0D/1D Cardiovascular Model Sensitivity Analysis

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Introduction

Blood flow is pulsatile and blood pressure propagates within the arterial tree as a wave. 0D/1D cardiovascular models represent the physics of pulse wave propagation and reflections in the arterial tree. One draw-back resides in the high number of parameters to be specified. A sensitivity analysis identifies those parameters that have a major effect on the output. Statistical emulators can be employed to catch models mean behaviour and to predict output for all the points in the parameter space. Emulator computational running time can be infinitely shorter than a single model run.

Methodology

The vascular model is based on the 1D form of the Navier-Stokes' equations for incompressible flows within narrow, thin-walled elastic tubes. Equations are linearised by means of integration along the vessel length. This results in a lumped-parameter model representing the physics of a segment of each vessel. The model is solved numerically by means of a first order Euler's scheme. Conservation of mass and total pressure was imposed to solve the flow at bifurcation location. The branching geometry follows Murray's law.

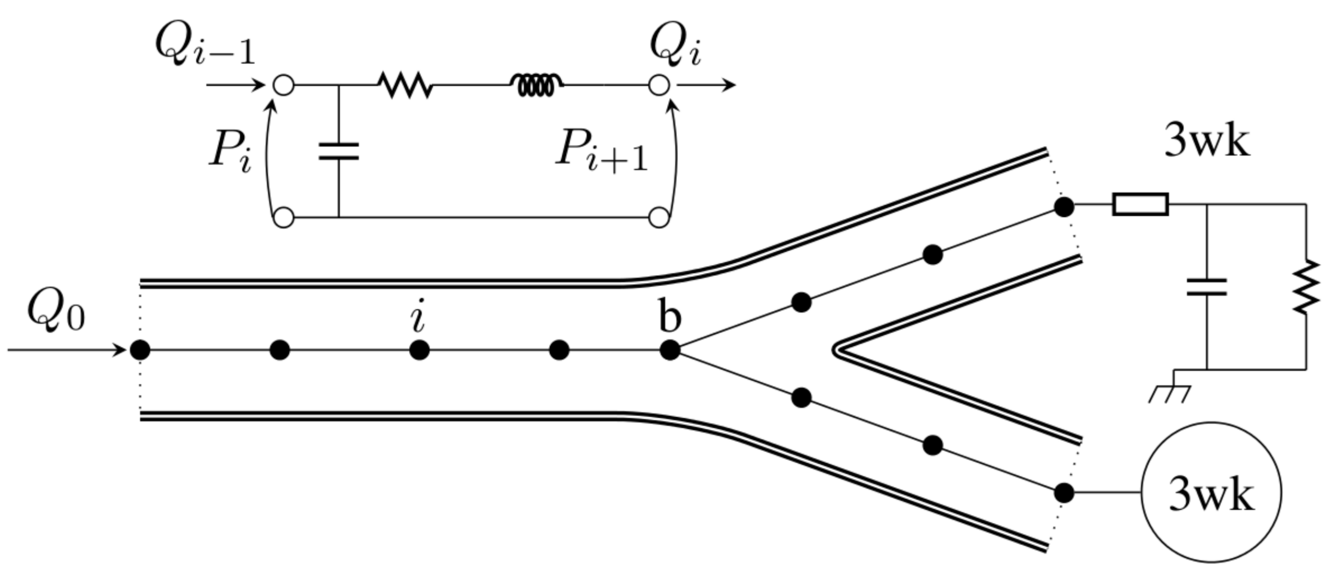

Fig. 1: Bifurcation model scheme. Three elastic vessels are connected at bifurcation point b. In between two computational nodes, a lumped parameter circuit is solved.

The emulator consists of a Gaussian process regression model trained on a set of 100 simulation outputs. A homogeneous coverage of the entire parameter space was ensured by means of Latin hypercube sampling. Sensitivity of the model output (pulse wave velocity PWV) to individual inputs or combinations of them was assessed by means of Sobol sensitivity indices. Total sensitivity indices were computed starting from 3200 predictions produced by the model emulator.

