A problem solving environment for the wood-based composites industry

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Abstract

Product quality and cost efficiency continue to grow in importance for the wood-based composites industry. The complex dynamics of the manufacturing process lends itself to the adoption of simulation models. Simulation models may be used to understand and manipulate the many parameters involved in the manufacturing process. However, most of the simulation models that have been developed over the last two decades have not been implemented due to a lack of continued technical support and a poor user interface. WBCSim is a prototype, Web-based, problem solving environment (PSE) that was developed to assist manufacturers and scientists in the design and manufacture of selected wood-based composite products. At the heart of WBCSim is a collection of legacy codes, which are described here. This PSE demonstrates the possibility of implementing scientific computing into a manufacturing application.

Introduction

The wood-based composites industry is primarily focused on mass production of commodity products. Profit margins are typically small, and certainly cyclical. Consequently, manufacturing costs and process efficiency are extremely critical. It is also commonly conceded that research expenditures as a percent of revenue are relatively small in comparison to industries that don't manufacture commodity products. Technological advances of the wood-based composites industry have been largely incremental. Today the wood-based composites industry is highly automated and has achieved a high level of efficiency in the utilization of raw materials. The manufacturing processes have become quite complicated, with an increasing dependency on automated process monitoring and control. The manufacturing experience of the plant personnel is extremely valuable for the successful operation of these complex processes. However, the complexity and the demands of the processes have exceeded the cognitive powers of even the most experienced operators. This paper presents a method of transferring scientific computing technology to industrial wood-based composite operations.

Process simulation models have been proposed, and to a limited extent implemented (Forintek, 2005), for some composite manufacturing operations. Simulation models are highly specialized tools that may be used to assist scientists, engineers, and manufacturers in the design of new composite products and processes, and for improved operation of existing manufacturing processes. Some of these models contain very sophisticated mathematics and numerical solution algorithms. Thousands of man-hours were required for their development. However, these models are not widely available, are highly specialized, have limited data manipulation utility, and have little or no technical support after they are completed. Their development has been largely an academic exercise, with the results typically lost within a short time of completion. In effect, these computer programs are legacy codes, orphaned programs that are not utilized and not supported. The question arises, how does one capture the value of simulation modeling research?

Conducting manual experiments in a laboratory or on a mill scale quickly becomes cost prohibitive with only a few simple variables in the experimental design. Obtaining results from experiments requires weeks or, as is often the case in university research, years. Computer modeling and simulation are used to assist in exploring the parameter space, thus reducing or eliminating subsequent physical experimentation. Simulation also permits exploration that goes beyond the physical limitations of existing equipment. Experimental error is eliminated. However, all simulation models are based on assumptions, which limit their range of applicability and accuracy. Often simulation models have incomplete data regarding material properties or process dynamics at the time the model is developed. Continued technical support and program development is required.

Of particular concern with highly specialized simulation models is their successful transfer from the developer to the users. Several barriers exist. Some computer codes are tied to a fixed computing environment. Others may not have been integrated with any visualization and optimization tools. Since the developers of the code are often the sole intended users, documentation is often poor and the user interface either cumbersome or nonexistent. Updates of the code may never be developed. The more sophisticated simulation models require a massive number of computations, which may only be reasonably accomplished on a high-end workstation or parallel computing system. It is not uncommon for a single simulation run to require more than a day to achieve a solution on a personal computer.

A new tool, or an evolution of existing tools, for solving complex manufacturing problems for the wood-based composites industry is necessary. One approach, a problem solving environment (PSE), is a computational system that provides a convenient set of high-level tools for solving problems from a specific domain. In this case, the domain is wood-based composite design and manufacture. A PSE commonly addresses many issues, such as: Internet accessibility to legacy codes, visualization, experiment management, multidisciplinary support, collaboration support, optimization, high performance computing, preservation of expert knowledge, design extensibility, and pedagogical uses (Watson et al. 2002). This paper describes a Web-based PSE called WBCSim (Virginia Polytechnic Institute, 2005), which has been developed as a tool to assist manufacturers with wood-based composite design and manufacture. WBCSim is a prototype PSE whose purpose is to demonstrate the application of scientific computing to practical manufacturing problems. It has also served as an example for the design, construction, and evaluation of small scale PSEs.

