Fusion Engineering and Design 221 (2025) 115392

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

As-built based method for virtual alignment and assembly of the ITER tokamak

Francesca Giovanna Lanzotti [a,b,c,e,*], Edoardo Pompa [a], Gianluca Picci [a], Alessandro Lo Bue [a], Giuseppe Di Gironimo [b,e], Domenico Marzullo [d,e], Gabriele D'Amico [a]

[a] Fusion for Energy, c/Josep Pla n.2, Barcelona E-08019, Spain
[b] University of Naples Federico II, P.le Tecchio 80 80125 Napoli, Italy
[c] University of Padua, Via Gradenigo, 6/a 35131, Padua, Italy
[d] University of Trieste, Via Alfonso Valerio 6/1 34127, Trieste, Italy
[e] Consorzio CREATE, Via Claudio 21 80125, Napoli, Italy

ARTICLE INFO

Keywords:
Requirement Management
As-built Management
Virtual Fitting
Assembly Requirements
Alignment
ITER tokamak

ABSTRACT

In the project development of large fusion machines, the alignment and assembly phases represent an open challenge. Each mechanical component that constitutes the whole machine assembly and fixtures is affected by an intrinsic geometrical variation due to manufacturing and assembly processes. The complexity of the assembly together with the unavoidable geometrical imperfection can affect the expected machine functionalities. In this context, Reverse Engineering activities, aiming at obtaining the as-built of the components, coupled with virtual fitting studies, defining optimum alignment using the real shape of the components, become powerful risk mitigation tools in the assembly phases. This work presents a systematic method, complementary to the methodology currently followed in the ITER project, for the as-built management and for the validation of alignment phases of such a complex assembly. The first phase is to identify the key assembly requirements which drive the alignment of the ITER assembly. Then, the database for the requirement collection is clearly organized following the proper nomenclature rules and its architecture for data collection and analysis is indeed set up. Four virtual fitting pilot studies are presented to show how the methodology is helpful to assess the assembly requirements in a defined alignment scenario.

1. Introduction

The International Thermonuclear Experimental Reactor, ITER, currently under construction in the Southern France, is one of the most ambitious world-wise projects. The sharing program of the component procurement of the ITER members has the purpose to gain direct knowledge and experience in cutting-edge fusion technology and industrial processes. The European contribution to ITER is managed by the European Domestic Agency, Fusion For Energy (F4E). Each component is unique and, in many cases, requires up to ten years to be manufactured.

The ITER tokamak fusion reactor includes 3 main superconducting magnet systems [1]: the Central Solenoid (CS), the Poloidal Field (PF) and Toroidal Field (TF) coil systems [1] in Fig. 1(a). The TF system consists of 18 D-shaped Nb_3Sn coils, in size around 16.5 m × 9 m and around 300t [2]. Fusion for Energy (F4E) is responsible for the supply of 10 TF coils to the ITER project, while the Japanese Domestic Agency (JADA) of 8 coils plus 1 spare coil [3,4]. Each D-shaped winding pack (WP) is encased in SS316LN steel cases (TFCC) which have the function of providing structural integrity and isolation for the superconductors, while ensuring proper connection to other components of the ITER machine. The TFCC is composed by two U-shaped part (AU and BU), two closing plates (AP and BP) and two spice plates in Fig. 1(b) [5].

The alignment and assembly phases among the large number of *first-of-a-kind* components that constitute the ITER tokamak are still an open challenge due to the huge dimensions, the tight assembly requirements and the intrinsic geometrical variability. Measured data representing the real shape of components, called as-built data, are acquired during metrology dimensional surveys. The compliance of the as-built machine with high level requirements directly impacts the final performance of the ITER machine [6]. After the manufacturing processes each mechanical component that constitutes the whole assembly is affected by

---

* Corresponding author.
E-mail address: francescagiovanna.lanzotti@unina.it (F.G. Lanzotti).

https://doi.org/10.1016/j.fusengdes.2025.115392
Received 16 January 2025; Received in revised form 6 August 2025; Accepted 8 August 2025

an intrinsic geometrical variability which may compromise the expected functionalities. A proper definition of metrology strategy and a proper acquisition of the as-manufactured geometry become crucial to guarantee the implementation of dimensional risk management for driving the assembly of the manufactured interfaces, especially when dealing with large-scale fusion machine components. To ensure a proper acquisition of geometry, the measurement equipment must be selected based on the requirements of the measurement process, adequately to deliver the tolerances to be verified. In the European Toroidal Field coil, as-built data were acquired through a combination of Laser Tracking and Photogrammetry techniques, whose system accuracy is reported in [5]. These measurement techniques are combined in terms of measurement process uncertainty at a confidence level of 2σ [6]. Moreover, the quality of measured data shall be assured by verifying the measurement uncertainty value lower than the defined threshold. Otherwise, rules in [7,8] shall be applied.

Internal quality standards define the mandatory requirements for dimensional control of components and assemblies for ITER providing guidance on best practices for large volume metrology applications [6]. To verify that the measurement process is adequate to the quality requirements, metrology supervision activities are planned and carried out at specific project stages.

Since the unicity of the major fusion components, individual parts are produced one at time or in parallel in different companies around the world. Those components cannot be rejected, and the engineering choices shall be optimized as much as possible to avoid remanufacturing activities. The best scenario would be that the component is accepted without requiring further machining operations. Studying the impact of the variability of the already manufactured components on the final assembly could allow to anticipate eventual out of tolerances supporting the decision-making process. However, a big challenge is to manage the as-built model of the whole system and to perform alignment studies in the virtual environment, instead of managing a simplified model through a Computer Aided Tolerancing (CAT) tool through time consuming Montecarlo simulations. Prior works concerns the definition of a Hybrid Model in the ITER project, affected by variations through Monte Carlo simulation in the 3DCS environment [9,10]. This work, instead, focuses on a structured methodology to support and streamline the complex assembly process, complementary to the methods and tools currently followed in the ITER project [9,10] with the aim to prevent out of tolerances and non assemblability issues during the on-site assembly.

In previous works, assembly requirements were identified at component level and assembly studies were developed accordingly among various parts of the same component. In the ITER European Toroidal Field Coil project virtual fitting was adopted for guiding the position and assembly of the TF winding pack (WP) inside the SS316LN steel case (TFCC) [5]. In the European Vacuum Vessel Sector#5 project, virtual fitting was adopted for the definition of the alignment strategy for fitting-up the segments before welding activities [11].

