full of fuel at a temperature of 324K while in the left tank compartment the fuel has a temperature of 321K. In addition, the left tank compartment has a fuel level of 12cm from the tank bottom. The ullage space in the left tank compartment has a temperature of 326K.

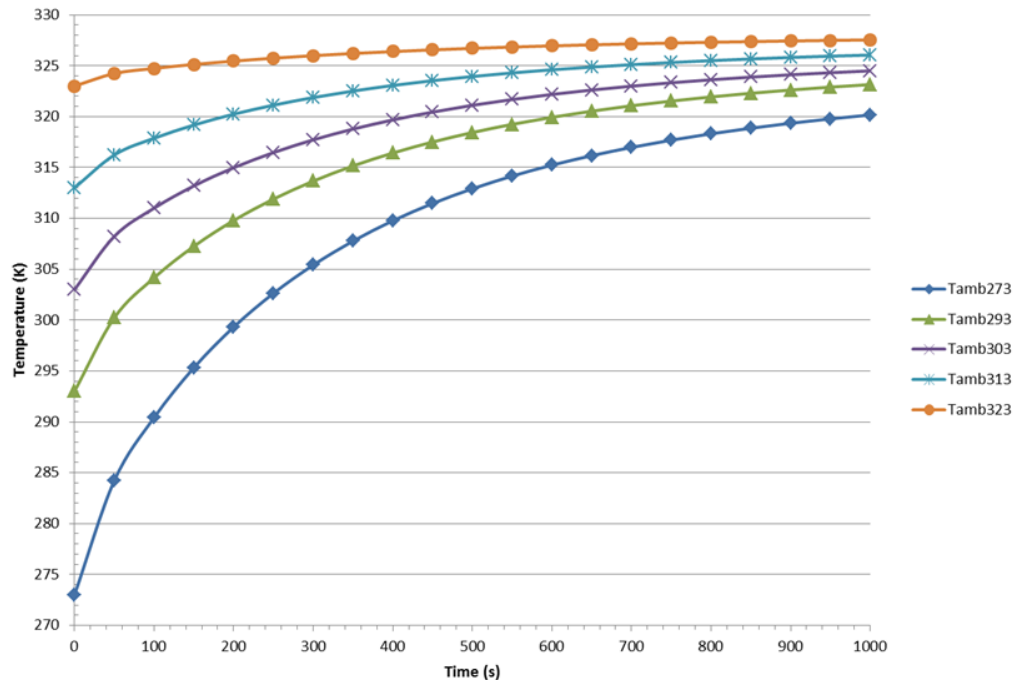


Figure 15: Temperature history of the front spar for different ambient starting conditions. The average temperature of the entire front spar is plotted.

Figure 15 shows the temperature history of the average temperature of the front spar with an output time step of 50 seconds. For different ambient starting conditions the final tempera-

ture approaches a value between 320K and 327K. Hence the effect of the hot bleed pipe is sufficiently compensated for by the cooling effect from outside venting air. Not all transient simulations have reached a final steady-state within 1000 seconds, but for all cases the steady-state temperature of the front spar is not expected to be significantly higher than that of the fuel inside the tank. Nevertheless, Figure 15 shows that the time it takes to reach the steady-state temperature depends on the ambient temperature, ranging from approximately 700 seconds for an ambient temperature of 323K more than 1000 seconds for 273K. The simulations are time consuming. A single analysis can take up to 2 days to run on a single cluster node with 20 cores. Application of such simulations is not practical for long transient simulations and in case the transient behaviour is to be predicted for ambient starting conditions additional to the ones depicted in Figure 15, e.g. during extensive trade-off studies at aircraft level in the early design stages. This is where a surrogate model of the transient behaviour is an added value.

## 5.2 Surrogate model

With the thermal model of the leading edge transient simulations can be performed. However the calculation time of one transient simulation is very long, e.g. up to 2 days for a simulation of 1000 seconds. The high computational effort makes it difficult to apply such simulation as part of efficient thermal analysis during the early design stage. Therefore a surrogate model has been derived using the transient surrogate modelling capability as described in subsection 4.3. The surrogate model of the leading edge predicts the wing spar temperature field at a certain time as a function of the wing spar temperature field during the previous time step and of the ambient air temperature. Equation 1 has been adapted to:

$$\vec{T}(t) \approx f(\vec{T}(t - \Delta t), T_{ambient}(t), \Delta t), \quad (3)$$

with  $\vec{T}$  the temperature field in K,  $T_{ambient}$  in K,  $t$  the simulation time,  $\Delta t$  the time step and  $f$  the analytical function representing the surrogate model. The ambient temperature remains constant during one transient simulation. Therefore a time delay of  $T_{ambient}$  – like applied in equation 1 on the input  $u$  – is not considered relevant here.

