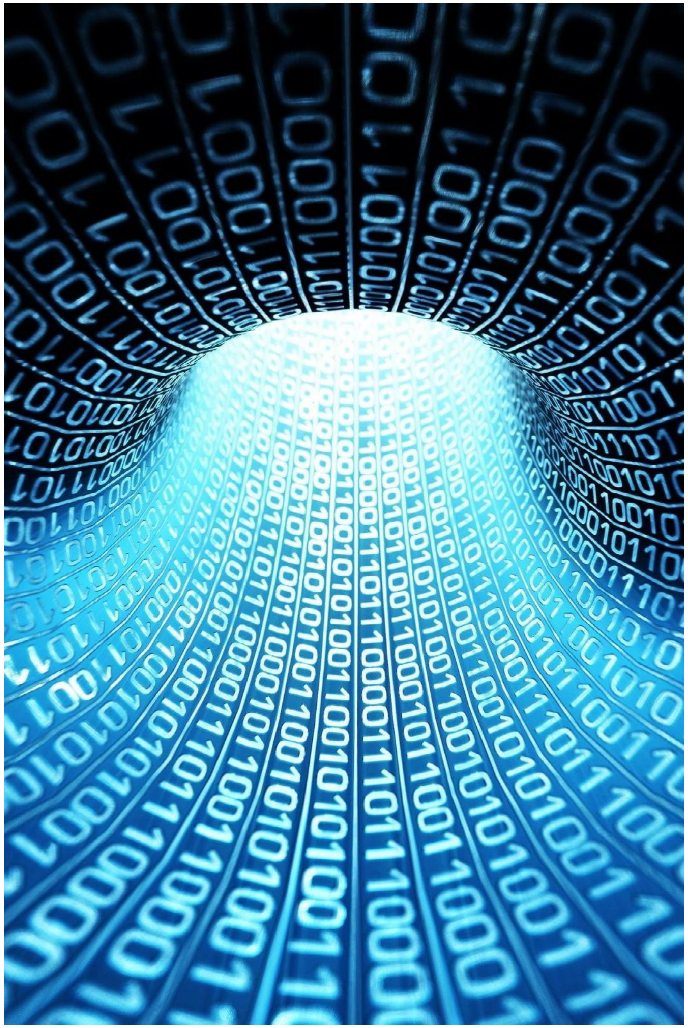
APPLICABILITY OF DIGITALIZATION IN SYSTEMS ENGINEERING

Constantin Suciu

Transilvania
University
of Brasov

What is digitalization?



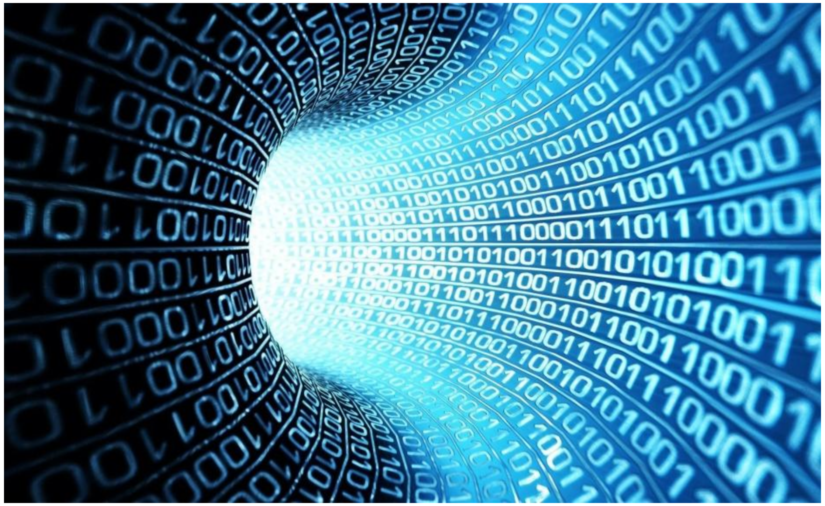
Digitalization is the use of ***digital technologies*** to change a business model and provide new revenue and value-producing opportunities;

It is the process of moving to a ***digital business***.

Digital business is the creation of new business designs by blurring the digital and physical worlds.

According to Gartner

Benefits and mechanisms of digitalization



Among pursued benefits of applying digitalization in systems engineering:

- o Increasing throughput;
- o Extending the life and reliability of the systems through optimal operation.

Among methods of achieving it :

o Generation of models that represent the process/system as close as possible to reality;

o Acquisition of data from the process/system as it is next door;

o Accelerated simulation of the customized models and , based on collected data, analyze and detect behavioral patterns in real time;

o Dynamically generate/manage commands for improving the supervised process/ business.

MODELS

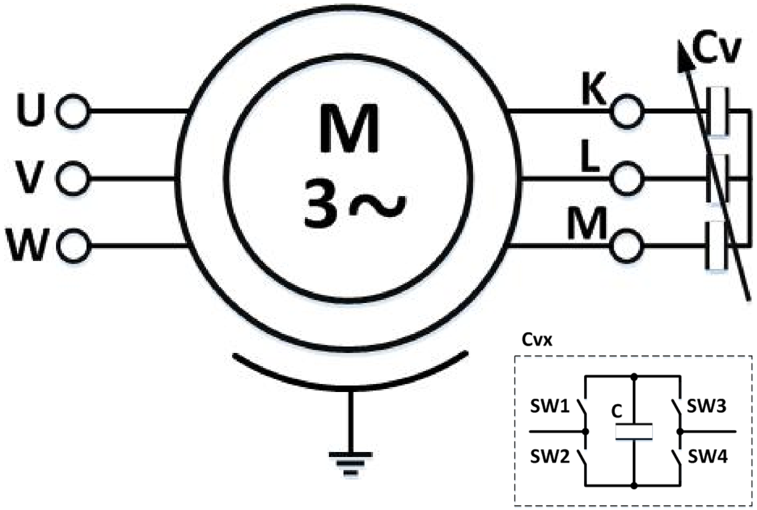
Transilvania
University
of Brasov

MODELS

Induction Motors with variable rotor impedance

Transilvania
University
of Brasov

Induction motor with variable rotor impedance (1)

