Black box/white box hybrid method for virtual prototyping validation of multiphysics simulations and testing

G D Todorov¹, K H Kamberov¹
¹Technical University – Sofia, FIT, TMMM, Laboratory “CAD/CAM/CAE in Industry”, 8, “Kl. Ohridski” Blvd., 1797 Sofia, Bulgaria

corresponding author’s e-mail address: gdt@tu-sofia.bg

Abstract. A hybrid method has been developed to predict the level of confidence in the results of multiphysical behavioural simulations of the object by virtue of virtual prototyping (VP) together with physical PP testing based on the stage of the virtual prototyping process and feedback from physical parameters tests. The method is based on three approaches to assessing the reliability of virtual prototype results - initial - for verification of boundary conditions, intermediate - to improve the accuracy of the results obtained and final - to validate the obtained results. A new method has been developed to improve the efficiency and effectiveness of Virtual Prototyping called "WHITE BOX / BLACK BOX" for the study of complex objects by applying VP as a "white box" and VP as a "black box" in iterative connectivity to achieve fine calibration of VP. The novelty of the method lies in the iterative connectivity of VP and PP, and in particular, the calibration of VP by feedback from PP data via a micro-cycle. The "WHITE BOX / BLACK BOX" method and the three approaches to verifying and validating VP have been demonstrated in three successfully completed projects with international industrial partners used as demonstration test cases.

1. State of the Art

Efforts in recent years have been focused on developing methods for virtual prototyping of products presented as complex objects with relatively small production data, allowing for the accounting of additional characteristics of the objects (material properties, object weight, kinematic and dynamic factors). Virtual prototyping (VP) introduces new approaches to engineering activities such as a predictive and prevent approach to minimize errors and reduce the number of physical prototypes (PP) and, accordingly, the cost of eliminating them.

In this connection, one of the great advantages of virtual prototypes can be pointed out - they reach the users of the product even before it is actually created. This also provides a kind of "feedback" through which the needs of the users reach the product developers. This is very important as it has a positive effect on reducing the time and investment involved in developing a new product. Often, more factors than just product characteristics must be considered when a prototyping approach is to be chosen. Liu argues that virtual prototypes are best suited to situations where physical prototyping is impractical [1], impossible or ineffective, while [2] emphasizes that physical and virtual prototypes are not competitive but complementary technologies. Campbell [3] also states that physical and virtual prototyping are two important technologies that must be used together to form a combined toolkit for prototyping complex products.

A critical element in Virtual Product Development (PDP) technology is the level of reliability of the results of engineering analysis and VP simulations. It is defined by two basic concepts:
- Stability, or, how well does the computational model describe the real physics of the state and processes and what is the impact of the model uncertainty (structural or parametric) on the simulation results?
  - Uncertainty of baseline physical condition and boundary conditions (How well are the initial / boundary conditions known?)
  - Engineering (structural) reliability (Does the model accurately reflect the physical process?): for instance - mathematical models of turbulence or model of combustion;
- Parametric stability (How accurately are the model parameters defined?): Condition equations and replacement models; Degrees of reaction and relaxation time;
- Geometric Stability (Does the geometric model accurately reflect the real object)? [4]
- Calculation error, or, how accurate are the results calculated according to the approximations made by a numerical method? [5] [6]

2. Motivation
This study focuses mainly on sustainability. It also looks at how physical modeling and testing can be integrated to increase the reliability of virtual prototyping results through feedback from test results.

Virtual prototyping as a technology involves the creation and use of virtual models to test and analyze a product before creating real physical models or optimizing parameters in parallel with physical prototypes. The application of VP in the study of multiphysical processes can be represented as a set of thermal, structural, thermos-fluid and others. models to simulate coupled processes, see Figure 1.

![Figure 1](image)

**Figure 1.** Simulation approach using Virtual Prototyping in multiphysics – connected processes as thermo structural or thermo fluid.

