BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg

CLASSIFICATION OF MODELS AND PARAMETERS IN COMPUTER-AIDED DESIGN SYSTEMS, CAD STRUCTURE, SYNTHESIS AND ANALYSIS PROBLEMS, AND A SYSTEM FOR FORMING ANALYTICAL AND NUMERICAL MODELS BASED ON CONCEPTUAL DESIGN

S.T.Safarova
General Education Teacher,
Bukhara Advanced Vocational Skills Technical School,
Bukhara, Uzbekistan

ABSTRACT: This fundamental scientific paper provides a systematic analysis of the theoretical and scientific foundations of Computer-Aided Design Systems (CAD/CAM/CAE), which serve as the cornerstone of modern engineering and manufacturing. The paper classifies the mathematical, geometric, and functional models utilized in design, along with their corresponding topological, geometric, and physical-mechanical parameters. The hierarchical structure and types of CAD systems are categorized by their technical, software, informational, and methodological components. Furthermore, the structural and parametric synthesis and analysis (FEA, CFD) problems within the system are elucidated using fundamental logical-mathematical methods. The mechanisms for constructing analytical and deterministic numerical models (Finite Element Method - FEM) starting from the conceptual design phase are scientifically validated through differential equations and error approximations.

Keywords: CAD, CAM, CAE, conceptual design, structural synthesis, parametric analysis, Finite Element Method (FEM), analytical modeling, approximation.

1. INTRODUCTION

The modern engineering industry (mechanical engineering, aerospace, microelectronics, and construction) faces critical challenges, including the increasing complexity of objects and the drastic reduction of Time-to-Market. Traditional engineering design methods, which rely on paper-based drawings and experimental physical testing, can no longer meet today's high-tech demands. The sole and universal solution to this problem lies in the fundamental digitalization of design processes—specifically, the implementation of Computer-Aided Design systems (referred to as ALTS in national practice, and globally known as CAD/CAM/CAE/PLM).

A CAD system is not merely a tool for drawing 3D models on a computer. It is a comprehensive and integrated cyber-engineering ecosystem that spans from the ideational (conceptual) formation of a designed object to the mathematical modeling of its physical properties, optimization, and the generation of manufacturing technologies.

However, the most critical and complex stage in the automated design of sophisticated objects is the accurate classification of an adequate model (one that matches real-world conditions) and its infinite parameters, while maintaining a balance between synthesis and analysis. Additionally, transforming abstract conceptual ideas—which are inherently vague during the initial stages of design—into precise mathematical-analytical and numerical computer models remains one of the most pressing scientific challenges in engineering and applied mathematics.

The purpose of this research paper is to systematize the hierarchy of models within the CAD framework, construct logical-mathematical models for synthesis-analysis processes, and scientifically synthesize the principles of creating analytical and numerical models (specifically, the finite element method) based on conceptual designs.

2. METHODOLOGY AND LITERATURE REVIEW

This study utilizes a methodology based on the systems approach, object-oriented modeling, the apparatus of differential equations, and numerical methods. For the transformation of a conceptual model into analytical and numerical models, the fundamental differential equations of continuum mechanics and elasticity theory were adopted as the mathematical foundation, alongside variational methods (Ritz and Galerkin methods) and the Finite Element Method (FEM) to approximate them.

To analyze the stress-strain state (SSS) of an object, the principle of minimum potential energy from variational calculus was applied:

$$\Pi = U - W \to \min$$

Where:

- Π is the total potential energy of the system;
- U is the internal strain energy of elastic deformation;
- W is the work performed by external forces.

By discretizing this variational functional into finite-dimensional elements, a system of linear and nonlinear algebraic equations is formulated, which is subsequently solved within the CAE (Computer-Aided Engineering) module of the CAD system.

According to the literature review, fundamental international research in the field of CAD has been conducted by prominent scholars such as Ibrahim Zeid (CAD/CAM theory), K.J. Bathe (Finite Element Procedures), and Nam Pyo Suh (Axiomatic Design) regarding design methodology. Russian scientists (Norenkov, Kapustin) developed the general theory and classification of computer-aided design systems. Meanwhile, domestic researchers have predominantly focused on applying CAD software to specific practical problems, such as structural calculations for construction or mechanical engineering. However, the systematic-logical chain of transforming a conceptual design into analytical and numerical models requires comprehensive and holistic investigation.