WBCSim lowers some of the barriers to user adoption of sophisticated simulation models. To be fair, the simulation models contained within WBCSim have limitations and some known flaws in their source code. They should be used with caution.

Background

Since the mid-1980s, several simulation models, which were intended to assist with the development or manufacture of wood-based composites, have been developed. Those models specifically directed at the hot-pressing process, are capable of simulating the spatial arrangement of wood elements in a mat (Dai and Steiner, 1994a and b; Zombori et al., 2001), heat and mass transfer within the mat during hot-pressing (Bolton et al, 1989a, b, and c; Dai et al, 2000; Harless, et al, 1987; Humphrey, 1989; Carvalho and Costa, 1998; Humphrey and Thömen, 2000; Thömen and Humphrey, 2003; Zombori et al., 2002, 2004; Fenton, 2003; Lee et al. 2006), degree of adhesive cure (Humphrey, 1989; Zombori et al., 2002, 2004; Lee et al. 2006), and the development of the vertical density profile (Dai et al, 2000; Humphrey, 1989; Carvalho and Costa, 1998; Humphrey and Thömen, 2000; Thömen and Humphrey, 2003; Zombori et al. 2004; Lee et al. 2006). The accuracy of the models depends on satisfaction of the underlying assumptions on which the models are based, the accuracy of the mathematical relationships that describe the physical and mechanical properties of the component materials, and the accuracy of the numerical solution. None of the models published to date provide adequate predictions of absolute values of internal conditions and density during hot-pressing. However, the representation of trends and relationships between temperature, pressure, adhesive cure, density, and time are quite good. The performance of these models would improve if better physical and mechanical property data become available, and if these models continue to be updated.

Methods

The utility of PSEs and the early development of WBCSim were described by Goel et al. (1999) and Shu et al. (2004). WBCSim leverages the accessibility of the World Wide Web to make simulations with legacy code available to scientists and engineers away from their laboratories. The computing environment is controlled by the host and updates easily managed. The user only needs a Web browser and an Internet connection. Downloads are limited to HTML code and data files. All of the executable code resides on the server. The user initiates the WBCSim Web page from the browser window. Tasks performed on the Web page include: selecting from a list of simulation models, inputting data, selecting the format of output data, obtaining user help, and initiating a simulation. The main Web page is shown in Figure 1. The user may select from the list of models to get more descriptive information or invoke the program.

In addition to the collection of simulation models, other software linked within WBCSim are an optimization program (DOT - Design Optimization Tool, 1985) and various visualization tools: VRML (Ames et al. 1996), Mathematica (Wolfram 1996), and the UNIX utility WhirlGif. DOT allows the user to provide ranges for the input parameters and get a solution that either maximizes or minimizes a given output value. Mathematica is used to generate static three dimensional graphs of the simulation output. The output is also translated to VRML. With a VRML viewer, the resulting graphs can be viewed from various directions in the three dimensional view space. The simulations also generate ASCII text output containing raw data that can be downloaded to the client computer.

The current software architecture of WBCSim follows a three-tier architecture: (1) the client layer – user interface, (2) the server layer – Web server and a PHP module, and (3) the developer layer – legacy simulation codes and various optimization and visualization tools running on the server. PHP is the acronym for Hypertext Preprocessor, which is an open source, server-side, and HTML embedded scripting language used to create dynamic Web pages. Upon any HTTP request, the server runs PHP scripts and sends plain HTML code back to the client, where no plug-in is needed. The client layer is the only layer visible to end users and the only layer running on the local machine. By separating the legacy simulation codes from the user interface, the server layer functions as the key to how WBCSim can run a text-only application from a Web browser. As its name suggests, the developer layer contains the legacy programs, which are the heart of WBCSim.

While each program has its own input and output format, the server layer communicates data with the developer layer via strings of parameters separated by white space (spaces and tabs). In order to cope with this string format, each legacy program is “wrapped" with a customized program code. The wrapper receives the string of parameters from the PHP module at the server, and converts those parameters into an appropriate format for the legacy program. Then the script calls the legacy program into action, feeding it the input, invoking any required optimization and visualization tools, packing all output in HTML and returning the results to the server layer, and then to the client layer. With this architecture, the developer layer is independent of the other layers, which makes the process of designing, and integrating new simulation codes relatively easy.

