Methodologies and Processes to Achieve Earlier Virtual Integration of Aircraft Systems

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Abstract

The design of modern aircraft is challenged by their continuous increasing complexity, driven by the competitive environment in which aircraft integrators operate. For this reason, airframers are constantly looking for methods to assess the interactions among systems as early as possible in the design phase, with the ultimate goal to ensure competitiveness in international markets. To support these needs, methodologies and processes based on Model Based System Engineering, Modeling and Simulations, Verification and Validation procedures, and on the typical aircraft and manufacturer organizational breakdown structures are presented in this paper. As a result, the complex modeling process is harmonized and secured, and the know-how developed within the organization is capitalized. Finally, an earlier integration of the models representing the aircraft systems can be achieved, their interactions evaluated, and different architectures compared. A use case will be presented to illustrate these methodologies.

1. Introduction

One of the main challenges of modern aircraft's design deals with their increasing complexity. New technologies, ecological and regulatory constraints, as well as economical competition are just a few factors that lead to the design of more interconnected systems and to their tighter integration on aircraft.

For this reason, aircraft manufacturers are striving to find means to accurately assess the interactions among systems and sub-systems since the beginning of their design, with the goal to produce better integrated products and reduce their time-to-market. As a result, this leads to costs reductions throughout the aircraft design and production phase, and an increase of operational reliability, ensuring competitiveness in international markets.

To successfully tackle these problematics, in the past years airframers began a paradigm shift towards Model Based System Engineering (MBSE) methods. However, this evolution is far from be completed. Modeling and Simulation (M&S) means are not used homogeneously within different fields: where tests are costly or only partially representative, the simulation capabilities are more developed than in domains where physical testing is easier. Moreover, skepticism towards numerical models that reproduce physical phenomena is still encountered, especially because of the difficulties to validate those models and the lack of expertise on these new methodologies[1] . However, the benefits from MBSE methods are undeniable, as confirmed by the growing interest towards them by important aircraft integrators[2] shown by several research projects on this topic[3][4] .

In order to answer to these needs of the the aerospace industry, a set of methodologies and processes supported by tools called *Virtual Integrated Aircraft* (VIA) is proposed and described in this paper.

As of now, it is common for the aircraft systems integration to take place during the test and validation phase of the program development by means of physical prototyping. Given the ever-increasing complexity of aircraft programs, both technological and organizational, it is likely that design issues found in this phase or the evolution of regulations and certifications during the program development lead to design changes, generating costly delays.

The purpose of the VIA methodology is to achieve the aircraft systems integration earlier in the development phase, bringing it forward from test and validation phase to development phase. This is illustrated in the diagram in Figure 1 representing the phase gate model[5] . The benefits of an earlier integration are not only related to the possibility to detect issues in a phase where design modifications are less expensive, but also to optimize, and therefore reduce, the use of expensive physical prototyping. As a result, the product can benefit of an improved quality and reliability. The achievement of these goals, and therefore the VIA methodology, relies on M&S techniques.

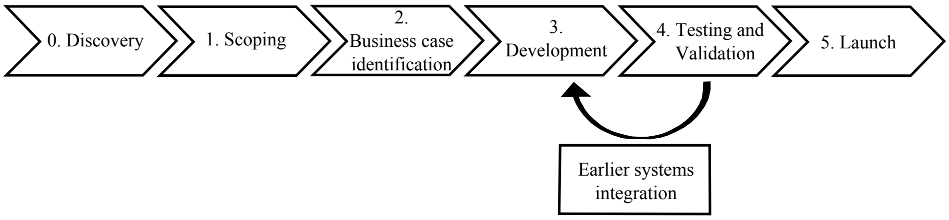


Figure 1: Phase gate model with methodology expected outcome to achieve earlier virtual integration.

2. Underlying Principles of Virtual Systems Integration

The virtual integration of aircraft systems is the outcome of the modeling process, starting with the creation of models and their assembly, and following with simulations and results analysis. As such, it depends on how this process and its supply chain are managed in the context of the extended enterprise and the final product. The following principles on which the virtual system integration is based are identified:

1. Model Based System Engineering principles;
2. Behavioral Modeling and Simulations;
3. The Vee cycle and the Verification and Validation procedures applied to it;
4. Aircraft functional decomposition and work breakdown structure;
5. Multidisciplinary Optimization Methodologies.

Model-Based Systems Engineering

Model-Based Systems Engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases[6] .

In the context of aircraft design, a correct implementation of MBSE processes allows to better handle systems complexities and enhances the communication among the actors of the design and integration process. The result is an earlier integration of the aircraft systems on a virtual platform.

Modeling and Simulations

M&S techniques have gained terrain in the past decades, especially due to the increase in the computing power. However, if they are not used in accordance to rigorous principles and following the good practices of MBSE, their effectiveness as a decision-making tool decreases. Furthermore, it is common that different platforms, procedures, and *modi operandi* are used among the actors participating to the modeling phase of the aircraft systems, making difficult to combine their efforts. As a results, M&S techniques are used as marginal standalone tools capable to tackle specific problematics, whereas they should be integrated and coordinated in the global context of the modeling phase involving the airframer and the supply chain (suppliers, subcontractors, ...). To this extent, they should be used within a well defined modeling process.

Vee Cycle and Verification and Validation Procedures

The Vee cycle (or Vee model), as shown in Figure 2, is a graphical representation of the distinct phases executed by systems engineers and developers to design, build, test, and integrate technological products. The left side of the V indicates the requirements decomposition into specifications allocated to components at lower levels, while the right side represents their integration and validation. The Verification and Validation (V&V) procedures are applied to check that systems meet requirements and specifications. In the project definition phase, these procedures are applied in cascade from top level systems down to sub-systems and components. In the same way, requirements are given for the top level and then adapted and decomposed in more detail. Components and sub-systems are verified in order to

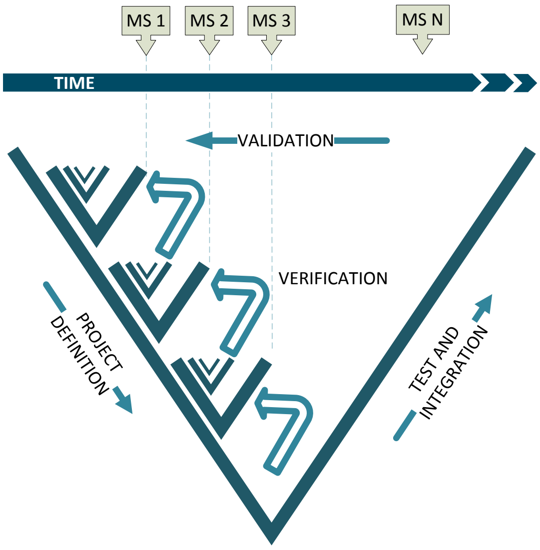


Figure 2: Vee cycle with MileStones (MS), V&V procedures, and sub-cycles. Note the fractal structure of the cycle.

evaluate if they comply with the requirements. In the test and integration phase, the developed items are validated to ensure they meet the needs identified at the beginning of the process.

