Development of Computer-Aided Process Planning Systems for Aircraft Structural Parts Using Blanking and Stamping Operations

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Abstract: Blanking and stamping operations, including both separating and forming processes, play an important role in the manufacturing of aircraft structural components. These operations account for approximately 60-70% of the total number of aircraft structural parts, while their labor intensity represents about 10-12% of the total manufacturing labor input. The increasing use of difficult-to-deform materials, such as high-strength steels, titanium alloys, and composite materials, further increases the importance of blanking and stamping technologies in modern aircraft production [1]. Under these conditions, the development of computer-aided process planning (CAPP) systems for blanking and stamping operations becomes an important element of the digital transformation of aircraft manufacturing. The implementation of such systems requires the integration of formal mathematical models describing production objects, including aircraft skins, spar webs, rib walls, ribs, and frames made of sheet materials. These models also represent manufacturing processes and the selection of technological tooling. The effectiveness of computer-aided manufacturing systems depends on compliance with the principles of system integrity, interoperability, scalability, and standardization. Their implementation is supported by international standards ISO 10303 (STEP) and ISO 13584 (Parts Library), which provide a framework for the representation and exchange of product and manufacturing data. These standards are conceptually based on the Structured Analysis and Design Technique (SADT) methodology. However, many existing process planning systems rely on empirical rules and heuristic decision-making procedures, which limits their universality and reproducibility. This study aims to develop and validate a computer-aided process planning system for blanking and stamping operations based on a hierarchical system of mathematical models implemented within the ISTRA framework. Industrial validation confirmed the adequacy of the developed models and the stability of the generated technological solutions, demonstrating the applicability of the proposed approach for automated technological process planning in aircraft manufacturing, with potential relevance for Industry 4.0-oriented manufacturing systems.

1 INTRODUCTION

The increasing complexity of aircraft structures and the growing requirements for manufacturing efficiency necessitate the development of advanced methods for technological preparation of production [1], [2]. One of the key directions for improving manufacturing efficiency is the automation of technological process planning based on the identification and formalization of relationships between the design-technological properties (DTP) of products and the elements of the production system, including technological operations, equipment, tools, and fixtures. The representation of these relationships in the form of mathematical models enables a formalized description of technological planning processes and provides a consistent basis for rational technological decision-making [3].

The proposed approach is aimed at comprehensive computer modeling of manufacturing objects and processes and is intended for application at different stages of the life cycle of complex technical systems, including design, production planning, and operation. The relevance of such methods is particularly evident in aircraft manufacturing, where technological processes are characterized by high structural complexity, multi-level organization, and strict requirements for the accuracy, reliability, and reproducibility of technological decisions [4], [5].

A hierarchical system for the mathematical modeling of production objects and manufacturing processes at different levels of abstraction — the ISTRA system — has been developed and implemented at several industrial enterprises, demonstrating its practical efficiency and applicability in industrial environments. Despite the significant progress in the development of CAPP systems, many existing solutions still rely heavily on empirical rules and heuristic decision-making procedures. Such approaches limit the formal representation of technological knowledge and reduce the reproducibility and scalability of technological solutions when designing complex manufacturing processes.

Therefore, an important scientific problem is the development of formalized methods for the automated synthesis of technological processes based on mathematical models of production objects and elements of the production system.

The objective of this study is to develop a computer-aided process planning system for blanking and stamping operations based on a hierarchical system of mathematical models implemented within the ISTRA framework.

1.1 Scientific Novelty

The scientific novelty of this study lies in the development of a formalized methodology for automated technological process synthesis for aircraft sheet-metal components manufactured by blanking and stamping operations. The methodology is based on an object-oriented representation of the production system and a hierarchical system of mathematical models implemented within the ISTRA modeling framework.

In contrast to conventional CAPP and CAD/CAM systems, which largely rely on empirical rules, technological templates, and expert-dependent decision procedures, the proposed approach provides a formal representation of relationships between the design-technological properties of parts and the elements of the production system, including technological operations, equipment, tools, and fixtures. The original scientific contribution of this research consists in the development of a hierarchical modeling structure integrating tabular and network mathematical models for automated technological process synthesis.