WBCSim contains an experiment management component, which integrates a Web-based graphical front end, server scripts, and a database management system to allow scientists to easily save, retrieve, and perform customized operations on experimental data (Shu et al. 2004). Upon submission of a simulation run, the experiment management system performs a search of all previous input data records to determine if a particular simulation has already been performed. If it has, the results are returned from the output database without re-executing the simulation run additional computation time. WBCSim also permits a user to graphically compare results from multiple runs. The use selects a completed simulation from a list and selects the parameter to compare. Results from the multiple runs are then displaced together.

Five simulation models are currently available on WBCSim:

- oriented strand board mat formation (OSB),
- rotary dryer simulation (RDS),
- hot Compression (HC),
- radio-frequency pressing (RFP), and
- composite material analysis (CMA).

All of these models were developed independent of WBCSim. As an example, the rotary dryer model in WBCSim was written using FORTRAN 77 over 20 years ago. As such, they are considered legacy code. A brief description of each simulation model follows.

Oriented Strand Board Mat Formation (OSB)

The mat formation model creates the three-dimensional spatial structure of a layered wood-based composite (e.g., oriented strand board and waferboard) and calculates certain mat properties by superimposing a mesh on the mat structure (Zombori et al. 2001). The model is based on a Monte Carlo simulation technique. It is assumed that the dimensions of the constituents (e.g., strands) of the mat follow certain probability distribution functions (e.g. normal, Weibull, gamma, etc.). The user selects which function is most appropriate for their data set. The parameters of the probability distribution functions have to be determined by measurement. The user inputs the number of layers. The total number of strands is determined by specifying target board density, board dimensions, and the mass fraction of each layer. The probability distribution functions of the length, width, thickness, and density of the strands are given by the user. Output from the mat formation model includes the horizontal density distribution, proportion of void space, and potential bonded surface area. Output data is available in a numerical format and two- or three-dimensional visualizations. The output from the mat formation model is required for the hot-pressing model. Although a default mat structure may be used.

The main menu for the mat formation model is shown in Figure 2. The user provides a name for each simulation run. A list of variables is then input. Depending on the number of layers defined for the mat, the user is given the opportunity to edit from one to three layers. Default values are provided as a starting point. Once all of the inputs are set, the run may be submitted to the server. If desired, inputs and outputs are saved to a common database and periodically deleted. The user interfaces for the other simulation models have a similar and consistent structure.

Rotary Dryer Simulation (RDS)

The rotary dryer simulation model assists in the design and operation of the most common type of system used for the drying of wood particles (Kamke and Wilson, 1985a and b). The rotary dryer is an integral part of the processes to manufacture particleboard and strand board products. It consists of a large, horizontally oriented, rotating drum (typically 3 to 5 m in diameter and 20 to 30 m in length). The wet wood particles are mixed directly with hot combustion gases, in a co-current flow pattern, at the inlet to the rotating drum. The gas flow provides the thermal energy for drying, as well as the medium for pneumatic transport of the particles through the length of the drum. Interior lifting flanges serve to agitate and produce a cascade of particles through the hot gases. The RDS model consists of coupled material and energy balance equations for each segment along the length of the drum. Each drum segment is defined by the cascading pattern of particle travel. The segment, or cycle, begins when a particle drops off a lifting flange and falls to the bottom of the drum. This is followed by travel along the periphery of the drum, where the particle is caught by a lifting flange. The segment ends when the particle attains its maximum angle of repose and tumbles off of the lifting flange. The user must supply the inlet conditions of the hot gases and wet wood particles, as well as the physical dimensions of the drum and lifting flanges, flow rates, and thermal loss factor for the dryer. The RDS model predicts the particle moisture content, temperature, gas composition, and energy consumption.

Figure 3 illustrates the input screen for the rotary dryer model. A parameter list is given, including a range of values that may be selected. A user may obtain more information about a parameter by selecting the help button (shown as a question mark in the figure) adjacent to the parameter. A similar input screen is available for each simulation model. Currently, the RDS model is locked for only one rotary dryer configuration.