For each milestone, V&V procedures are iterated at a smaller scale, *i.e.* at deeper sub-level of the cycle, shaping it as a *fractal structure*. The interest of this fractal dimension resides in the predisposition for the *scalability* of methodologies which address these particular aspects. From a MBSE and M&S perspective, this design paradigm gives the possibility to create models that can grow in size and/or complexity accordingly to the cycle evolution. For example, at the beginning of the design phase top level requirements are given, such as the overall system power consumption. At this stage, a model representative of these requirements can be created to assess the power generation, losses, and consumption. Once power is allocated to sub-systems and components, more detailed models of these elements can be created to address problematics concerning their peculiar behavior on a smaller scale (*e.g.* water hammer, cavitation phenomena). The integration process must take into account and guarantee the models heterogeneity, ensuring communication among models created with different software. Finally, their evolution process must be secured by an appropriate software infrastructure.

Aircraft Functional Decomposition and Work Breakdown Structure

Aircraft can be considered as *complex systems*, as they are composed by a network of interacting systems, such as Electric Power System, Hydraulic Power System, Air Systems, Flight Control Systems, etc., each of them fulfilling different functions in order to safely operate the aircraft. In order to ease the design, assembly and maintenance of aircraft, the so-called ATA-chapters classification[7] , established by the Air Transport Association (ATA), are commonly used to structure the sub-system responsibilities and define interfaces among them. This classification represents a functional breakdown of the whole aircraft and defines the perimeters of each system. As this decomposition is widely accepted by the aerospace community for several decades, and it is consistent for the aircraft certification purposes, it is taken as a reference by the methodology proposed.

A Work Breakdown Structure (WBS) is a product-oriented family tree that identifies the resources required to achieve a project objective. To this extent, it divides the work content into manageable elements, with increasing levels of detail, with the purpose of easing the planning and control of cost, schedule, and technical content of a project[8] . For this reason, engineering branches of aircraft manufacturers companies, as well as their work-flow, are organized around the product complexity. By adopting a functional organization structure as depicted in Figure 3, each unit or department is responsible for one aircraft system (or more than one if strictly related). These units are in turn organized in a similar way: for each program, key roles are assigned to individuals according to their competences, in order to coordinate the design and the integration process. This internal WBS is repeated in different projects and at different steps of the process. As for the V&V procedures, the WBS allows the application of scalable methodologies throughout the whole organization.

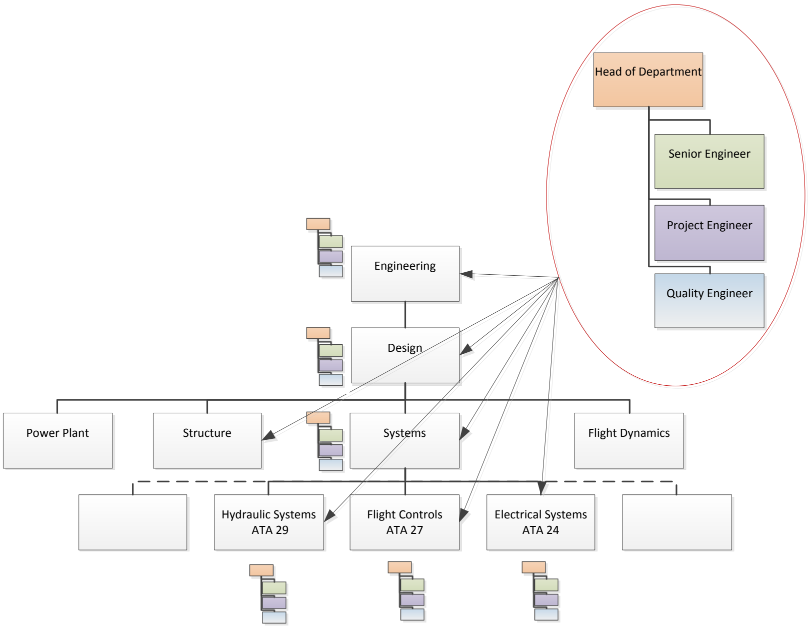


Figure 3: Typical organizational structure of an aircraft manufacturer. The same functions (roles) are found in several units/departments.

Multidisciplinary Optimization Methodologies

The virtual system integration falls into the perimeter of the so-called multidisciplinary optimization methodologies, which focus on the physical interaction among different components. MDO is defined as an approach to the design of complex systems that takes into account the existence of interdependent physical phenomena at several level of detail that allow *"to decide what to change, and to what extent to change it, when everything influences everything else"*[9][10] .

Thanks to improvements in computing power, and solvers efficiency in the last decades, the role of M&S in the design cycle of complex systems has definitely changed. Aircraft manufacturers rely more and more on numerical simulations for the design of their products, complementing physical tests, and allowing engineers to validate the integration of all the systems earlier in the design cycle. This positions M&S as a critical decision-making tool for the engineers. Therefore, it is important to ensure that the creation of these models is controlled and secured.

3. VIA Methodology

The VIA is defined as a set of methods that enables the virtual integration of complex systems since the early stages of the aircraft design process. It is proposed as an evolution of the current state of the art, and it is based on the principles illustrated in the previous section. In particular, the methodology complements the modeling process transition towards a MBSE, paving the way to the models integration. It embraces the Vee cycle design paradigm, capitalizing its intrinsic notion of scalability, and fitting into the aircraft classification and company organization.