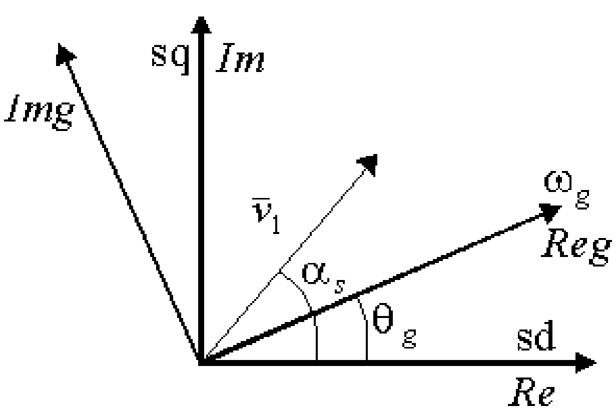


$$\frac{di_{sx}}{dt} = \frac{-R_s L_r i_{sx} + \omega_r L_m^2 i_{sy} + R_r L_m i_{rx} + \omega_r L_m L_r i_{ry} + L_r u_{sx} + L_m u_{cx}}{L_s L_r - L_m^2}$$

$$\frac{di_{rx}}{dt} = \frac{R_s L_m i_{sx} - \omega_r L_m L_s i_{sy} - R_r L_s i_{rx} - \omega_r L_s L_r i_{ry} - L_m u_{sx} - L_s u_{cx}}{L_s L_r - L_m^2}$$

$$\frac{di_{sy}}{dt} = \frac{-\omega_r L_m^2 i_{sx} - L_r R_s i_{sy} - \omega_r L_r L_m i_{rx} + L_m R_r i_{ry} + L_r u_{sy} + L_m u_{cy}}{L_s L_r - L_m^2}$$

$$\frac{di_{ry}}{dt} = \frac{\omega_r L_m L_s i_{sx} + L_m R_s i_{sy} + \omega_r L_r L_s i_{rx} - L_s R_r i_{ry} - L_m u_{sy} - L_s u_{cy}}{L_s L_r - L_m^2}$$



$$\frac{du_{cx}}{dt} = \frac{i_{rx}}{C_r} - \omega_r u_{cy}$$

$$\frac{du_{cy}}{dt} = \frac{i_{ry}}{C_r} + \omega_r u_{cx}$$

Induction motor with variable rotor impedance (2)

$$\left|\bar{i}_r\right| = \frac{\omega_2 L_m \left|\bar{u}_s\right|}{\sqrt{A_m\omega_2^2 + B_m\omega_2 + C_m + \dfrac{D_m}{\omega_2^2}}}$$

$$A_m\omega_2^4 + (B_m - E_m)\omega_2^3 + C_m\omega_2^2 + D_m = 0$$

$$\left|\bar{i}_s\right| = \frac{\sqrt{R_r^2 + \omega_2^2\left(L_r - \dfrac{1}{\omega_2^2 C_r}\right)^2}}{\omega_2 L_m}\left|\bar{i}_r\right|$$

$$P_{cu} = \frac{t_e}{p}\left(\omega_2 + \frac{R_s}{R_r}\frac{R_r^2 + \omega_2^2\left(L_r - \dfrac{1}{\omega_2^2 C_r}\right)^2}{\omega_2 L_m^2}\right)$$

$$P = \frac{3}{2}\frac{\left|\bar{u}_s\right|^2\left(R_r V_m + \omega_2 W_m\left(L_r - \dfrac{1}{\omega_2^2 C_r}\right)\right)}{V_m^2 + W_m^2}$$

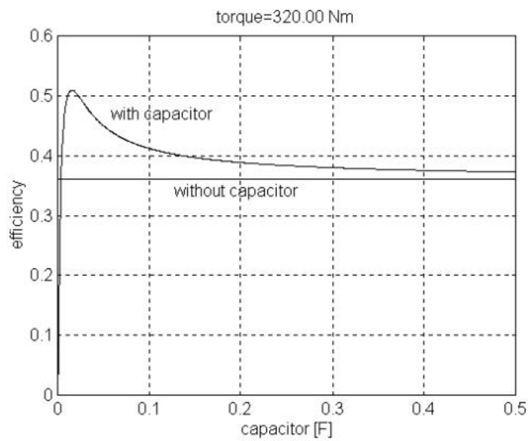
$$Q = \frac{3}{2}\frac{\left|\bar{u}_s\right|^2\left(R_r W_m - V_m\omega_2\left(L_r - \dfrac{1}{\omega_2^2 C_r}\right)\right)}{V_m^2 + W_m^2}$$