Hot Compression (HC)

The hot compression model simulates the mat consolidation and adhesive cure that occurs during hot-pressing of wood-based panels (Zombori et al., 2002 and 2004). The model is based on fundamental engineering principles and uses the output from the mat formation model to establish the starting spatial structure of the mat. Six primary variables are considered: mat density, air content, vapor content, bound water content, temperature within the mat, and the extent of the cure of the adhesive system characterized by the cure index. The heat is transported by conduction and bulk flow, while the water phases are transported by bulk flow and diffusion.

A nonlinear viscoelastic relationship was used to describe the compression behavior of the mat. This relationship separates the geometric nonlinear response of the cellular structure of the wood elements from the linear viscoelastic response of the wood cell wall polymers. The behavior of the cellular structure is modeled with a modified Hooke's Law. The viscoelastic properties of the flakes are described by the time-temperature-moisture equivalence principle of polymers. The resulting differential algebraic system of equations is solved by a semicontinuous finite difference method (method of lines for parabolic partial differential equations). The spatial derivatives of the conduction terms are discretized according to a central difference scheme, while the spatial derivatives of the bulk flow terms are discretized according to an upwind scheme. The resulting ordinary differential equations (ODEs) in the time variable are solved by DDASSL, a public domain differential-algebraic system solver. The model predicts temperature, moisture content, partial air and vapor pressures, total pressure, relative humidity, extent of adhesive cure, and the spatial density profiles within the mat. The model assists users in the understanding of the interacting mechanisms involved in a complex production process. The model may also be used to optimize the hot-pressing parameters for improved quality of wood-based panel products, while minimizing processing cost.

A set of three-dimensional graphical profiles illustrates the evolution of these primary variables with time, in the thickness and width dimensions of the mat (Figure 4). In this example only one frame out of 55 is shown. An alternative output selection is a movie file (in a GIF format created by Mathematica), so that the user gains a perspective of the dynamics of the process.

Radio-Frequency Pressing (RFP)

The radio-frequency pressing model was developed to simulate the consolidation of wood veneer into a laminated composite (Resnik and Kamke, 1998). The energy needed for cure of the thermosetting adhesive is supplied by a high-frequency electric field. Radio-frequency pressing is commonly used for thick composites and for nonplanar laminated composites. The model may be used to help design alternative pressing schedules. The RFP model consists of a collection of nonlinear PDEs that describe the heat and mass transfer within the veneer layers. The primary variables are temperature and moisture content. The moisture content is further divided into three phases: bound water, liquid water, and water vapor. These water phases must satisfy a criterion of local thermodynamic equilibrium as represented by a nonlinear algebraic equation. The model is one-dimensional, with a fixed resistance to heat and mass flux at the boundary. The RFP model predicts the time-dependent temperature and moisture content profiles in the veneer layers, as well as the extent of adhesive cure. Among the user-supplied input data are the initial density, thickness, moisture content, and temperature of the veneer, as well as the electric field strength.

Composite Material Analysis (CMA)

The composite material analysis model was developed to assess the stress and strain behavior and strength properties of laminated materials (e.g., plywood and fiber-reinforced composites). The user defines the layer sequence of the laminate. The graphical user interface was designed to allow easy specification of the material, thickness, and orientation at each layer. The mechanical and failure properties of the layer materials may be selected from a predefined list. The model can perform design and analysis functions, where the user either defines the loading condition, or defines the deformation. The calculations are based on the classical lamination theory (CLT) and the Tsai-Wu failure criteria. The "Design" and "Analysis" models (selected from the main CMA interface) calculate the induced stresses and strains in the primary laminate (x; y) and principal fiber (1; 2) directions within each layer based on the CLT, and check for the integrity of the layers of the laminate by the Tsai-Wu failure criteria. In the design mode, the model calculates the stresses and strains caused by the combination of different loading conditions, such as tension, moment, torque, or shear. In the analysis mode, the normal and shear stresses, together with the strains and curvatures induced by a user-defined deformed shape, are calculated. The model predicts the tensile strength, bending strength, and shear strength of the composite material.