The developed modeling framework enables automated synthesis of technological process structures based on formalized design-technological properties of aircraft sheet-metal components. Tabular models formalize the correspondence between the design-technological properties of parts and admissible technological operations, while network models represent precedence relations between operations and enable the generation of feasible technological routes. Industrial validation conducted at the Tashkent Mechanical Plant confirmed the adequacy of the developed mathematical models and the stability of the generated technological solutions for aircraft sheet-metal component manufacturing.

The interpretation of the developed system in the context of object-oriented digital manufacturing is considered a potential direction for further development within the Industry 4.0 paradigm.

1.2 Novel Methodological Contributions

Within the proposed modeling framework, the representation of production system objects is performed across several levels of abstraction. The following principal levels of object representation are distinguished:

- the verbal (linguistic) level, where the object is described using the natural language employed by the system developer or user;
- the set-theoretical level, providing a formal representation of the object using the mathematical apparatus of set theory and graph theory;
- the logical level, where relationships between elements and properties of the modeled objects are formalized using the tools of mathematical logic;
- the quantitative level, where quantitative characteristics of the system are described using mathematical methods such as algebra, geometry, and mathematical analysis.

2 MATERIALS AND METHODS

2.1 General Modeling Approach

The proposed approach to formalization and mathematical modeling is based on the analysis of the design-technological properties (DTP) of aircraft structural components and the elements of the production system (PS). Relationships between these elements are identified and represented using typical mathematical models, including tabular and network models. Computer-aided process planning (CAPP) for blanking and stamping operations is considered a system-level problem and represented as a hierarchy of interconnected mathematical models (see Fig. 1) [3], [6].

This structure provides a unified description of the production object, technological process, and production environment, ensuring the consistency and reproducibility of technological decisions. The developed modeling framework integrates production objects and manufacturing processes at the set-theoretical, logical, and quantitative levels. Mathematical and information support are organized according to the block principle, while the software architecture follows a modular design typical for CAPP systems.

2.2 Structure of the Mathematical Models

The production system is described using a set of typical mathematical models implemented in the developed CAD system. These models formalize production objects and technological processes at different levels of detail. Tabular and network mathematical models are used for technological process synthesis (see Fig. 2). Their application enables the generation of technological processes with different levels of unification.

Figure 2 shows the internal structure of the mathematical models used in the CAD system. A logical vector (VL) is used to represent the design-technological properties of the part, including geometry, material characteristics, and technological constraints [7]-[9]. Based on this vector, contour matrices of the technological process (ML1) and the production system (ML3) are generated. Relationships between technological operations and production system elements are represented using Boolean matrices (ML2 and ML4). Quantitative evaluation of technological alternatives is performed using labor-intensity models (ML5, MN5), while matrix MS ensures structural connectivity between all elements of the modeling environment.

In partially unified processes, the sequence of operations remains fixed while equipment and tooling may vary. In this case, technological processes are synthesized using network operator models (see Fig. 3).

The required input data differ for tabular and network models. Tabular models rely mainly on classification information about product contours, whereas network models require more detailed numerical parameters affecting the selection of technological operations.

In addition to operator models, the system includes models for selecting technological tooling (see Fig. 4) and quantitative models for labor-intensity estimation. The interaction of these models ensures the consistency of technological process synthesis.

Technological process planning can be performed in automatic or interactive modes. In the automatic mode, all elements of the production system are present in the modeling environment. If some technological resources are unavailable, decisions may be made by the process engineer or the missing elements may be introduced into the system model.

2.3 Algorithmic Structure of the System

The CAD system algorithm has a hierarchical modular structure and includes universal, unified, and specialized design operations.

Universal algorithms perform computational procedures independent of the model type, such as numerical calculations, combinatorial operations, and path determination in graphs.

Unified algorithms implement procedures specific to particular classes of modeling environments and incorporate modules of universal operations.

Specialized algorithms solve complete technological design tasks and combine modules of universal and unified operations.

2.4 Information Support of the System

The information support of the system includes data describing both the product and the production system. It defines the composition of information, the structure of information links, the level of detail, and the form of data representation.