Therefore, this work faces the challenge to extend the virtual fitting model, for the first time, to more than one component with the following original objectives:

I. to manage the as-built data of tokamak components;
II. to assess the key assembly requirements between adjacent systems;
III. to facilitate the comparison of different alignment scenarios;
IV. to start testing the as-built methods and tools on the toroidal magnet system.

The as-built based method for supporting the alignment and assembly phases of the ITER tokamak enables the virtual fitting studies for aiming at defining optimum alignments using the real shape of the components by combining the requirement identification and the as-built acquisition activities.

2. Requirement identification

In the ITER project high-level geometrical requirements are cascaded from the project to system, sub-system until component level [6]. The sub-systems of the tokamak machines are characterized by many functional geometrical assembly requirements, which evolve during the later development phases. The identification of key assembly requirements in a huge project with many involved working groups and geographically dispersed manufacturers requires a strong effort. Those requirements shall be identified in a set of drawings, called functional tolerance drawings in the ITER project. Those drawings shall indicate the

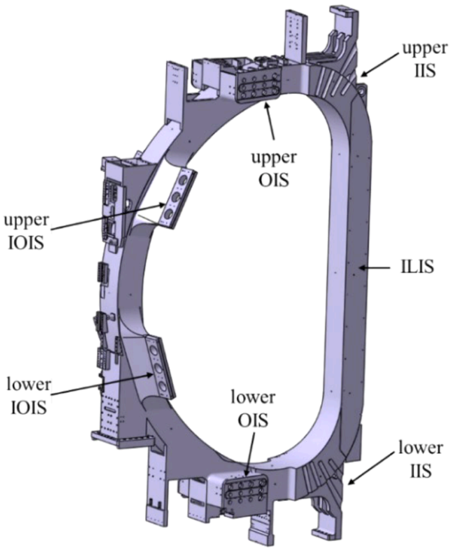

Fig. 2. TF coil connecting structure.

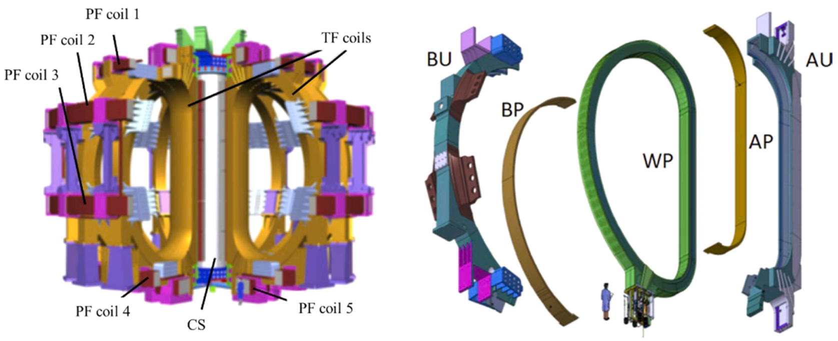

Fig. 1. (a) Magnet System. (b) Exploded view of one toroidal field coil [5].

functional interfaces (see Fig. 2) and were developed only after the production strategy of the Toroidal Field Coil components with the availability of information from qualification processes [12]. In addition, details on assembly processes are needed to complement the drawings and are collected through internal technical reports, documents or dedicated meetings. As the first step of the proposed methodology, key assembly requirements are needed to be identified and collected in the proper tool. Those requirements drive the alignment phase, since their fulfilment compromises the functionality of the ITER machine.

2.1. Traceability rules

A set of rules is defined for assigning a proper identifier to each requirement. The structure, reported in Table 1, is defined for the assembly requirements. The first field is a markup, identified as the requirement short name, composed by the letter “A”, the interface name and a positive number. The other columns indicate to which system the requirement is referred to - System I and System II - then respectively the relative interfaces - Interface I and Interface II. In case of multiple interfaces with the same name, a unique identifier (Markup ID) is associated to each of them. The adopted acronyms in the assembly requirement name are drawing-based. The last field is the nominal interface feature which the requirement is referred to. Features are classified depending on type, the surfaces are indicated with the letter “S”, while the holes are indicated with the letter “H”. In both cases three numbers follow the first letter. Each requirement is then characterized by a unique identifier, the Requirement ID, as reported in Table 2. The Requirement ID (RQM ID) is univocally defined by combining the first three fields in the Table 2. In case of part requirements, the rules are the same apart from the letter “F” at the beginning and the only System I is needed. Nomenclature rules are essential to be defined and to clearly and univocally define the naming of each geometrical requirement. This also allows the requirement traceability in the alignment studies.

3. As-built definition and acquisition

Components, affected by geometric variation due to many factors, are included for simulating the assembly of non-nominal geometries. The models are characterized by geometrical variability due to manufacturing processes and are also affected by alignment variability and position errors in mechanical assembly. In the manufacturing process the main sources are caused by surface machining, welding shrinkage, while in assembly processes the main sources are related to the supporting configuration, tools, deadweight and position errors in the final assembly. The geometric variation is quantified as vector deviation from nominal and is the output of the assessment workflow (see par. 5.1). Dimensional inspections are crucial to guarantee the high-quality of the measured data and discuss the metrology strategy for driving the alignment of the as-manufactured interfaces in their final position to fulfil tight assembly requirements. The components are acquired through on-field surveys to obtain the as-built of the interfaces with their real shapes.

Data are filtered during the metrology survey, in case of the toroidal field coil project, point measurements were taken with no need of volumetric scans. This means that the control of the reliability of geometrical measurements is carried out by imposing a Root Mean Square (RMS) threshold on each measurement, to minimize the risk of introducing additional uncertainty sources into the process. After the raw data post-processing, the whole as-built of the component is ready to be used as input for the assembly model. Fig. 3 shows the whole as-built acquisition of the Toroidal Magnet at the acceptance phase of the component. The use of colours allows to visualize the distribution of measured data and highlights the non-uniform points density on the whole system, showing the amount of data concentrated around some geometrical features. The density increases in those areas with critical geometrical requirements where information is needed for a more accurate reconstruction of the associated integral and derived geometrical features.