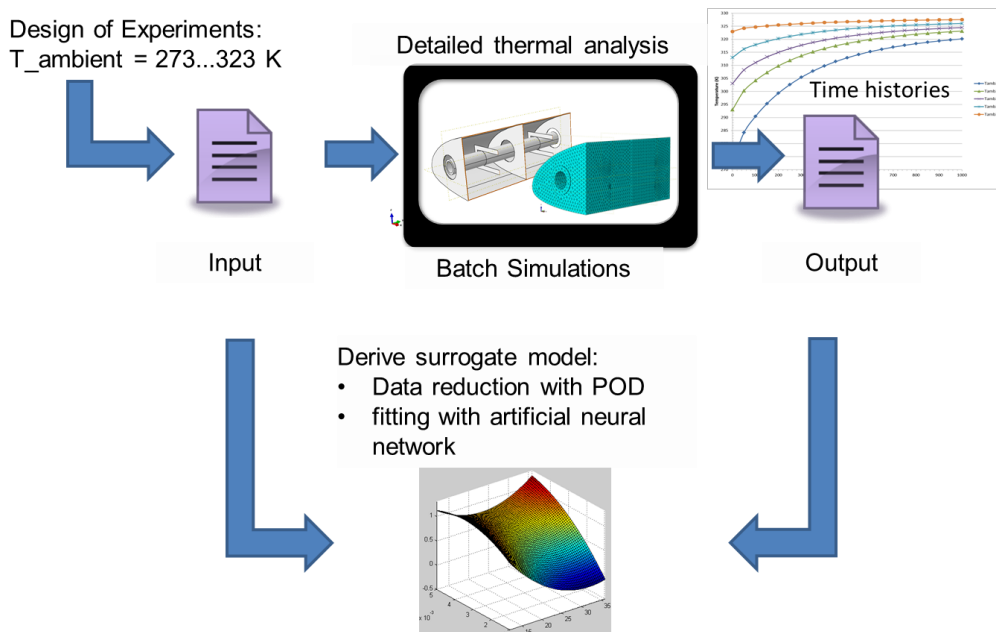


Figure 16: Surrogate modelling process scheme of the leading edge model.

Figure 16 illustrates the process of deriving the surrogate model. Five transient simulations have been performed, starting at different ambient temperatures. The ambient temperature has been varied between 273K and 323K. It is assumed that the temperature of the ventilation air through the leading edge is equal to the ambient temperature. Each transient simulation runs for 1000 seconds with an output time step of 50 seconds (cf. Figure 15). The resulting data represents the temperature field on the wing spar, calculated by the FEA analysis on 2700 nodes.

The spatial dimension of the data has been reduced using POD. The dimensionality has been reduced from 2700 nodes to 5 POD vectors that represent the relevant spatial behaviour over time. The data fitting problem is now reduced to fitting the time history of the POD coefficients, see also equation 2. A recurrent artificial neural network has been applied using a hidden layer of 5 nodes (see also Figure 9). The POD transformation functions have been integrated into the surrogate model such that the surrogate model predicts the complete temperature field at the 2700 spatial nodes. The predictions have a maximum error of 1.6K measured over the full data set of nodal temperatures.

Figure 17 depicts the surrogate model predictions over time together with the FEA data points compared by their spatial mean values. The transient predictions by the surrogate model have been extended to 2000 seconds in order to test the prediction of the steady-states. Within the time interval between 1000 and 2000 seconds the results have been compared with a number of simulation results from additional transient runs with the detailed FEA/CFD model, with output time step 250 seconds. Figure 17 shows that the predictions by the surrogate model between 1000 and 2000 seconds are close to the FEA data points, even though the surrogate model is extrapolating in this region. Close to 2000 seconds the extrapolation starts to give undesired effects: the curves bend downwards again. However, the surrogate model provides a useful means to estimate the steady-state temperatures and the times when they have been reached.