Product information describes the design-technological properties of stamped components, including geometric parameters, dimensional characteristics, and data required for calculating technological and economic indicators. Reference information is also included for generating output technological documentation. Normative reference data are used to evaluate technological planning alternatives and include formulas for calculating labor intensity, technological cost, and production cycle duration. These data are organized as dictionaries describing elements of the production system.

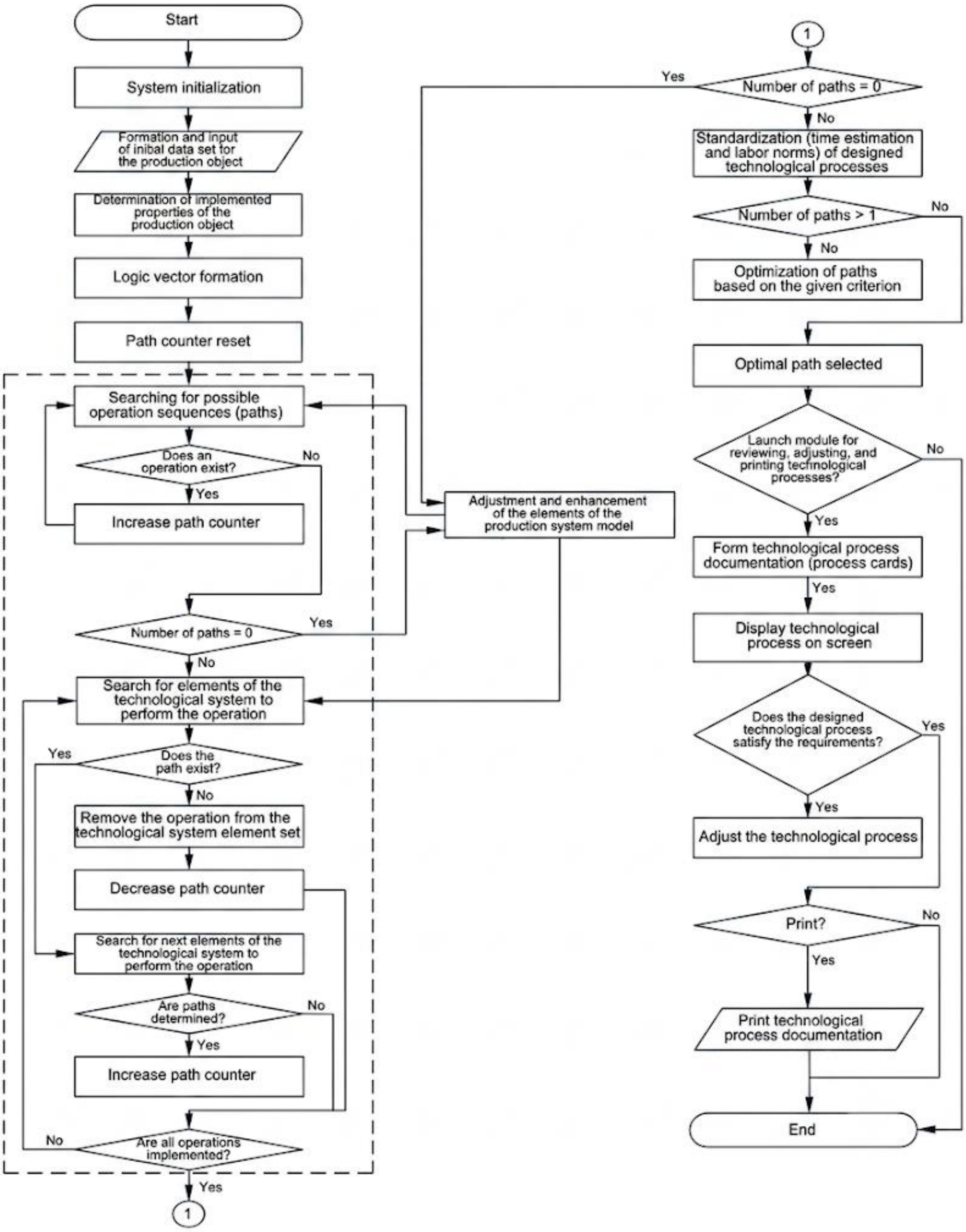


Figure 1: Block diagram of the operational algorithm of the CAD system for technological processes of blanking and stamping operations (BSO).