The practical applications of CFD analysis have been increasing significantly in recent years because it is already considered an industry-leading technology that can significantly contribute to the design, development and optimization of complex products incorporating fluid and / or thermos-fluidic systems. [7] [8]
This is due to the possibility of significantly reducing the cost of development and minimizing physical tests through the implementation of HR, which can also significantly reduce the time to reach the market and development costs.

3. New hybrid approach for virtual prototyping validation of multiphysics simulations
A new hybrid method is proposed here for assessment of the level of confidence in the results of analyzes of the behavior of an object under study through virtual prototyping (VP) using CFD, combined with physical testing on PP.

3.1. Alternative preliminary approach for VP validation by physical prototypes
Possible approaches for the implementation of physical prototyping for verification and validation of virtual prototyping results are considered. The following figure (figure 2) shows the different stages of the simulations and the location of the physical tests in the process.

![Stages of building a model of conducting an engineering analysis and a place of physical prototyping](image)

As can be seen from the figure, description and sequence of process steps, there are three possible approaches to applying physical tests to assist virtual prototyping - according to the stage of their use:

- Preliminary Verification Approach VP - the purpose in this case is to assist in defining / verifying boundary conditions - both in type and in parameters. This is a convenient approach to check the applied known boundary conditions, especially when using a hypothesis that does not fully cover the modelled physical case.
- VP Intermediate Validation Approach - mainly used to validate the simulation model constructed using intermediate measurements using the PP, very often on a partial physical prototype (of a process element or type) or an PP prepared from different material or different from the final production process;
• Approach for validation of VP through the results of PP. This type of assessment is integral to the behaviour of the prototyped object, as it is usually a "checkpoint" that proves not only the validity of the model but also the accuracy of the results.

Each of these approaches is demonstrated in the study through three examples of industrial projects undertaken by the author and team and demonstrated below.

3.2. Demonstration of an approach for pre-verification of VP

The specific example relates to the study of the design of a temperature sensor for the automotive industry in order to improve its operating parameters (response time and measurement accuracy) by means of a multiphysical engineering analysis (thermo-fluid). The example demonstrates the pre-physical testing approach. The reproduced physical process refers to an experimental setup in which the sensor's AF is placed in a flow of hot gas flowing at a controlled rate and temperature in a test tube - analogous to an ICE exhaust pipe (internal combustion engines). Figure 3 shows the experimental setup for physical testing.

The sequence of the experiment involves inserting the prototype of the sensor in the middle of the heated air flow into the tube in less than one second and starting the temperature measurement.

The purpose of the test is to determine the response time (dynamics) of the sensor by two main characteristics - a time to reach 63% (t63) and 90% (t90) at the final set temperature - that of the air flow (loss accounting). The VP via the computational model aims to replicate this experiment by simulation under the same conditions.

The main problem in modeling this experiment is related to the initial boundary conditions. The computational model includes only the tip of the sensor that is submerged in the air stream, while the rest, outside the tube, is not represented. In this way, the heat flow through the part outside the pipe cannot be correctly taken into account, nor can the “immersion” of the sensor itself into the pipe be reproduced. Although the introduction of the sensor into the heating zone occurs in a relatively short time, there is no real possibility to reflect this, nor to account for the volume of ambient fluid brought together into the sensor at this early stage of heating, which is also characterized by high intensity of the process.

In reality, there is no convenient way to reproduce this process and this is a source of uncertainty in its modeling.

The boundary conditions applied to the computational model are also shown on figure 4. They include convective heat exchange along the outer surface of the tube of the sensor, represented as a
convection coefficient to ambient temperature. In fact, there is insufficient data on this factor, which should reflect the heat dissipation outside the pipe.

![Figure 4](image)

**Figure 4.** Computational model and set boundary conditions for temperature sensor (air flow and convective heat exchange on the outer surfaces of the sensor).