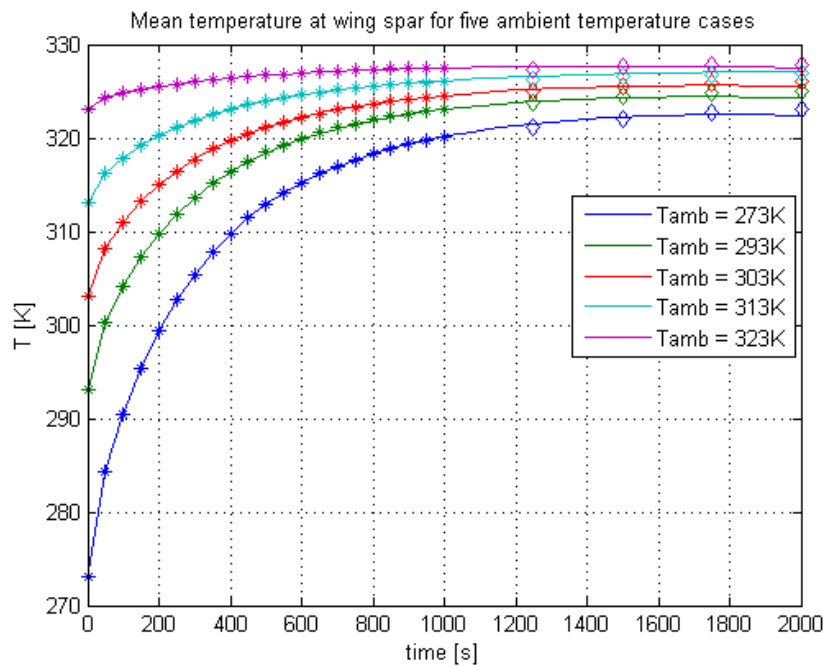


Figure 17: Spatial mean values of the surrogate model predictions (solid lines), fit data points provided by FEA (stars) and additional verification data points provided by FEA (diamonds) for the five simulation cases with ambient temperature variations.



### 5.3 Integrating the collaborative engineering capabilities

The integrated thermal analysis of a wing fuel tank usually involves experts from different disciplines and possibly different departments and organisations. Disciplines involved could concern fuel systems, wing structure, pylon, fuselage, and thermal analysis (FEA/CFD and systems). Organisations involved could be aircraft manufacturers, system and component suppliers, and simulation solution providers. This distributed process can be performed as a collaborative workflow, using Brics for orchestration and data exchange, and using surrogate modelling to bridge the gaps between different simulation tools of the disciplines and organisations. To demonstrate such distributed process a part of it has been realised, namely the derivation of the leading edge surrogate model as described in the previous section.

The calculation of the simulation FEA/CFD data set for creation of the leading surrogate model is a time-consuming process. Furthermore it may be challenging to obtain time slots and permissions for performing the simulation on appropriate computer hardware while using the specific software licenses that are needed. And when all simulations have been performed the generated data may be contained in very large files which are difficult to handle and access. Extraction of the relevant data needed for fitting is still to be performed in a post-processing step. It has been experienced that structuring the whole data calculation process into a workflow improves the efficiency of deriving the surrogate model. Brics supports the implementation of such a workflow, especially when the FEA/CFD thermal simulations are to be calculated by another partner than the one who derives the surrogate model. Figure 18 illustrates the implementation of the workflow. The detailed thermal analysis by means of batch simulations as illustrated in the upper part of Figure 16 is now realised through a distributed process with Brics. This process results in a data set from which the surrogate model can be derived.

