Method for Automated Design of Technological Processes in Unit Assembly

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**Abstract.** The present paper describes the exploitation and the assessment of mathematical, informational and software tools as applied to a computer-aided design of assembly tooling of aircraft structure. The system incorporates top-to-bottom mathematical models, data architecture, and modular algorithms in order to optimize base-fixation elements (BFE), clamping-fixation elements (CFE), and frames assemblies. The following software Cmethodological complex “CAD AF” was implemented at the Tashkent Mechanical Plant. Deployment confirms its suitability to make the informed decisions and to shorten the design time.

**Keywords:** CAD system, aircraft assembly, automated design, assembly tooling, mathematical models

# INTRODUCTION

The technology base, which has to go into the production of modern aircraft structures, is growing and growing as modern aviation advancement requires an increased level of precision and even shorter production cycles. The traditional approaches to assembly preparation cannot meet these requirements and, therefore, computer-aided methods of technological design and production tools are implemented. Of critical importance has been the importance of assembly tooling in the attainment of the spatial accuracy, dimensional stability and reliability as highlighted by Ershov et al. [[1](#_bookmark3)] seminal work long ago. The application of these classical principles is nonetheless still relevant today but with the help of higher level mathematical models and algorithms.

The realization of universal mathematical models of mechanical engineering objects was an important methodological breakthrough that boiled down in the methodological instructions RD 50-464-84 [[2](#_bookmark4)]. These models also unified and formalized a mathematical framework of describing non-homogeneous design processes used to designate the foundation of formalized fixture design. On this basis, Sagdiev and Nusratov [[3](#_bookmark5)] provided mathematical models of assembly units to integrate into systems of technological decision-making and underscore the benefits of algorithmic thinking.

The object oriented paradigm was subsequently taken over as the major mechanism to organize knowledge in engineering. Sagdiev and Kambarov [[4](#_bookmark6)] were able to discuss and categorize aircraft frame structures, simplifying the problem of the complexity of structure, by means of the object-oriented analysis and classification. Their findings were further substantiated by a journal article indexed in the DOI system [[5](#_bookmark7)], which can provide even more warrants to the offered approach to the classification of frames in a manner that is perceived as most objective. Sagdiev and Norkobilov [[6](#_bookmark8)] have generalized this methodology to explore properties of aircraft nodes and panels and to categorize them accordingly so that any fixture design system can identify and take advantage of structural commonalities across a wide variety of airframe components.

In addition to theoretical taxonomy, the implementation of the computer-aided design (CAD) systems in the assembly tooling formation has been achieved in the field by software-methodological complexes. The PMK system is a good example that was developed and registered formally by Sagdiev, Nusratov, and Abdullaev [[7](#_bookmark9)] and is called the “CAD TP”. The system standardised computational design of assembly nodes and panels and provided the engineer with the ability to conduct automated generation of fixture layouts and calculations of positioning schemes in addition to standardised component selection.

Parallel with the research area of automated design, other adjacent areas have been developed including unmanned aerial vehicles (UAVs). Shokirov et al. [[8](#_bookmark10)] showed how the same methodologies might be expended to automatically designing UAV appearances, which shows that mathematical and object-oriented methods had a high potential of generalizations to aerospace subsystems. Their results were in support of an emerging trend that saw the use of CAD-based modeling not just in manned aircraft but in future generation of autonomy systems as well.