It is appropriate to use this preliminary approach to help determine the parameters of convective heat transfer. A physical test is performed using the experimental setup, and then a series of analyzes varying the convection parameters is made to iteratively reach their correct values. This is a good basis for further engineering analyzes on various design variants that use the already determined convective heat transfer parameters.

![Figure 5](image)

**Figure 5.** Comparison of data from a simulation model with test results with a physical prototype under the same conditions.
After validation of some VP parameters, which cannot be theoretically determined (e.g. convective heat transfer on the outer surfaces for a very short time) by comparison with the AF, a high degree of adequacy of the VP is achieved in a few steps. A comparison between the physical prototype test data and the virtual test data is shown in figure 5, together with the results for the calculated sensor response times. It shows good correspondence, which shows the adequacy of the preliminary approach applied.

Thus, VP can be used with a higher level of validity for testing various design modifications by conducting so-called planned virtual experiments with VP, which saves a lot of time and means of producing physical prototypes and testing them under the same conditions.

3.3. Demonstration of an VP Intermediate Validation Approach

The example given for the implementation of the proposed "Intermediate Validation Approach for VP" in practice is exemplified by a specific example of an industrial design for improving the functional parameters of a convection module, which is an important component of microelectronics production equipment of the tunnel kiln for heat treatment "Components - Solder" Surface Mounted Device (SMD) PCBs. This process equipment is part of a mass production line utilizing SMD technology that soldered the pins of the components to the circuit boards using pre-applied paste.

The process of SMD technology with lead-free formulations imposes high requirements on the thermal profile of the heating (mainly the duration, the rate of heating and the temperatures reached in the respective stages of the process), which is provided by this technological module.

In addition to the requirements for:

- precise heating rate (dynamics);
- allowable blowing speeds of heated objects (to avoid displacement);
- a very high uniformity of heating over the entire active area of the electronic circuit board is also required, taking into account the differences in their mass and size.

![Figure 6. Examined design of a convective module, part of the technological equipment for SMD Line.](image)

These high requirements have necessitated the use of virtual prototyping technologies that allow the evaluation of these parameters in a very large detail by applying a "dual" VP <-> PP counter.

The end goal in this approach is again a reliable analysis of the thermo fluid process and the more accurate calibration of the model to adequately simulate the behavior of the structure in order to improve the required parameters and to achieve the best possible operating mode of the module in terms of the observed parameters for convective heat transfer.

A schematic of the structure under study is shown in principle on figure 6.

The model under consideration is well defined as geometry, which allows one to construct a geometrically accurate computational model and to set boundary conditions adequate to the modeled physical process.
The challenge in this task comes from several significant nonlinearities related to the temperature dependent properties of the materials, which lead to a strong nonlinear behavior of the system under study and require a definite need for validation of the results obtained by physical tests. The calculation model used is presented on figure 7.

![Figure 7. Calculation model (based on more than 1 700 000 finite elements) and boundary conditions for the convective module computational model (heated air outlet, plate heat and turbine flow).](image)

Existing nonlinearity in the modeled object requires an intermediate verification of the results. This check is performed by comparing simulation data with physical test data on the functional prototype of the convective module. Air flow velocity measurements on the physical prototype are performed using calibrated high temperature anemometers.

The physical prototype designed for this purpose and the locations of the probes for measuring the flow velocity are shown on figure 8.

![Figure 8. Physical prototype of the system and anemometers location for measuring air flow velocity at specific points of monitoring.](image)

The results of the simulation thermal analysis using the virtual prototype created and the comparison with the measurements on the physical prototype are shown on figure 9.

The correspondence between the data of the physical prototype test and that of the simulation analysis of the virtual prototype is clearly visible. In fact, this correspondence is achieved through several iterations of model parameter values such as turbulence coefficients, as well as some boundary conditions adjustments (for example, a fan operating point that depends inversely on the system impedance).
These repetitions are performed at the "Model Verification" stage, as well as small modifications at the "Simulations" stage, and is a typical example of the approach described above to increase the reliability of the results of intermediate simulations.

