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USER INTERFACES CAD SOFTWARE FOR PRE- AND POST-PROCESSING OF MODELS ACCOMPANYING PAK FE CODE

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Abstract

This paper introduces the CAD user interface software developed to support example-driven simulations using the PAK finite element code. Built upon years of research and development by the authors, CAD represents a custom-built platform for three-dimensional model setup and result visualization, tightly integrated with the PAK solver. It facilitates the creation of simulation-ready models and enables dynamic rendering and animation of computed results. The software is versatile, supporting a broad spectrum of applications, including solid mechanics, fluid dynamics, heat transfer, electrophysiology, drug transport, and composite material modeling. By integrating advanced meshing algorithms and numerical solvers, the software streamlines the workflow, making high-fidelity simulations accessible to researchers, engineers, and educators. Beyond its core capabilities, CAD has evolved into a modular and extensible framework, incorporating specialized tools for multi-physics and multi-scale modeling. Its architecture draws on a lineage of domain-specific simulation platforms, now unified into a single environment that supports complex coupled phenomena. The paper first outlines the structure and development of the CAD interface, followed by practical guidance for executing selected examples available through the online repository, including applications in biomechanics, cardiovascular modeling, and porous media transport

Keywords: User interface software, PAK FE solver, CAD visualization tool, preprocessing, post processing

1. Introduction

Finite element (FE) simulations play a crucial role in solving complex multi-physics and multi-scale problems in engineering and biomedical sciences. Software that solves problems using finite elements requires the use of specialized user interface software that can create adequate 2D and 3D models, boundary conditions, and prescribed conditions, convert them into a form that FE code can read and understand, and finally, after performing FE calculations, load the solutions and visualize the results. This paper presents CAD, a user interface software designed for the pre- and post-processing of FE models within the PAK FE code framework. Developed over years of research, CAD serves as a comprehensive tool for model generation, simulation execution, and visualization of computational results. By integrating advanced meshing algorithms and numerical solvers, the software streamlines the workflow, making high-fidelity simulations accessible to researchers, engineers, and educators

The software supports a wide range of applications, including solid mechanics, fluid dynamics, heat transfer, electrophysiology, drug transport, and composite material modeling. Through an intuitive graphical user interface (GUI), users can define model parameters, apply boundary conditions, execute FE simulations, and analyze results using various visualization tools. The post-processing module allows for contour plotting, time-dependent analysis, and interactive model interrogation, providing insights into complex physical phenomena.

The CAD software associated with the PAK finite element code is structured into two main components: a preprocessor and a postprocessor. The preprocessor facilitates the construction of simulation-ready models by enabling the definition of geometry, mesh discretization, boundary conditions, applied loads, and material properties. Once the model setup is complete, the data are saved in a .dat file format, which serves as input for the PAK FE solver. Upon completion of the simulation, output data—such as displacement fields, velocity profiles, pressure distributions, and concentration maps—are stored in a .unv file. This file is automatically interpreted and visualized by the CAD postprocessor module. Therefore, the postprocessor is responsible for importing results, followed by visualization and analysis, allowing users to plot various representations such as field vs. time and field vs. distance.

The CAD platform incorporates several external libraries to support mesh generation, including Triangle for two-dimensional domains (Shewchuk, 1996; 2002) and TetGen for three-dimensional meshing (Si, 2015). Given that TetGen produces tetrahedral elements by default, a supplementary algorithm has been implemented to convert these into non-uniform hexahedral elements, as described by Milasinovic et al. (2020). CAD also utilizes Libigl (geometry processing) (Jacobson et al., 2018). The software is developed using Visual Studio 2017 and is designed for Windows OS. It is available in both x32 and x64 versions, with dependencies including Microsoft C++ Redistributables 2017 and MSChart (mschrt20.ocx) for visualization functionalities. The CAD software is openly accessible via GitHub at https://github.com/miljanmilos/CAD-Solid-Field. The repository also includes a user manual containing detailed explanations of interface elements, dialog windows, and available functionalities.

The foundational architecture of the CAD system has served as a development framework for several specialized applications, such as SOFTDISKUS, SOFTKARDIO, SOFTEHO, CFDAL, MedCFD, and Lizza-PAKP, as documented in (Filipovic et al., 2005; Filipovic et al., 2006; Filipovic et al., 2010). All of this software is freely available for download from the BioIRC website. In this paper, we detail the software's evolution, architectural framework, and key functionalities. The workflow diagram of the software is shown in Fig. 1.

