Constraint-Based Modeling for Automated Technological Process Planning in Aircraft Airframe Maintenance

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Abstract: This paper proposes a formalized constraint-oriented approach to structural modeling of assembly units of an aircraft airframe, aimed at supporting the automated selection of an optimal technological process of maintenance and repair. The approach addresses maintenance planning under conditions of limited accessibility, high structural density, and complex spatial configuration of airframe components. The study focuses on the formalization of geometric constraints and design-and-technological properties that determine the parameters of accessibility zones during aircraft maintenance and repair operations. Restrictive properties are represented as parameterized logical-mathematical models describing admissible displacements, feasibility of tool placement and orientation, and interaction between geometric, kinematic, technological, and operational factors. Accessibility zones are modeled as multidimensional feasibility domains governed by logical conditions and technological constraints. An object-oriented approach is employed to represent airframe components, technological equipment, and constraints as interconnected analytical objects with explicitly defined parameters, ensuring scalability and reuse of models across different aircraft configurations. The proposed method enables systematic identification and classification of restricted accessibility zones, objective assessment of technological feasibility, and rational selection of technological equipment at early stages of technological process design. Comparative analysis demonstrates that the developed framework provides higher formal rigor, reproducibility, and automation than conventional geometry-based, expert-driven, and simulation-based methods. The results establish a methodological basis for integration with intelligent CAD systems and digital twin environments, supporting optimization- and AI-driven maintenance planning of complex aircraft airframe structures.

1 INTRODUCTION

The development of modern aircraft is characterized by increasing structural complexity, enhanced functional integration, and stricter reliability and safety requirements. Under these conditions, the efficiency of maintenance, repair, and overhaul (MRO) processes directly influences life-cycle cost, airworthiness assurance, and operational availability. As aircraft systems become more integrated and spatially compact, maintenance accessibility emerges as a critical design factor. Consequently, the automation of MRO process design has become a priority direction of digital transformation in the aerospace industry.

A key scientific challenge in the development of computer-aided design (CAD) systems for MRO lies in the analytical representation of geometric design-and-technological properties (GDTP) and accessibility zones. These zones are defined not only by the spatial and topological characteristics of elements forming an assembly unit (AU), but also by operational constraints, safety regulations, and prescribed maintenance procedures. The absence of a unified analytical representation of these factors significantly complicates systematic optimization of maintenance technologies [1], [2].

From an engineering perspective, accessibility zones constitute spatially restricted domains characterized by limited clearances, constrained mobility, non-uniform load transfer, and safety constraints. These parameters determine the feasibility, labor intensity, duration, and quality of maintenance actions. In practical conditions, even minor geometric or kinematic restrictions may lead to substantial increases in execution time or the need for specialized technological equipment (TE) [1]. Therefore, rigorous modeling of accessibility conditions is essential for optimizing inspection, disassembly, restoration, adjustment, and reassembly procedures within CAD-supported environments.

The properties of accessibility zones define requirements for TE, including tools, fixtures, and auxiliary devices. The selection and configuration of TE represent a multi-criteria optimization problem involving geometric compatibility, admissible displacement domains, structural load-bearing capacity, ergonomic limitations, safety compliance, and conformity with maintenance documentation. The complexity of this decision-making process increases significantly in cases of spatially congested assemblies and integrated structural layouts.

In the absence of formal GDTP-based models, technological decisions remain largely heuristic and expert-driven, limiting reproducibility, scalability, and algorithmic support while reducing the overall degree of automation [3]. The effectiveness of CAD-supported MRO planning therefore depends on the development of unified mathematical and information models capable of integrating geometric, technological, and operational parameters within a consistent analytical framework [4]-[6].

The proposed formalization is applicable throughout the aircraft life cycle. During early production preparation, it enables proactive incorporation of maintainability requirements into structural design, thereby reducing the probability of costly redesign. During operation, it supports adaptive and resource-efficient MRO strategies based on analytically defined accessibility domains, contributing to reduced downtime, improved structural reliability, and enhanced maintenance predictability.