Figure 9. Virtual prototype results and comparison with measured values on a physical prototype.

The resulting parameters for the computational model setup are used to further optimize the design. The final result is tested on the physical prototype by directly measuring the basic operating parameter of the product - the heating temperature and its distribution on the surface of the circuit board.

4. A new white box / black box method, developed for practical applications and tests
This forms a well-structured approach for benchmarking, goal setting, model validation, parameter input, hybrid modeling, etc., which will contribute significantly to the overall goal of creating methods for faster, cheaper, and better development of new products.

On this basis, an innovative treatment of the ideology and philosophy of using PPs and VPs is formed as a dual method of implementing VPs and PPs in non-exclusive reciprocal application and with significantly improved quality and time indicators of the development process. The proposed new method for assessing the level of confidence in the results of virtual object prototype (VP) behavior tests and physical prototype testing is based on three approaches to applying physical tests to assist virtual prototyping - by stage of use, them:

- Approach for pre-validation of the HR - the objective in this case is to help define / verify the boundary conditions - both in type and in parameters. This is a convenient approach to test the known boundary conditions applied, especially when using a hypothesis that does not fully cover the modelled physical process. [9] [10]
- VP Intermediate Validation Approach - Mainly used to validate the simulation model constructed for the adequacy of the results obtained through intermediate measurements using the FP, very often on a partial physical prototype (of elements or process type) or PP prepared from different material, or with a different production process.
- Approach for verification of VP through the results obtained from the PP. This type of evaluation is integral to the behaviour of the prototyped object, as it is usually a "checkpoint", but is limited to be effective in the eventual negative results of the comparison of experimental data from the PP, which does not quickly lead to useful guidance on how to refine the simulation model.

From the point of view of the information that is entered and received accordingly from the prototype tests, they can be distinguished into two main categories: 'white box' - using the VP and 'black box' testing - using the PP.

The definition of "white box" is known as a tool mainly in the software industry and refers to systems for which structure and interconnections are known and can analyze the results based on the traceability of input / output processes [11]. The white box implies that we have full visibility of the
internal workings of the system, in particular the logic and structure of the processes. Using white box testing techniques, the engineer can design test cases that are well investigated at the structural level, but very accurate quantitative results cannot be obtained due to the simulation type of virtual calculations.

White box testing (also called "comprehensible box" or "transparent box") assumes that the analyst designer knows and understands how the VP works - they can "see inside" in the simulation models, figure 10. Application of "white box" it is usually for designers as experience in modeling and simulation is required to create and use VPs.

Black box testing (also called "behavioral testing") is applied to physical tests. It requires the test specialist to understand what they need to do during the tests, but it is not necessary to understand exactly how the system under study works - the tests are not able to "see inside" the structure and logic of the processes in the AF. Here, the author proposes a new method for investigating complex objects by combining the application of HR as a "white box" and PP as a "black box" in an iterative connection.

Once the initial type of VP has been built, test simulations are conducted at points in the parameter space that can be adequately reproduced and tested with a physical prototype considered as "Black Box".

![Diagram: Physical Prototyping and Virtual Prototyping](image)

**Figure 10.** The method of combining the "WHITE BOX" using the VP and testing of the “BLACK BOX” using the PP.

The test results obtained from the AF are generally more accurate than the simulation accuracy. The quantitative results of the physical tests obtained are appropriately interpreted in the coefficients of the VP models, which are not well defined theoretically (e.g. friction coefficients, energy dissipation coefficients, contact effects, etc.). This process is repeated iteratively until a good level of agreement is obtained between the simulation results of the VP and the measurements from the PP tests. The test cases discussed above, prove the effectiveness and efficiency of this method.

Figure 11 shows the combination of the implementation of VP as a "white box" and the PP as a "black box".