Optimization

Two of the simulation models have been configured on WBCSim to interact with numerical optimization software. DOT (Design Optimization Tools) can be used to solve a wide variety of linear or nonlinear optimization problems. The simulation model (in this case RDS or RFP) is wrapped with a script that calls DOT. This configuration effectively creates an optimization program. The simulation program has a set of inputs that DOT places in a vector called the "vector of design variables", and a set of outputs called "responses". One of the responses can be chosen to be the objective function. DOT will change the vector of design variables in order to minimize or maximize the user defined objective. To achieve this, DOT calls the simulation program repeatedly, with the aid of the program wrapper, while searching for the optimum. Lower and upper bounds can be placed on other responses. Very little formal knowledge of optimization techniques is needed to make efficient use of DOT. Thus, a very powerful capability is awarded the simulation programs, which were not originally designed to perform optimization.

Summary

The organization and utility of a problem solving environment called WBCSim was described. WBCSim consists of five independent simulation models (legacy codes), as well as several other software utilities brought together in a seamless manner. A brief description of each simulation model was provided. Without the PSE a user would need to have access to each of the component computing utilities and a means of translating the necessary data between them – a task that would be very time consuming. As a Web-based PSE, WBCSim is readily accessible. WBCSim is a prototype PSE. The simulation models are intended to demonstrate the possibilities of using scientific computing tools to assist with the design and manufacture of wood-based composites. New functionality and models, as well as improved performance of existing models, may be added to WBCSim in the future.

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Figure Captions

Figure 1. Main Webpage for WBCsim showing the simulation model selections and two choices for optimization using DOT.

Figure 2. Main menu for the OSB mat formation simulation model illustrating selections for input data and output control.

Figure 3. Interactive window for input data, as an example from the rotary dryer simulation.

Figure 4. Example of graphical output from the hot compression simulation. One frame of a time series movie is shown. Outputs shown include temperature, moisture content, adhesive cure index, total pressure, partial air pressure, and partial water vapor pressure.