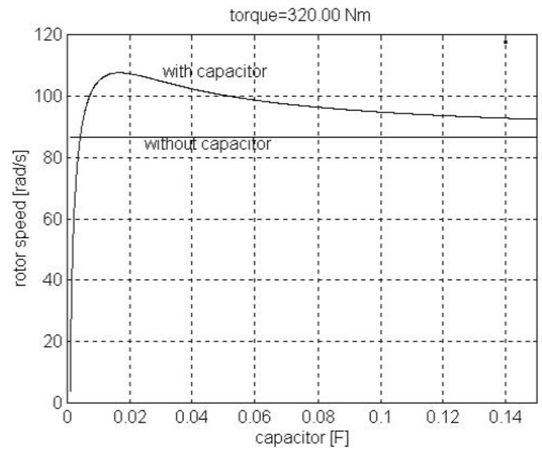
$$P_M = t_e\Omega_r$$

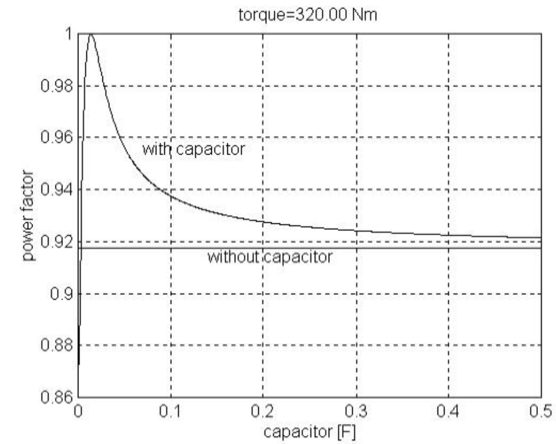
$$\eta = \frac{P_M}{P}$$

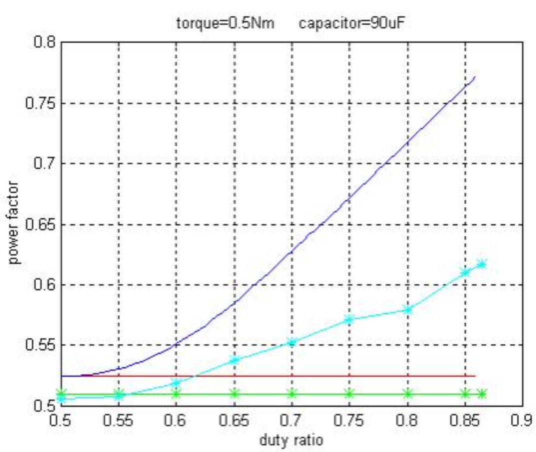
where $A_m, B_m, C_m, D_m, E_m, V_m, W_m$ *are functions* of $\omega_1, \omega_2, R_s, R_r, L_s, L_r, L_m, C_r, t_e, p$

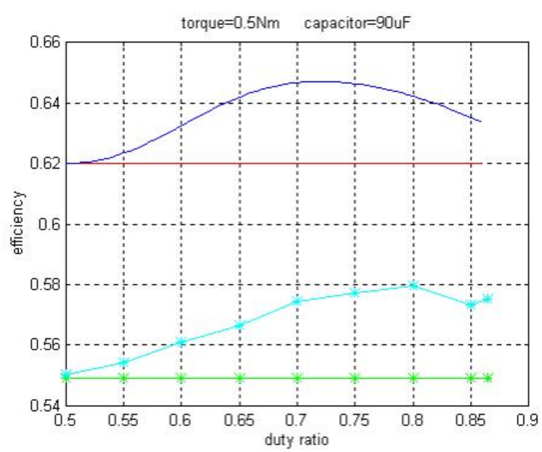
Induction motor with variable rotor impedance (3)

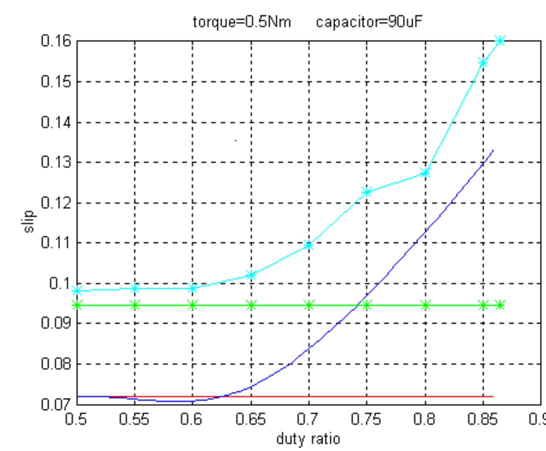










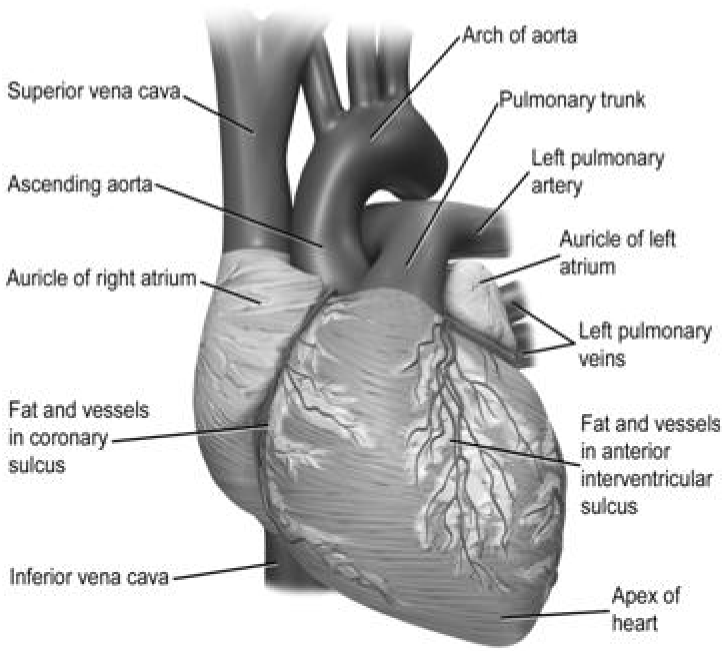


MODELS

Cardiovascular stenosis evaluation

Transilvania
University
of Brasov

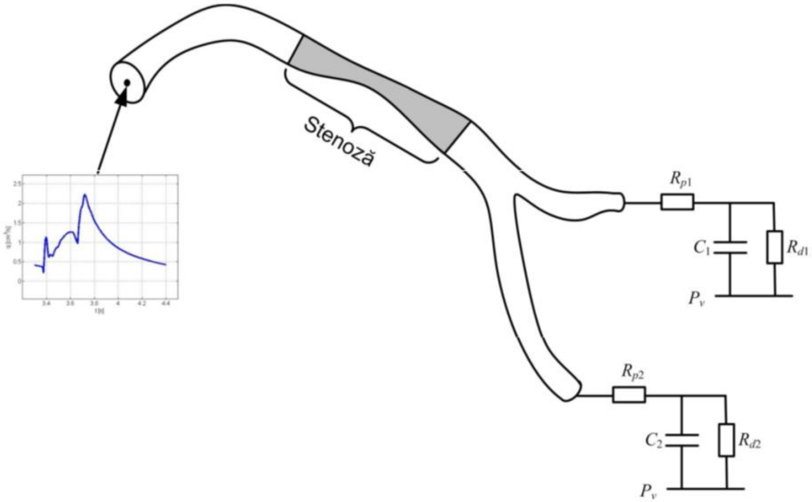
Opportunities of digitalization in medical field



Superficial Heart Anatomy (Anterior)

- Develop, integrate and validate patient-specific multi-scale computational models with high predictive power for coronary circulation in healthy and diseased vessels:
- Efficient multi-scale coupling with the state-of-the-art heart models for advanced patient-specific simulations;
- Assessment of functional parameters and subsequent validation of the models;
- Improve the clinical management of coronary artery disease by leveraging the computational models to create specific therapeutic interventions;
- Simulation based methods for intervention planning (using computational models).