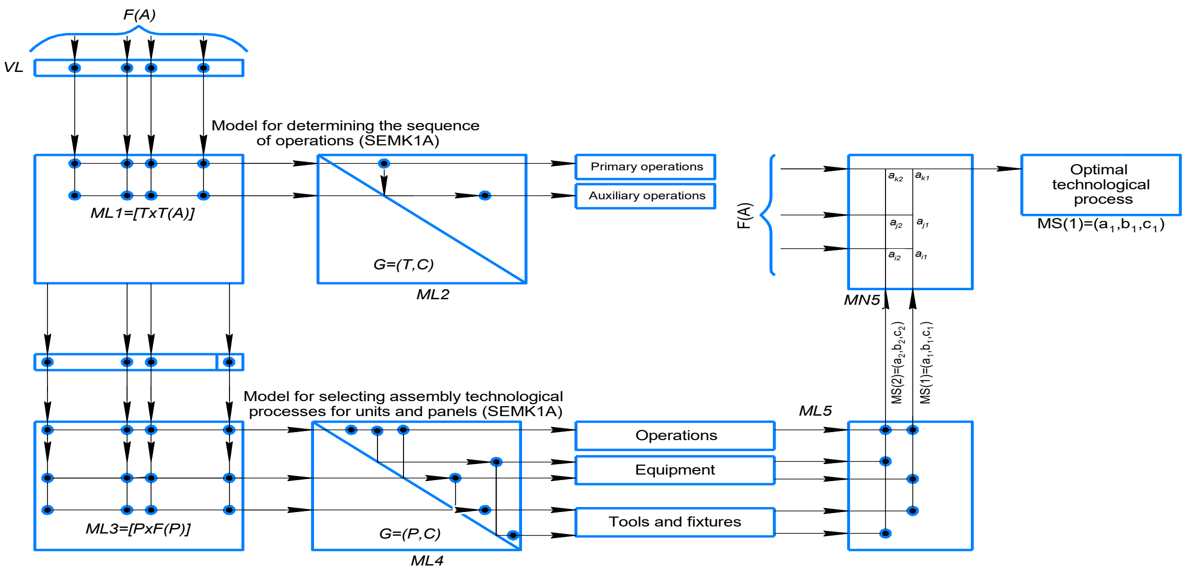
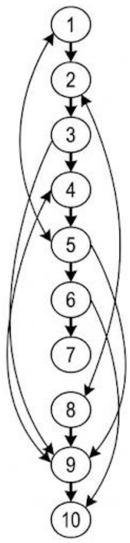


Figure 2: Structure of mathematical models of the CAD production system for technological processes of blanking and stamping operations (BSO). *Note:* VL - logical vector describing part properties; ML1 - contour matrix of the technological process; ML2 - Boolean matrix representing precedence relations between operations G(T,C); ML3 - contour matrix of the production system; ML4 - Boolean matrix describing relations between production system elements G(P,C); ML5, MN5 - matrices used for labor-intensity evaluation; MS - matrix ensuring structural connectivity of the modeling environment.

a)

				Surface shape		Board		Flange		Cut-outs and holes			
				Single curvature	Double curvature	With a board	Without a board	With a flange	Without a flange	Hole	Cut-out	Hole and cut-out	Not available
				F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Operations	Auxiliary	Material grade control	r1	•	•	•	•	•	•	•	•	•	•
		Cut the blank	r2	•	•	•	•	•		•	•	•	•
		Marking	r3	•	•	•	•	•	•	•	•	•	•
		Flange	R4	•	•	•		•	•	•	•	•	•
		Cut-out	R5	•	•	•	•	•		•	•	•	•
		Open up the cut-outs/holes	R6	•	•	•	•	•	•	•	•	•	
		Final control	R7	•	•	•	•	•	•	•	•	•	•
	Main	Debur	R8	•	•	•	•	•		•	•	•	•
		Correct	R9	•	•	•	•	•	•	•	•	•	•
		Saw	R10	•	•	•	•	•	•	•	•	•	•

b)



a) Matrix of interrelations between operations and the implementable and limiting properties of the production object
b) Graph of interrelations and sequence of determining operations

Figure 3: Fragment illustrating informational content of the network model defining the sequence of technological operations.