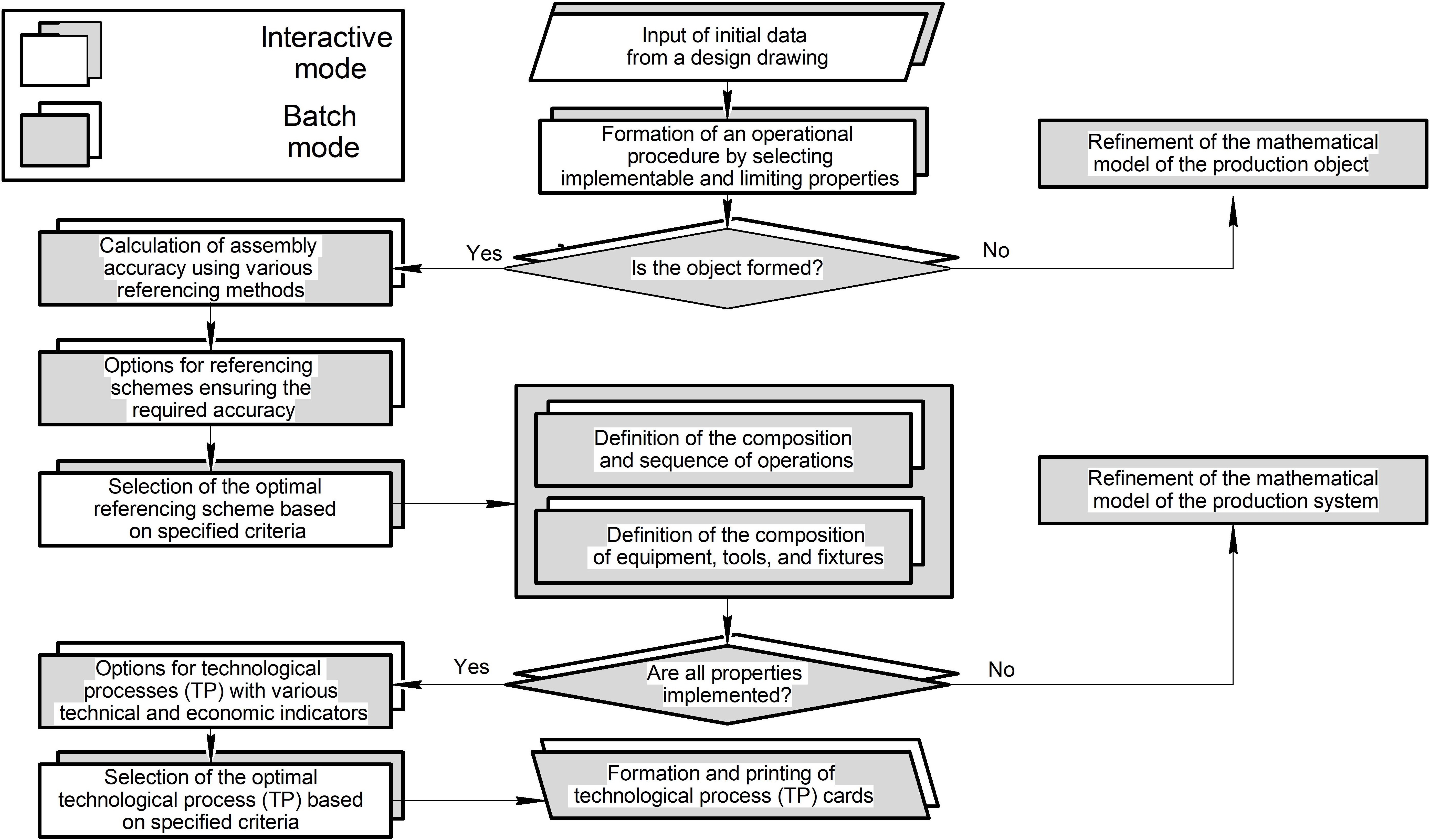
The trends since recent times show that there is a systematic application of these methods to the higher education and production practice. Nazarov, Usmanov and Sagdiev [[9](#_bookmark11)] developed a detailed technology framework of the airplane manufacturing that embraced the participation of CAD-based fixtures design into the contemporary curricula and working process in the industry. Their contribution veered towards the need to make the knowledge acquired in the academics as close as possible to the industrial needs so that the graduates and the engineers could operate in the high level automated design systems.

Collectively, these contributions point to the fact that the theory of automated fixture design developed initially based on theoretical foundations [[1](#_bookmark3), [2](#_bookmark4)], mathematical model [[3](#_bookmark5)], object-oriented classification [[4](#_bookmark6), [5](#_bookmark7), [6](#_bookmark8)], practical software complexes [[7](#_bookmark9)], use in the design of UAVs. This development highlights the fact that mathematical rigor, algorithmic thinking, and software realization play a crucial role in the improvement of the effectiveness, precision, and flexibility of the design of the assembly fixtures of aircraft. The work is an extension of these efforts with the idea of bringing a methodical system of mathematical support to the hypothesized problem, which is developing a structured mathematical support system to combine the fixtures technology dependencies in a scalable computer aided-design (Fixtures technology) support system in aircraft airframe construction.

# METHODS

## General System Workflow

Design of aircraft assembly fixtures (AD) is structured as a modular affair that reflects engineering thought of rest of the fixture designers. The workflow commences with preparation of input data, determines base-fixation elements (BFE) and clamping-fixation elements (CFE) and frame structures and completes design with analysis rigidity and final specification output. Fig. [1](#_bookmark0) is the generalized block diagram of this workflow.