Functional assessment of stenosis



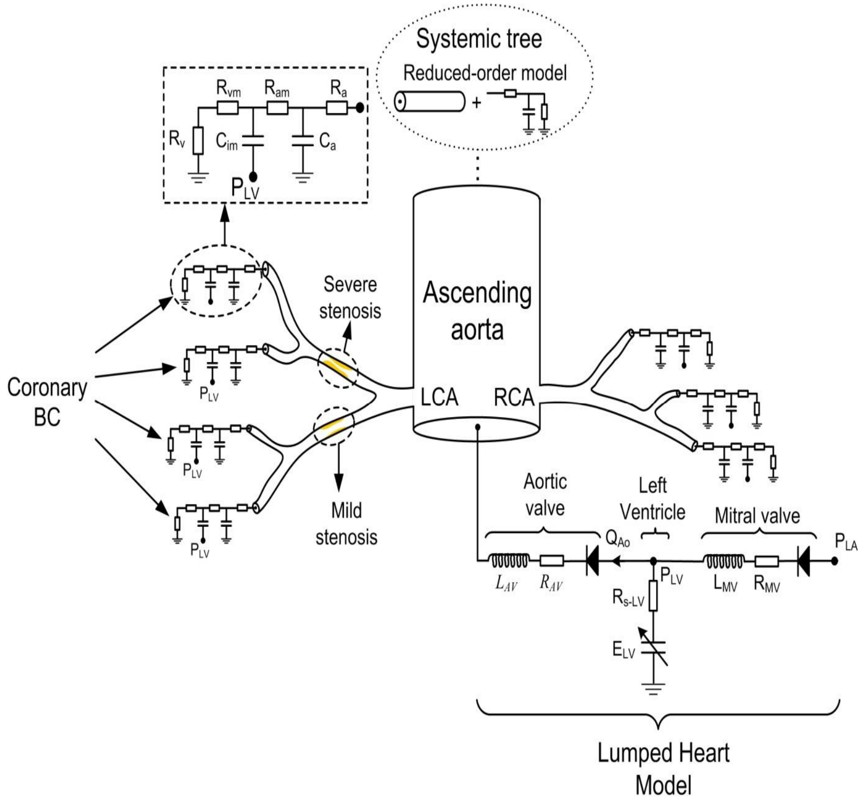
o Accurate estimates of the anatomy (amount of narrowing blockage in the coronary) as seen in the diagnostic images, can vastly underestimate or overestimate the severity of the blockage;

o Functional assessment of such a blockage, implies incorporation of multi-faceted information from the hemodynamics and cellular mechanisms from multiple scales, resulting a complex computational model that demands high computational capabilities;

o Fractional Flow Reserve

$$FFR = \frac{Q_{\max}^{S}}{Q_{\max}^{N}} = \frac{P_d}{P_a}$$

Modeling cardiovascular system



o Heart model - lumped parameter model customized through patient-specific data

o Large (epicardial) vessels - simulated through 1D blood flow models to get pressure and flow rate values used for wave propagation phenomena too;

o Coronary microvascular beds - modeled through lumped or 0D models:

- § Systemic beds - represented by regular windkessel elements;
- § Coronary beds - represented by specialized lumped models which account for the influence of the myocardial contraction on the flow waveform.

1D model and outflow boundary conditions

One-dimensional blood flow model is derived from:

- Simplified three-dimensional Navier-Stokes equations based on a series of simplifying assumptions;
- Having a state equation related to the pressure inside the vessel to the cross-sectional area with vessel wall modeled as a pure elastic material.

$$\frac{\partial A(x,t)}{\partial t}+\frac{\partial q(x,t)}{\partial x}=0$$

$$\frac{\partial q(x,t)}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{q^2(x,t)}{A(x,t)}\right)+\frac{A(x,t)}{\rho}\frac{\partial p(x,t)}{\partial x}=K_R\frac{q(x,t)}{A(x,t)}$$

$$p(x,t)=\Psi_{el}(A)+p_0=\frac{4}{3}\frac{Eh}{r_0}(x)\left(1-\sqrt{\frac{A_0(x)}{A(x,t)}}\right)+p_0$$

1D model and outflow boundary conditions

$$p = q \cdot R$$

$$\frac{\partial p}{\partial t} = R_1 \frac{\partial q}{\partial t} - \frac{p}{R_2 C_T} + \frac{q(R_1 + R_2)}{R_2 C_T}$$

- *Resistance boundary condition* - considers a flow rate proportional to the pressure; difficult to choose the correct value for the peripheral resistance, the pressure and the flow are forced to be in phase;

- *Windkessel boundary condition* - a three-element model, consisting of two resistances and a compliance, total resistance being equal to the value chosen for the resistance boundary condition.

Outflow boundary conditions implementations

$$\begin{cases} p^{n+1} = q^{n+1} \cdot R \\ \dfrac{p^{n+1} - p^n}{\Delta t} = R_1 \dfrac{q^{n+1} - q^n}{\Delta t} - \dfrac{p^{n+1}}{R_2 C_T} + \dfrac{q^{n+1}(R_1 + R_2)}{R_2 C_T} \end{cases}$$

o *Implicit Lax-Wendroff* - both pressure and flow rate are considered at the new time-step, equations are subsequently solved using Newton-Raphson's method for nonlinear equations;

$$\begin{cases} p^{n} = q^{n+1} \cdot R \\ \dfrac{p^{n} - p^{n-1}}{\Delta t} = R_1 \dfrac{q^{n+1} - q^n}{\Delta t} - \dfrac{p^{n}}{R_2 C_T} + \dfrac{q^{n}(R_1 + R_2)}{R_2 C_T} \end{cases}$$