2.5 Software Implementation

The system is implemented as a software-methodological complex “Computer-Aided Design System for Technological Processes of Blanking and Stamping Operations for Aircraft Structural Components” (CAD TP BSO) developed according to the modular principle [5].

Software modules are divided into unified, specialized, and standard modules forming a common program library. Unified modules implement algorithms of unified design operations, while specialized modules solve complete technological design tasks and may operate either within the integrated system or independently.

2.6 Automation Modes and Industrial Validation

The developed system supports both automatic and interactive technological process planning. In the automatic mode, all elements of the production system are available in the modeling environment, enabling fully automated technological decision-making. In the interactive mode, technological decisions may be refined by the process engineer when input data are incomplete. Industrial validation of the proposed approach was carried out in a real aircraft manufacturing environment. The results confirmed the adequacy of the developed mathematical models and the stability of the generated technological solutions, demonstrating the applicability of the proposed system in practical industrial conditions.

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2.8 Algorithm of Technological Process Synthesis

To improve the reproducibility of the proposed methodology, the technological process synthesis procedure implemented in the developed computer-aided process planning (CAPP) system is defined as a sequence of formalized computational operations based on mathematical models of the production system.

At the first stage, a logical vector (VL) is generated from the design-technological properties extracted from the CAD model of the part. The vector includes geometric parameters, material characteristics, sheet thickness, and the presence of structural features such as flanges, holes, cutouts, and stiffening ribs. The logical vector provides a formalized representation of the part properties and serves as the initial input for the technological process synthesis.

			Restrictive properties										
			Type workpiece		Workpiece dimensions			Thickness			Material		
			Free-form	Circle	D=500-800 mm	Up to LxB=80x330 mm	Up to LxB=1000x3000 mm	<0.8 mm	0.8..1.2 mm	1.2..1.5 mm	Aluminum alloys	Titanium alloys	Steels
			P11	P12	P13	P14	P15	P16	P17	P18	P9	P20	P21
Equipment	Hydraulic press for deep drawing YW82	$\pi 1$		●	■								
	Hydraulic press HID-600	$\pi 2$	●	●	■	●	●						
	Hydraulic press HVQ2-250	$\pi 3$	●	●	■	●							
Tools and fixtures	Hand shears	$\pi 4$						●	▲		■		
	Shears (engl)	$\pi 5$						●	●		■		
	Hammer from 400 gr.	$\pi 6$						●			■	▲	▲
	Hammer from 500 gr.	$\pi 7$							●		■	▲	▲
	Hammer from 800 gr.	$\pi 8$								▲	■	▲	▲
	Stamp set	$\pi 9$	●	●	●	●	●	●	●	●	●	●	●

Figure 4: Fragment illustrating informational content of the network model for selecting technological tooling (equipment, tools, fixtures).

Based on the logical vector, the system performs a search in the contour matrix ML1, which establishes the correspondence between the design-technological properties of the part and the admissible technological operations required for their realization.

Precedence relations between technological operations are represented by the Boolean matrix ML2, which defines an oriented graph G(T,C), where T denotes the set of technological operations and C represents precedence constraints determining the permissible sequence of their execution. On the basis of this graph, feasible technological routes are generated.

Production resources are assigned using the contour matrix ML3, which describes the available elements of the production system, including equipment, tools, and fixtures, and the Boolean matrix ML4, which determines the compatibility between technological operations and production resources.

Alternative technological routes are evaluated using parametric labor-intensity models implemented in matrices ML5 and MN5, which contain the formulas and parameters required for calculating technological indicators. If several feasible routes are identified, the optimal technological process is selected according to predefined criteria such as labor intensity, technological cost, and the degree of process standardization.