3. CLASSIFICATION OF MODELS AND PARAMETERS IN COMPUTER-AIDED DESIGN

Within a CAD environment, any real-world object being designed (such as an aircraft wing, a microchip enclosure, or a hydraulic pump) is represented in computer memory as a specific set of models. A model is an artificial replica that reflects the most critical characteristics of the real object for the design process while abstracting away secondary, non-essential features.

3.1. Hierarchical Classification of Models

Models in CAD are divided into the following fundamental classes:

1. **Conceptual (Functional) Models:** These describe the relationship between the object's functions and its input-output signals (flows) during the initial stage of design when the physical form of the object does not yet exist. These are often represented as block diagrams, graphs, and logical rules.

2. **Geometric (Topological) Models:** These define the spatial shape, dimensions, and mutual arrangement of the object's components. They are further sub-divided into:

   - *Wireframe Models:* The object is represented using only lines and vertices (the simplest type, with a small internal data volume).
   - *Surface Models:* The external shell of the object is defined using mathematical surfaces (Bezier, NURBS), which are crucial for aerodynamic shapes and industrial design.
   - *Solid Models:* Not only the surface but also the internal volume and mass of the object are mathematically represented (forming the core of modern CAD systems).

3. **Mathematical-Physical Models:** Systems of differential and algebraic equations that express the behavior of the object across various physical fields (mechanical stress, thermal conductivity, aerodynamics, electromagnetic waves).

3.2. Classification of Design Parameters

Model characteristics are managed through variables and constants known as parameters. Based on their functional role, parameters are categorized into three major groups:

- **External Parameters (X):** Environmental and operational influences exerted on the designed object. Examples include ambient temperature, applied load force, wind speed, and input voltage.
- **Internal (Structural and Design) Parameters (Y):** Characteristics intrinsic to the object itself that the engineer can modify. These include geometric dimensions (length, radius), material properties (Young's modulus, density, viscosity), the number of elements, and their interconnection schemes.
- **Output (Performance and Quality) Parameters (Z):** Characteristics that determine the final quality of the design. Examples include the total mass of the structure, maximum stress ($\sigma_{\max}$), efficiency coefficient, cost, and reliability.

The primary mathematical objective of design is to find the optimal internal parameters (Y) under given external conditions (X) such that the output parameters (Z) do not exceed allowable thresholds:

$$Z = f(X, Y) \le Z_{\text{allowable}}$$

4. STRUCTURE AND TYPES OF COMPUTER-AIDED DESIGN SYSTEMS (CAD)

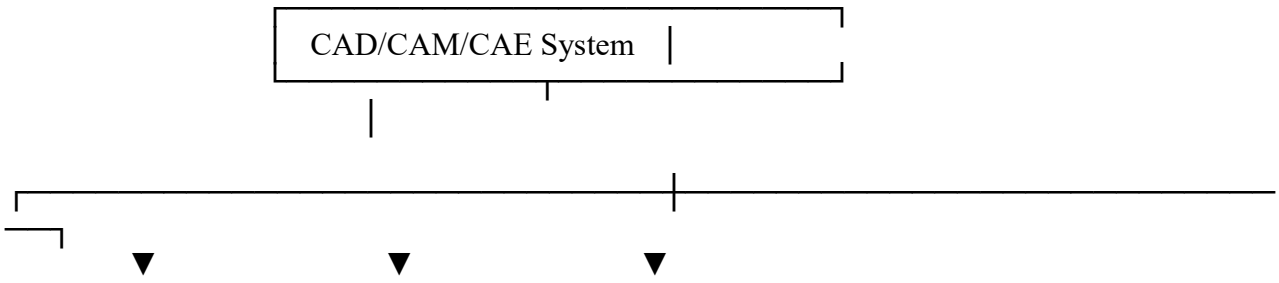
A CAD system is a complex complex of interrelated subsystems that enable design automation. Its structure is divided into functional and supporting components.