The novelty of the method is the iterative connectivity of the VP and the AF, and in particular the calibration of the VP by feedback to the PP data through an internal micro-iterative cycle. This task is
essentially a "reverse" - given exact output results and identical input effects, determine the parameters of the VP's computational models to achieve them. Multiple problem solving is applied to solve this inverse problem - the values of the corresponding coefficient in PP are set and the outputs of the simulations are monitored, and micro-iterations are applied within the VP to achieve good consistency of the obtained output results from the simulations, compared to those measured by the PP tests, with the same input parameters. Thus postulated, the method provides a great opportunity to achieve rapid and accurate research by iteratively matching the VP in the process of its construction and tuning, by rational and effective use of black box test data in the development phase of new products. In the presence of verified and validated VP, a large number of virtual simulations can be performed with it to investigate variants or to optimize different aspects of the product, while maintaining the structure and process identity within the validity range.

![Diagram of Virtual and Physical Prototypes](image)

**Figure 11.** Combining the application of the VP as a "white box" and the PP as a "black box".

### 5. Conclusions

A hybrid method has been developed to predict the level of confidence in the results of multiphysical behavioral simulations of the object by virtue of virtual prototyping (VP) together with physical PP testing based on the stage of the virtual prototyping process and feedback from physical parameters tests.

Three approaches to assessing the reliability of the results of virtual prototypes - initial - for verification of boundary conditions, intermediate - to improve the accuracy of the results obtained and final - to validate the obtained results.

A new method has been proposed to improve the efficiency and effectiveness of Virtual Prototyping called "WHITE BOX / BLACK BOX" for the study of complex objects by applying VP as a "white box" and VP as a "black box" in iterative connectivity to achieve fine calibration of VP. The novelty of the method lies in the iterative connectivity of the HF and the PP, and in particular the calibration of the VP by feedback from PP data via a micro-cycle.
The "WHITE BOX / BLACK BOX" method and the three approaches to verifying and validating VP have been demonstrated in three successfully completed projects with international industrial partners used as demonstration test cases.

Acknowledgments
This work was supported by the European Regional Development Fund within the Operational Programme “Science and Education for Smart Growth 2014 - 2020" under the Project CoE “National centre of mechatronics and clean technologies” BG05M2OP001-1.001-0008.

6. References

[1] Liu B & Campbell R I 2008 Real time integration of user preferences into virtual Undisciplined! Proceedings of the Design Research Society Conference 2008 (Sheffield UK)
[2] Grimm T A 2005 Virtual Versus Physical: Will Computer-Generated Virtual Prototypes Obsolete Rapid Prototyping Time-Compression Technologies vol 13 no 2
[3] Campbell R I 2004 A comparative study of virtual prototyping and physical prototyping International journal of manufacturing technology and management vol 4 no 6 pp 503-522
[4] Jivkov V Zahariev E Nikolov N 2018 Rotating cantilever beam with variable geometry – Frequencies and modal vectors Comptes Rendus de L'Academie Bulgare des Sciences vol 71 iss 8 pp 1108-1115
[5] Barth T 2011 A Brief Overview of Uncertainty Quantification and Error Estimation in Numerical Simulation (NASA Ames Research Center)
[6] Brinkgreve R 2013 Validating Numerical Modelling in Geotechnical Engineering (NAFEMS)
[7] Desai S 1999 Growth of CFD as an engineering tool for design and analysis of aerospace vehicles Current Science vol 77 no 10 pp 1283-1294
[8] Hellen T Becker A 2013 Finite Element Analysis for Engineers – A Primer (NAFEMS)
[9] Nedelchev K Kralov I 2019 Acoustic method for identification of railway wheel disc structural vibrations using COMSOL Journal of the Balkan Tribological Association vol 25 iss 3 pp 546-557
[10] Sofronov Y P Stoyanova Y P Kopravec N E Todorov G D 2019 Kinematic study of the articulated trucks operating layout of turn for articulated vehicles IOP Conference Series: Materials Science and Engineering vol 618 iss 1 article no 012044
[11] Beizer 1995 Black-box testing: techniques for functional testing of software and systems (New York: John Wiley & Sons, Inc.)