Table 1
Assembly requirement structure.

Assembly Requirement Name					
Markup ID	Sys I	Sys II	Int I-Int ID	Int II-Int ID	Feature

Table 2
Requirement ID rules.

Type	RQM ID
Part	F _ Interface _ N _ System I
Assembly	A _ Interface _ N _ System I - System II

The as-built contains information on the real shape of the manufactured components and are preprocessed for selecting, grouping and renaming those data related to the interfaces which play a role in the assembly phase. From the whole point cloud, the points related to the interfaces of interest are selected to lighten the model. The number of points depend on the metrology survey and on the procedures defining the minimum as-built information. The whole point group associated with the interface feature is entirely selected by proximity to the nominal model. Through the reference datum system, the as-built data are directly aligned to the nominal CAD model which enables to visualize the disposition of the measured data on the relative surface. The alignment targets are defined and each as-built is aligned to those targets. The nominal CAD model is previously simplified, and the critical interfaces are dissected and renamed according to the traceability rules to be associated with the relative as-built data. Reverse Engineering processes allow to handle discrepancies between design models (as-designed) and actual manufactured components (as-built) by designing and developing shims and custom machined interfaces for accommodating geometrical deviations. Otherwise, if the as-manufactured component is within tolerances, the methodology is applied to study the assembly of as-manufactured components which include the real shape with the additional contribution of the variability sources due to assembly process or position errors.

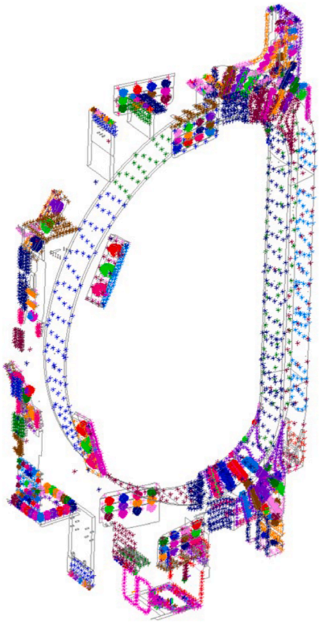

Fig. 3. A whole as-built of the Toroidal Field coil.

4. Virtual fitting technique

The virtual fitting technique is a methodology based on measured data which allows to virtually study the best relative position among manufactured parts to optimize a set of assembly requirements. Multiple alignment scenarios, based on defined constraints and the experience of the experts, can be studied with the aim to find the best compromise between the compliance with geometrical requirements and the assemblability of components. Virtual fitting studies allow to find an alternative alignment which optimizes the selected requirements, assigning to each of them a different priority level, and for evaluating the impact of this alignment on any other requirement at each assembly step [11]. In the assembly processes, the priority level assigned to the requirements is decided based on many factors related to the interface's accessibility, the strictness of requirements with respect to the others and the allowable adjustability margins. The variations from nominal of the manufactured component can be foreseen before the real assembly phase to discuss corrective actions in advance. The criteria for assessing the success of virtual fitting are usually based on a set of control points that are measured in different stages of the project. Performing virtual fitting studies can allow to spot eventual out of tolerances in advance and to find an alternative alignment configuration for mitigating manufacturing and/or assembly non-conformities. Each large component is aligned with respect to fiducials this is the reason why classical stack up analyses need to be complemented by such alignment studies in view of the assembly phase. The consistency of alignment requirements is ensured through on-site and real time metrology checks. The assembly model can be updated with the as-assembled data, when available, at each phase of the assembly. In the assembly processes, material deformations can also be considered by performing another metrology survey and include the updated measured data in the model.

5. Model architecture set up for data collection and analysis

The implementation of the as-built based method requires a proper model architecture structure for collecting requirements, as-built data and simulation results. This allows to enlighten the simulation file, managing quickly the data. In Fig. 4 the building blocks of the architecture are shown. The first block concerns the preparation of the Requirement Management Document (RMD), an Excel-based table, with the whole set of key part and assembly requirements. Following the traceability rules, information collected from part and assembly drawings, technical reports and expert knowledge are organized. The second block is the as-built data of the components available for the analysis. The third block is the initial transformation frame that enables to define the assembly conditions as initial target alignment. Combining the information of the first three blocks, the instance of each component of the assembly is defined as a Slave file in the simulation tool. Finally, the third block allows to assemble all the information imported from the Slaves in the Master file and measure the key assembly requirements. The Master generates the vector plots and the measured data as output of each simulation.

The database is composed of a set of Slave files, one per each system. The as-built data are organized in different point groups, one per each interface. Each Slave file contains: the nominal CAD model, the as-built data, the reconstructed geometrical entities, *i.e.* planes, axes, cylinders, the associated derived features from geometrical entities and the initial transformation frames.

In the database, nomenclature conventions for nominal surfaces, as-built data and reconstructed geometrical entities are defined according to the nomenclature of the Systems, Interfaces and Features defined in par. 2.1.

It is roughly estimated that the measured data of the whole toroidal magnet system will be around hundreds of thousands of data for total

