

## Information System Supporting Analysis of Heat and Water Transport in Agro-food and Forest Products

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### ABSTRACT

Computer-based analysis of heat and water transport in agro-food and forest products is difficult due to material complexity of the products, lack of reliable data on product material properties, and imperfections of software. Therefore an information system was developed to enhance estimation of values of material properties, and to improve quality of computer analysis of thermo-mechanical behavior of agro-food and forest products. It was based on original algorithms of image analysis and 3D finite element mesh generation, geometry modeling and inverse coefficient problem solving. Original authors' software modules were improved and integrated to support the overall analysis. The resulting information system was able to enhance identification and analysis of geometric and physical properties of selected agro-food products subjected to thermo-mechanical processing, and accuracy of the analysis of heat and water transport in the products examined was significantly improved.

**Keywords:** image-based measurements, 3D geometry modeling, heat & mass transport, inverse finite element analysis, Poland.

### 1. INTRODUCTION

Representation of material properties of agro-food and forest products in mathematical models of heat and water transport is difficult due to material complexity of the products, and direct determination of these quantities is usually impossible. The shape of such products is irregular, their material structure is non-homogeneous and anisotropic, properties vary with temperature and moisture content changes, and behavior strongly depends on variations in microclimate conditions. Heat and water transport during storage of agro-food and forest products decisively affect their end-use quality required by consumers. Knowledge of material properties is essential in analyzing, designing and managing advanced systems of processing and storage of such products. It is also essential to have an efficient, reliable information system to perform all necessary computer-aided analyses (Weres and Jayas, 1994; Pabis et al., 1998; Olek and Weres, 2007).

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Due to development of image analysis algorithms it is now possible to measure complex geometry of 3D objects (Gonzalez and Woods, 2008; Frączek and Wróbel, 2009; Shih, 2010; Weres, 2010). The image data can provide the basis for the finite element mapping and visualization of investigated products in the 3D domain (Zienkiewicz et al., 2005; Frey and George, 2008; Weres, 2010). Next, optimization methods (Nocedal and Wright, 2006; Rusczyński, 2006) and original inverse finite element analysis algorithms (Weres and Olek, 2005; Weres et al., 2009; Olek et al., 2011) constitute the basis for more accurate predictions in the finite element analysis of heat and water transport processes. Recent advances in software engineering (Sommerville, 2010; Gomaa, 2011) and availability of cutting edge software development environments (Intel Fortran Compiler, 2013; MSDN Library, 2013; Nagel et al., 2012) support development of an information system appropriate for the overall analysis of heat and water transport in the examined products.

The objective was to improve efficiency and accuracy of the analysis of heat and water transport in agro-food and forest products by developing and using an innovative information system of desired functionality and reliability.

## 2. MATERIAL, METHODS AND RESULTS

Investigation methods, referenced in 1. INTRODUCTION, were integrated to construct an information system (Fig. 1) for analysis of heat and water transport in agro-food and forest products. The methods were based on:

- 1) 3D product geometry measurements with the use of image analysis (Fig. 2). The following procedures were developed: acquisition of digital photographs of consecutive product layers, image processing, edge detection based on improved Canny algorithm, construction of the 3D finite element mesh for the whole product and automatic measurement of nodal coordinates in 3D.
- 2) 3D geometry modeling for a given product based on nodal coordinates for a mesh of 3D isoparametric finite elements enhanced with NURBS and textures (Fig. 3). Available operations to enhance visualization of the product model and property changes: moving, rotating, scaling, plane-cutting and time-stepping.
- 3) Identification of unknown material properties represented by coefficients of the mathematical model of heat and water transport (Fig. 4). Several procedures were developed to collect experimental data, to construct original inverse finite element algorithms, to simulate examined processes by original direct finite element software, and to assess quality of the approach. Due to quality assessment it was possible to select appropriate algorithms to ensure the lowest modeling inaccuracy and the best performance.
- 4) Software development based on modeling language UML 2.4.1 and programming environments: Visual Studio 2012 (C#, C++/CLI) and Intel Parallel Studio XE 2013 with VS2012. Essential practices of software engineering were followed.

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Heat and water transport processes were examined for cereal kernels, carrot slices, pine and beech wood, and wood-based panels (non-homogeneity, anisotropy and 3D shape irregularity of investigated biomaterials). Geometry, thermal conductivity, moisture transport coefficient, and convective heat/moisture transfer coefficients were identified and analyzed to test the information system (Fig. 5).