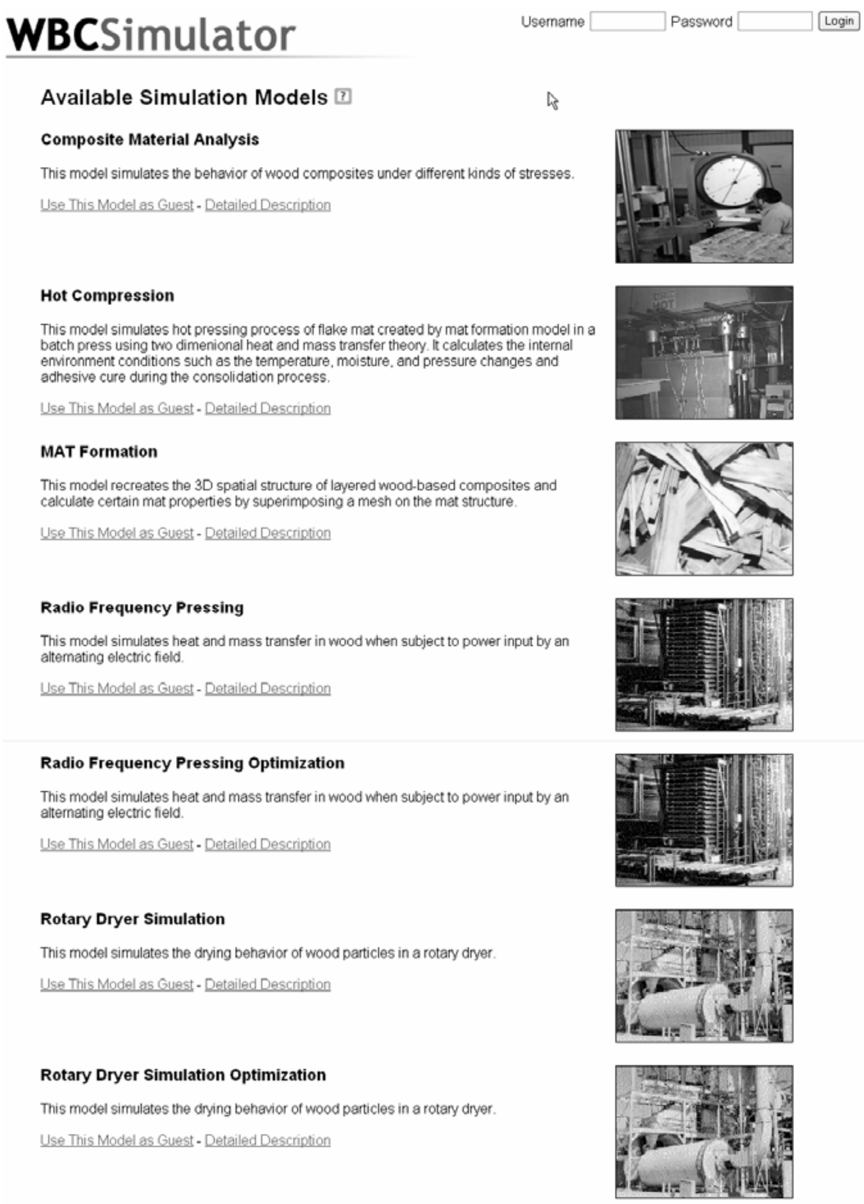

WBCSimulator
Username
Password
Login
Available Simulation Models
Composite Material Analysis
This model simulates the behavior of wood composites under different kinds of stresses.
Use This Model as Guest - Detailed Description
Hot Compression
This model simulates hot pressing process of flake mat created by mat formation model in a batch press using two dimenional heat and mass transfer theory. It calculates the internal environment conditions such as the temperature, moisture, and pressure changes and adhesive cure during the consolidation process.
Use This Model as Guest - Detailed Description
MAT Formation
This model recreates the 3D spatial structure of layered wood-based composites and calculate certain mat properties by superimposing a mesh on the mat structure.
Use This Model as Guest - Detailed Description
Radio Frequency Pressing
This model simulates heat and mass transfer in wood when subject to power input by an alternating electric field.
Use This Model as Guest - Detailed Description
Radio Frequency Pressing Optimization
This model simulates heat and mass transfer in wood when subject to power input by an alternating electric field.
Use This Model as Guest - Detailed Description
Rotary Dryer Simulation
This model simulates the drying behavior of wood particles in a rotary dryer.
Use This Model as Guest - Detailed Description
Rotary Dryer Simulation Optimization
This model simulates the drying behavior of wood particles in a rotary dryer.
Use This Model as Guest - Detailed Description

Figure 1.