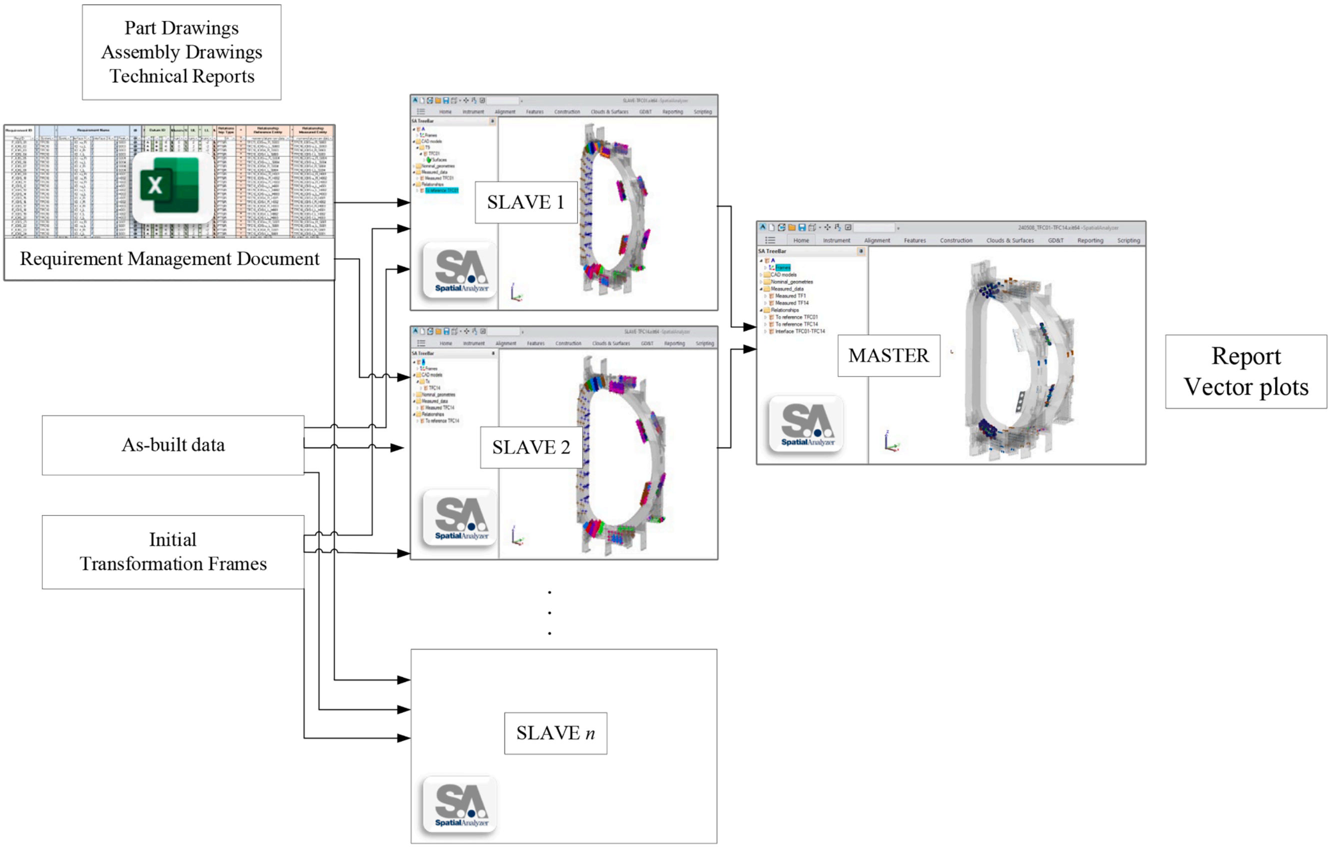

Fig. 4. Model architecture set up.

number of TF coils. Indeed, a dedicated Slave file is needed per component. Spatial Analyzer (SA) is selected as the 3D Graphical Software for Metrology and Reverse Engineering purposes in the ITER project. It has been tested to be a suitable tool for the management of as-built data and to enable virtual fitting technique. To define the best-fit alignment of mechanical components, advanced best-fitting algorithms available in SA are used. It is possible to manage optimizations of huge amounts of data in the order of thousands of points in a relatively short computational time. Moreover, SA allows both single component optimization and advanced fit optimization using available algorithms. The default SA optimization algorithm is the Gauss-Newton method which is the most used solution for solving non-linear least squares problems. In addition, in SA thermal expansion and contraction of a measured part can be included by applying to the measurements a scale factor depending on the material. The Slave files are SA files as well as the Master file, where only that information needed for the simulations is imported, for having a light and easy to manage model.

5.1. Assessment workflow

The assessment of the compliance/non-compliance of assembly requirements follows the workflow shown in Fig. 5. Firstly, in the pre-processing phase two or more systems of interest and their assembly requirements are identified and written in the RMD following the traceability rules. After the metrology acquisition, the as-built data of the assembly-relevant features are extrapolated from the whole as-built. Measured data, acquired in the metrology dimensional inspections, are grouped and renamed according to the nomenclature rules for enabling the traceability of the measures related to the relative surface. In this way a Slave file is prepared for each system of interest. Then the assembly requirements to be assessed, defined as control requirements, are chosen and the alignment of each system is identified. Each requirement is characterized by its own importance in the process, a sub-set of requirements driving the alignment is needed to be identified. This plays a key role in the implementation phase for defining the alignment strategy for assembling the different components of the whole assembly. In addition, an initial transformation frame, which defines the alignment conditions, is needed for each system. Then in the Master file the requirements are implemented among systems and then each system is aligned using the initial transformation frame. Therefore, virtual alignment studies are carried out in the Master file by applying the transformation frame to each component. Starting from the as-built acquisition, Spatial Analyzer environment, as computational tool, is used for developing the simulation file by integrating the measured data from the Slave file and applying to each component the relative alignment frame. Finally, the control requirements are assessed, and the Master file is stored. The results are postprocessed, studied and compared. The whole set of chosen requirements is analyzed for tracking the impact. An approach based on the Nominal is the Best loss function is adopted to quantify the misalignment risk. Assuming an equal likelihood of each assembly strategy, the risk level is proportional to the severity, identified as the loss value under the model assumption. The higher is the distance from the target value, the higher is the risk of not fulfilling the key characteristic. If the control requirements are fulfilled, the assessment is positively completed, and no further actions are needed. Otherwise, remedial actions must be conceived and verified to mitigate the risks.

6. Virtual Fitting pilot case studies

The model architecture enables the virtual fitting technique for performing assembly studies. The variability due to the manufacturing processes is included in the information provided with the as-built data, while the variability sources due to assembly processes are introduced as