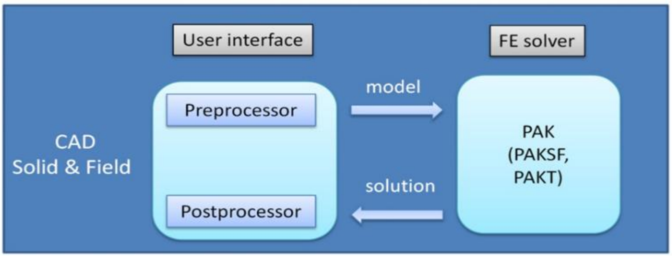

Fig. 1. Workflow diagram of the CAD software and interconnection with PAK FE code (according to Kojic et al. 2022).

2. History of CAD

Computational modeling and simulation have become indispensable tools in biomedical and engineering research, enabling precise analysis of complex physiological and mechanical systems. Over the years, various specialized software solutions have been developed to address challenges in biomechanics, cardiology, hemodynamics, respiratory analysis, and structural engineering. These software packages streamline simulation processes, providing valuable insights for researchers, engineers, and medical professionals. This section presents an overview of key CAD-based computational tools designed for finite element analysis (FEA), fluid dynamics, medical imaging, and patient data management, developed through extensive research and collaboration. As these tools were developed, the C++ library, which is the basis of the user interface of CAD software, was also expanded and upgraded.

2.1 SOFTDISKUS: Computational Analysis of Spinal Load Distribution

SOFTDISKUS is a specialized software used for the determination of loads, force, and momentum acting on spinal discs during static exertion (Fig. 2). It provides detailed calculations of intradiscal pressure, deformation, and stress distribution in spinal segments, utilizing computational-numerical simulations to improve understanding of spinal biomechanics.

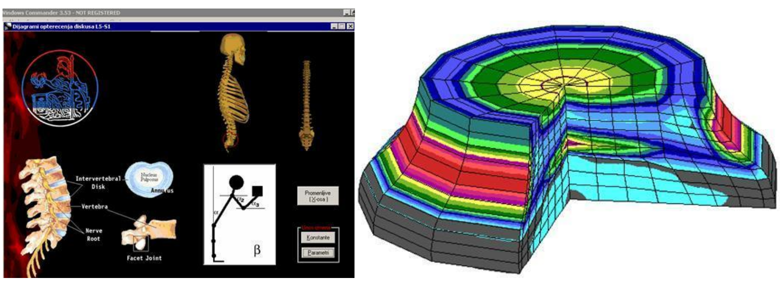

Fig. 2. SOFTDISCUS demonstration (http://www.bioirc.ac.rs/index.php/software/6-softdiskus)

2.2 SOFTEHO: Cardiological Ultrasound Protocol Management

SOFTEHO is designed for echocardiographicists and clinicians, enabling efficient registration, sorting, and documentation of cardiological ultrasound data (Fig. 3). This software enhances diagnostic workflows by providing quick access to patient data for medical analysis, research, and documentation.

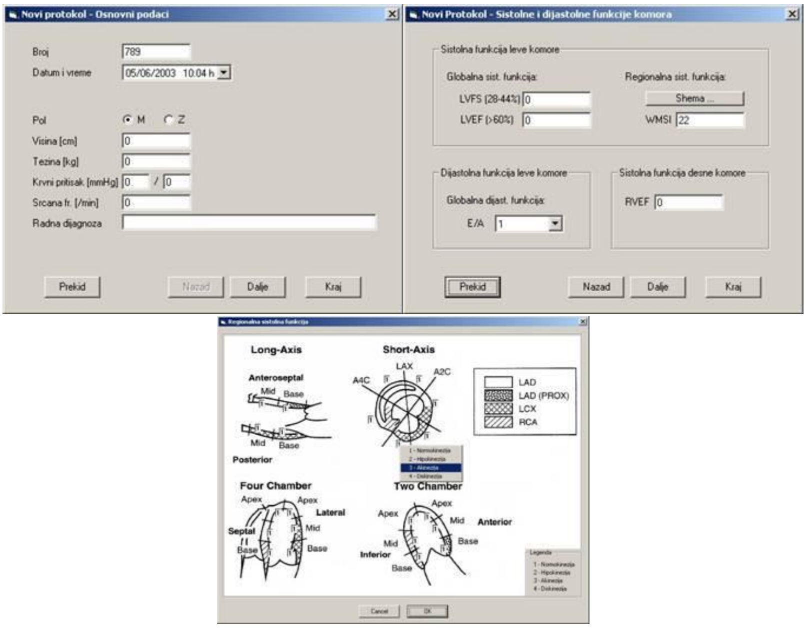

Fig. 3. SOFTEHO demonstration (http://www.bioirc.ac.rs/index.php/software/8-softeho)

