Sequential Screening Approach for the Identification of Potential Critical Supply Chain Conditions on Product Quality

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Outline:

I. Motivation and Scope

The *shelf life* of a product is defined as the length of time in which a product is safe to consume and/or has a satisfactory quality to consumers.

The shelf life is modeled around a parameter (i.e. concentration of a chemical compound) and it's influenced by several factors: exposure to light and heat, transmission of gases, mechanical stresses, and contamination.

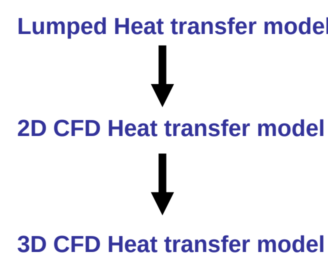
One important factor that affects the shelf life of almost all products is the surrounding temperature which can cause freezing, melting, chemical or biochemical degradation of the product.

This work aims at building a simulation-tool that will be used to determine the impact of supply chain conditions on product quality.

II. Sequential Screening Approach

The great number of possible transport and weather scenarios make the simulation time the bottleneck for the screening process.

The idea behind a sequential screening approach is to analyze the weather scenarios using three different heat transfer models of increased complexity.



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Lumped Heat transfer model

Predicts a uniform temperature within the container and incorporates:

- ambient temperature
- wind speed
- solar and atmospheric radiation
- some basic characteristics of the shipping container (type of container, dimensions, solar reflectivity)

The heat transfer model is divided into three parts:

- heat transfer at the wall of the shipping container
- heat transfer from the wall to the inside air
- heat transfer at the cargo on the pallets

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Heat transfer at the wall of the shipping container

$$M_w \cdot Cp_w \cdot \frac{\Delta T_w}{dt} = \overbrace{h_{FC} \cdot A \cdot (T_{air.out} - T_w)}^{\text{Forced convective heat transfer}} + \overbrace{h_{NCout} \cdot A \cdot (T_w - T_{air.out}) + h_{NCin} \cdot A \cdot (T_{air.in} - T_w)}^{\text{Natural convective heat transfer}} +$$

$$\underbrace{\frac{k \cdot A \cdot (T - T_w)}{\Delta x}}_{\text{Conductive heat transfer}} + \underbrace{A \cdot \alpha_w \cdot G_{solar}}_{\text{Solar radiation heat transfer}} + \underbrace{A \cdot \varepsilon \cdot \sigma \left(T_{Sky}^4 - T_w^4\right)}_{\text{Atmospheric radiation}}$$

Heat transfer from the wall to the inside air

$$M_{air} \cdot Cp_{air} \cdot \frac{\Delta T_{air}}{dt} = h_{NC} \cdot A \cdot (T_w - T_{air}) + k_{air} \cdot A \cdot (T_w - T_{air})$$

Convection **Conduction**

Heat transfer at the cargo on the pallets

$$M_C \cdot Cp_C \cdot \frac{\Delta T_C}{dt} = h_{NC} \cdot A \cdot (T_{air} - T_C) + \frac{k_C \cdot A \cdot (T_{air} - T_C)}{\Delta x}$$

Convection **Conduction**

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2D CFD Heat transfer model

The air velocity and pressure fields inside the container are obtained by solving numerically the incompressible Navier-Stokes equations under the Boussinesq Approximation for natural convection.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

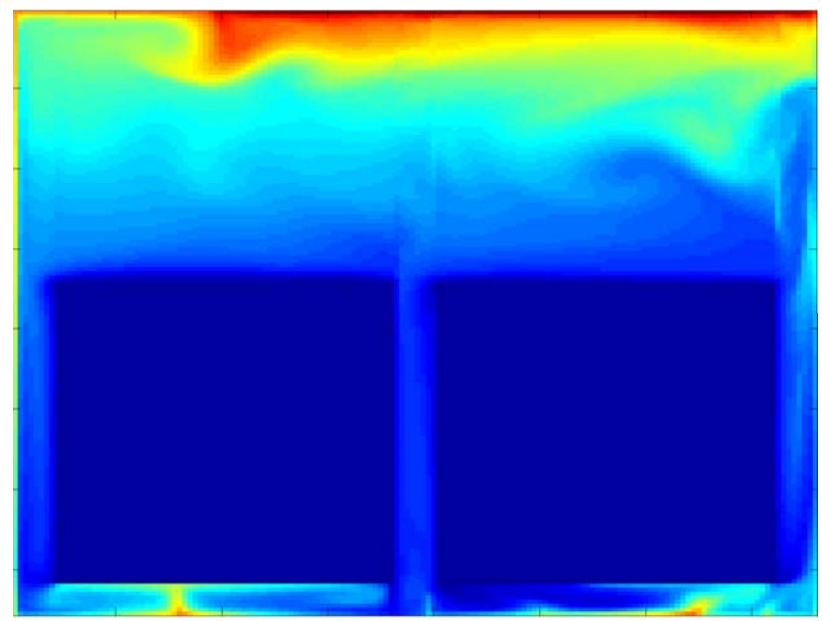
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \gamma\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \gamma\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta(T - T_0)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = -\frac{\partial p}{\partial y} + \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + q$$

where:

u – velocity component for x direction [m/s];
v – velocity component for y direction [m/s];
T – temperature [K];
To – reference temperature [K];
p – pressure [kg/m3];
g – gravitational acceleration [m/s2];
β – coefficient of volume expansion [K-1] (β = 1/T for ideal gases);
α – thermal diffusivity of air [m2/s];
γ – kinematics viscosity of air [m2/s];
q – heat that enters the system from natural convection transport near the wall.



Simulation results of the 2D CFD heat transfer model. Initial air temperature is 20 °C, west and bottom wall are set at 35 °C.

3D CFD Heat transfer model

Fully discretized 3D model of the shipping container.

The mode incorporates:

- ambient temperature
- wind speed
- solar and atmospheric radiation
- some basic characteristics of the shipping container (type of container, dimensions, solar reflectivity)
- Navier-Stokes + Boussinesq Approximation for natural convection
- detailed product model

Conclusions

The models can be used to simulate:

- **shipping containers of all sizes**
- **insulated and non-insulated**
- **loaded with different types of pallets**

The model can be used to indentify potential critical weather scenarios that will cause damage to products in the supply chain