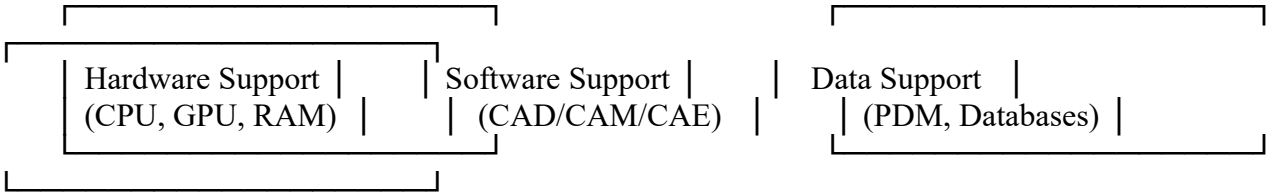
4.1. CAD Structure by Components

For any professional CAD system to function efficiently, the following integrated types of support (components) must be present:

1. **Hardware Support:** High-performance graphical workstations, multi-core central and graphics processing units (CPUs/GPUs), random-access memory (RAM), high-capacity storage systems (SSD / NVMe RAID clusters), and input-output devices (3D manipulators, plotters).
2. **Software Support:** System-wide software (operating systems, network protocols) and specialized application software suites for design (CAD/CAM/CAE kernels and modules).
3. **Informational Support (Data/Information Support):** Libraries of standard components, materials databases containing physical properties, archives of past projects, and Product Data Management (PDM) systems to control them.
4. **Methodological and Mathematical Support:** Design algorithms, numerical methods, national and international standards (ISO, GOST), and a collection of engineering calculation methodologies.

Plaintext





4.2. CAD Types and Their Global Classification

Based on their industrial application and functional capabilities, CAD systems are classified into the following tiers (levels):

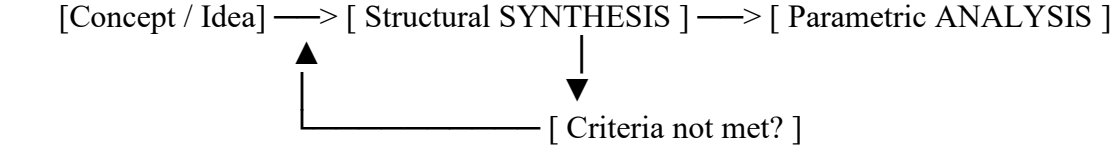
- **Low-end / 2D Systems:** These primarily perform 2D drafting and documentation tasks (e.g., early versions of AutoCAD). They have low computational power requirements.
- **Mid-range / 3D Solid Modeling Systems:** These enable the creation of powerful parametric 3D solid models and allow for basic engineering analysis (e.g., SolidWorks, Autodesk Inventor, Solid Edge). Today, this is the most widely used category in the industry.
- **High-end / Heavy CAD Systems:** These possess the capacity to design highly complex assemblies consisting of thousands of details (such as aircraft, ships, and automobiles), process intricate surfaces, and integrate with global Product Lifecycle Management (PLM) systems (e.g., CATIA, Siemens NX, Creo Parametric).

Furthermore, depending on specialization, they are categorized into **MCAD** (Mechanical CAD), **EDA / ECAD** (Electronic Design Automation for microchips and electronics), and **AEC** (Architecture, Engineering, and Construction, currently driven by BIM technology).

5. SYNTHESIS AND ANALYSIS PROBLEMS IN DESIGN

The computer-aided design process is a spiral, iterative process consisting of the continuous alternation of two major logical phases: the Synthesis stage and the Analysis stage.

Plaintext



5.1. Design Synthesis Problems

Synthesis is the process of generating or creating a new form, structure, or parameters for an object. The synthesis process is always directed "from the objective to the means" (an inverse problem). In CAD, synthesis is split into two stages:

1. **Structural Synthesis:** Determines the components that will comprise the designed object and outlines their mutual logical and topological interconnection scheme. This stage is the most difficult to automate and frequently relies on the engineer's experience, intuition, or intelligent systems (AI, generative design).
2. **Parametric Synthesis:** Once the structure of the object is established, this stage involves searching for the optimal values of its internal parameters (Y). This is a purely mathematical optimization problem that can be fully automated using algorithms (e.g., Genetic Algorithms, gradient methods) designed to drive the objective function to an extremum (maximum or minimum).