As illustrated in Figure 4, the VIA methodology aims, on one hand, to harmonize the modeling process among its contributors (company's departments, suppliers, subcontractors). This is done by identifying common procedures and protocols to be adopted in the frame of a coordinated process. On the other hand, it aims to consolidate the modeling phase in order to capitalize the know-how generated, to trace the models created and their use with respect to the decision making process, and to reduce the risks related to this critical phase. With the help of dedicated tools, *i.e.* a platform able of integrating models generated with different tools, and a software that provides versioning capabilities relying on Roles Based Access Control (RBAC), it is possible to put together an infrastructure that supports the methodology presented in this paper.

In order to optimize the model production, their creation should obey to a set of rules clearly established in the context of the company or extended-enterprise. To this end, the process is decomposed and analyzed, and good practices are recommended.

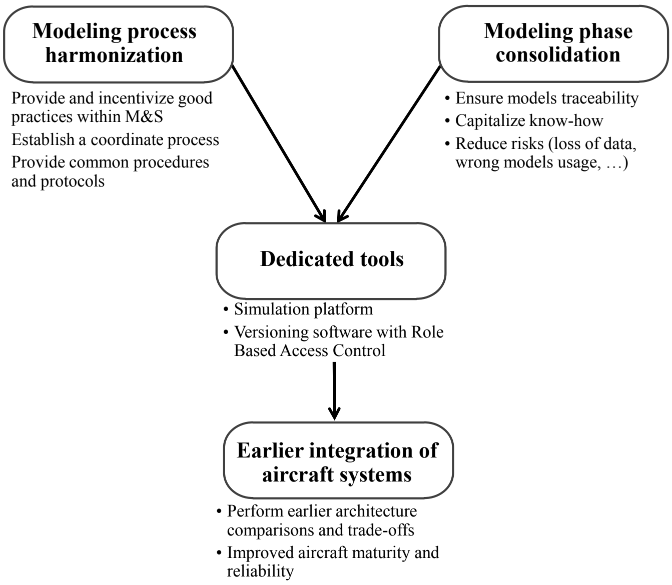


Figure 4: VIA methodology.

Analysis Definition

The design phase involves analysis to be performed in order to control the impact of a design choice on the system. Their request is initiated by the system architect who must perform the trade-off, and it is executed by the expert of the relevant domain. Numerical models are questions formulated to a computer to provide an answer to an analysis request. To get the most out of them, *i.e.* more efficient analysis, it is important to clearly define the expected outcome: their purpose must be clearly understood and agreed between the customer and the supplier. As a consequence, a list of requirements for these models is determined during this phase. In order to thoroughly define the analysis, the following aspects must be considered:

1. Purpose of the analysis;
2. Boundary conditions, intended as:
   (a) Physical environments in which the model operates;
   (b) Assumptions made on the model and therefore its limitation. Assumptions are needed in order to compensate for the lack of information or to reduce the model complexity in order to achieve the intended goals more efficiently;
   (c) Time duration of the analysis;
   (d) Definition of the computational means to perform the simulations;
3. Results definition, in particular with respect to the:
   (a) Accuracy (against experimental data when possible);
   (b) Sensitivity of results to parameters variation;

Model Production

Once the analysis is clearly defined, the first step towards the harmonization and standardization of the process is to define a communication protocol among models. Its purpose is to eliminate compatibility issues during their integration, and provide the means to asses different kind of analysis keeping the same model organization. The implementation of this protocol is called Interface Contract Definition (**ICD**), a notion taken from the mechanical integration of real equipment into the airframe. It consists of a functional decomposition of the system which is represented by the model, identifying what information it exchanges. The ICD contributes to the definition of the responsibilities associated to each element (systems as well as components), and its ultimate goal is to link the different models during the integration phase. Its practical purpose is to differentiate between the content of the model, which can vary according to the needs, and the way it communicates with other models. This principle is valid at all levels of the design cycle.

For example, it is possible to apply this concept to the model of a landing gear and braking system, as illustrated in Figure 5. Firstly, the interface is defined: five connections (or ports) are identified. A thermal port allows to exchange information concerning the heat dissipated by the system which is used to compute the temperature of the structural parts. Through the hydraulic and electric connection, the system receives the pressure and voltage provided by the respective systems and it requests the flow rate and electric current needed to operate. The mechanical port connects the landing gear with the boundary conditions representing the ground and the aircraft body, so to compute the ground reaction. Finally, control signals are exchanged through the signal port to monitor and command the system.

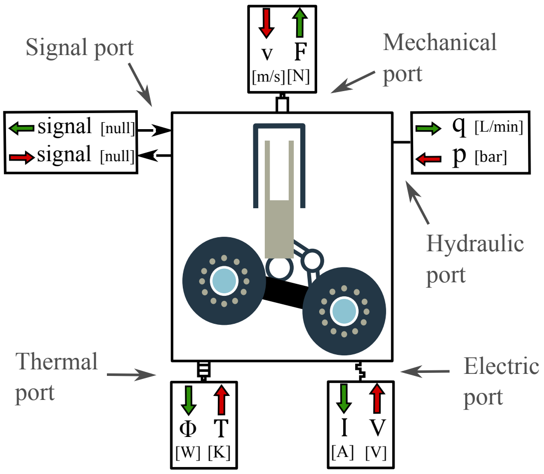


Figure 5: Example of ICD for the landing gear and braking system (ATA 32). For each port, the quantities exchanged are specified along with their causality: inwards arrows indicate the inputs, outwards the outputs.

After that, the models requirements and ICD are defined, and it is possible to look for models already available within the company to satisfy the request. In case such a models do not exist, their production must start.

Quality Control and Sharing

At this stage of the modeling process, the model of the component, sub-system, or system is completed. The next step consists in three actions:

1. Check the quality of the model and validate it;
2. Assess the model's reliability, *i.e.* their fidelity and uncertainty with respect to experimental data and to which extent they impact important decisions.
3. Share it among the actors involved in the modeling process at the same or at higher levels.

At this point, a version control software with RBAC is necessary to provide a consistent support to these actions. The primary purpose of this software is to establish a connection among a common data repository, where all the models are stored and shared, and the local machines, where these models are produced and used. Once shared, the relevant actors of the modeling process can make a local copy of the model they need in order to integrate them with their current tasks. However, in order to coordinate this process and secure the contribution of every actor, a lean hierarchy is established by using rights allocated to the users. Roles and the associated rights are particularly convenient to manage intellectual properties and confidential data attached to the models, as the access to the information stored in the common repository is regulated through them. Roles are assigned by the software administrator, who is in charge of managing the virtual infrastructure.