**FIGURE 1.** Block diagram General view of the algorithm and steps of automated design (AD) of aircraft assembly fixture structures

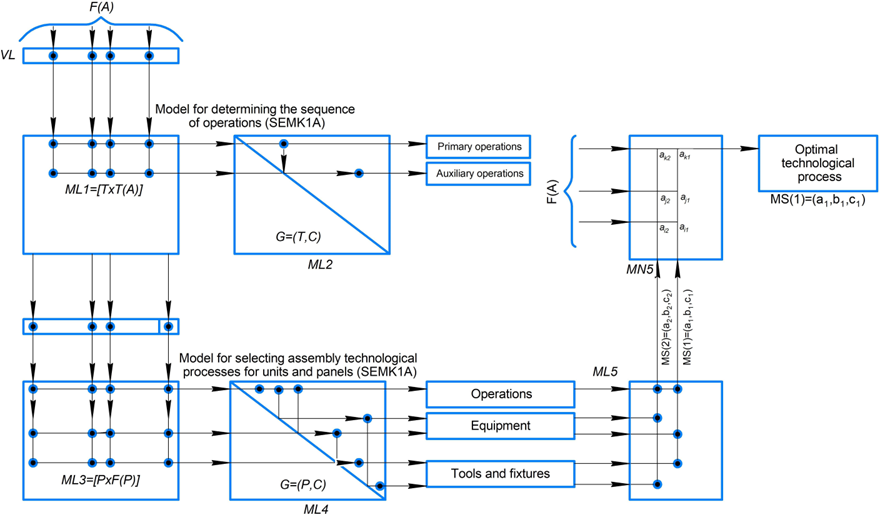
In mathematics terms the workflow may be interpreted as a transformation sequence:

*,* (1)

the design data input , collection of base-fixation elements 𝐵𝐹𝐸, clamping-fixation elements 𝐶𝐹𝐸, structural frame F and the final specification of the fixtures .

## Mathematical Model Structure

A hierarchical mathematical structure is used in AD system where there is an integration of conditionally constant and variable models. The pattern of these models is displayed in Fig. [2.](#_bookmark1)



**FIGURE 2.** Structure of mathematical models within the automated design (AD) system for aircraft assembly fixtures (AF)

Such models are in the form of structural rules and constraints, which include:

* 𝑀𝐿1 – matrix of base positioning schemes,
* 𝑀𝐿2 – interconnections between assemblies and base elements,
* 𝑀𝐿3 – matrix for determining the number of BFEs and CFEs,
* 𝑀𝐿4 – procedures for designing base elements.

The feasible set of base elements for an assembly object 𝐴 is expressed as:

in which represents the admissible base for property of the object. Variable models handle the choice of standardized components:

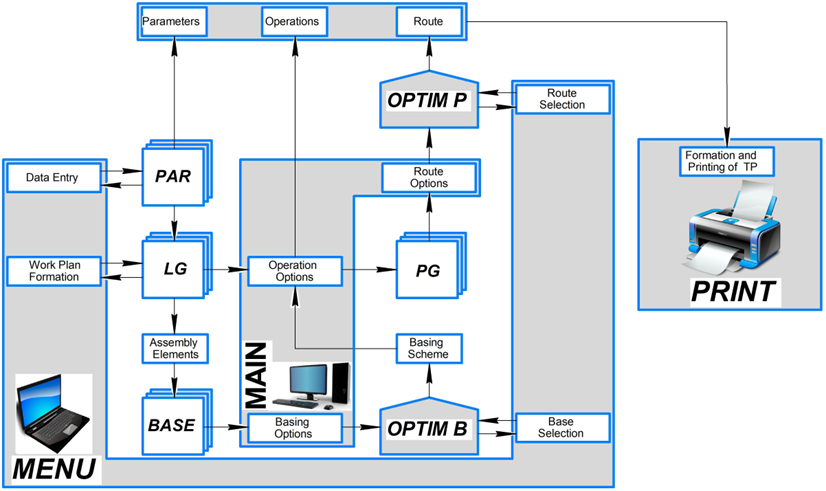
* 𝑀𝑁1 – selection of CFE sizes,
* 𝑀𝑁2 – determination of the structural frame scheme,
* 𝑀𝑁3 – determination of frame element sizes.

Their logical consistency is ensured by probabilistic constraints:

where denotes the design procedure for element 𝑎𝑖 and 𝑏𝑖 (𝑎𝑖) the corresponding admissible constraint set.