2.3. SOFTKARDIO: Electronic Documentation for Cardiological Patients

SOFTKARDIO facilitates the digital management of patient records in cardiology departments. It allows quick input, retrieval, and modification of patient data, ensuring efficient record-keeping (Fig. 4). With its modular design, the software can be adapted to meet specific user requirements.

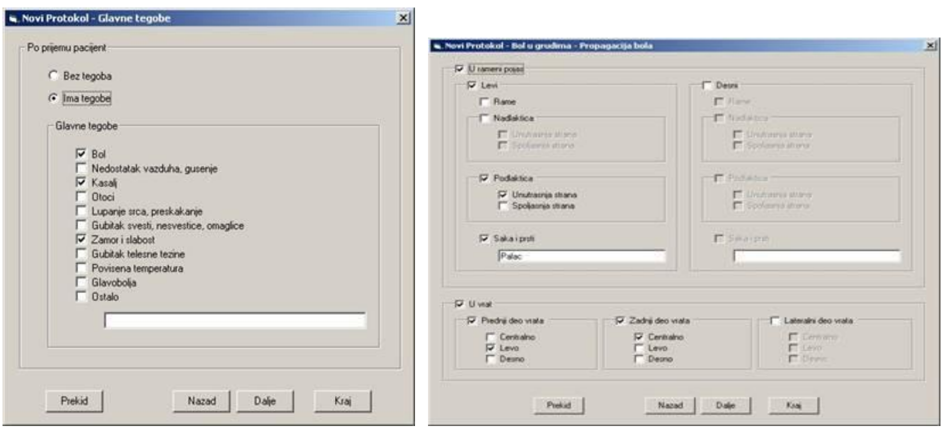

Fig. 4. SOFTKARDIO demonstration (http://www.bioirc.ac.rs/index.php/software/7-softkardio)

2.4 SOFTVASK: Computational Analysis of Doppler Ultrasound Signals

SOFTVASK is a computational tool for processing sound signals from blind-Doppler ultrasound devices. It extracts clinically relevant parameters such as resistance index and pulsatory index, offering functionality comparable to advanced ultrasound systems. This software is designed for physicians, engineers, and researchers involved in vascular diagnostics and hemodynamic studies.

2.5 CFDAL: Simulation of Airflow in the Respiratory System

CFDAL is a software tool developed for modeling airflow through alveoli, with applications in respiratory physiology and biomedical engineering (Fig. 5). It enables the study of cyclical alveolar movement during breathing, using finite element-based CFD simulations. The key capabilities of CFDAL include:

- automatic model generation with arbitrary number and dimension of alveoli,
- radial and axial velocity, pressure field representation,
- streamline representation, and
- mass and mass-less particle tracking.

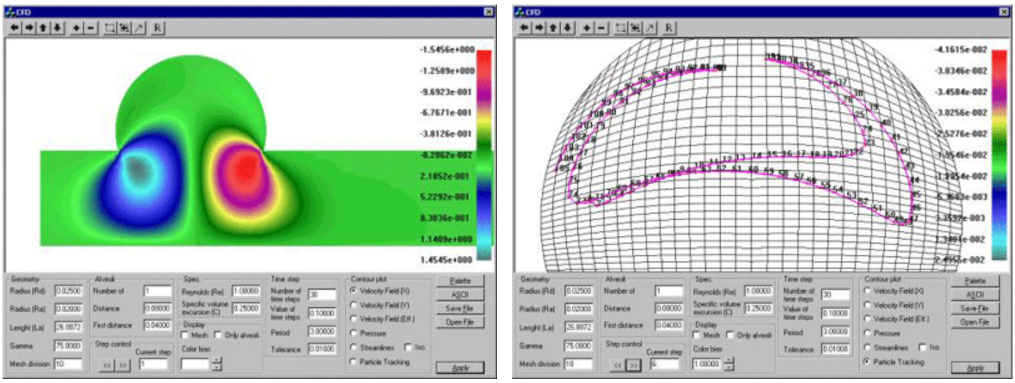

Fig. 5. CFDAL demonstration (http://www.bioirc.ac.rs/index.php/software/10-cfdal)