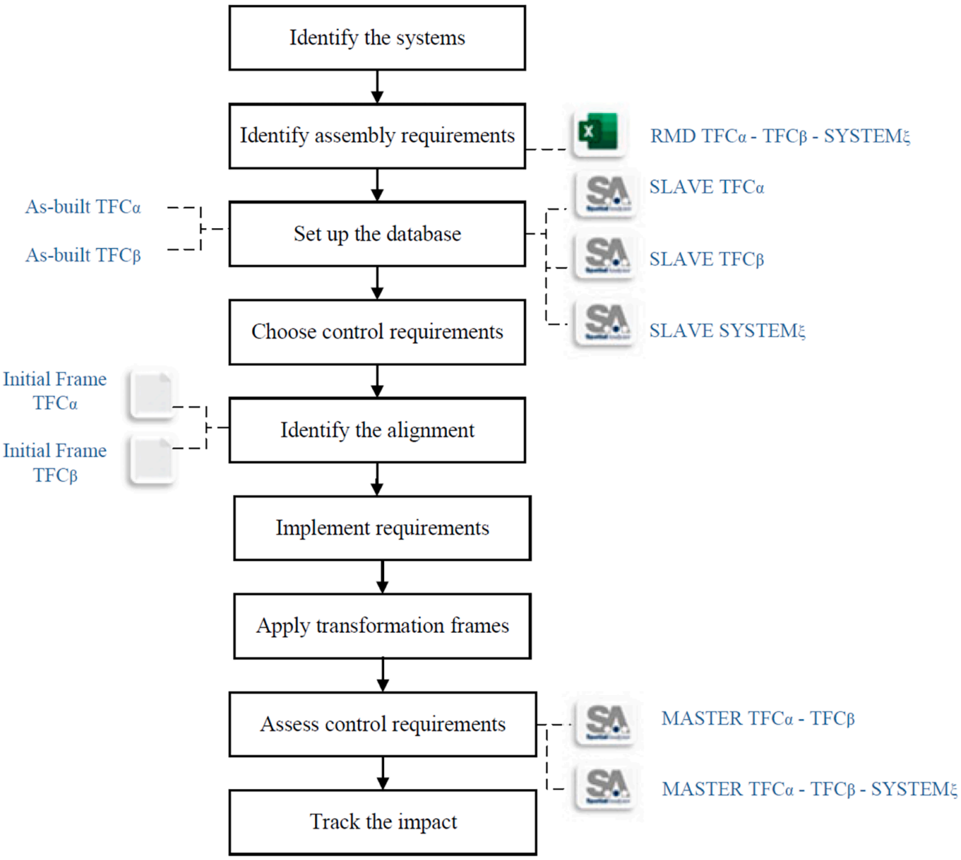

Fig. 5. Assessment workflow step-by-step.

position errors. For demonstrating the capabilities of the model, four different pilot case studies of multiple sub-systems are considered under different hypotheses by using “pseudo as-built” data created on purpose, called p-as-built. The hypotheses are reported in Table 3. Firstly, a toroidal field pair assembly is considered and then the whole triplet - two Toroidal Field Coils (TFCs) with the relative Vacuum Vessel Sector (VVS) - under different hypotheses (see Table 4) for investigating four pilot case studies. Fig. 6 shows the systems in their final positions inside the Tokamak Complex, where the alignment conditions of each pilot, corresponding to different hypotheses, are simulated.

6.1. *Pilot 1: Impact study at nominal assembly*

The first pilot study focuses on the virtual assembly of a TF pair assembly (TFC_α - TFC_β) following the assessment workflow. Both TFCs are aligned to the target Current Centre Line (CCL). Ten control requirements to be assessed are chosen and reported in Table 5.

In these pilot studies an approach, based on the risk evaluated by expert metrologists, is proposed to classify the results if misalignments occur. The approach based on the loss function, described in par 5.1, is followed. Three risk levels - High, Medium, Low - are assumed for the gap requirement in toroidal direction, corresponding to three intervals of gap values as elicited by the experts. Minimum values of gaps are critical and require in-depth analysis. Table 6 shows an example of risk levels associated to three intervals of gap values. Fig. 7 gives an overview of the toroidal gaps as vector deviations and allows the association with the corresponding interface.

Three risk levels – High, Medium, Low - are also assumed for the coaxiality requirement, corresponding to the intervals of misalignment as elicited by the experts. Maximum values of coaxiality are critical and require in-depth analysis. Table 7 shows an example of risk levels associated to symmetrical and decreasing intervals of misalignment. Fig. 8 gives an overview of the coaxiality misalignments as vector deviations and allows the association with the corresponding interface.

Control requirements are implemented in the simulation file and the maximum deviations for coaxiality and the minimum deviations for toroidal gaps are within the low-level risk. In Pilot 1, control requirements are positively assessed under Hypothesis I: TFC nominal alignment.

6.2. *Pilot 2: Impact study simulating real assembly*

The second pilot study deals with the virtual assembly of two TF pair assembly (TFC_α -TFC_β), starting from the alignment described in Pilot 1, under Hypothesis II: position errors of both TFCs within the maximum admissible margins ($\pm 1mm$) starting from the nominal CCL target alignment. Same control requirements, as in Pilot 1, are chosen, the same approach is adopted for evaluating the risk levels associated to the interval levels for each control requirement. The initial transformation frame for the TFC_β is characterized by a pure rotation in toroidal direction ($R_z = -0.0053°$) and the initial transformation frame for the TFC_α by a pure translation in radial direction ($T_x = -1mm$). In Pilot 2 control requirements are positively assessed under Hypothesis II.

6.3. *Pilot 3: Impact study simulating real assembly and geometrical NCRs*

Table 3
Hypotheses.

Hypothesis	Description
I	TFC Nominal alignment
II	TFC Position error after landing
III	VVS Position error after landing
IV	Corrective action

Table 4
Sub-systems and hypotheses per pilot.

Pilot	Sub-system	Hypotheses
1	TFC_α -TFC_β	I
2	TFC_α -TFC_β	I, II
3	TFC_α -TFC_β-$VVS_{\alpha\beta}$	I, III
4	TFC_α -TFC_β-$VVS_{\alpha\beta}$	I, III, IV

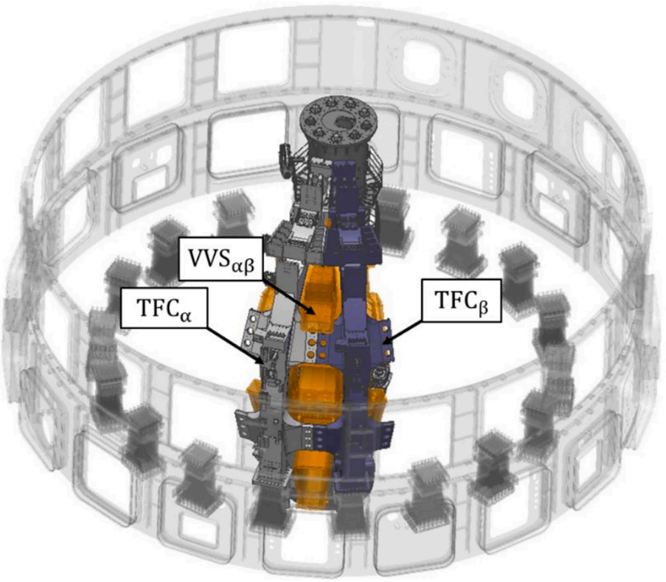

Fig. 6. Toroidal Field Coils and the relative Vacuum Vessel Sector inside the Tokamak Complex.