1.1 Scientific Novelty

The scientific novelty of this work lies in the development of a formal constraint-oriented methodology for modeling accessibility in aircraft airframe maintenance and repair, in which accessibility is treated as a rigorously defined space of admissible states rather than as a derivative of geometric clearances.

For maintenance and repair tasks involving airframe assembly units, maintenance execution zones are represented as multidimensional feasibility domains defined by logical-mathematical constraints on admissible tool displacement, placement, and orientation. Restrictive properties of structural elements are formalized as parameterized predicates integrating geometric, kinematic, technological, and operational factors into a unified constraint system.

An additional novel aspect is the application of an object-oriented representation of constraints and technological equipment as interacting analytical objects, enabling model scalability and reuse across different aircraft configurations. The proposed formalization transforms accessibility analysis from a heuristic procedure into a constraint satisfaction and decision-making problem, providing a methodological basis for algorithmic optimization, intelligent maintenance planning, and integration with digital twin environments.

1.2 Novel Methodological Contributions

This study proposes a formal constraint-oriented methodology for modeling accessibility in aircraft airframe maintenance and repair. Accessibility is defined as a multidimensional feasibility domain governed by logical-mathematical constraints on admissible tool displacement, placement, and orientation, rather than as a by-product of geometric clearances.

Maintenance execution zones are represented as structured state spaces defined by parameterized predicates integrating geometric, kinematic, technological, and operational constraints. This formulation enables accessibility assessment to be treated as a constraint satisfaction and decision-making problem suitable for algorithmic evaluation.

An object-oriented representation of constraints and technological equipment is introduced, ensuring modularity, scalability, and reuse of models across different aircraft configurations. The proposed methodology establishes a formal link between accessibility conditions and technological process selection, providing a foundation for optimization-based planning, intelligent decision support, and integration with digital twin environments.

2 METHODS

2.1 Methodological Basis

The methodological basis for constructing a decision-making system in the CAD of technological designation is the object-oriented approach (OOA) [7], in which any design object is described and modeled by the same means at three levels:

- set-theoretical;
- logical;
- computational (quantitative).

As design objects, products, technological processes, equipment, or their fragments may be used.

The OOA is based on the principles of unification and mathematical modeling based on the generation of solutions and description by methods of system analysis in information technologies using a set of tools and methods for collecting and processing data and formalized presentation of them in the form of typical mathematical models of the ISTRA system [8], [9].

2.2 Modeling of Constraints

The structure of the set of geometric properties of the connected elements $a_i \in A$ of the products as a whole in the assembly position determines the area of the working zone for MRO operations.

The nature of the working zone, depending on the composition of constraints under the conditions of approach and operation of the TE, determines the structural and dimensional series of possible elements of the technological system required for performing MRO operations.

The composition of constraints concerning the functioning of the elements of the technological system includes:

- Ω_1 - constraints of geometric properties of the connected elements in the joint zone affecting access to the working zone;
- Ω_2- constraints affecting the orientation of the TE elements relative to the surface of the AU being processed and determining their properties;
- Ω_3 - constraints affecting the working functioning of the TE elements in the course of MRO operations;
- Ω_4 - constraints affecting the withdrawal of TE elements from the working zone.

If the movement of the elements of the technological system into and out of the working zone is considered reciprocating, then the nature of constraints Ω_1 and Ω_4 can be considered similar.

The study of the influence of the shape of the working zone on the possible movements of material objects within it is carried out by modeling, which consists in generating constraints on possible translational movements of the object in various directions relative to the reference system.

2.3 Classification by Mobility

The classification of properties and parameters of the modeled object is advisable to perform by classes of mobility [5], [10], taking into account the constraints determined by the shape of the working zone.

As a reference system, for example, the axes of disassembly or assembly of the base part of the AU, the axes of connection of structural elements of the product (riveted, bolted, screwed, etc.) may be taken, which coincide with the y-axis, and the x- and z-axes describe the planes and volumes relative to which the working zone of MRO operations is formed.