2.6 MedCFD: Blood Flow Simulation and Hemodynamics Analysis

MedCFD is a three-dimensional CFD-based finite element solver designed for modeling blood flow in arteries (Fig. 6). It accounts for fluid-structure interactions, wall shear stress, viscoelastic behavior of vessel walls, and aneurysm growth predictions. MedCFD provides automated computational modeling, reducing manual input errors and ensuring efficient pre-processing and simulation workflows.

At its current stage, MedCFD enables interactive simulations of blood flow in aneurysms, allowing users to analyze complex flow characteristics such as reattachment and separation points. The software also supports automatic generation of realistic geometric aneurysm models, making it a valuable tool for vascular surgeons, biomedical engineers, and physicians. More information about MedCFD is available at: http://www.bioirc.ac.rs/CFDVasc/index.php.

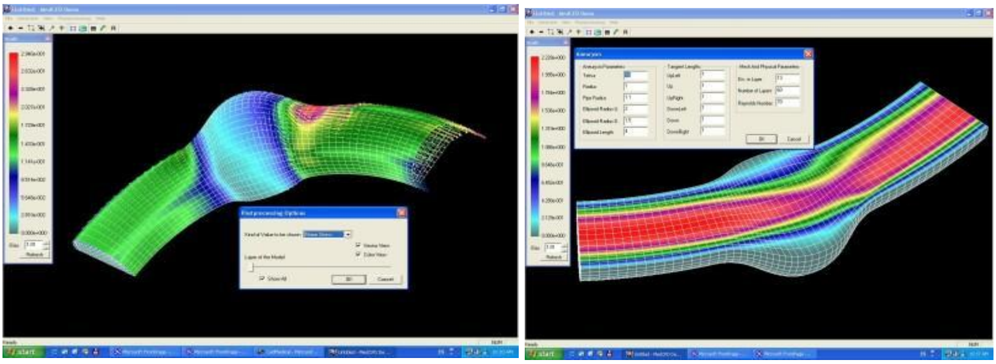

Fig. 6. MedCFD demonstration (http://www.bioirc.ac.rs/index.php/software/11-medcfd)

2.7 Lizza-PAKP: Groundwater Flow Simulation System

Lizza-PAKP is a groundwater flow simulation system which consists of solver based on finite element method (PAKP) and user interface (Lizza). It was developed in cooperation between Institute for Water Resources "Jaroslav Cerni", Belgrade and Bioengineering Research and Development Center - BioIRC, Kragujevac, Serbia.

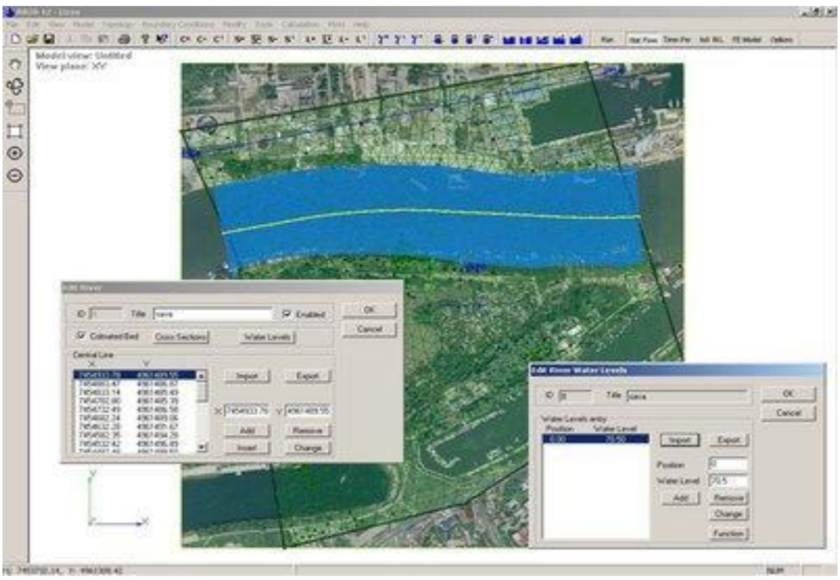

Fig. 7. Lizza-PAKP demonstration (http://www.bioirc.ac.rs/index.php/groundwater-flow-software)