Before uploading (or publishing) a model to the common repository, it must undergo a quality check to be labeled as validated against the requirements expressed by the analysis request. In order to limit errors and make the process more robust, the clearance must be authorized by a different person than the engineer who built the model, such as by a qualified engineer with relevant experience. Furthermore, the completion of the uploading phase can be achieved only upon provision of attributes describing the model (*e.g.* purpose, author, hypothesis, credibility, etc), along with documentation if needed. This information can be thought as a label attached to the model and it is necessary to understand its goal, limitations, and reliability concerning the impact it has on the decision making process[11] .

Model Usage, Integration and Assembly

At this point, the model is available and ready to be used. It passed a quality check and it comes along with the necessary information (documentation, attributes) that describes its purpose, reliability, and assumptions. In some circumstances, there might be no need to integrate it in larger models. It can be the case of the analysis of a single component where the boundary conditions are well known, the interaction with interconnected system is deemed as negligible or simply not important at the present design phase. Therefore, simulations can be run and results analyzed, terminating the analysis request and the given modeling process. It is possible that the answers provided by the model are not completely satisfactory, or new questions may arise requiring a more detailed or a different model. In this case the modeling process restarts.

A more interesting scenario for the VIA methodology, consists of the integration of validated models, assembling thereby the expertise coming from different actors and expressed as numerical models. In fact, the process described allows the system engineer to assemble the models they need in order to answer to analysis requests given at system level. Supported by the version control software, they have access to all the validated sub-systems/components models shared in the repository. Thanks to the ICD applied to each of this model, the integration process is straightforward, as all the connections among models have been declared and identified *a priori*. Clearly, if the final assembly consists of models created with different platforms, simulations must be run with software that allows to interface them or by means of co-simulation tools.

Architectures & Solutions Comparison

The purpose of this phase is to compare the simulated behavior and performance of different systems architectures or technological solutions. The chief engineer or system architect, who is in charge to select the best configuration, relies on their expertise and on the models and simulations results available. However, it is not always the case that they have a deep knowledge of the modeling techniques, or simply the time, necessary to create the assemblies and analyze them. At this stage, a system architecture management tool is needed to capitalize all the previous phases of the modeling process. This tool is able to provide a continuity between the engineers working on the models development and the final customers who make use of them to support important decisions concerning the system design.

The process here described can be envisaged to cover the whole product development, and it can be incorporated into the Vee cycle. As each milestone involves questions with a precise level of details that a model is required to answer, with the correct model management it is possible to address all the levels of details needed during the design phase, as depicted in Figure 6. It is clear that a high level analysis, such as the assessment of the power needs of the global system, does not require the same detailed modeling techniques and resources as the study of the flow separation over a wing. By adapting the level of refinement of each model in order to provide an answer to precise questions, *i.e.* by defining the *model intent*, it is possible to optimize and speed up the modeling process.

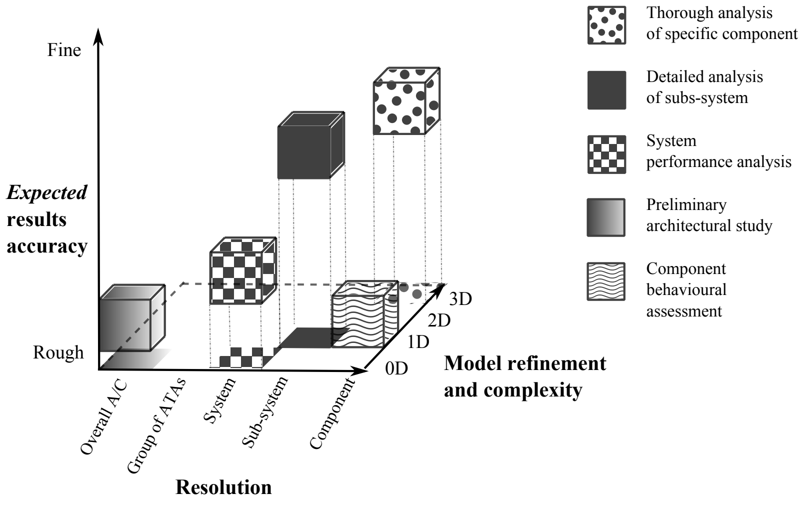


Figure 6: Examples of models needed for different kind of studies that take place at different stages of the development phase. The cubes represent distinct models.

During the design cycle, the first iteration of the model production is based on the requirements expressed by the aircraft manufacturer (or systems integrator) to the appropriate departments or suppliers. These requirements are usually expressed with mathematical envelopes, describing the expected systems behavior, the operational limits, and the assumed boundaries conditions. Suppliers use the provided environment to design a technical solution that could satisfy the requirements and comes to an acceptable solution. This solution is then associated to others systems to include mutual interactions to get an overall understanding and to check the validation with respect to the requirements expressed during the analysis definition. Such an approach allows the integrator to have a more realistic definition of boundary conditions for each system, hence relaxing the analysis conservatism and optimizing the development. More realistic environments are then used together with the refined requirements to update the design and potentially refine the selected solution. This down cascading and up streaming process is reproduced at every single level of the system integration.

Now that the interface is defined, the model content can be adapted to the needs of the design phase. For instance, at the beginning of the Vee cycle of an hydraulic system, when the main interest is placed on the estimation of a the flow/power balance during a sizing scenario, it is acceptable to disregard high frequency dynamics of the hydraulic components. Instead, at deeper phases of the Vee cycle, where the purpose of the analysis might be to investigate cavitation in the suction line caused by the pump fast dynamics, then the models accuracy must be refined to capture the frequencies of interest. However, the interface remains the same: other models can be connected with no disruption. It is important to ensure a consistency in the level of detail of interconnected models: to optimize the simulation, the information exchanged must contain the same level of precision. Otherwise, it is likely that the more detailed model will slow down the simulation, while the less detailed will not be able to exploit all the data it receives.

The modeling process presented in this section, from the requirements expression to the production and then validation, is schematized in Figure 7.