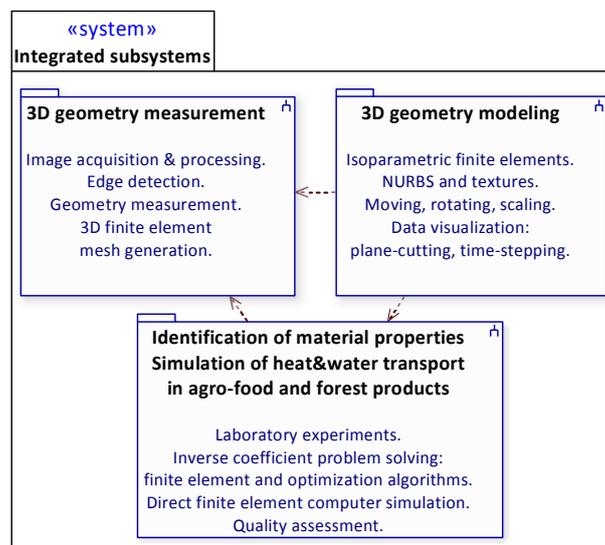


Figure 1. Integrated system supporting analysis of heat and water transport in agro-food and forest products represented by the UML nested subsystem packages.

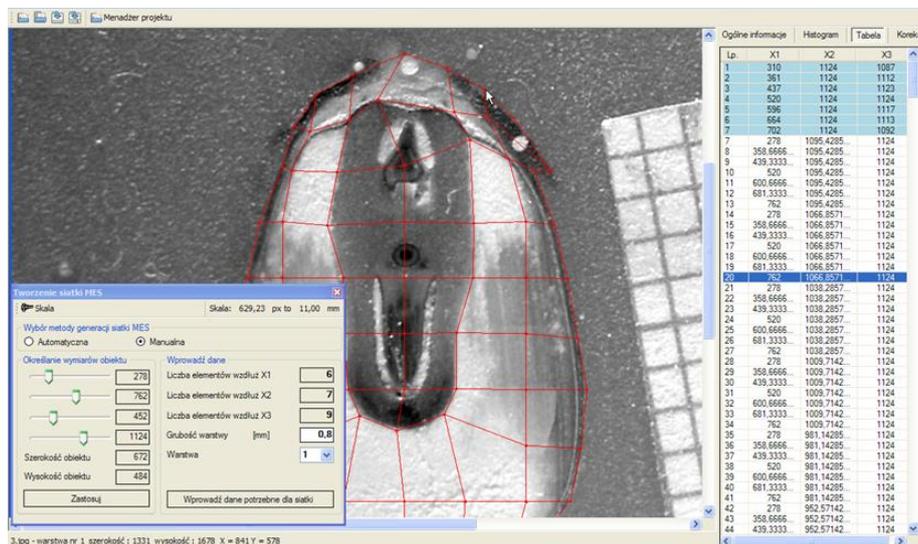


Figure 2. Subsystem for geometry measurement and mesh generation. Input: parameters of the 3D finite element mesh for the product. Output: array of the mesh node coordinates in 3D.