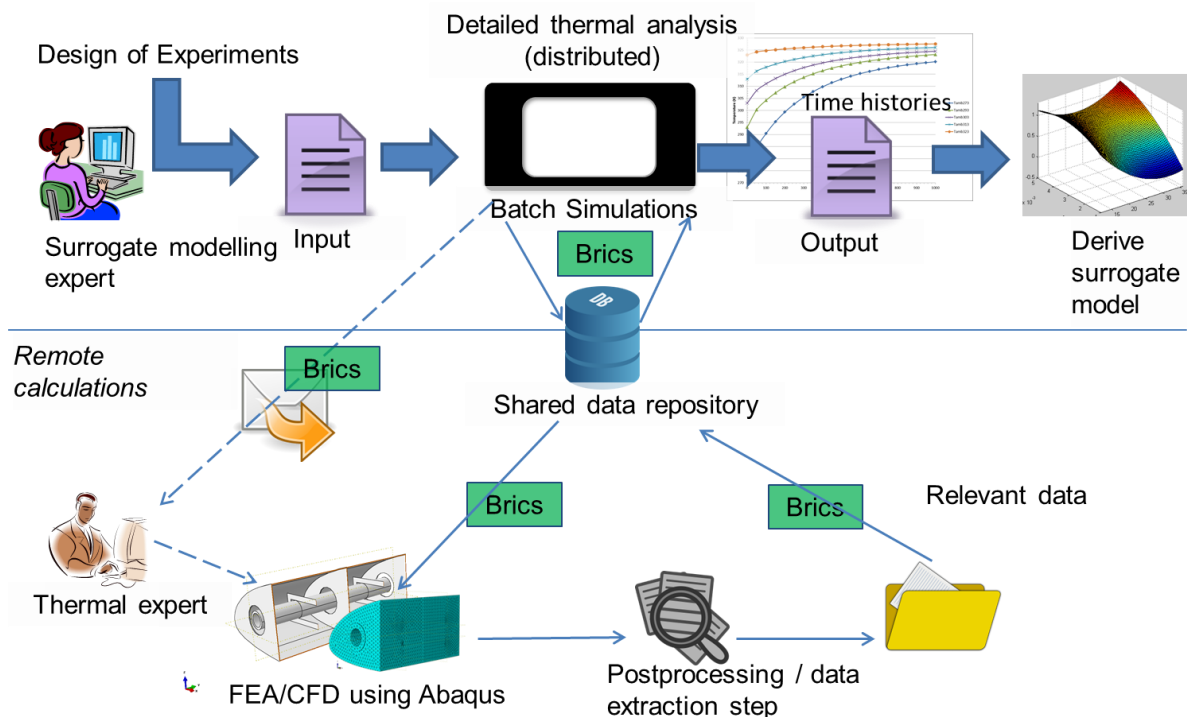


Figure 18: Distributed process for obtaining the data for a surrogate model of the leading edge. The upper half covers Figure 16, while in this figure the detailed thermal analysis is performed in a distributed way.



The surrogate modelling expert does not need to worry about how the data set of thermal behaviour of the leading edge is derived (and how the relevant parts are accessed). This is being performed by a thermal expert who may be part of another organisation or another department. The orchestration of the distributed calculation process and the exchange of the data is performed by Brics. At NLR thermal analysis, surrogate modelling, and distributed collaboration with Brics have been combined in order to derive a surrogate model of the leading edge thermal behaviour in an efficient way.

## 6 CONCLUSIONS

In the paper, we presented two collaborative engineering capabilities that support the need for high level of integrated system design of the aircraft and its subsystems: surrogate modelling and smooth cross-organisation workflow execution. The development of the capabilities took place in past projects, driven by needs and requirements from and discussions with stakeholders, and based on experiences gained with collaborative engineering and simulation solutions built. The capabilities have been further developed based on needs and distributed multi-partner simulation scenarios in the TOICA project. The application of the technologies has been illustrated by realistic examples of collaborative thermal analysis conducted in TOICA. An integrated application of the technologies has been demonstrated in a specific use case: wing leading edge thermal simulation for the thermal analysis of fuel tank.

Based on the experiences with solutions for distributed multi-partner scenarios based on Brics, and successful demonstrations thereof, we conclude that Brics enables the smooth cross-organisation execution of engineering workflows in a world full of security rules and measures, while still complying with the overall and organisation-specific security policies. Through its flexible integration with a variety of standard and COTS software, Brics also demonstrated to be applicable through the various organisations with minimum effort. The impact on the business of the individual organisations is kept to a minimum, apart from the ability to connect to extra-organisation workflows. As such, we conclude that Brics responds to the challenges of distributed cross-organisation collaboration, and hence contributes to effective and efficient collaboration among aircraft manufacturers and their supply chains.

As demonstrated in the fuel tank thermal modelling case, surrogate modelling has proven to make expensive, time-consuming and typically complex simulations of aircraft component behaviour available for quick thermal analysis. In collaborative simulations, it also caters for use of models that may not or cannot be shared with partners for intellectual property preservation reasons or that are restricted by their implementation tools. As such, surrogate modelling has proven providing valuable technology for cost and time efficient simulation during the preliminary design phase.

Furthermore, the detailed modelling of the thermal behaviour of a wing leading edge, based on FEA and CFD analysis, has been described. Such thermal modelling capability caters for detailed analysis of aircraft components that are to be manufactured with innovative materials, such as composites, in order to support certification of these components.

The capabilities have been further developed and demonstrated in the context of collaborative thermal analyses orchestrated by the aircraft manufacturer and performed throughout the supply chain, including small to medium enterprises. More generally, the capabilities can be applied beyond thermal analysis to support modelling and simulation for high level of integrated aircraft design in general, which increases the competitiveness of the European aeronautics industry. The generic character of the capabilities suggests investigating the applicability in other areas, such as automotive and ship-building.

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ment no. 604981 (TOICA, [2]). The authors would like to acknowledge all colleagues from the TOICA project partners who contributed to the success of the collaborative engineering and simulation studies that provided valuable input for the research described in this paper.

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