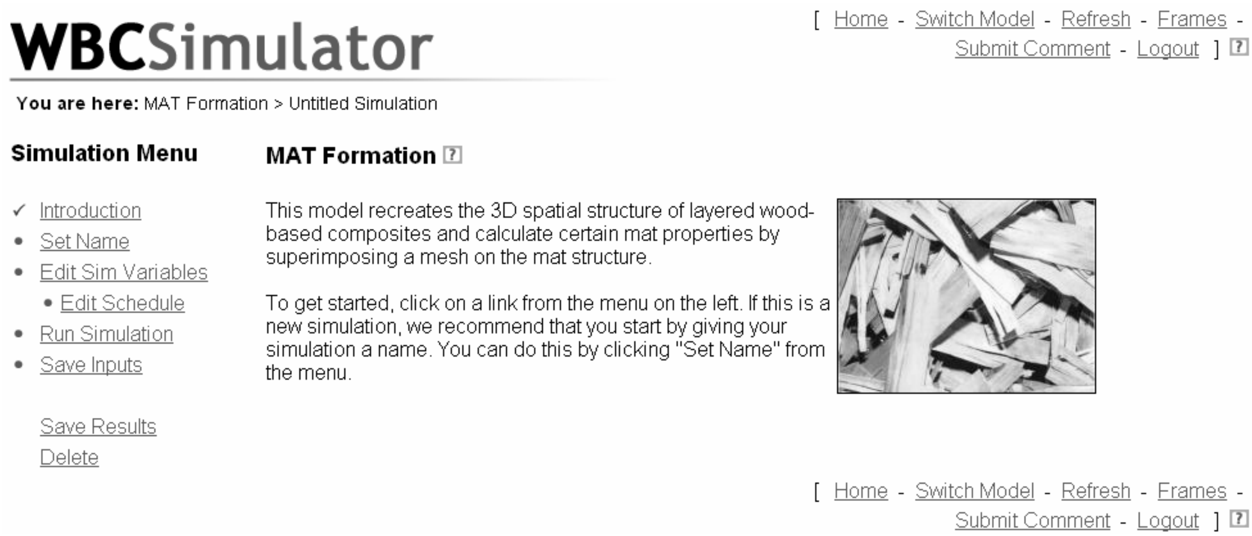
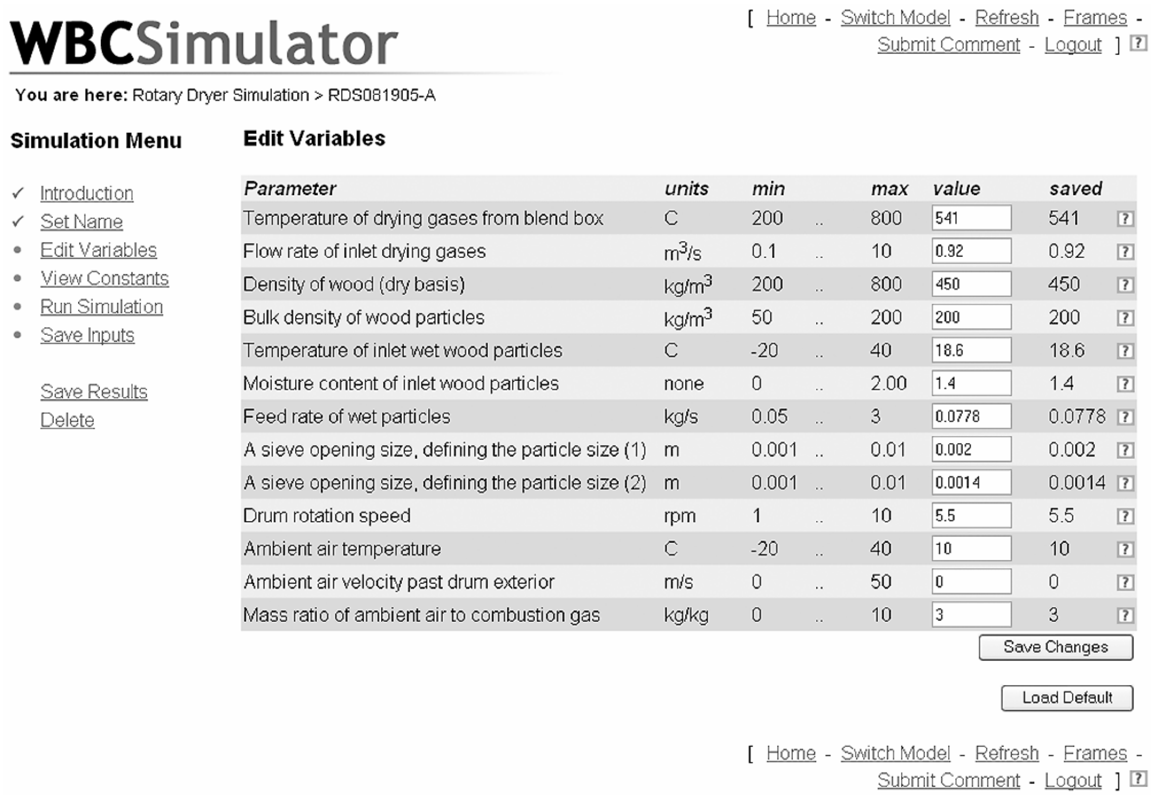

WBCSimulator
[Home - Switch Model - Refresh - Frames - Submit Comment - Logout]
You are here: MAT Formation > Untitled Simulation
Simulation Menu
Introduction
Set Name
Edit Sim Variables
Edit Schedule
Run Simulation
Save Inputs
Save Results
Delete
MAT Formation
This model recreates the 3D spatial structure of layered wood-based composites and calculate certain mat properties by superimposing a mesh on the mat structure.
To get started, click on a link from the menu on the left. If this is a new simulation, we recommend that you start by giving your simulation a name. You can do this by clicking "Set Name" from the menu.
[Home - Switch Model - Refresh - Frames - Submit Comment - Logout]

Figure 2.



WBCSimulator

[Home - Switch Model - Refresh - Frames - Submit Comment - Logout] [?]