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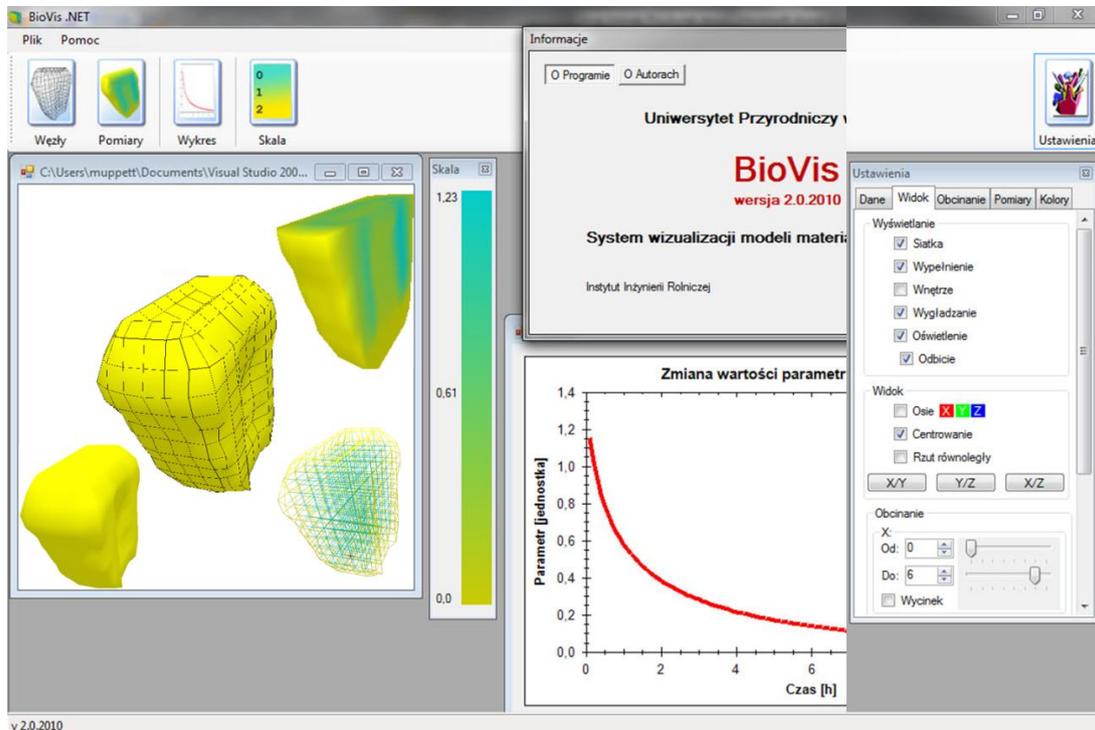


Figure 3. Subsystem for geometry modeling. Isoparametric elements enhanced with NURBS. Moving, rotating and scaling. Plane-cutting and time-stepping to visualize property changes.

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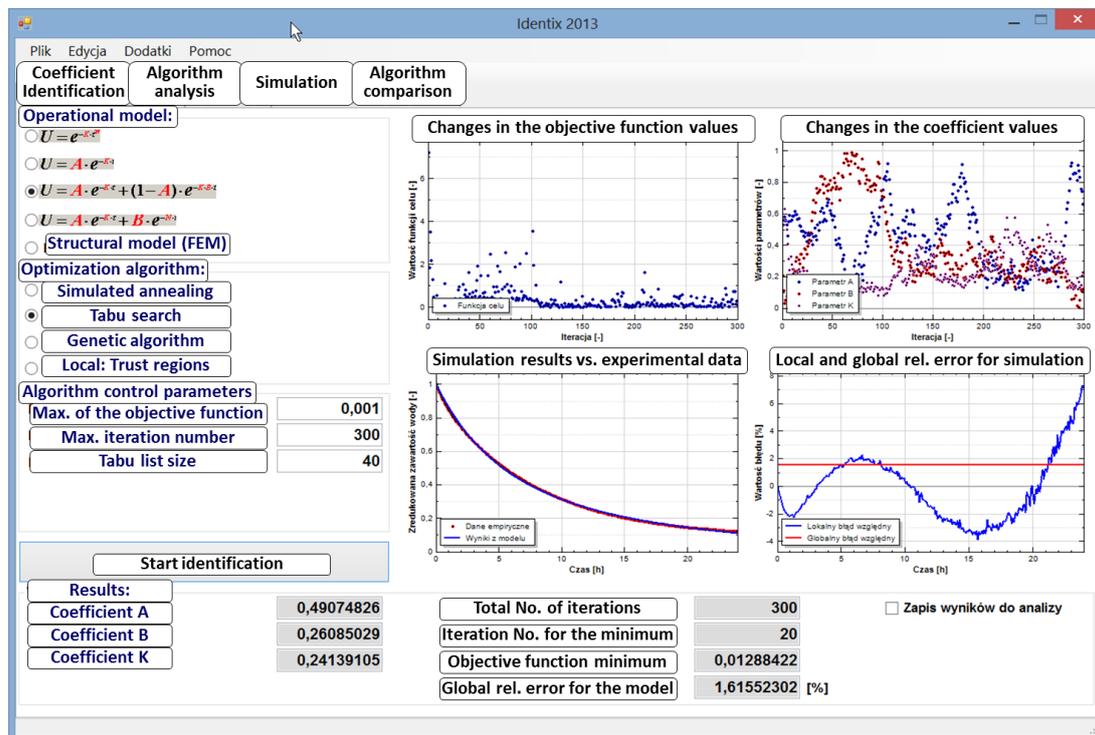


Figure 4. Subsystem for running inverse and direct finite element analysis (identification of coefficients and simulation of the heat and water transport processes), and for assessing quality of algorithms.