Table 5
Association between requirements.

Interface		Control Requirements	
IIS	Upper	Coaxiality of four semiholes	A_IIS_37
	Lower		A_IIS_38
IIS	Upper	Gap in toroidal direction	A_IIS_33
	Lower		A_IIS_34
OIS	Upper	Coaxiality of six hole pattern	A_OIS_01
	Lower		A_OIS_02
OIS	Upper	Gap in toroidal direction	A_OIS_06
	Lower		A_OIS_05
IOIS	Upper	Gap in toroidal direction	A_IOIS_05
	Lower		A_IOIS_06

Table 6
Pilot 1: Risk Level – gaps in torodial direction.

Risk level	High	Medium	Low
Control requirements	Interval H [mm]	Interval M [mm]	Interval L [mm]
A_IIS_33	[1.0, 1.9]	[2.0, 3.9]	[4.0, 7.5]
A_IIS_34			
A_OIS_06	[1.0, 1.9]	[2.0, 4.9]	[5.0, 10.0]
A_OIS_05			
A_IOIS_05	[10.0, 11.9]	[12.0, 17.9]	[18.0, 26.0]
A_IOIS_06			

The third pilot study deals with the virtual assembly of a TF pair assembly (TFC_α-TFC_β), one VV Sector ($VVS_{\alpha\beta}$) with its relative Thermal Shield (VVTS) for studying the triplet. The TFCs are aligned to the target CCL and the VV sector is aligned to the target position after landing with a position error within the maximum admissible margins (±3 mm [4]). The VV upper port is, moreover, characterized by a manufacturing error within tolerances. Two requirements are assessed: the coaxiality

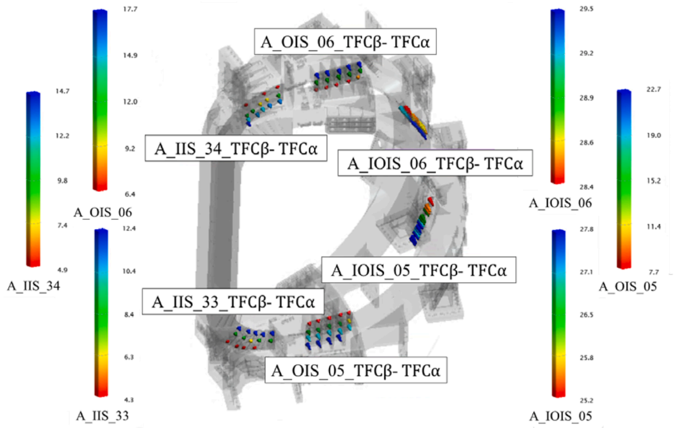

Fig. 7. TFC pair assembly: vector deviations of gaps in toroidal direction.

Table 7
Pilot 1: Risk Levels - coaxiality.

Risk level	High	Medium	Low
Control requirements	Interval H [mm]	Interval M [mm]	Interval L [mm]
A_IIS_37	[7.0, 9.0] [− 9.0, − 7.0]	[4.0, 6.9] [− 6.9, − 4.0]	[− 3.9, 3.9]
A_IIS_38			
A_OIS_01	[3.0, 4.0] [− 4.0, − 3.0]	[2.0, 2.9] [− 2.9, − 2.0]	[− 1.9, 1.9]
A_OIS_02			

between the upper port and the alignment axis of an external sub-system and the clearance between the Vacuum Vessel Sector and the VV Thermal Shield (see Table 8). Three risk levels are evaluated per each assembly requirement and reported in Table 9. The control requirements are implemented in the simulation file and the minimum deviation of the clearance and the maximum deviations from the alignment axis of an external sub-system are assessed. The first requirement is within the medium-level risk and the second requirement is within a high-level risk (see Fig. 9). Remedial actions are needed.

In case of ports allocated to the additional heating systems, the alignment with the VV port axis, such as the equatorial port for the Neutral Beam Injector [13], shall be properly controlled because eventual misalignments could impact negatively the efficiency of the heating system.

6.4. Pilot 4: Definition of an optimized alignment scenario

The optimization study starts from Pilot 3 to define a different alignment scenario that should compensate deviations of the p-as-built data without corrective actions. The proposed action is to re-think the

Table 8
Pilot 3: Control requirements.

Interface	Control Requirements	
OS	VVS outer shell-VVTS clearance	A_OS_01
EXT	Coaxiality	A_EXT_01

Table 9
Pilot 3: Risk levels.

Risk level	High	Medium	Low
Control requirements	Interval H [mm]	Interval M [mm]	Interval L [mm]
A_OS_01	[10.0, 15.9]	[16.0, 34.9]	[35.0, 60.0]
A_EXT_01	[7.8, 9.0] [− 9.0, − 7.8]	[4.5, 7.8] [− 7.8, − 4.5]	[− 4.5, 4.5]