3. Component architecture, interoperability and use-cases

The procedure for running FE simulations is divided into three steps: pre-processing, FE simulation, and post-processing, Fig. 1. This modular approach enhances interoperability with external tools, allowing users to import, manipulate, and visualize computational models effectively. The pre-processing stage involves defining the computational model, including geometry generation, meshing, material properties, constraints, and loading conditions. CAD provides an intuitive interface for setting up these parameters, either manually or by importing models from third-party software. The FE simulation stage is performed using PAK, a robust solver capable of handling multi-physics and multi-scale problems (Kojic et al., 1998a, Kojic et al., 1998b, Kojic et al., 1998c, Kojic et al., 1998d, Kojic et al., 2018). Once the simulation is completed, the post-processing stage enables users to analyze results through contour plots, time-dependent visualizations, and parameter-driven insights. A key strength of CAD lies in its interoperability with external software and data formats, enabling seamless integration with third-party FE solvers and visualization tools. For example, stent modeling is a critical application where CAD supports importing FE meshes from ABAQUS and exporting results in industry-standard formats such as .unv and .vtk, ensuring compatibility with Paraview and other visualization platforms. The following use case demonstrates how CAD facilitates stent modeling, simulation, and analysis within this framework

3.1 Software Modules and Capabilities

Over the years, various user interface software tools have been developed to aid in pre-processing and post-processing of numerical simulations. Many of these tools have been consolidated into a version CAD Field & Solid, available at https://github.com/miljanmilos/CAD-Solid-Field, providing a comprehensive and unified platform for FE simulations. The software comprises several specialized modules, each designed for specific simulation tasks. The following modules are integrated within the CAD Field & Solid framework:

1. PAKSF (PAK for Solid and Fluid) – Enables simulation of mechanical behavior in solids and fluids, as well as their interactions. It includes the Composite Smeared Finite Element Method (CSFEM) for efficient modeling of complex solid structures.
2. PAKT (PAK for Heat Conduction, Diffusion, and Electrophysiology Transport) – Designed for modeling heat transfer, molecular diffusion, and electrophysiological processes, including applications in drug transport within biological tissues, convective-diffusive transport in capillary networks, and electrical transport in cardiac tissue.
3. PAFIS (PAK for Field and Solid) – Focused on multiphysics problems involving solid-fluid interaction, integrated with models for drug diffusion, thermal conduction, and electrical transport.
4. PAKSF 2D – Supports solid-fluid interaction problems in 2D, including deformable particle transport within a fluid.
5. PAKSF 3D – Extends PAKSF 2D to three-dimensional problems, enabling the modeling of complex 3D solid-fluid interactions and particle transport.
6. Composite Modules – Comprising five submodules for composite material modeling:
    - 2D Fibers – Models 2D nanofibers in confined spaces.
    - 3D Fibers – Simulates 3D nanofiber composites.
    - Partitioning – Examines the influence of hydrophobic partitioning on drug movement across different media.
    - Nano Fibers (Detailed Model) – Provides a detailed representation of drug transport from nanofibers.
    - Nano Fibers (Smeared Model – KTM) – Implements the KTM (Kojic Transport Model) for drug release from nanofibers.
7. PAKC (PAK for Stents and Structural Analysis) – A specialized module for stent modeling and in-silico simulation of standard ISO tests, aimed at optimizing stent designs (not included in this book).
8. Cell Tissue Module – Simulates drug transport in tissues with cells, capillaries, and lymphatic systems, leveraging PAKT for biological modeling.

9. Parametric Space Module – Supports parametric studies (spherical tumor embedded in pancreatic tissue).
10. Metastatic Tumor Module – Designed for specialized simulations such as perfusion in liver with a small metastatic tumor, utilizing PAKT for advanced tumor modeling.

These modules collectively extend CAD Field & Solid's functionality, allowing it to be used for a diverse range of applications in biomechanics, materials science, and computational fluid dynamics. The integration of pre-processing, FE simulation, and post-processing ensures a seamless workflow for researchers, engineers, and clinicians working with finite element-based simulations.