Further, possible movements of TE elements during the implementation of MRO operations are modeled.

In a Cartesian coordinate system, there exist six different logical (Boolean) vectors of possible translational displacements collinear with the coordinate axes $D^{-\bar{x}}$, $D^{+\bar{x}}$, $D^{-\bar{y}}$,. $D^{+\bar{y}}$,. $D^{-\bar{z}}$,. $D^{+\bar{z}}$.

In general form, possible translational displacements relative to the reference system are described by a logical equation of the form:

$$D_{i(j)} = (D^{+\bar{x}} \veebar D^{-\bar{x}}) \vee (D^{+\bar{y}} \veebar D^{-\bar{y}}) \vee (D^{-\bar{z}} \veebar D^{+\bar{z}}). \quad (1)$$

(sentential connections of disjunctive $\veebar$ - “either…or” and non-disjunctive $\vee$ - “and/or”).

Possible displacement $|D^{\bar{\alpha}}|$, in the absence of a restriction on translational movement in direction α relative to the reference point, is considered a logical variable:

$$D^{\bar{\alpha}} = \begin{cases} 1, \ldots \text{if } \exists\, \Omega_i^{\alpha} \in \Omega(\Omega_i^{\alpha} = 0) \\ 0, \ldots \text{if } \forall\, \Omega_i^{\alpha} \in \Omega(\Omega_i^{\alpha} = 1) \end{cases}. \quad (2)$$

3 RESULTS

The presence of constraints Ω_i^{α} on movement in a particular direction characterizes a limited possible translational displacement $|D^{\bar{\alpha}}|$, which is realized to the magnitude of its modulus d^{α}.

In a CAD-based environment, the proposed framework operates as a sequential algorithm for technological process selection. Constraint satisfaction is first performed on the evaluated constraint system Ω_i^α to determine the admissible accessibility domain of the assembly unit. Within this feasible domain, technological equipment configurations are generated and validated with respect to displacement, placement, and orientation conditions. The admissible alternatives are subsequently evaluated using predefined multi-criteria performance indicators, ensuring automated and reproducible technological process selection.

The magnitudes of the moduli of limited possible displacements in each class are considered as parameters.

The zone of possible movement, in the presence of constraints, lies within a certain range; the magnitude of the limited translational displacement is determined from the condition:

$$|D^{\bar{\alpha}}| = \begin{cases} 1, \ldots \text{if } d^\alpha > \Delta^\alpha \\ 0, \ldots \text{if } d^\alpha \leq \Delta^\alpha \end{cases}. \quad (3)$$

where Δ^α is the allowable value specified for a particular design or maintenance task.

When considering possible access to the working zone and the method of orienting technological equipment (TE) in the working position, it is necessary to take into account the set of parameters of the material elements of the technological system.

The composition of the elements of the technological system P^α, as a system of material objects, is characterized by its own parameters, and the structure of these parameters is determined depending on their type and composition, represented as a set:

$$P^\alpha \subset (P^{+x}, P^{-x}, P^{+y}, P^{-y}, P^{+z}, P^{-z}). \quad (4)$$

The configuration and placement of constraints within the coordinate system are of great importance when determining the possible access to the working zone.

The presence of constraints in several directions determines the need to verify the condition for the placement of TE or its working parts within the working zone.

Placement R^α at the logical level is considered as a variable:

$$R^\alpha = \begin{cases} 1, \ldots \text{if } P^\alpha < d^\alpha \\ 0, \ldots \text{if } P^\alpha \geq d^\alpha \end{cases}. \quad (5)$$

In this case, the parameters of these constraints define the geometric characteristics of the positioning of the working elements of the technological system within the working zone.