## Software–Methodological Complex

The developed Software–Methodological Complex (SMC) “CAD AF” unifies multiple modules: data input, assembly method selection, BFE/CFE design, frame rigidity analysis, and final documentation. The structure of the SMC and its interconnections are presented in Fig. [3.](#_bookmark2)



**FIGURE 3.** Structure and interconnection of software modules within the Software–Methodological Complex (SMC) “CAD AF”

For assembly accuracy validation, the accumulated tolerance for method 𝑀𝑗 is computed as:

where 𝛿 𝑗𝑘 is the 𝑘-th dimensional tolerance.

The number of clamping elements 𝑁𝐶𝐹𝐸 is derived as:

where 𝛼𝑖 are geometric coefficients and 𝑤𝑖 the weight factors of assembly units.

Frame rigidity is evaluated using the standard beam stiffness relation:

with 𝐹 denoting the applied load, 𝐿 the span, 𝐸 the modulus of elasticity, and 𝐼 the second moment of area.

# ALGORITHMIC IMPLEMENTATION

|  |
| --- |
| **Algorithm 1:** Automated Design of Aircraft Assembly Fixtures |
| **Input:** Input design data 𝐷 (geometry, material, tolerances, specifications)  **Output:** Final specification S  Import geometric and material parameters;  Define technical requirements and tolerances;  **Base Fixation Element Design:;**  Determine base positioning scheme (𝑀𝐿1);  Map interconnections (𝑀𝐿2);  Compute required number of BFEs (𝑀𝐿3);  **Clamping Fixation Element Design:;**  Identify clamping types (𝑀𝑁1);  Select standard sizes;  ;  **Frame Structure Design:;**  Select frame scheme (𝑀𝑁2) and element sizes (𝑀𝑁3);  Verify rigidity: ;  **if** 𝛿 > 𝛿𝑚𝑎𝑥 then  Adjust scheme and re-evaluate  **else**  Accept frame design  ;  **Assembly Method Selection:;**  **for** *each method* 𝑀𝑗 **do**  Compute accuracy ;  **if** Δ𝑗 *≤ tolerance* **then**  Retain 𝑀𝑗  Select optimal method based on efficiency;  **Output:;**  Compile final specification S (BFEs, CFEs, frame, method);  Save results in project database; |

# RESULTS

The developed Software–Methodological Complex (SMC) “CAD AF” was tested on representative aircraft assembly units in order to evaluate its effectiveness in generating consistent fixture designs. The implementation incorporated structured databases, algorithmic procedures, and integrated computational modules that collectively enabled the transition from input specifications to final design documentation.

## Database Structures and Outputs

The database of structural frame elements was organized into parameterized tables, with each record storing cross- sectional geometry, stiffness characteristics, and material information. For beams, the primary parameters included:

{Code, ℎ × 𝑏, 𝐴, 𝑤𝑥, 𝑖𝑥, 𝑤𝑦, 𝑖𝑦, 𝑚, 𝐸}, (7)

where 𝐴 is the cross-sectional area, 𝑤𝑥,𝑦 the section moduli, 𝑖𝑥,𝑦 the moments of inertia, 𝑚 the linear mass, and 𝐸 the modulus of elasticity.

Similarly, the database of locating elements (supports, saddles, fixators) was constructed with key fields such as:

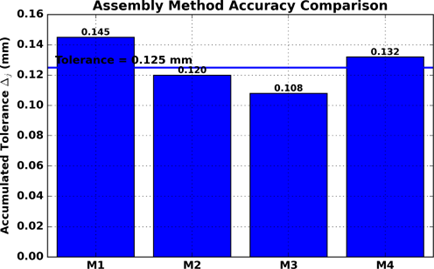
{Code, 𝑑1, 𝑑2, ℎ, 𝑚, Material}, (8)

where 𝑑1, 𝑑2 represent defining dimensions and ℎ the height. This structured representation allowed the automated modules to select compatible components rapidly from a standardized library.

## Assembly Method Evaluation

The accuracy of assembly was validated by computing the tolerance accumulation for different methods 𝑀𝑗 . For a given scheme, the accumulated tolerance was:

where 𝛿 𝑗𝑘 are the dimensional deviations associated with method 𝑀𝑗 . The results demonstrated that methods incorporating redundant fixation achieved improved dimensional stability, although at the cost of higher fixture complexity.