3.2 Use-case: stent modeling

The CAD pre-processor is used to generate a model that can be run using the PAK FE solver. Users can configure several parameters within the CAD interface, including stent type, test conditions, material properties, and time steps. Stents can be modeled externally using software such as ABAQUS and exported as .inp files, or directly imported from manufacturer-provided mesh files (Fig. 8). These FE mesh files, containing nodes and elements, are loaded into CAD, where users can adjust positioning, orientation, and other model properties through dedicated dialogs.

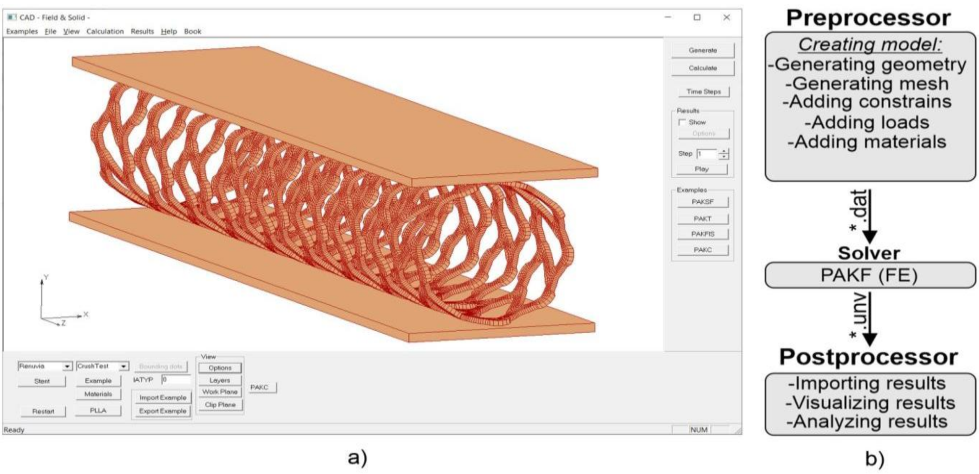

Fig. 8. a) Graphical interface of the CAD Field and Solid software, supporting both pre-processing and post-processing functionalities (https://github.com/miljanmilos/CAD-Solid-Field). b) Schematic representation of the internal data flow, illustrating input/output structure and module interactions, adapted from Milosevic et al. (2022).

The pre-processing workflow includes geometry and mesh generation, application of boundary conditions, constraints, and loads, and specification of material properties. CAD provides a built-in database of stent models, ranging from metal stents (e.g., Synergy) to bioresorbable stents (e.g., Absorb, Phantom Encore, Renuvia). Once the setup is complete, the model is exported as a .dat file, which serves as input for the PAK solver.

Upon FE simulation completion, the results—including displacement fields, velocity distributions, pressure variations, and stress-strain data—are stored in .unv files, which are automatically loaded by the CAD post-processor. Additionally, results can be exported in .vtk format for visualization in Paraview, enabling advanced data exploration and interactive analysis. The post-processor provides multiple visualization options, allowing users to inspect results based on different parameters, plot time-dependent behaviors, and examine spatial distributions of key physical fields.

This structured approach ensures that CAD Field & Solid can efficiently handle complex stent modeling and simulation workflows, making it a valuable tool for biomedical research and computational engineering.

3.3 Use-case: CTC and platelet generation

Model setup and pre-processing for simulating circulating tumor cells (CTCs) and platelet behavior are performed using the CAD FiS (Fields and Solids) platform, as shown in Figure 9. The process begins by selecting the appropriate module within the CAD interface, followed by defining the model geometry, assigning material properties, and specifying temporal parameters such as time step duration. Dedicated dialogs allow users to configure geometric attributes of individual solid components (e.g., capillary channels, CTCs, platelets), fluid flow characteristics, boundary conditions, mesh generation, and material parameters. Once the model is fully defined, simulation data are saved in a .dat file format, which serves as input for the PAK finite element solver. Upon completion of the simulation, output data—including displacement fields, velocity vectors, pressure distributions, and other physical quantities—are stored in a .unv file and automatically loaded into the CAD postprocessor for visualization. Additionally, results can be exported in .vtk format for compatibility with external visualization tools such as ParaView. These output files contain nodal-level information on various physical fields, including displacements, shear stresses, and velocity components. The CAD FiS software supports multiple visualization modes, such as scalar and vector field rendering, point-based representations, and slicing through cutting planes.