5.2. Design Analysis Problems

Analysis is the process of determining the output parameters (Z) and evaluating how the model of the synthesized (created) object behaves under external influences (X). Analysis is

directed "from the means to the result" (a forward problem). In modern CAD environments, analysis tasks are executed within CAE (Computer-Aided Engineering) modules:

- **FEA (Finite Element Analysis):** Mechanical calculations regarding structural strength, deformation, vibration frequencies, and durability.
- **CFD (Computational Fluid Dynamics):** Modeling the flow characteristics of gases and liquids, hydraulic losses, and heat transfer processes.

If the analysis results (Z) do not satisfy the requirements of the technical specification (for instance, if a component fails under stress or proves excessively heavy), the system reverts to the synthesis stage to modify the parameters.

6. CREATING ANALYTICAL AND NUMERICAL MODELS BASED ON CONCEPTUAL DESIGN

The most critical and initial phase of design is Conceptual Design. During this stage, the physical principles of the object are determined, though exact geometry does not yet exist. For example, the concept for a new type of shock absorber might dictate that it will be a piston-and-spring system. Below, we examine the chain of transforming this abstract conceptual model into precise analytical and numerical (digital) models for computer evaluation.

6.1. Formulating Analytical Models

Analytical modeling involves representing the state of an object in a precise (closed-form) appearance using continuous mathematical functions and differential or algebraic equations.

For example, based on Newton's second law and the principles of elasticity and viscosity, the analytical model for the aforementioned shock absorber (or vibration system) conceptual design is formulated as the following second-order ordinary differential equation:

$$m \frac{d^2u(t)}{dt^2} + c \frac{du(t)}{dt} + ku(t) = F(t)$$

Where:

- m is the mass of the system;
- c is the damping (attenuation) coefficient;
- k is the stiffness (elasticity) coefficient of the spring;
- $u(t)$ is the displacement (deformation) function;
- $F(t)$ is the external dynamic force.

Advantages of analytical models: They offer a fundamental understanding of the system's operating principles, and their computational time is virtually zero.

Disadvantages: Closed-form solutions exist only for highly simplified geometries and linear problems. For real, complex components (such as an intricately shaped automobile body), it is impossible to write and integrate such equations precisely.

6.2. Creating Numerical Models (Discretization and FEM)

To solve complex conceptual and geometric designs, the analytical model is transformed into a Numerical Model that a computer can compute. In this process, the continuous medium is divided into a finite number of points and elements (the discretization process). The most universal and industry-standard method for this is the Finite Element Method (FEM).

The continuous displacement field $u(x,y,z)$ to be determined within the domain is approximated within a finite element using basis (shape) functions N_i and unknown nodal values u_i as follows:

$$u \approx [N]\{u\}_e$$

By substituting this approximation into the variational functional (Equation 1) and minimizing it, the stiffness matrix $[k]_e$ and the force vector $\{f\}_e$ are determined for each individual element:

$$[k]_e = \int_{V_e} [B]^T [D] [B] dV$$

Where:

- $[B]$ is the geometric differentiation (strain-displacement) matrix;
- $[D]$ is the material elasticity (Hooke's law) matrix;
- V_e is the volume of the element.

Once the matrices of all individual elements are assembled into a unified global system, the CAD system generates the primary governing system of algebraic equations for the numerical model:

$$[K]\{U\} = \{F\}$$

Where $[K]$ represents the global stiffness matrix of the entire structure, $\{U\}$ is the vector of unknown nodal displacements across all nodes, and $\{F\}$ is the vector of external nodal forces. The computer solves this massive algebraic system (which sometimes contains millions of unknowns) using Gauss elimination or iterative methods, thereby determining the deformation and stress at every point of the structure and presenting these to the user as a color-coded visual field.