The operating mode of the system depends on the completeness of production resource data within the production system model. The synthesis is performed in automatic mode when at least one feasible production resource is available for each technological operation. Otherwise, the system switches to interactive mode, enabling the process engineer to refine the technological route or supplement the production system model with additional resources.

Thus, the proposed algorithm ensures a formalized and reproducible synthesis of technological processes within the computer-aided process planning environment. The practical performance of the proposed approach and its applicability under real manufacturing conditions are evaluated in the following Results section.

3 RESULTS

3.1 System Implementation and Validation Protocol

The developed computer-aided process planning (CAPP) system for blanking and stamping operations was implemented and experimentally validated at the Tashkent Mechanical Plant (TMP), an industrial enterprise specializing in the production of aircraft sheet-metal structural components.

To ensure transparency and reproducibility of the validation procedure, the experimental evaluation was conducted using a dataset consisting of 12 representative aircraft structural parts manufactured by blanking and stamping operations. The dataset includes several typical classes of aircraft sheet-metal components used in airframe structures:

- aircraft skins (3 parts);
- ribs (4 parts);
- frames (3 parts);
- spar webs (2 parts).

These components differ in contour complexity, geometric configuration, and technological constraints, enabling evaluation of the proposed approach across different classes of aircraft structural elements.

For each part, technological process planning was performed using two alternative approaches:

- manual technological planning, carried out by an experienced process engineer using conventional planning procedures and existing technological documentation;
- automated planning using the developed CAPP system.

The manual baseline included determination of the technological route, selection of equipment and tooling, and estimation of technological parameters required for production preparation.

The adequacy, reliability, and stability of the generated technological solutions were evaluated using the following validation criteria:

- correctness of the generated sequence of technological operations;
- compliance of the selected technological equipment and tooling with production constraints;
- feasibility of the generated technological process under real manufacturing conditions;
- stability of technological solutions across different classes of aircraft structural components.

During the experimental evaluation, the following performance indicators were recorded:

- technological process planning time;
- number of corrective iterations required to finalize the technological solution;
- consistency and reproducibility of technological decisions.

The reported values correspond to average results obtained for the analyzed dataset comprising 12 parts (n = 12). For each evaluated case, the planning time and the number of corrective iterations were recorded. The reported values represent the mean values calculated across the analyzed dataset, while the ranges indicate the observed variation of planning time for different classes of aircraft structural components.

A quantitative comparison of manual and automated technological process planning is presented in Table 1.

The obtained results demonstrate a substantial reduction in technological process planning time when the proposed CAPP system is applied. In addition, the automated approach significantly reduces the number of corrective iterations and improves the reproducibility and consistency of technological decisions.

To provide a more transparent comparison across different classes of aircraft structural components, a case-wise analysis of planning time was performed (see Table 2).

To further illustrate the operation of the proposed CAPP system and to provide a transparent demonstration of the technological process synthesis procedure, an illustrative planning case was analyzed for a representative rib-type aircraft sheet-metal component included in the experimental dataset.

The design-technological properties (DTP) extracted from the CAD model included material type (aluminum alloy), sheet thickness (2.5 mm), contour complexity, the presence of six holes, and two local flanging elements. Based on these properties, the system generated the logical vector VL, which provides a formalized representation of the technological attributes of the part within the modeling environment (see Table 3).

Using this vector, the system identified admissible technological operations through the contour matrix ML1, which establishes the correspondence between part properties and feasible technological operations. Precedence relations between operations were then analyzed using the Boolean matrix ML2, which forms a directed graph G (T, C) representing permissible sequences of technological operations.

Subsequently, production resources were assigned using the contour matrix ML3 and the compatibility matrix ML4, ensuring consistency between technological operations and available equipment, tools, and fixtures within the production system. Alternative technological routes were evaluated using parametric labor-intensity models implemented in matrices ML5 and MN5, after which the optimal technological route and corresponding production resources were determined according to predefined technological criteria. In the analyzed rib-type case, Route A (B-P-F-T) was selected as optimal because hole punching was performed on the flat blank before flanging, which reduced setup complexity and yielded lower estimated labor intensity than Route B (B-F-P-T), where punching after flange formation would require additional positioning and decrease process stability.