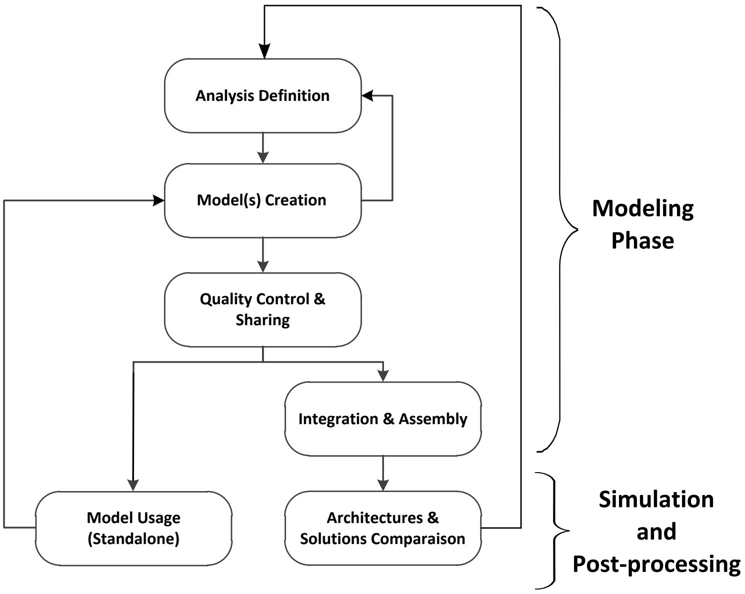
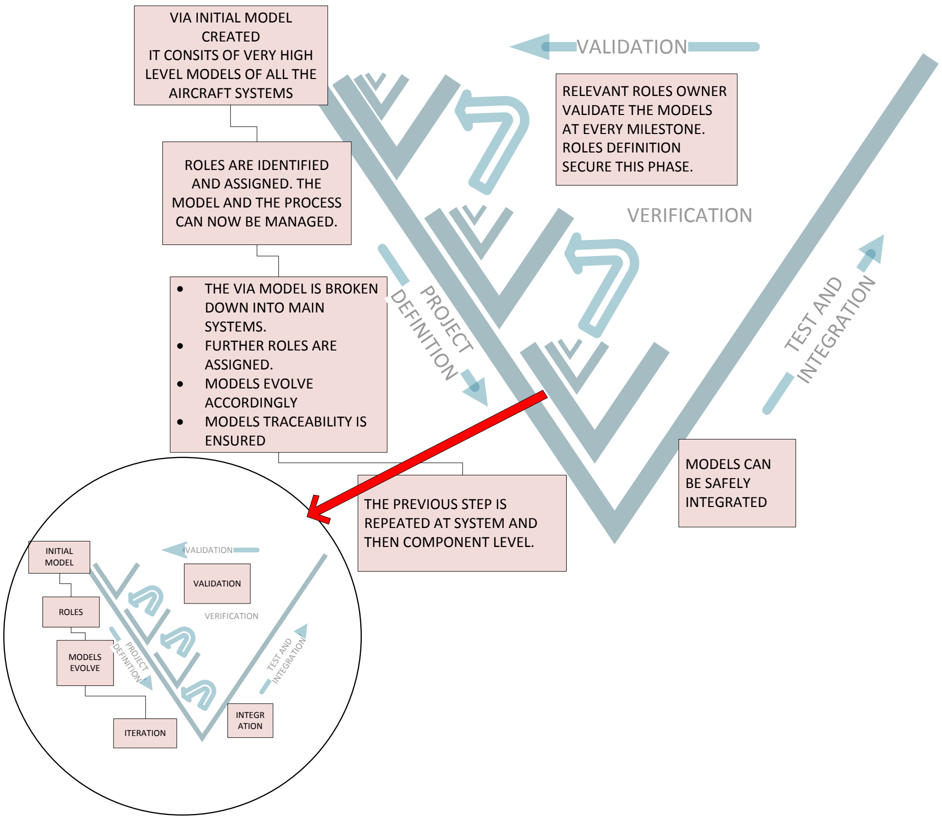


Figure 7: Modeling Process and Simulation.

After the completion of the phases described, the Vee cycle supported by the VIA methodology would then look like represented in Figure 8.

At program level, the first step is to create the very first VIA model, which consists of a high level representation of the aircraft systems to be designed. It is a preliminary translation of the top-level requirement into a numerical mock-up. Successively, as the global entity is broken down into more detailed models, the version control software with RBAC is extensively used to assign roles and therefore to coordinate and manage the data and the work flow. Model are stored and managed on a shared repository, keeping track of their evolution and making them available for further studies. A syndication service notifies the actors involved in a project of relevant events (*e.g.* publications, updates). As the Vee cycle (or sub-cycle) progress on the integration phase, the ICD applied to the models ensures an easier integration. Finally, at each step, verification and validation are managed by relevant and competent personnel as established during the roles assignment phase.



VIA INITIAL MODEL CREATED IT CONSITS OF VERY HIGH LEVEL MODELS OF ALL THE AIRCRAFT SYSTEMS

ROLES ARE IDENTIFIED AND ASSIGNED. THE MODEL AND THE PROCESS CAN NOW BE MANAGED.

- THE VIA MODEL IS BROKEN DOWN INTO MAIN SYSTEMS.
- FURTHER ROLES ARE ASSIGNED.
- MODELS EVOLVE ACCORDINGLY
- MODELS TRACEABILITY IS ENSURED

THE PREVIOUS STEP IS REPEATED AT SYSTEM AND THEN COMPONENT LEVEL.

RELEVANT ROLES OWNER VALIDATE THE MODELS AT EVERY MILESTONE. ROLES DEFINITION SECURE THIS PHASE.

MODELS CAN BE SAFELY INTEGRATED

Figure 8: Vee cycle coupled with VIA methodology.

4. Use case

To illustrate this methodology, the *LMS* (today *Siemens PLM Software*) contribution to a use case scenario developed in the context of the European research project *CRESCENDO*[3] is presented. This project, concluded in October 2012, aimed to develop more efficient aircraft in shorter timescales with greater cost efficiency by challenging the traditional design methods. Furthermore, it calls for a more collaborative environment of the extended enterprise contributing to the virtual products supported by an adequate interoperability. To accomplish this, the importance of M&S means is highlighted to analyze, test, validate, and thus optimize the aircraft design.