7. DISCUSSION AND RECOMMENDATIONS

To successfully implement computer-aided design methodologies within national industrial sectors and research institutes, attention must be paid to the following fundamental aspects:

1. **Verification & Validation of Conceptual and Numerical Models:** The numerical model computed by a computer (FEM results) cannot always be taken as absolute truth. It is highly dependent on the density of the finite element mesh and the correct application of boundary conditions. In engineering practice, checking for mesh convergence must be established as a mandatory standard.

2. **Transitioning to Comprehensive PLM (Product Lifecycle Management) Systems:** When CAD, CAM, and CAE modules are used in isolation, data loss occurs, and the numerical model fails to update automatically (asynchrony) when the conceptual design changes. It is recommended to introduce PDM/PLM systems in local enterprises to manage design data within a single, centralized hub.

3. **Adopting Cognitive and Generative Design Systems:** To reduce human error in modern synthesis problems, Topology Optimization and AI-driven Generative Design methods should be integrated into engineering practice. Based on given external parameters (X) and output criteria (Z), these methods can independently synthesize the optimal geometric shape of an object without human intervention.

8. CONCLUSION

Computer-Aided Design (CAD) systems form the intellectual core of modern high-tech manufacturing. Based on this scientific research, the following fundamental conclusions have been formulated:

1. The strict hierarchical systematization of models and parameters used during the design process (conceptual, geometric, and mathematical models) enables the correct design and management of digital twins of complex objects.

2. Logical processes within CAD rely on a continuous, iterative equilibrium between structural and parametric synthesis and analysis phases. While synthesis creates new forms and structures, analysis (FEA, CFD) verifies their viability and suitability.

3. Analytical models (differential equations) governed from the conceptual design stage fundamentally express the physical nature of the system. By transforming them into modern numerical models through methods like the Finite Element Method (FEM) via discretization and

approximation, CAD systems acquire the capacity to perform cyber-engineering calculations of geometrically arbitrary, real-world objects with exceptionally high precision.

REFERENCES

1. Zeid, I. (2009). *Mastering CAD/CAM* (2nd ed.). McGraw-Hill Education.
2. Bathe, K. J. (2014). *Finite Element Procedures* (2nd ed.). Klaus-Jürgen Bathe.
3. Suh, N. P. (2001). *Axiomatic Design: Advances and Applications*. Oxford University Press.
4. Norenkov, I. P. (2002). *Osnovy avtomatizirovannogo proektirovaniya* [Fundamentals of Computer-Aided Design]. MGTU im. Baumana.
5. Zienkiewicz, O. C., Taylor, R. L., & Fox, D. D. (2014). *The Finite Element Method for Solid and Structural Mechanics* (7th ed.). Butterworth-Heinemann.
6. Lee, K. (1999). *Principles of CAD/CAM/CAE Systems*. Addison-Wesley Longman.
7. Reddy, J. N. (2019). *An Introduction to the Finite Element Method* (4th ed.). McGraw-Hill Education.
8. Jalolov, T. S. (2024). развитие технологий искусственного интеллекта в самодвижащихся роботах. *Methods of applying innovative and digital technologies in the educational system*, *1*(2), 1-7.
9. Jalolov, T. S. (2024). экологический системы искусственный в мониторинге интеллект технологий приложение. *Advanced methods of ensuring the quality of education: problems and solutions*, *1*(3), 86-92.
10. Jalolov, T. S. (2024). matnni qayta ishlash orqali til o ‘rgatish ilovalarini rivojlantirish. *Modern digital technologies in education: problems and prospects*, *1*(2), 103-108.
11. Jalolov, T. S. (2024). эффективное использование технологий искусственного интеллекта в экономическом моделировании. *Methods of applying innovative and digital technologies in the educational system*, *1*(2), 27-32.
12. Jalolov, T. S. (2024). avtonom robotlarda sun'iy intellekt texnologiyalarini rivojlantirish. *Ensuring the integration of science and education on the basis of innovative technologies.*, *1*(3), 56-61.
13. Jalolov, T. S. (2024). создание диагностических систем на основе искусственного интеллекта в системе здравоохранения. *Methods of applying innovative and digital technologies in the educational system*, *1*(2), 14-20