You are here: Rotary Dryer Simulation > RDS081905-A

Simulation Menu

- ✓ Introduction
- ✓ Set Name
- • Edit Variables
- • View Constants
- • Run Simulation
- • Save Inputs

Save Results
Delete

Edit Variables

Parameter	*units*	*min*		*max*	*value*	*saved*	
Temperature of drying gases from blend box	C	200	..	800	541	541	[?]
Flow rate of inlet drying gases	m^3/s	0.1	..	10	0.92	0.92	[?]
Density of wood (dry basis)	kg/m^3	200	..	800	450	450	[?]
Bulk density of wood particles	kg/m^3	50	..	200	200	200	[?]
Temperature of inlet wet wood particles	C	-20	..	40	18.6	18.6	[?]
Moisture content of inlet wood particles	none	0	..	2.00	1.4	1.4	[?]
Feed rate of wet particles	kg/s	0.05	..	3	0.0778	0.0778	[?]
A sieve opening size, defining the particle size (1)	m	0.001	..	0.01	0.002	0.002	[?]
A sieve opening size, defining the particle size (2)	m	0.001	..	0.01	0.0014	0.0014	[?]
Drum rotation speed	rpm	1	..	10	5.5	5.5	[?]
Ambient air temperature	C	-20	..	40	10	10	[?]
Ambient air velocity past drum exterior	m/s	0	..	50	0	0	[?]
Mass ratio of ambient air to combustion gas	kg/kg	0	..	10	3	3	[?]

Save Changes

Load Default

[Home - Switch Model - Refresh - Frames - Submit Comment - Logout] [?]

Figure 3.

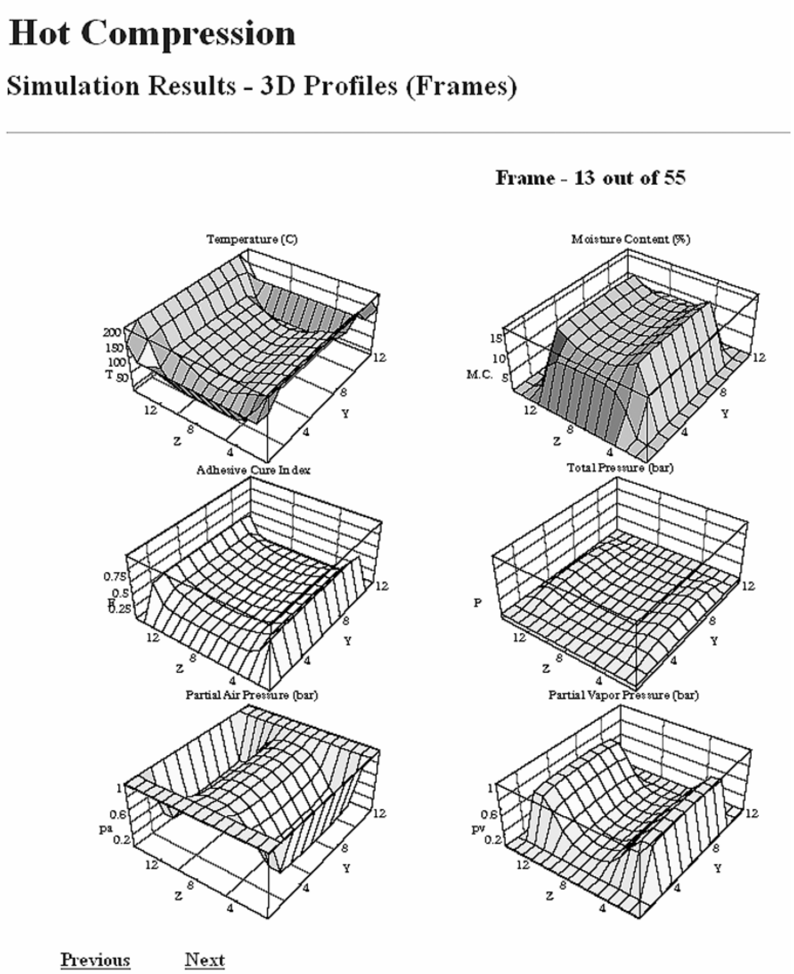

Hot Compression
Simulation Results - 3D Profiles (Frames)
Frame - 13 out of 55
Temperature (C)
Moisture Content (%)
Adhesive Cure Index
Total Pressure (bar)
Partial Air Pressure (bar)
Partial Vapor Pressure (bar)
Previous
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Figure 4.