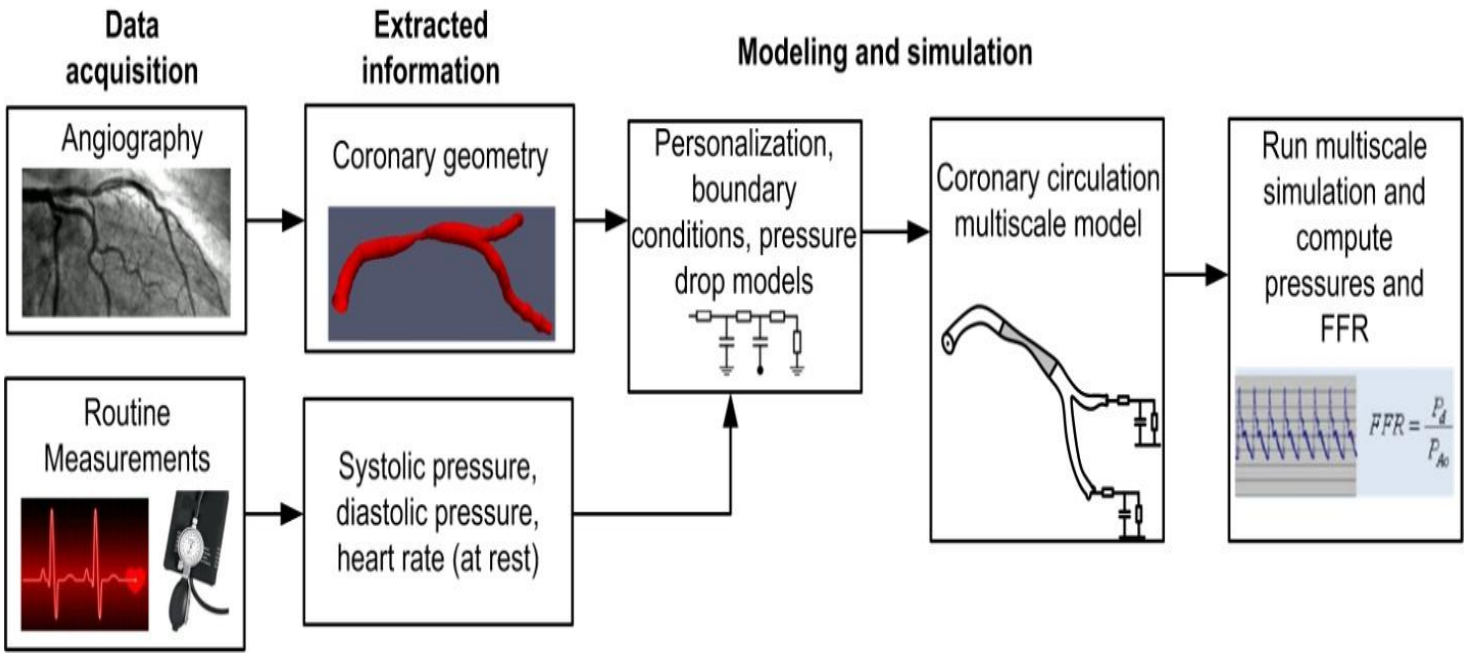
o *Explicit Lax-Wendroff* - only the flow rate is considered at the current time step, the pressure values are taken over from the previous time steps;

$$A_M - A_R + \frac{q_M - q_R}{-q_R / A_R + c_R} = H_R^{+} \Delta t$$

o *Implicit method of characteristics* - Since the pressure is only related to the area, a non-linear equation will be obtained where the area at the outflow point is unknown and it is determined using Newton-Raphson's method.

A -area, *q* -flow rate , *H* - viscous losses ,*M* - current grid point, *R*e point on the characteristic at the previous time step respectively

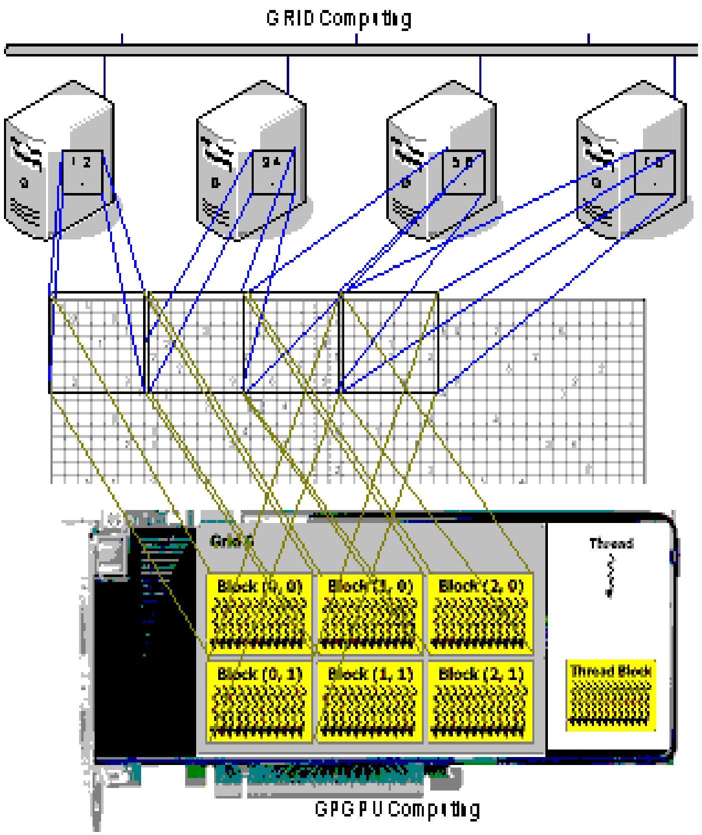
Simulation flow



DATA PROCESSING & SIMULATION

Transilvania
University
of Brasov

Why High Performance Computing - HPC?