The use case mimics an analysis request issued by the aircraft architect in order to evaluate the thermal integration of two different electrical architecture configurations. This example is intended as a proof of concept of the methodology described, not as a thorough study of the aircraft thermal environment. The two configurations are presented in Figure 9. On the left, a centralized Electric Power Distribution System (EPDS) is depicted. The electric generators supply the Primary Electric Power Distribution Center (PEPDC) which feeds the Secondary Electric Power Distribution Centers (SEPDC) located in the avionics bay. Here, the electric power is processed and fed to the different aircraft electrical loads. On the right side of Figure 9, a semi-distributed architecture is illustrated. It utilizes several Electric Power Distribution Centers (EPDC) distributed around the aircraft to improve the system power density and reliability[13] . They are installed along the fuselage and supply the most adjacent loads[14][15] . Concerning the Environment Control System (ECS), a conventional bleed configuration is considered for the trade-off.

Once the request is issued by the architect, the systems engineer in charge of the study defines the analysis by following the procedure described in Figure 7: the models requirements are established, the systems (ATAs) involved in the trade-off determined, their ICD is agreed. The actors of the modeling phase are identified within the company and its supply chain, and their contribute is organized with the support of a RBAC versioning software. At this point, the simulation engineers charged of producing the models consult the common repository to check their availability from previous studies that can answer to the needs of the current analysis. If not, new ones are created and shared with all the stakeholders of the modeling process upon validation. Once the system engineer in charge of the analysis has retrieved all the models needed, their integration takes place and the simulations concerning the whole group of ATAs involved in the trade-off is initiated.

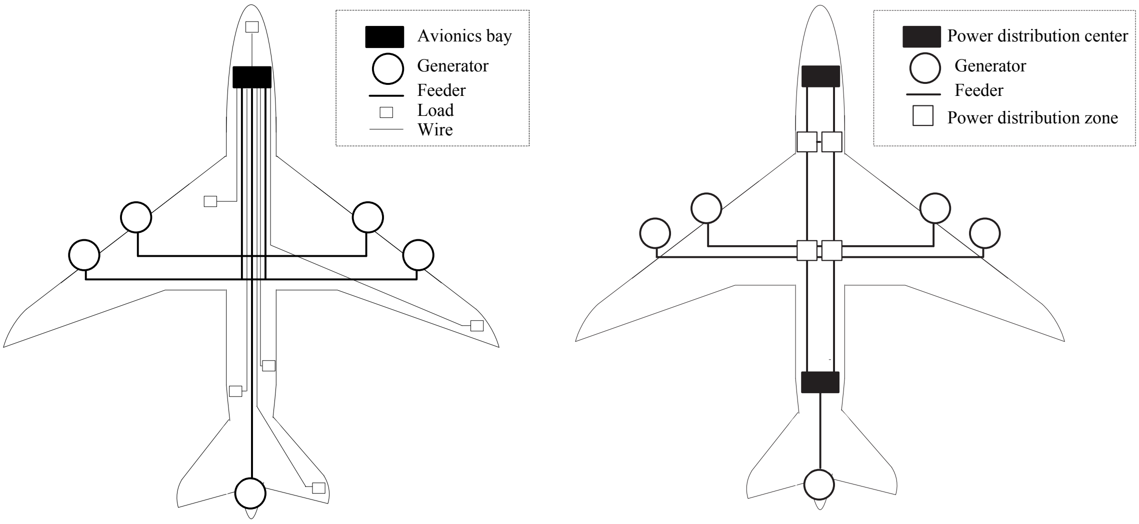


Figure 9: Trade-off illustration. Centralized architecture on the left, semi-distributed on the right[12] .

In this particular example, the following ATAs are identified:

ATA 21: the air conditioning system that controls the temperature and the pressure in the cabin and other aircraft compartments such as the avionics bay;

ATA 24: the electrical power generation and distribution;

ATA 36: the pneumatic system that distributes the pneumatic power from the engine bleed to the interface with the ATA 21;

ATA 53: for the thermal integration of the equipment in the fuselage structure;

ATA 75: the bleed air extraction that extracts compressed air from the low pressure and high pressure turbofan compressors.

Other pneumatic consumers, such as deicing devices grouped in the ATA 30, were not taken into account as their impact on the analysis was deemed negligible.
The model was created with *LMS Amesim*[16] , a multi-physics 1D simulation software, and an overview is presented in Figure 10. On the left side, two components with no connections contain the information and the operating conditions necessary for the study. The first contains all the data describing the gases, liquids and materials properties needed for the thermal computations, such as the structure material thermal conductivity, the air physical properties for the convection exchanges, etc. The second describes the mission profile, defined as the atmosphere conditions as a function of the altitude and aircraft Mach number based on the standard atmosphere model[17] atmosphere model. The central part of the sketch consists of four interconnected blocks. Clockwise, they are: the thermal structure, the aircraft systems, the flight dynamics, and the power-plant block. The ports through which they communicate are a consequence of the ICD, and the data they exchange allow to consider the interdependencies among systems during the computation.

For the current study, flight dynamics plays a marginal role and therefore it is not considered. The relevant ATA identified in the power-plant is the bleed air system which provides the boundary conditions for the ECS (more in detail, to the pneumatic system), *i.e.* the temperature and pressure of the compressed air depending on the flight phase. For the purpose of the analysis, a tabulated model is sufficient to provide the detail of data required. ATAs 21, 24, and 36 are located in the aircraft systems block. The modeling intent of the electrical system for this analysis is to compute the heat to be dissipated by the EPDCs. Therefore, a high level network with heat loads depending on the flight phase was sufficient to cover the need. The ECS, intended as the chain of pneumatic power distribution system and air conditioning (ATA 36 and 21 respectively), was modeled in more detail, as its performance has a high impact on the thermal integration. A functional scheme of an aircraft air conditioning system is presented in Figure 11. The primary heat exchanger (HE1) and the secondary heat exchanger (HE2) are used to cool down the hot bleed air from engine. A control valve restricts the flow as necessary to maintain the desired pressure for downstream systems. Ram air is used as cool flow for both heat exchangers. The air cycle machine is composed by an expansion turbine which drives the compressor and expands the air cooling it even further. The work extracted by the turbine is transmitted to