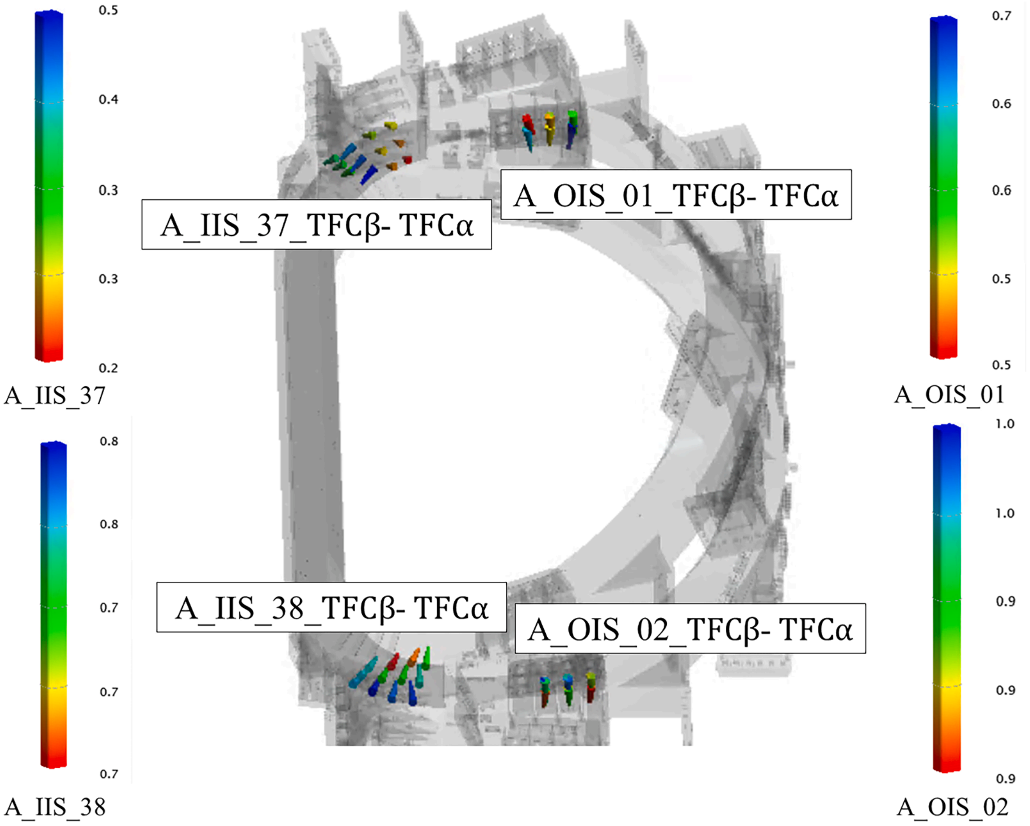

Fig. 8. TFC pair assembly: vector deviations of coaxiality.

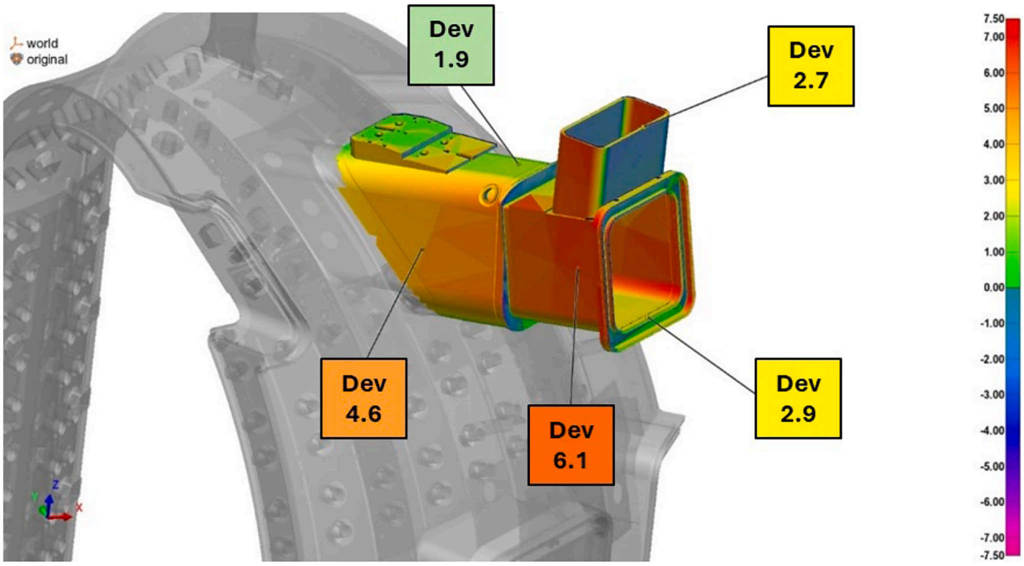

Fig. 9. Pilot 3: deviation of the as-built port with respect to nominal – high risk level.

alignment strategy with the *trial-and-error* approach through the virtual fitting technique. The same two requirements as in Pilot 3 are assessed. Pilot 4 is based on the Hypothesis IV: the sub-systems have been already accepted after the manufacturing phase and the assembly tools enable a control of the alignment as accurate as needed to compensate (see Fig. 10).

After having identified the new alignment conditions, the impact this re-alignment would have on the other interface systems, directly or indirectly involved in the assembly, can be studied. This model could allow to study possible risk situations for finding new optimized alignment configurations. The impact of this alignment strategy on other interfaces can be further studied.

7. Discussion

The as-built based methods and tools can be a valid risk mitigation tool to assess the impact of assembly requirements in a defined alignment condition. The as-built data of tokamak components, acquired in geographically dispersed sites, can be integrated into the assembly model. This methodology can be implemented during the manufacturing phase and then can be updated in the assembly phase of the ITER machine. The described pilot studies regard an application of the proposed methodology whose results can support not only to assess the compliance of the requirements, but also to understand eventual misalignments in advance. In pre-assembly phase this process allows to assess assembly requirements in specified alignment conditions for each component, as described in Pilot 1 and Pilot 2, to understand the impact of non-conformities during and after manufacturing and to simulate the impact of allowable position errors after landing. Pilot 3, therefore, demonstrates how the proposed methods can be useful to assess the impact a defined alignment could have, even when components are within tolerances. Finally, Pilot 4 is developed to show that this tool is useful to simulate conceived corrective actions.