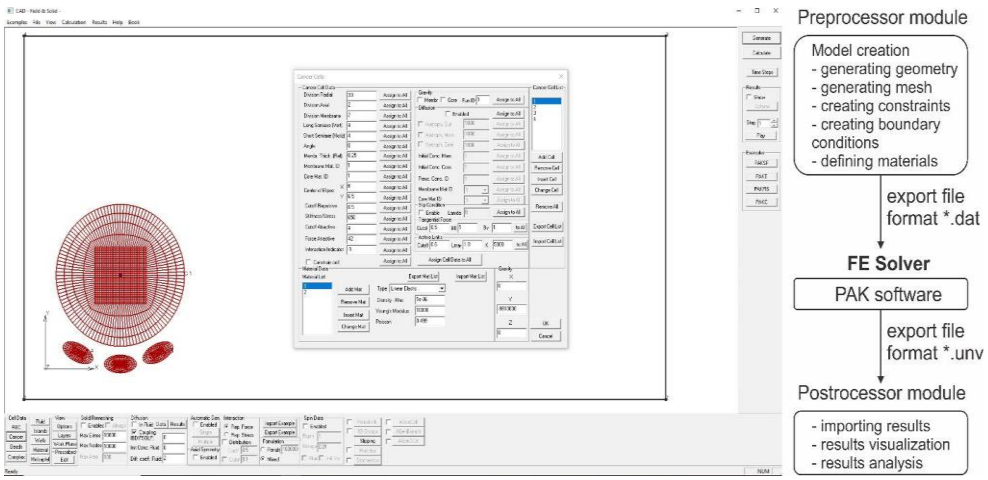

Fig. 9. Graphical interface of the CAD Field and Solid software, showcasing dialog windows for configuring CTC and platelet simulations, along with a schematic overview of input/output data flow during pre- and post-processing stages (according to Simic et al. 2025).

3.4 Use-case: Left ventricle modeling

In this section we will demonstrate two left ventricle models: parametric and echocardiography-based LV model. Parametric model’s geometric layout, adjustment of the geometric parameters and boundary conditions are presented in the Fig 10. To refine the mesh quality, adjust division settings like Base Division, Atrium Division, and Arteries Division. For modeling the solid structure, check the Solid Wall box located in the Solid Wall group and define its geometric features, including wall thickness, which is a key parameter. To represent multiple tissue layers, modify the Solid Wall Division setting—the default is a single layer. The lower part of the LV (apex) can also be customized by changing the length and radius of the bottom base. If multiple tissue layers are needed at the apex, change the Bottom Base Division parameter accordingly.

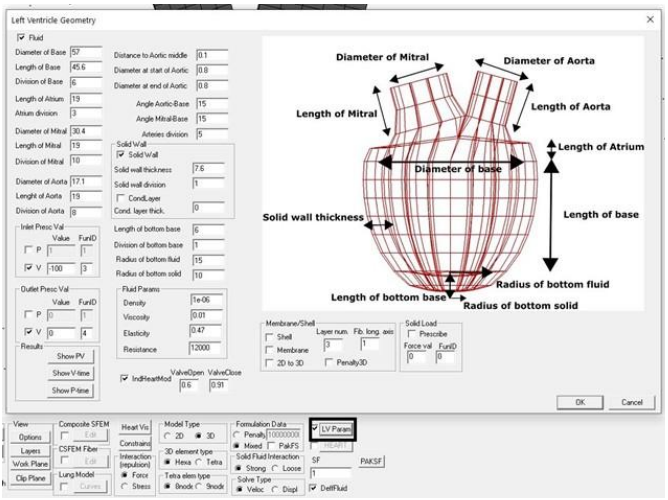

Fig. 10. Geometry of the parametric left ventricle model (according to Kojic et al., 2022)

Next example demonstrates how to generate a 3D model of the left ventricle (LV) using echocardiographic data within the CAD software (Fig. 11).