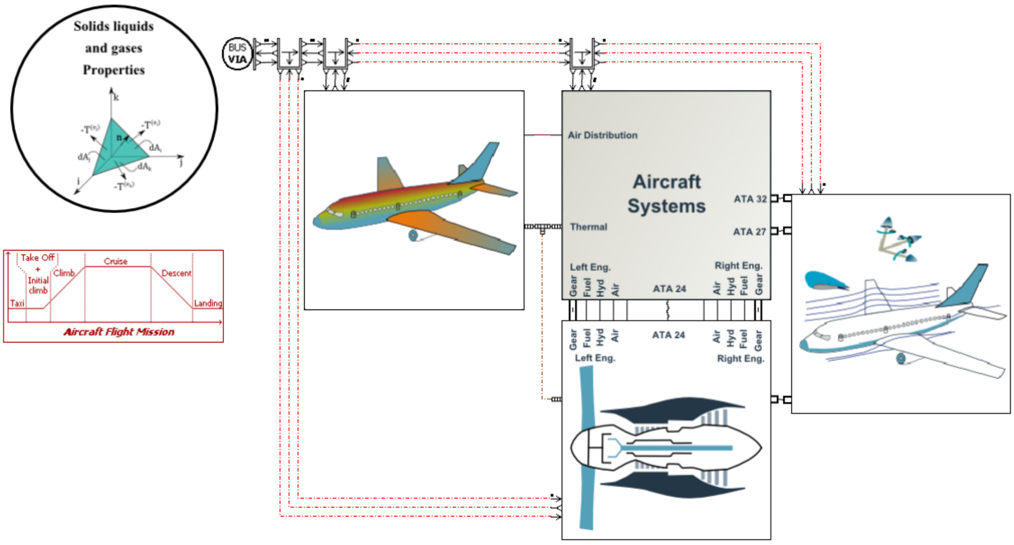


Figure 10: Global integrated model. Information are passed through the connection ports according to the ICD.

the compressor which increases the air pressure. The extracted work from the turbine is transmitted to a fan fixed onto the same shaft in order to supply ram air to the heat exchangers. The control valve allows to control the air temperature, pressure and humidity by mixing air from the cooling system outlet and bleed air from the engine.

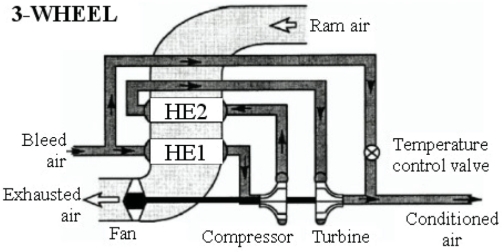


Figure 11: Air cycle conditioning system with a 3-wheel machine[18] .

The fuselage structure, as well as its volume, were discretized in order to describe more in detail the A/C thermal behavior. The structure serves as a heat conductor, whereas the zones, or air volumes, act as nodal heat capacitances where temperature is computed as a result of the heat fluxes applied. Heat dissipated by the electrical distribution network, electrical consumers, and passengers are directed towards these zones as per their distribution on the aircraft. Heat generated from the electrical equipment is function of the power consumed which depends on the flight phase. The heat released by the passengers is propagated into the cabin zones during the flight phases from taxi-out up to landing and taxi-in and it is calculated to be constant as $70W$ per person[19] , 85 passengers were considered for this study. Given that the analysis takes place during the preliminary design, some hypothesis were made in order to cope with the scarcity of data that characterizes this phase. The structure thermal model accounts for the convection between the outer skin and the boundary layer, solar radiation impacting the outer skin, conduction through the walls and structural parts, convection between the interior surfaces and the air, convection from internal heat sources. The heat flux computed by the structural part and the flow air coming from the ECS are then injected into a model of an air volume in order to compute the pressure and temperature evolution associated to the zone.

Thanks to the ICD, it is possible to change the electrical configuration (*i.e.* the destination of the heat fluxes dissipated by the EPDCs to the fuselage discretization) by keeping all the other models unvaried.

Some of the outcome of the simulations comparing the two configurations are plotted in Figure 13. These results are a consequence of the interactions among the systems which are mutually interfaced thanks to the ICD. The first subplot shows the altitude and static and total temperature of the aircraft during the mission. The atmospheric model considered is the ISA standard at ΔISA 0. In the second and third graphics, the temperature evolution of the avionics

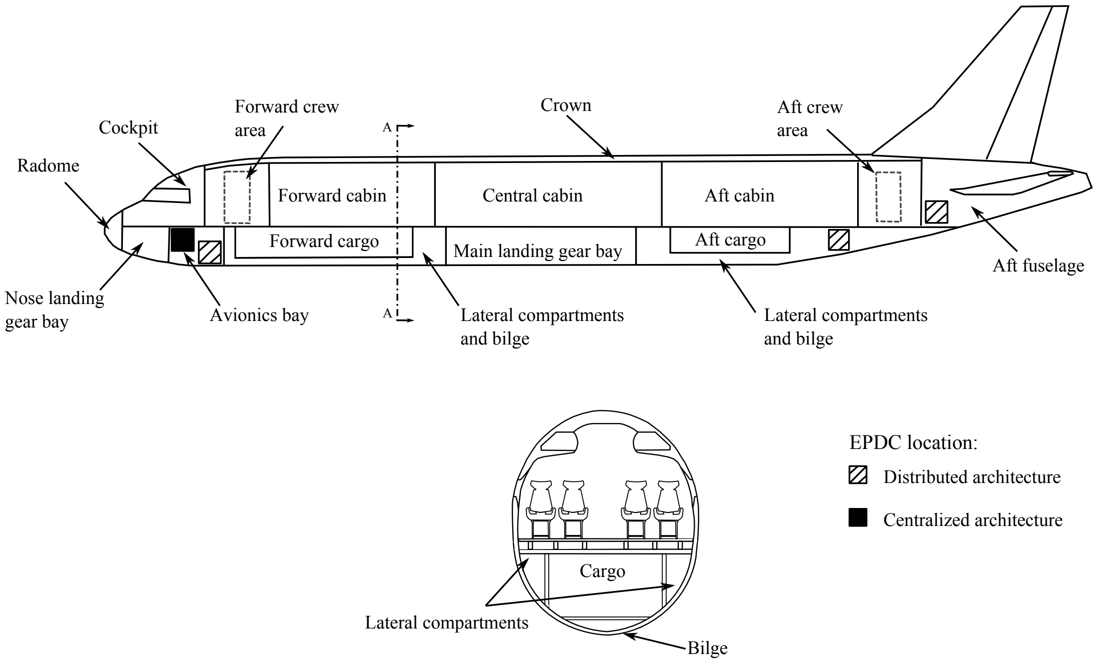


Figure 12: Fuselage discretization and EDPCs locations for distributed and centralized configurations. Lateral and sectional view.