If the orientation of the equipment relative to the processing contour in the working position is taken as a logical variable υ=1 when the orientation is achieved, and υ=0 otherwise, then the logical variable υ takes the following values depending on the minimum clearance $\Delta_{\min}^\alpha$ between the limiting elements and the working organ of the equipment:

$$\upsilon = \begin{cases} 1, \ldots \text{if} \ldots (d^\alpha - \Delta^\alpha) \geq P^\alpha \ldots \text{or } \Delta_{\min}^\alpha \geq P^\alpha \\ 0, \ldots \text{otherwise} \end{cases}. \quad (6)$$

where $\Delta_{\min}^\alpha$ is the minimum clearance between the limiting elements and the working organ of the equipment in the given direction.

When υ=0, the impossibility of orienting TE in this limited zone determines the impracticality of using the considered equipment, tools, or auxiliary fixture elements.

When performing maintenance, repair, and overhaul operations on an actual structure, it is necessary to account for the geometric constraints imposed by adjacent components on the required working displacements $D_{\text{req}}^{\bar{\alpha}}$.

In general form, the required translational displacement of the equipment and tools of the technological system relative to the reference system is described by a logical equation of the form:

$$D_{\text{req}}^{\bar{\alpha}} = (D^{+\bar{x}}) \vee (D^{-\bar{x}}) \vee (D^{+\bar{y}} \wedge D^{-\bar{y}}). \quad (7)$$

where $D_{\text{req}}^{\bar{\alpha}}$ is a Boolean vector of required displacements during the working stroke of the technological system.

The admissibility of this displacement defines the feasibility of performing MRO operations within the considered zone.

The required displacement of TE, in the presence of constraints at the logical level, is considered as a logical variable:

$$]\, D_{req}^{\bar{\alpha}} \,[= \begin{cases} 1, \ldots if \ d_{req}^\alpha > (\Delta^\alpha + \Delta_{min}^\alpha) \\ 0, \ldots if \ d_{req}^\alpha \leq (\Delta^\alpha + \Delta_{min}^\alpha) \end{cases}. \quad (8)$$

To ensure access to a restricted zone, at least one of the six spatial directions must remain unobstructed.

The classification of zones based on the composition and nature of constraints enables their reduction to the principal types summarized in Table 1, corresponding to specific mobility classes:

- Free - $\Pi_{\text{I}} \wedge \Pi_0^{\text{w}}$;
- Limited - $\Pi_{\text{I}} \wedge \Pi_{\text{I}}^{\text{w}}$;
- Constrained - $\Pi_{\text{I}} \wedge \Pi_{\text{IIA}}^{\text{w}}$; $\Pi_{\text{I}} \wedge \Pi_{\text{IIB}}^{\text{w}}$;
- Hampered access- $\Pi_{\text{I}} \wedge \Pi_{\text{IIIA}}^{\text{w}}$; $\Pi_{\text{I}} \wedge \Pi_{\text{IIIB}}^{\text{w}}$;
- Difficult-to-access - $\Pi_{\text{I}} \wedge \Pi_{\text{IIA}}^{\text{w}}$; $\Pi_{\text{I}} \wedge \Pi_{\text{IVB}}^{\text{w}}$;
- Combined, including mobilities of different classes.

To demonstrate the applicability of the proposed constraint-oriented modeling framework, a representative maintenance scenario involving rivet removal in a rib-stringer joint of a wing panel was analyzed. The geometric parameters of the working zone were h=80 mm with lateral clearance c=22 mm.

The technological equipment had a characteristic dimension $P^{\alpha} = 16$ mm and a minimum clearance $\Delta^{\alpha}_{\min}$=5 mm.

The constraint system $\Omega = \{\Omega_1, \Omega_2, \Omega_3, \Omega_4\}$ representing geometric, orientation, operational, and withdrawal restrictions, was evaluated. Since $P^{\alpha} < c$, the placement condition R^{α}=1 and the orientation condition υ=1 are satisfied. According to the accessibility classification presented in Table 1, the working zone corresponds to the limited accessibility class $F_2(A)$. Based on the resulting admissible accessibility domain, the CAD-based selection procedure identifies a standard pneumatic rivet removal tool as the optimal technological equipment for the maintenance operation. This example confirms the applicability of the proposed model for analytical accessibility classification and automated technological equipment selection in constrained airframe maintenance conditions.