Increase in:

o Models complexity (e.g. Biosciences ,weather, fluid dynamics, molecular interactions, astronomical calculations , engineering design, etc.) that incorporate multi-scale information ;

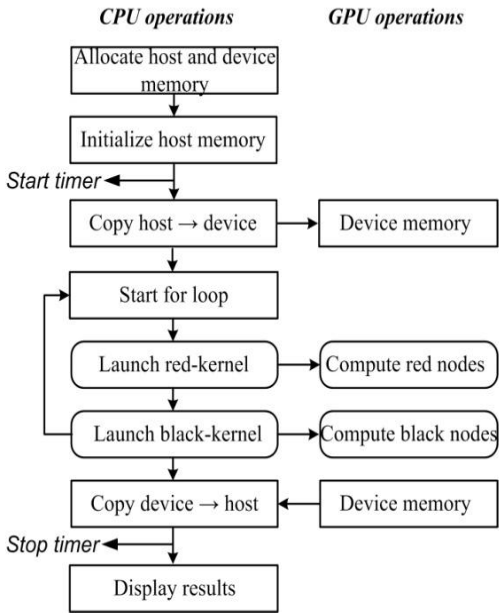
o Data collection (Big Data) from processes (industry, financial, weather, etc.) with the requirement to be analyzed on the fly.

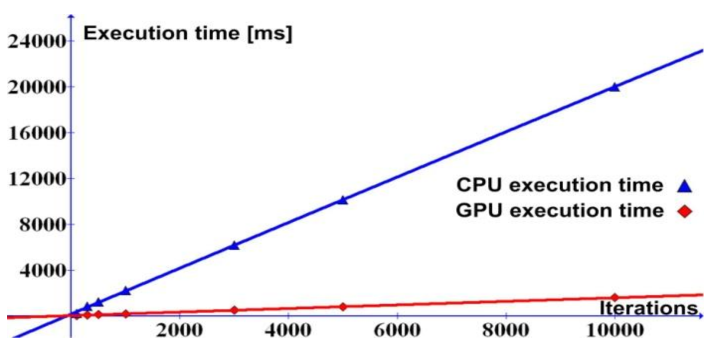
HPC architectures offer:

o The implementation parallel processing algorithms and systems by incorporating both administration and parallel computational techniques;

o Teraflop /Petaflop computational power.

Mathematical apparatus





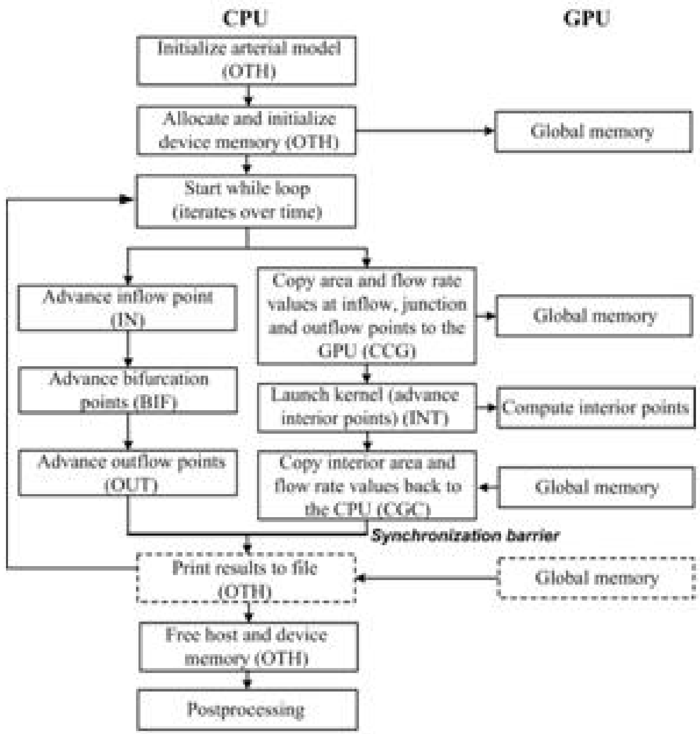
o Elliptic equations are a fundamental building block in fluid dynamics;

o Solution methods for elliptic equations can be divided into :

- direct methods - have the disadvantage that they consume more time and they are susceptible to round-off errors;

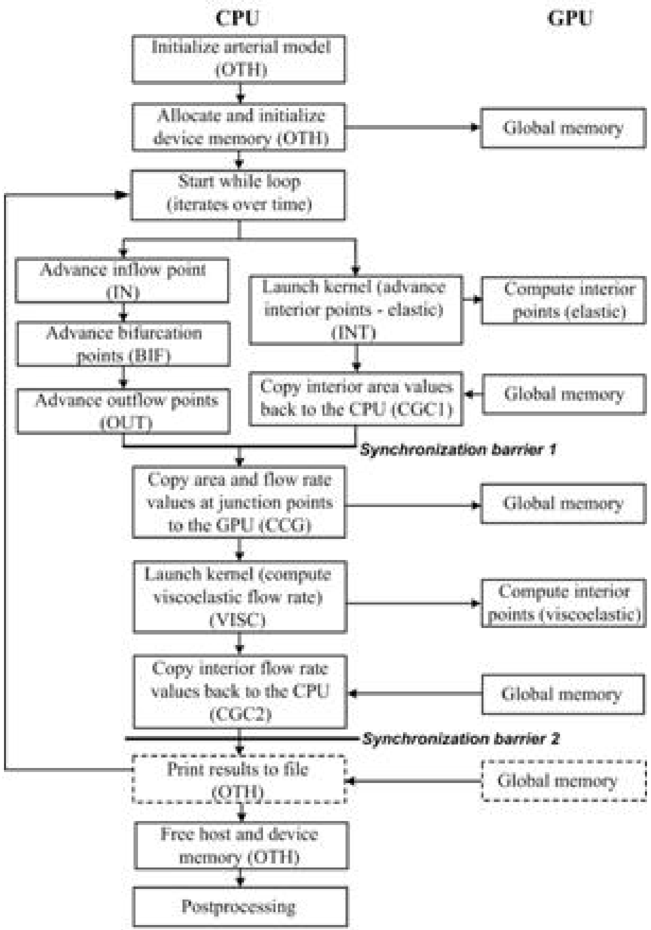
- iterative methods - are faster and round-off errors are corrected in subsequent iterations.