bay (ebay) and the aft fuselage for the two different architectures are compared. The cabin temperature for the two cases does not vary as it is properly regulates by the ECS. The last two subplots indicate the heat loads applied to the zones under study for the two configuration. The heat dissipated by the electrical loads varies according to the flight phase. The heat in the cabin depends in particular to the passengers heat dissipation and to the light and entertainment system to a lesser extent. As expected, with the distributed architecture the avionics bay temperatures are lower, but the aft fuselage compartment becomes hotter. This is a first assessment of the thermal integration analysis requested. It provides the architect with the information needed to conclude the trade-off, steering the design process since from the beginning thanks to the systems virtual integration.

5. Conclusion

The Virtual Integrated Aircraft methodology presented in this paper aims to achieve the virtual integration of aircraft systems earlier in the development phase by means of M&S. The benefits are not only directly linked to the shorter timescale and greater cost efficiency enabled by numerical techniques, but also to a more efficient modeling process with an emphasis on the collaborative environment, and the capitalization of the know-how developed during this phase available for future programs.

This methodology, supported by adequate tools, is then applied to a use case presented in the frame of the European project *CRESCENDO*, which involves a simulated trade-off initiated by the aircraft thermal architect at the beginning of the program development. The analysis compares the impact on the overall thermal integration of two possible aircraft electrical configurations: a distributed and a centralized one. Actions are undertaken by the actors of the extended enterprise in order to answer to the architect request. These are described, as well as the roles of the actors in the frame of the collaborative environment, and it is shown how the modeling process is secured and capitalized. The study outcome highlights the interactions among distinct interconnected systems, and the results provide relevant information to successfully support and conclude the trade-off in a preliminary phase of the aircraft design.

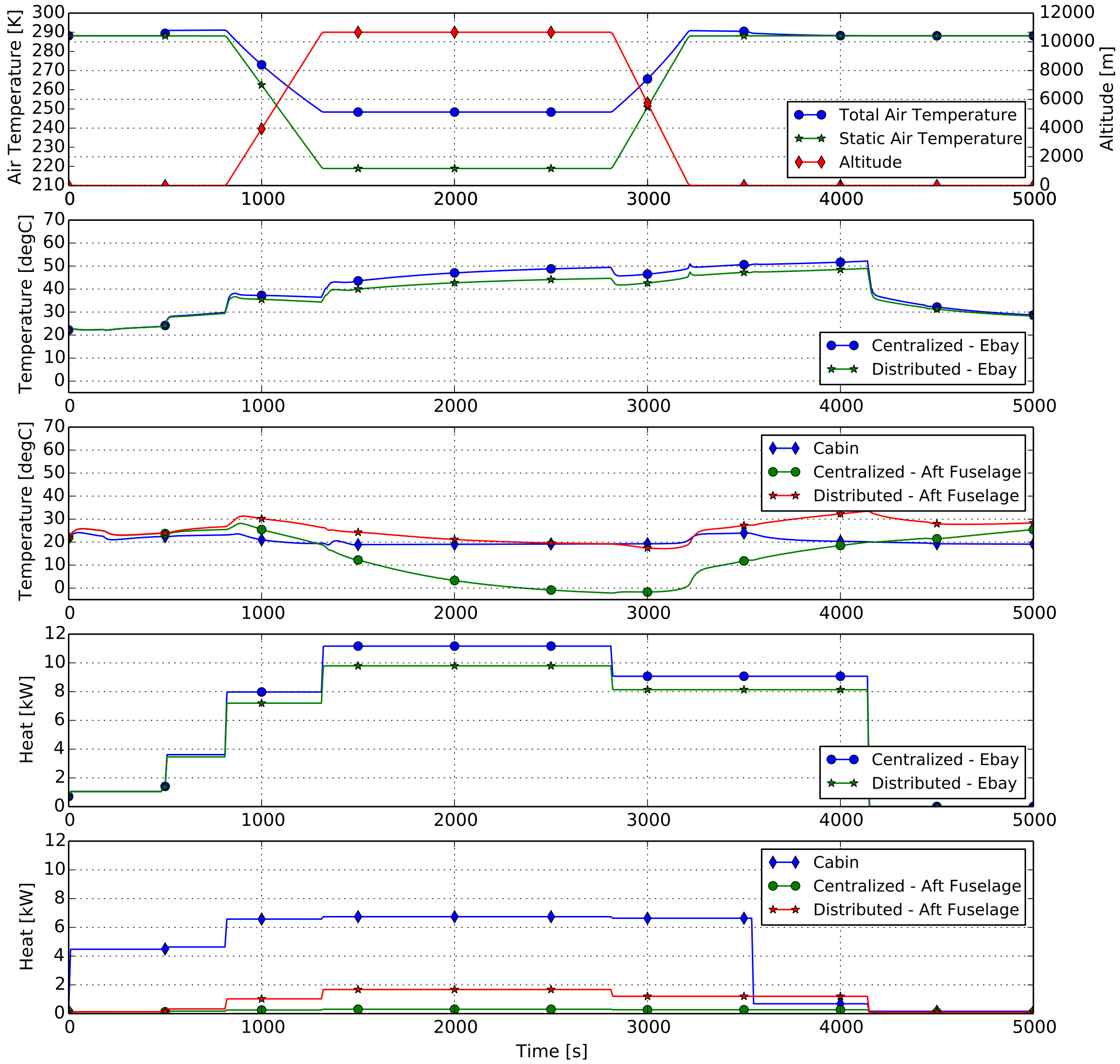


Figure 13: Simulations results. Comparison between distributed and centralized architectures during the aircraft mission. Atmospheric conditions at ΔISA 0 (ISA standard).

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