4 DISCUSSION

The obtained results demonstrate that effective analysis of accessibility and technological feasibility in aircraft maintenance and repair cannot be reduced to static geometric clearance verification. A review of existing approaches indicates that most CAD-based solutions rely on isolated geometric checks, expert-driven heuristics, or post-processing simulation, which are insufficient for complex assembly units characterized by the simultaneous interaction of multiple constraints.

In practical maintenance scenarios, accessibility is determined by the combined influence of geometric, kinematic, technological, and operational constraints. These constraints form dynamic accessibility zones whose characteristics depend on the configuration of airframe components and the selected technological equipment. Conventional methods typically consider these factors independently, which limits decision consistency and reduces applicability in real maintenance environments.

Table 1: Fragment of classification of zones according to the nature of possible constraints and their formalization.

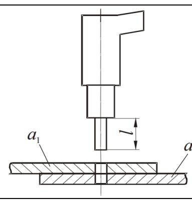
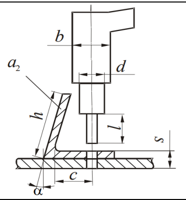
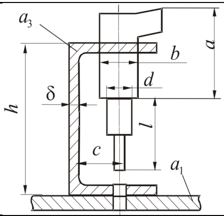
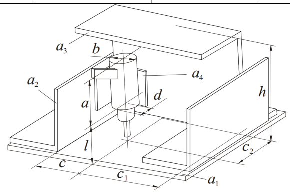
Free		$F_1(A) - \Pi_I \wedge \Pi^W_0$
Limited		$F_2(A) - \Pi_I \wedge \Pi^W_I$ $R^{\alpha} = 1, \left\{\frac{d}{2} < (c - h\sin\alpha)\right\} \rightarrow l = s + \Delta^{\alpha};$ $R^{\alpha} = 0, \left\{\frac{d}{2} \geq (c - h\sin\alpha)\right\} \rightarrow l = h\cos\alpha + s + \Delta^{\alpha}$
Constrained (Group II)		$F_4(A) - \Pi_I \wedge \Pi^W_{II\text{B}}$ $R^{\alpha} = 1, \left\{\left(\frac{d}{2} < c\right) \wedge \left(l < (h - 2\delta)\right)\right\};$ $\upsilon = 1, \left\{(a < (h - 2\delta - l)) \wedge \left(\frac{b}{2} < c\right)\right\}$
Difficult-to-access		$F_7(A) - \Pi_I \wedge \Pi^W_{IV A}$ $R^{\alpha} = 1, \left\{\left(\frac{d}{2} < c\right) \wedge \left(\frac{d}{2} < c_1\right) \wedge \left(\frac{d}{2} < c_2\right) \wedge (l < h)\right\};$ $\upsilon = 1, \left\{(a < (h - l)) \wedge \left(\frac{b}{2} < c\right) \wedge \left(\frac{b}{2} < c_1\right) \wedge \left(\frac{b}{2} < c_2\right)\right\}$

Table 2: Comparison of the proposed method with existing approaches for maintenance accessibility analysis.

Criterion	Geometry-based CAD	Expert /heuristic	Simulation-based	Proposed method
Constraint representation	Geometric clearances	Experience-based rules	Embedded simulation constraints	Formal logical-mathematical constraints
Constraint classes	Geometric	Partial	Geometric, kinematic	Geometric, kinematic, technological, operational
Constraint interaction	Not considered	Informal	Limited	Explicitly modeled
Decision reproducibility	Medium	Low	Medium	High
Suitability for early planning	Medium	High	Low	High
Computational efficiency	High	High	Low	High
CAD automation level	Partial	Low	Medium	High
Scalability	Limited	Very limited	Limited	High
Digital-twin integration	Indirect	Not supported	Partial	Direct

The proposed constraint-oriented modeling approach addresses these limitations by representing restrictive properties as parameterized logical-mathematical entities. This formulation enables the description of accessibility zones as multidimensional feasibility domains governed by logical conditions and admissible displacement functions. As a result, accessibility analysis is transformed into a formal decision-making problem that can be systematically solved within CAD environments.