The analyzed dataset includes several classes of aircraft sheet-metal components with varying contour complexity and technological constraints. The results show consistent reductions in planning time for all component classes when the proposed CAPP system is applied, confirming the robustness of the planning approach with respect to variations in part geometry and structural complexity.

3.2 Algorithmic Efficiency and Interaction of Models

The invariance of the algorithmic framework with respect to part geometry and type enables the reuse of algorithmic modules for different classes of aircraft structural components, including skins, ribs, frames, and other stamped parts.

The use of the network mathematical model makes it possible to formally represent precedence relationships between technological operations and ensures reproducible generation of operation sequences. Integration of tooling-selection models eliminates infeasible technological solutions at early stages of process planning, thereby reducing the number of corrective iterations and improving the overall stability of technological decisions.

Table 1: Comparison of technological process planning performance.

Indicator	Manual planning	Proposed CAPP system	Improvement
Planning time, mean (range)	20 h (14-28 h)	15 min (8-25 min)	~80× faster
Corrective iterations, mean	4	1	4× reduction
Reproducibility of decisions	engineer-dependent	reproducible	qualitative improvement
Consistency of technological data	medium	high	improved consistency

Table 2: Planning time comparison for different classes of aircraft structural parts.

Part class	Number of parts (n)	Manual planning time (h)	CAPP planning time (min)
Aircraft skins	3	20-28	15-25
Ribs	4	14-18	8-12
Frames	3	18-24	12-20
Spar webs	2	16-22	10-18

Table 3: Illustrative example of technological process synthesis using the proposed CAPP system.

Stage	Model / Procedure	Result
Extraction of DTP properties	CAD model analysis	Material - aluminum alloy; thickness - 2.5 mm; holes - 6; flanges - 2
Identification of admissible operations	Contour matrix ML1	Blanking → Hole punching → Flanging → Final trimming
Generation of technological routes	Boolean matrix ML2	Route A: B-P-F-T; Route B: B-F-P-T
Evaluation and resource assignment	Labor-intensity models ML3-ML5	Optimal route: B-P-F-T, press 250 kN, standard tooling; selected due to lower estimated labor intensity and simpler setup sequence.

3.3 Effects of Technological Process Standardization

The use of tabular and network mathematical models enables different levels of technological process standardization. Tabular models are applied for generating standard technological processes with predefined sequences of operations and fixed sets of technological tooling. Network models are used for partially standardized processes in which the sequence of operations remains fixed while equipment and tooling may vary.

This approach allows the modeling strategy to be automatically selected depending on the completeness of input data and the complexity of the part. As a result, the level of technological process standardization increases while maintaining flexibility in technological decision-making, which improves reproducibility and scalability of process planning solutions.

3.4 Industrial Validation and Reproducibility of Results

The proposed methodology and the developed CAD system were validated under real aircraft manufacturing conditions at the Tashkent Mechanical Plant. The conducted industrial evaluation confirmed the adequacy of the developed mathematical models, the stability of the generated technological solutions, and the practical applicability of the system for technological process planning of aircraft sheet-metal components.

The obtained results indicate the feasibility and reproducibility of the proposed technological process planning approach under real manufacturing conditions. At the same time, several limitations of the present study should be acknowledged. The validation was conducted at a single industrial enterprise using a dataset comprising 12 representative aircraft structural components. Therefore, further studies involving larger datasets and validation across multiple industrial sites would be beneficial for assessing the broader applicability and statistical robustness of the proposed approach.

A more detailed analysis of the methodological implications of the obtained results and their relationship to existing CAD/CAM and digital manufacturing approaches is presented in the following Discussion section.

4 DISCUSSION

4.1 Comparison with Traditional CAD/CAM Systems

Traditional CAD/CAM systems used for technological process planning of blanking and stamping operations are typically based on rule sets, templates, heuristic decision procedures, or specialized algorithms tied to specific part geometries and manufacturing scenarios. Such systems are effective for repetitive and well-standardized tasks; however, their adaptability becomes limited when applied to complex aircraft structural components, particularly under conditions of variable part geometry, differences in material properties, and changing production resources.