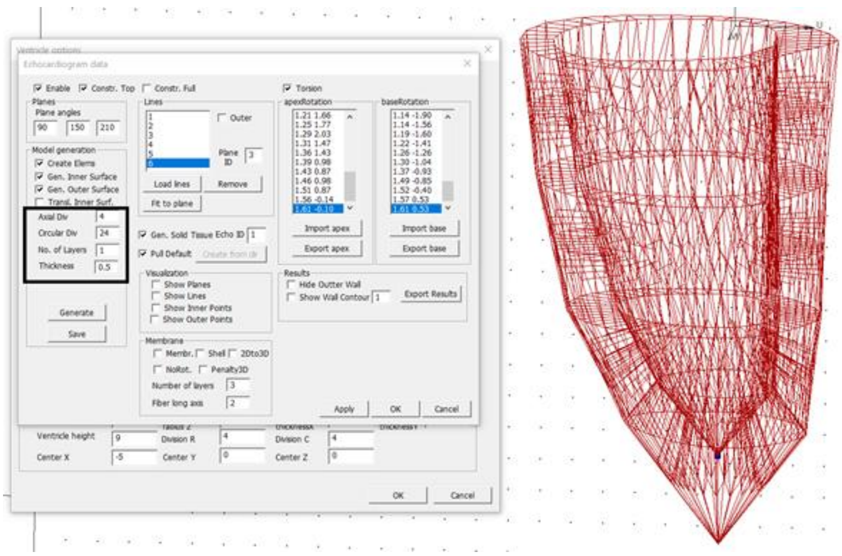

Fig. 11. Generated echocardiography-based LV model with axial division 4 and circular division 24 (according to Kojic et al., 2022)

The model is built using contours (inner and outer wall) for each plane. These contours can be loaded from default files (echo_input) or user-defined sets (echo_input_user), and they must be fitted to their respective planes. Torsional motion can also be applied via built-in or imported functions. Following parameters are crucial in defining mesh quality and model accuracy:

Axial Division: Determines the number of divisions along the longitudinal (apex-to-base) axis of the ventricle. Higher values produce more detailed vertical resolution.

Circular Division: Controls the number of divisions around the circumference (cross-sections) of the ventricle. A higher number results in a smoother and more precise surface geometry.

Number of Layers: Refers to how many radial layers exist between the inner and outer wall surfaces, impacting the thickness detail of the 3D mesh.

For detailed simulations, increasing these values improves accuracy but also increases computational load.

4. Conclusions

The development of CAD represents a significant advancement in computational modeling, providing a comprehensive framework for finite element (FE) simulations. Over the years, this software has evolved from a collection of separate simulation tools into an integrated pre- and post-processing platform, supporting a diverse range of multi-physics and multi-scale applications. This progression has been driven by extensive research and collaboration, resulting in a flexible, modular architecture that enhances computational efficiency and user accessibility.

The foundation of CAD is built upon previous numerical simulation tools developed for biomechanics, material science, hemodynamics, and structural engineering. These include SOFTDISKUS for spinal biomechanics, SOFTEHO and SOFTKARDIO for cardiology applications, CFDAL and MedCFD for airflow and blood flow simulations, and Lizza-PAKP for groundwater flow modeling. Each of these tools contributed to refining CAD's pre-processing, solver integration, and post-processing capabilities, allowing it to support complex computational fluid dynamics (CFD), solid mechanics, heat transfer, electrophysiology, and drug transport models.

At its core, CAD is structured into three key simulation stages: pre-processing, FE simulation, and post-processing. The pre-processing module provides an intuitive interface for geometry definition, meshing, boundary condition assignment, and material selection, ensuring seamless model generation. The FE simulation stage leverages PAK, a high-performance solver capable of handling coupled multi-physics problems. Finally, the post-processing module offers robust visualization tools, enabling users to extract meaningful insights through contour plots, time-dependent analysis, and parametric studies. The interoperability of CAD with third-party software such as ParaView, and TetGen further expands its usability, making it a versatile solution for researchers and engineers.

The integration of multiple specialized modules within CAD Field & Solid has extended its applicability to a broad spectrum of computational challenges. Modules such as PAKSF, PAKT, and PAFIS enable advanced modeling of solid-fluid interactions, heat conduction, and electrophysiology transport, while additional tools support stent modeling, composite materials analysis, and tumor growth simulations. These capabilities make CAD Field & Solid a valuable resource for biomedical research, materials science, and computational fluid dynamics.

In conclusion, the evolution of CAD Field & Solid reflects the growing need for efficient, interoperable, and scientifically rigorous computational modeling tools. By consolidating pre-processing, solver integration, and post-processing into a unified framework, the software enhances the efficiency, accuracy, and accessibility of finite element simulations. As research continues to advance, CAD Field & Solid will remain a critical tool for engineering, medical, and scientific applications, driving innovation in computational modeling and numerical analysis.

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