Parallel Hybrid CPU – GPU (PHCG)



- Interior points are computed on the GPU;
- Inflow/bifurcation/outflow points are computed on the CPU;
- Advantage: each device is used for computations for which it is best suited (CPU – sequential, GPU – parallel);
- Drawback: memory copies are required at each time step in order to interchange the values near the junction points.

Parallel GPU Only (PGO)

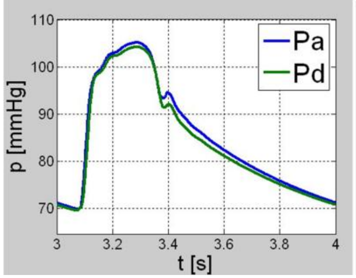


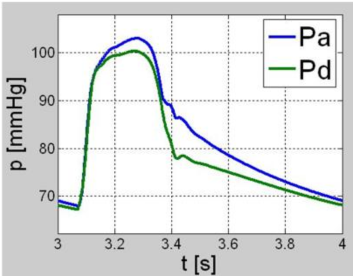
- o All grid points are computed on the GPU;
- o The CPU is only used to initialize and to control the execution on the GPU;
- o Advantage : no memory copies between the CPU and the GPU are required;
- o Drawback : parallelizable operations need to be performed on the GPU.

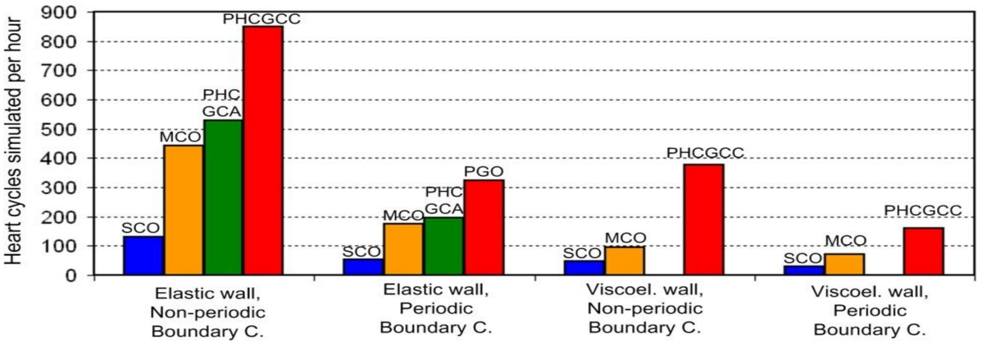
HPC based Simulations

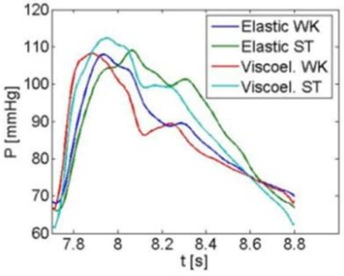
STENOSIS DISTAL AND PROXIMAL AVERAGE PRESSURES [MMHG]

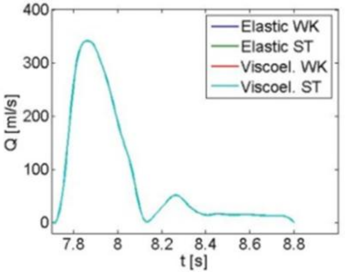
State	Stenoses 1 (48% AR)		Stenoses 2 (67% AR)		Stenoses 2’ (84% AR)	
	Pa	Pd	Pa	Pd	Pa	Pd
At Rest	85.39	84.98	85.16	84.23	85.12	78.13
Hyperemia	83.31	81.37	83.09	78.57	82.93	58.16

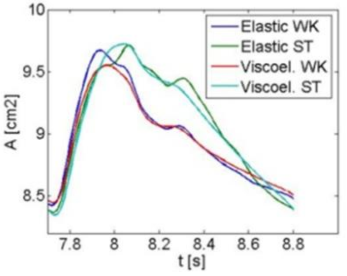








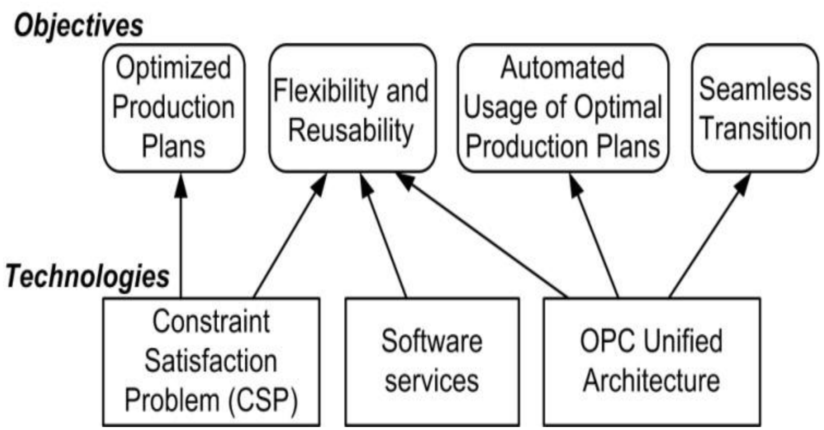




AGILE PRODUCTION PLANNING

Transilvania
University
of Brasov

Optimization of Industrial Applications



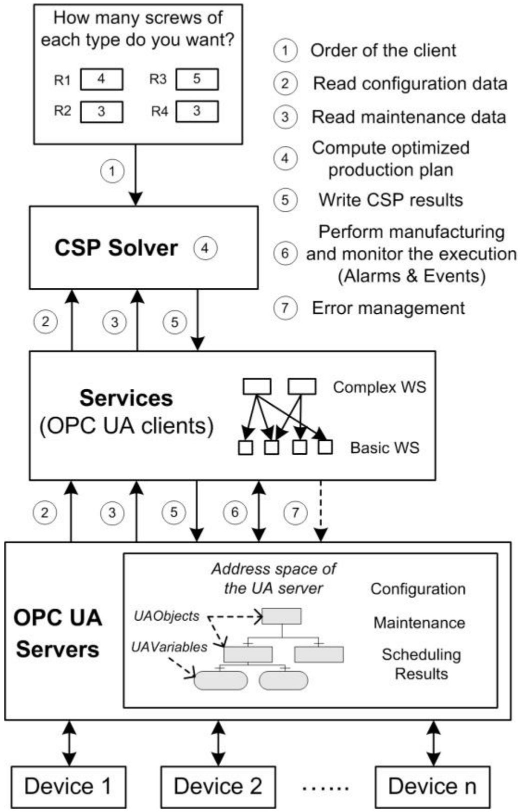
- Optimization of manufacturing processes through the computation of optimal production plans;

- Automated usage of the optimal production plans;

- Flexible and reusable architecture, which shortens the maintenance, installation and setup times and consequently improves the ability to react to changes in the market demand;

- Seamless transition from existent setups.