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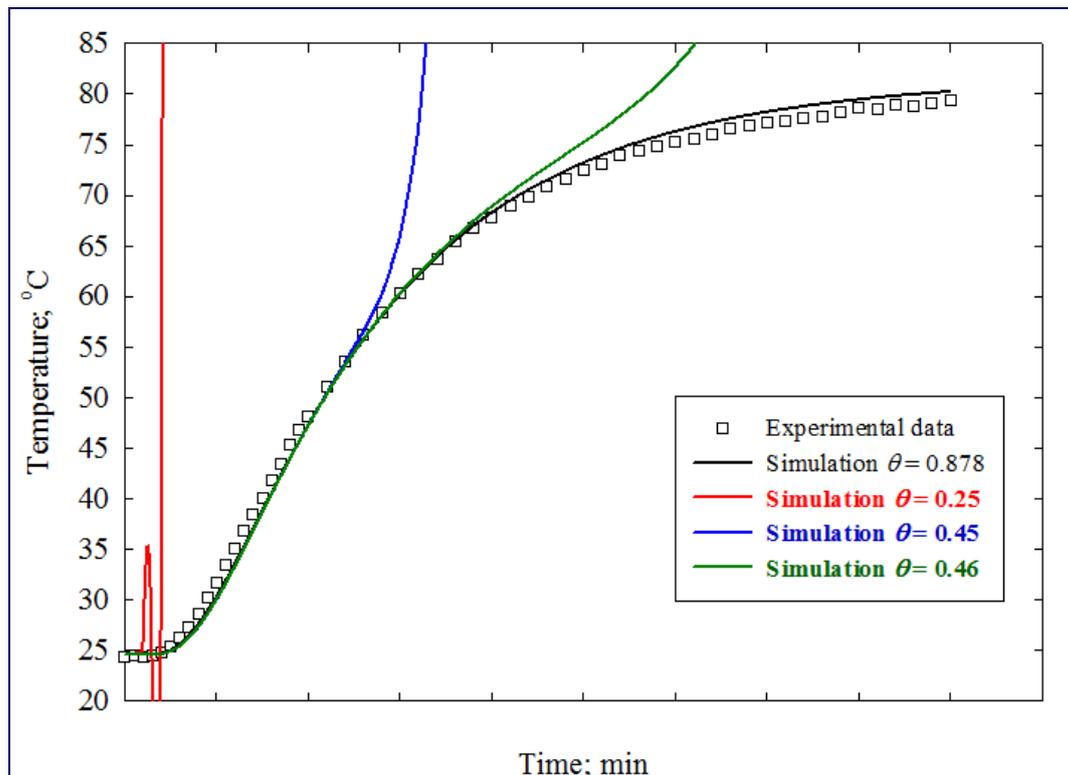


Figure 5. Validation of temperature predictions for the FE structural model supported by identified coefficients. The developed algorithm, absolutely stable for non-linear problems for  $\theta \geq 0.5$ , was compared to unstable algorithms for  $\theta < 0.5$ . Material: particle board of density  $693 \text{ kg m}^{-3}$ . Identified coefficients: specific heat  $c = 1890.3 \text{ J kg}^{-1} \text{ K}^{-1}$ , thermal conductivity in-plane  $k_{\parallel} = 0.3976 \text{ W m}^{-1} \text{ K}^{-1}$ , thermal conductivity transverse  $k_{\perp} = 0.2154 \text{ W m}^{-1} \text{ K}^{-1}$ . Global relative error of the model varied from 1.57 to 2.66%.

### 3. CONCLUSIONS

The information system composed of the developed and integrated subsystems showed appropriate functionality (including accuracy and suitability), and also usability, effectiveness and efficiency. Functional and non-functional requirements were fulfilled by the software. Predictions of heat and water transport processes in investigated agro-food and forest products, performed with the software developed, resulted in significantly lower values of the local and global errors of the developed model.

### 5. ACKNOWLEDGMENTS

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