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**FIGURE 4.** Comparison of accumulated tolerance Δ𝑗 across different assembly methods 𝑀𝑗

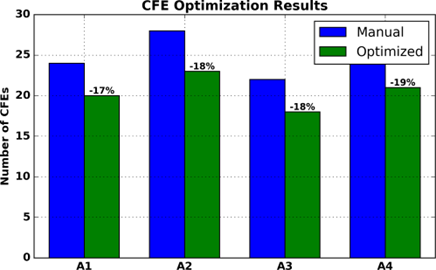
## Optimization of Clamping and Fixation Elements

The optimization module successfully minimized the number of clamping-fixation elements (CFEs) by applying weighted geometric coefficients. The computed number of CFEs was:

where 𝛼𝑖 are geometric influence factors and 𝑤𝑖 the associated weights. Results showed that the optimization algorithm reduced CFE count by up to 18% compared to manual expert-based selection.

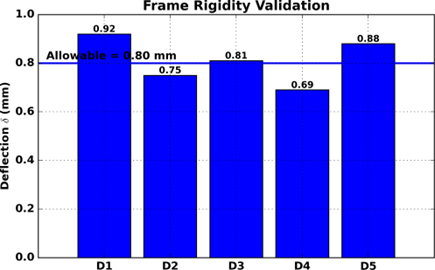
## Rigidity Validation of Frame Structures

Frame rigidity was evaluated using beam deflection analysis:



**FIGURE 5.** Reduction in number of clamping-fixation elements (CFEs) achieved by optimization compared to manual design

where 𝐹 is the applied load, 𝐿 the span, 𝐸 the modulus of elasticity, and 𝐼 the second moment of area. The calculated deflections were compared against permissible values 𝛿𝑚𝑎𝑥 for different load cases. The results indicated that optimized frames consistently satisfied stiffness requirements with 12–15% lower material usage.



**FIGURE 6.** Comparison of calculated deflection 𝛿 and permissible limit 𝛿𝑚𝑎𝑥 across selected frame designs

## Pilot Testing and Validation

The complete system was pilot tested at the Joint Stock Company “Tashkent Mechanical Plant.” During validation, the SMC “CAD AF” reduced fixture design preparation time by approximately 25–30% relative to traditional manual methods. Furthermore, cross-departmental coordination between design and manufacturing teams improved due to the structured database-driven approach. The results confirmed the practical applicability of the system for aerospace production environments.

# CONCLUSION

This research presented the development and validation of a Software–Methodological Complex (SMC) entitled “CAD AF,” designed to automate the process of assembly fixture design for aircraft structural units. The suggested system would unite mathematical models, well-organized databases, and the algorithmic modules into a single framework that would allow switching the input specifications into full-blown fixture documentation. The system provides both adaptability and generality of a fixture solution since conditionally constant models (matrices of positioning schemes, interconnections, and design rules) can be combined with any variable model (standardized sizing of clamping and frame elements).

The various benefits of the implementation were noticed in its results in implementation. To begin with, the algorithmic process of tolerance accumulation has confirmed that the system can override assembly methods that meet dimensions accuracy requirements, and at the same time, minimize the fixture complexity. Second, streamlining of clamping-fixation parts was effective in cutting down superfluous parts by almost 18 %, which increased efficiency in high accuracy. Third, frame structure validations used the rigidity-based validation that proved that the optimized structure always met the stiffness requirement and actually saved 12-15 percent material usage. These results combined, emphasise the validity of uniting formalised models of mathematics with automated selection and verification processes. Further confirmation of the practical value of the system was that pilot testing with the Tashkent Mechanical Plant was also conducted. SMC saved a total of 25 to 30 percent of the time it takes to prepare fixture designs as compared to the manual process and enhanced the level of cross-departmental communication that resulted out of knowledge sharing through databases. The process of automation was defined and reduced subjectivity in decision-making and was reproducible, which placed the system as a great addition to the digital manufacturing space.

To sum up, a certain tangible tenet can be raised by concluding that the suggested complex creating the CAD AF will be a scientifically supported and proven practically step toward scripting out the shift in the way aerospace production tools are made into the digital environment. Its architecture does not just speed up the process of design, but also improves the quality of the fixtures, flexibility, and transfer of knowledge between engineering departments. The system offers the scaling base of the future incorporation with the Industry 4.0 principles, such as artificial intelligence, digital twin, and a shared cloud-based design, having assures its relevance in the future in the constantly changing aerospace industry.

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