Compared with expert-based methodologies [3], the proposed approach ensures reproducibility and objectivity through explicit formalization of constraints. In contrast to simulation-centric techniques [11], [12], the developed framework enables analytical feasibility assessment at early planning stages, significantly improving computational efficiency while maintaining formal rigor.

An important feature of the proposed approach is its object-oriented representation of constraints and technological equipment. Each constraint is modeled as an independent analytical object with explicitly defined parameters and interaction rules. This structure supports reuse of constraint models across different aircraft configurations and maintenance tasks, improving scalability and standardization of technological solutions (see Table 2).

From the perspective of digital engineering, the developed framework provides a methodological basis for integration into digital twin architectures of aircraft maintenance systems [6], [10]. Unlike conventional digital twins focused primarily on structural behavior monitoring, the proposed approach explicitly incorporates technological feasibility and accessibility assessment, enabling intelligent maintenance planning and adaptive process optimization.

Overall, the discussion confirms that formalized constraint-based modeling constitutes a key element of modern CAD-supported maintenance planning, providing a balanced combination of computational efficiency, scalability, and methodological rigor suitable for application in conference-oriented engineering research.

5 CONCLUSIONS

This study formulates a constraint-oriented theoretical framework for the formal modeling of geometric design-and-technological properties of assembly units and accessibility zones in aircraft maintenance, repair, and overhaul operations. The proposed framework is based on the representation of restrictive properties as parameterized logical-mathematical models that define admissible state spaces, displacement domains, and feasibility conditions for technological actions within computer-aided design environments.

The integration of geometric, kinematic, technological, and operational constraints into a unified formal model enables the transformation of maintenance accessibility analysis into a well-posed decision-making problem. Within this formulation, the feasibility of tool placement, orientation, and motion is evaluated through logical predicates and constraint satisfaction conditions, which allows the systematic derivation of admissible technological solutions.

The comparative analysis presented in Table 2 confirms that such a formulation provides a higher level of rigor, reproducibility, and scalability than existing geometry-based, heuristic, or simulation-centric approaches. The proposed method was validated on a representative maintenance scenario, demonstrating that the accessibility zone could be classified as limited ($F_2(A)$) and that a standard pneumatic rivet removal tool could be selected as the optimal equipment, confirming the practical applicability of the framework.

The object-oriented structure of the proposed models establishes a modular representation of constraints, enabling their reuse and composition across heterogeneous aircraft configurations. This modularity creates a direct foundation for optimization-based maintenance planning, where accessibility constraints can be incorporated into multi-objective optimization problems involving labor intensity, operation time, tool selection, and safety margins.

As a result, the proposed framework supports both deterministic optimization and stochastic or learning-based optimization strategies.

From the perspective of artificial intelligence, the formalized constraint representation provides a structured state and action space suitable for data-driven methods, including reinforcement learning, rule induction, and hybrid symbolic-numeric reasoning.

The explicit parameterization of constraints enables the construction of knowledge bases and structured datasets suitable for intelligent decision-support systems [5], [6].

Furthermore, the proposed framework constitutes a fundamental component of digital twin architectures for aircraft maintenance systems. By embedding formal accessibility and feasibility models into digital twins, it becomes possible to perform predictive simulation, adaptive reconfiguration of maintenance processes, and continuous optimization based on real-time operational feedback. This extends the functionality of digital twins beyond structural monitoring toward closed-loop technological decision-making.

In summary, the proposed formal framework establishes a mathematically grounded basis for integrating constraint modeling, optimization, artificial intelligence, and digital twin technologies within intelligent aircraft maintenance systems. The generality of the formulation allows its extension to other complex engineering domains characterized by dense structural layouts and stringent accessibility requirements, thereby contributing to the advancement of formal methods in intelligent engineering design and life-cycle optimization.

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