Results

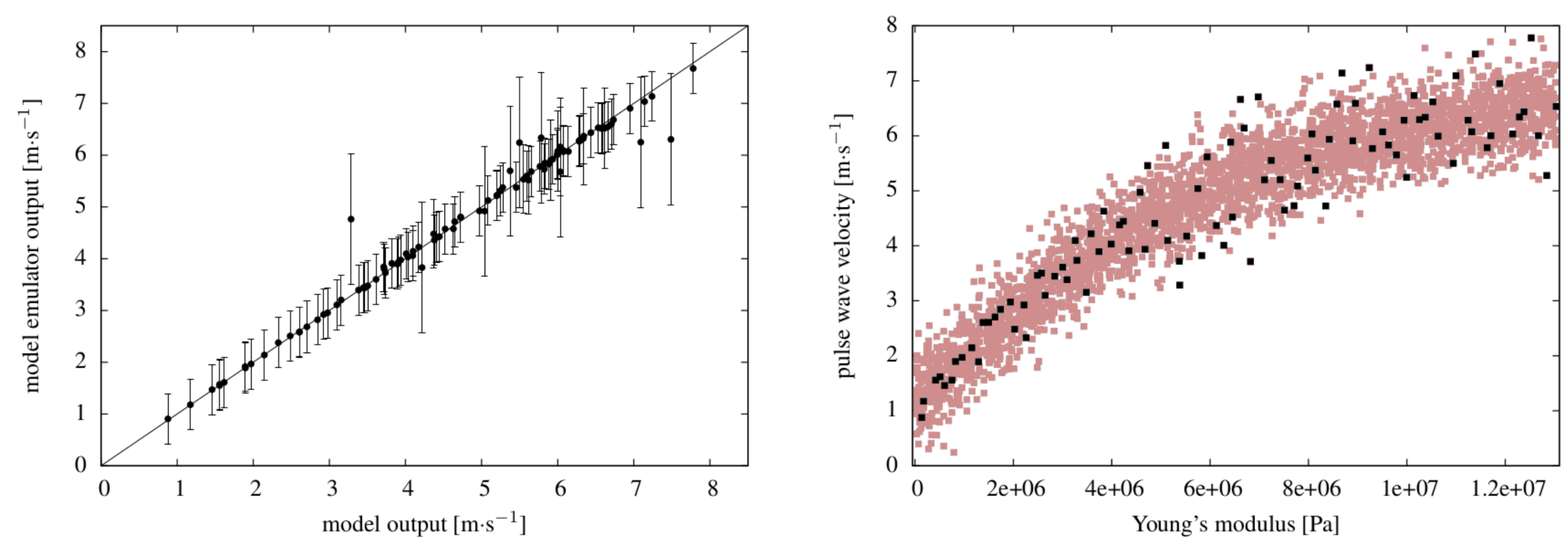

Fig. 2: (Left) Comparison between emulator and model outputs. (Right) Emulator outputs (red) and model training runs (black).

Emulator outputs are plotted against model outputs in Fig.2. Points lying on the line of equality indicate a good agreement between the two methods. Outliers indicate areas where emulator predictions can be improved. Scatter plot shows that the influence of E on PWV is captured by both model and emulator outputs. Scatter plots for other input parameters showed no influence on PWV.

Sensitivity indices giving an insight about the relative influence of each model input on PWV are reported below

Parameter	Range	Total effect
viscosity μ [cP]	[1, 4]	0.052 ± 0.012
length ℓ [m]	[0.2, 0.8]	0.048 ± 0.011
radius r [m]	[0.005, 0.040]	0.046 ± 0.010
thickness h [m]	[0.001, 0.005]	0.051 ± 0.012
Young's modulus E [kPa]	[30, 13000]	0.707 ± 0.098

With the exception of the index for E, all other indices are low, meaning a weak correlation to the output of interest, PWV. The main source of variation for the output resides in the variation of Young's modulus.

The computational time required to run the 100 training simulations of the 0D distributed model was of about 32.6 hours. On the other hand, the entire process of Gaussian process training, optimisation, and prediction of 3200 new outputs required roughly 1 minute, 0.0018 seconds of which for the prediction part.

Conclusions

There is a good agreement between model and emulator outputs. Variation of parameters other than E was not significant. The introduction of the Gaussian process emulator reduced significantly the computational time required by a robust sensitivity analysis. Further work will focus on development of the vascular model to represent the entire arterial circulation.