8. Final remarks and future works

The proposed methods and tools combine requirements identification and the as-built management for enabling the virtual fitting technique. Starting from the success of this technique at component level, this proposed methodology has been extended to the virtual assembly studies of more than one component. Traditional alignment approaches are visual and manually driven, the components are physically moved step-by-step wasting a lot of time and the impact of the alignment can be studied only afterwards. This systematic method, instead, enables to carry out a large number of simulations to find the best target configuration which minimizes the time to move the components and the

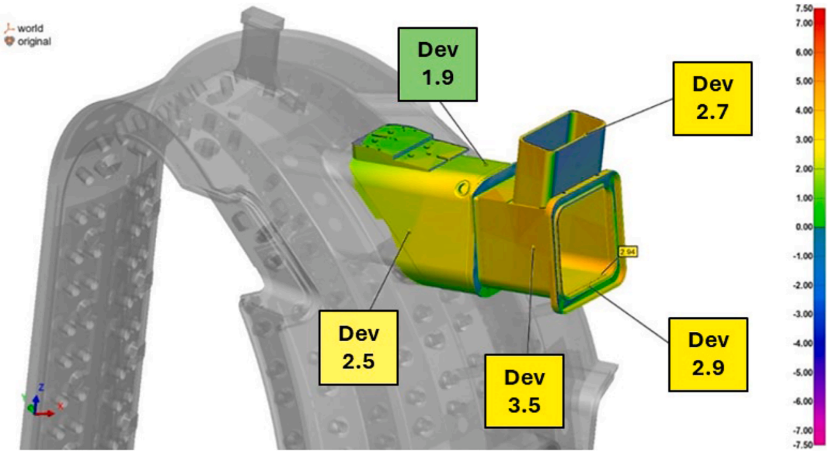

Fig. 10. Pilot 4: deviation of the as-built port with respect to nominal – low risk level.

associated cost. Through this approach the as-built data of the whole reactor could be managed in a well-structured and organized database for the assessment of the key assembly requirements. Traceability rules are proposed to manage the available knowledge on dimensional variations. Four pilot studies are discussed to demonstrate the applications of the proposed methods to assess the impact of the assembly requirements having identified a specific alignment scenario. The virtual fitting technique, indeed, easily enables the visualization and speeds the results comparing different alignment scenarios, based on the gained F4E experience in this field. To this end, the p-as-built, created on purpose, shows that the tool properly works for the assembly assessment and can help to reduce risk of misalignments in the assembly of the Toroidal Magnet assembly. The possibility to manage the full as-built of the assembly and to carry out virtual alignment studies makes it a valuable tool as the as-built based “digital twin” useful for the lifecycle management of the whole tokamak. Further work will include even other systems of the ITER machine for further simulations of the assembly. Future results using this methodology can be helpful when a redefinition of the alignment process for ITER could be needed. Moreover, in future development, morphing tools [14] can also be used to integrate the deformed shape of the components within the assembly model. Finally, this methodology can be extended to other large-scale projects which face with the same issues as DEMO and Divertor Tokamak Test (DTT) facility. While in the ITER project this methodology is adopted using as-built data, in future large scale industrial and scientific projects, further development will concern how to combine the measured data with simulated data affected by variability with the main aim to anticipate similar issues in the design phase.

Finally, since many emerging technologies are developed to enhance the quality of the virtual assembly [15]. A participative approach in the virtual assembly of large fusion devices using Virtual Reality (VR) and Augmented Reality (AR) technologies could be promising and will be further investigated in future works.

CRediT authorship contribution statement

Francesca Giovanna Lanzotti: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Conceptualization. **Edoardo Pompa:** Writing – review & editing, Validation, Resources, Methodology, Conceptualization. **Gianluca Picci:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Conceptualization. **Alessandro Lo Bue:** Resources, Methodology, Conceptualization. **Giuseppe Di Gironimo:** Writing – review & editing, Supervision, Resources, Methodology, Investigation. **Domenico Marzullo:** Writing – review & editing, Investigation. **Gabriele D’Amico:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Data availability

The data that has been used is confidential.

References

[1] N. Mitchell, et al., The ITER magnet system, IEEe Trans. Appl. Supercond. 18 (2008) 2.
[2] A. Bonito Oliva, et al., About the first 6 toroidal field coils and 2 poloidal field coils completed by EU for ITER, IEEe Trans. Appl. Supercond. 32 (2022) 6.
[3] C. Sborchia, A. Bonito Oliva, H. Rajainmäki, A. Vostner, Procurement of the ITER magnet components supplied by F4E, Fusion Eng. Des. 84 (2009) 1716–1722.
[4] M. Nakamoto, et al., Completion of the first ITER toroidal field coil in Japan, Nucl. Fusion 61 (2021) 116044.
[5] A. Lo Bue, E. Pompa, B. Bellesia, M. Jimenez, M. Ferrater, G. D’Amico, A. Bonito Oliva, Metrology In-process control for the European Toroidal Field Coil Project, IEEe Trans. Appl. Supercond. (6) (2022) 32.
[6] G. D’Amico, F.J. Fuentes, A. Jimenez, F.G. Lanzotti, G. Picci, The management and cascading of geometrical requirements from designer to manufacturer in the ITER life cycle, Fusion Eng. Des. 218 (2025) 115223.
[7] BS EN ISO 14253-1:2017 - Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment.
[8] BS EN ISO 14253-2:2011 - Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment.
[9] F.J. Fuentes, V. Trouvé, J.J. Cordier, J. Reich, Methodology for dimensional variation analysis of ITER integrated systems, Fusion Eng. Des. 109-111 (2016) 315–320.
[10] F.J. Fuentes, et al., Methodology for reverse engineering analysis of ITER as-built integrated systems, Fusion Eng. Des. 146 (2019) 2268.
[11] A. Lo Bue, E. Pompa, M.G. Fernandez, F.G. Lanzotti, G. D’Amico, B. Bellesia, Application of virtual fitting in the manufacturing of the ITER European vacuum vessel sectors, Fusion Eng. Des. 215 (2025) art. no. 114998.
[12] J. Reich, J.J. Cordier, A. Foussat, F.J. Fuentes, Integral tolerance assessment on TF coil cases on the basis of manufacturing input, in: IEEE 26th Symposium on Fusion Engineering (SOFE), Austin, TX, USA, 2015, 2015, pp. 1-5.
[13] M.J. Singh, D. Boilson, A.R. Polevoi, T. Oikawa, R. Mitteau, Heating neutral beams for ITER: negative ion sources to tune fusion plasmas, New. J. Phys. 19 (2017) 055004.
[14] E. Pompa, P. Leonard, T. Popa, L. Reccia, M.E. Biancolini, G. D’Amico, F.J. Fuentes, Validation of vacuum vessel thermal shield deformation via finite elements and morphing techniques based analysis, Fusion Eng. Des. 215 (2025) art. no. 11493.
[15] M. Eswaran, M.V.A. Raju Bahubalendruni, Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review, J. Manuf. Syst. 65 (2022) 260–278.