The proposed CAPP system for blanking and stamping operations employs a formalized object-oriented representation of both the product and the production system. In this framework, technological process planning is formulated as a structural synthesis problem, solved using interconnected tabular and network mathematical models. This approach provides a higher level of formalization of technological knowledge, improves the level of automation, and ensures the reproducibility of technological decisions.

Furthermore, the invariance of the algorithmic structure with respect to part geometry and type reduces dependence on subjective expert decisions and increases the scalability of the system when applied to different classes of aircraft structural components.

4.2 Positioning with Respect to Digital Twin Technologies

Digital twin technologies are increasingly employed in manufacturing to create virtual representations of products and production systems for monitoring, modeling, and optimization purposes [4], [5], [7], [8]. Most existing digital twin implementations are primarily data-driven and rely on real-time data streams, machine learning techniques, and predictive analytics.

However, such approaches are less applicable at the early stages of technological process planning, when reliable operational data are not yet available. In this context, the developed CAPP system for blanking and stamping operations may be regarded as an object-oriented technological planning layer, enabling the a priori synthesis and verification of technological decisions and serving as a methodological precursor for future integration with digital twin-enabled manufacturing systems.

Within this framework, the mathematical models formally describe logical, structural, and quantitative relationships between part properties, operation sequences, and production resources, thereby providing a deterministic and interpretable basis for technological decision-making.

4.3 Object-Oriented Intelligence and Data-Driven Approaches

Within the Industry 4.0 paradigm, artificial intelligence is often associated with machine learning and neural network approaches [6], [10]. However, in engineering domains such as aircraft manufacturing, methods that ensure explainability, reproducibility, and verifiability of decisions remain critically important. The proposed CAPP system represents an intelligent decision-support system in which intelligent behavior emerges from the interaction of structured mathematical models and hierarchical algorithms rather than from statistical learning on large datasets. This approach ensures predictable system behavior when production constraints change and eliminates the need for large training datasets, which are often unavailable during early stages of manufacturing planning.

4.4 Implications for Manufacturing Digitalization

The presented analysis indicates that the developed CAPP system occupies an intermediate methodological position between traditional CAD/CAM systems and fully developed digital twin solutions. By enabling automated and interactive synthesis of technological processes, supporting multi-level process standardization, and ensuring the reproducibility of decisions, the proposed approach contributes to the digitalization of aircraft manufacturing at the technological planning stage [9], [11], [12].

From the perspective of Industry 4.0, the system may be considered a foundational digital layer that links product design with manufacturing execution. Its integration with higher-level analytical platforms, production monitoring systems, and data-driven digital twins represents a promising direction for future research. These considerations highlight the methodological role of the proposed system in the digital transformation of technological planning processes in aircraft manufacturing. The principal findings and their implications are summarized in the following Conclusions section.

5 CONCLUSIONS

This study proposes an object-oriented approach to computer-aided process planning for blanking and stamping operations used in the manufacturing of aircraft structural components. The developed CAPP system for blanking and stamping operations is based on a formalized representation of the design-technological properties of parts and elements of the production system using interconnected tabular and network mathematical models.

The obtained results demonstrate the feasibility of systematic synthesis of technological processes with improved reproducibility of technological decisions, reducing dependence on subjective expert experience. Industrial validation confirmed the adequacy of the developed mathematical models and the practical applicability of the system, ensuring a significant reduction in planning time, a decrease in corrective iterations, and improved consistency of technological data compared with conventional manual and template-based approaches.

The study shows that the proposed CAPP system occupies an intermediate methodological position between traditional CAD/CAM systems and data-driven digital twins and may be interpreted as an object-oriented component of the technological process planning stage. The proposed approach therefore provides a methodological basis for further digitalization of technological production planning in aircraft manufacturing and may support future integration with Industry 4.0-oriented manufacturing systems [13].

Future research directions include integration of the system with operational-level digital twins, further development of mathematical methods for multi-criteria optimization of technological processes, and adaptation of the proposed methodology to other forming and separating manufacturing processes in the aerospace and mechanical engineering industries.

Thus, the proposed approach provides a formalized and reproducible basis for automated technological process planning in aircraft manufacturing.

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