Levels of Architecture

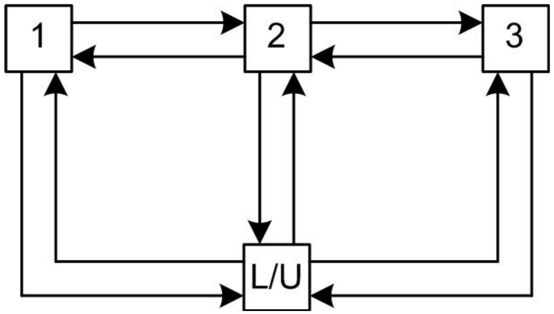


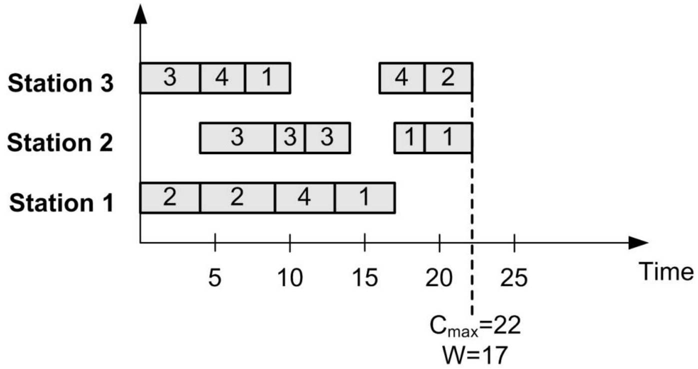
o OPC UA servers - collect data from all devices, sensors and actuators, model them in a standardized and unified way and assure real-time communication with the devices;

o SW service layers - backbone of the architecture in guaranteeing flexibility and adaptability;

o Constraint Satisfaction Problem(CSP) solver – optimizes the production plans and schedules.

Optimization use case





o Mixed integer programming (MIP) models used to optimize the execution plan;

o Two different approaches are considered for the defined use case:

- an integrated approach (a large monolithic MIP model is used to simultaneously take the loading and scheduling decisions) – implies longer execution periods;

- an hierarchical approach (two different MIP models are solved sequentially, the first one for the balancing of the workloads and the second one for the detailed scheduling of the tasks by using the results of the first model) – near optimum solutions in a shorter time than the previous model.

OUTCOMES & NEXT STEPS

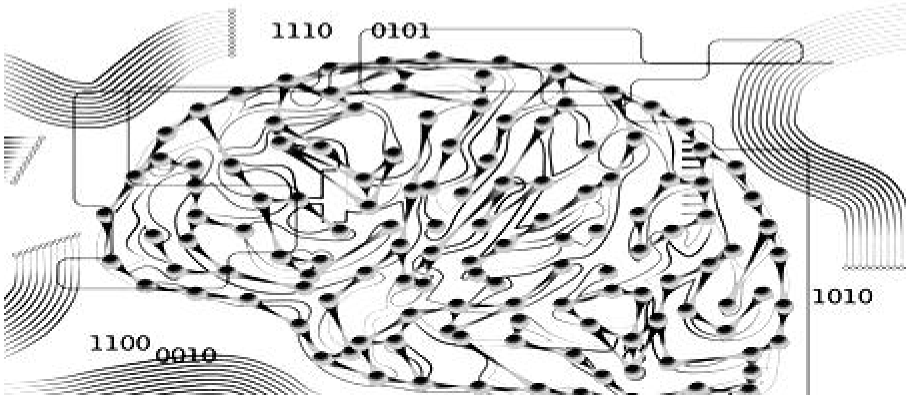
Transilvania
University
of Brasov

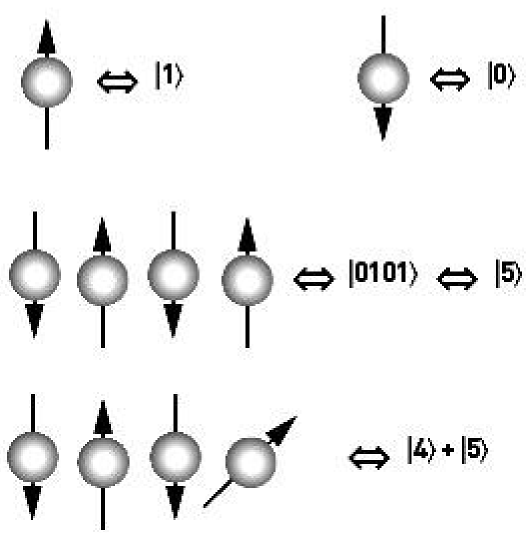
Scientific outcome

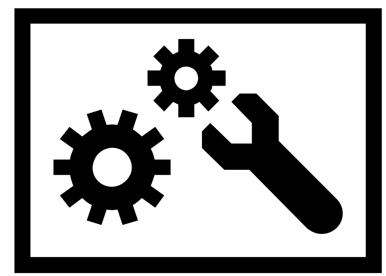
Contributions to ...

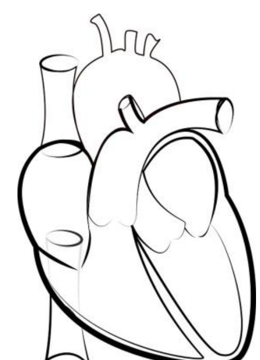
- o 9 ISI journal publications;
- o 28 ISI conference papers;
- o 20 BDI articles;
- o 7 international and 4 national funded projects.

What is next?









THANK YOU FOR ATTENTION

Transilvania
University
of Brasov