Introduction to Digital Twins, Models and Parameter Estimation

Goal of the presentation

Introduce

1. the concept of digital twins
2. models that develop digital twins
3. and, parameter estimation models

In order to

1. mobilize the existing knowledge for further design of digital twins of residential buildings
2. easily identify and apply the models appropriately for future research

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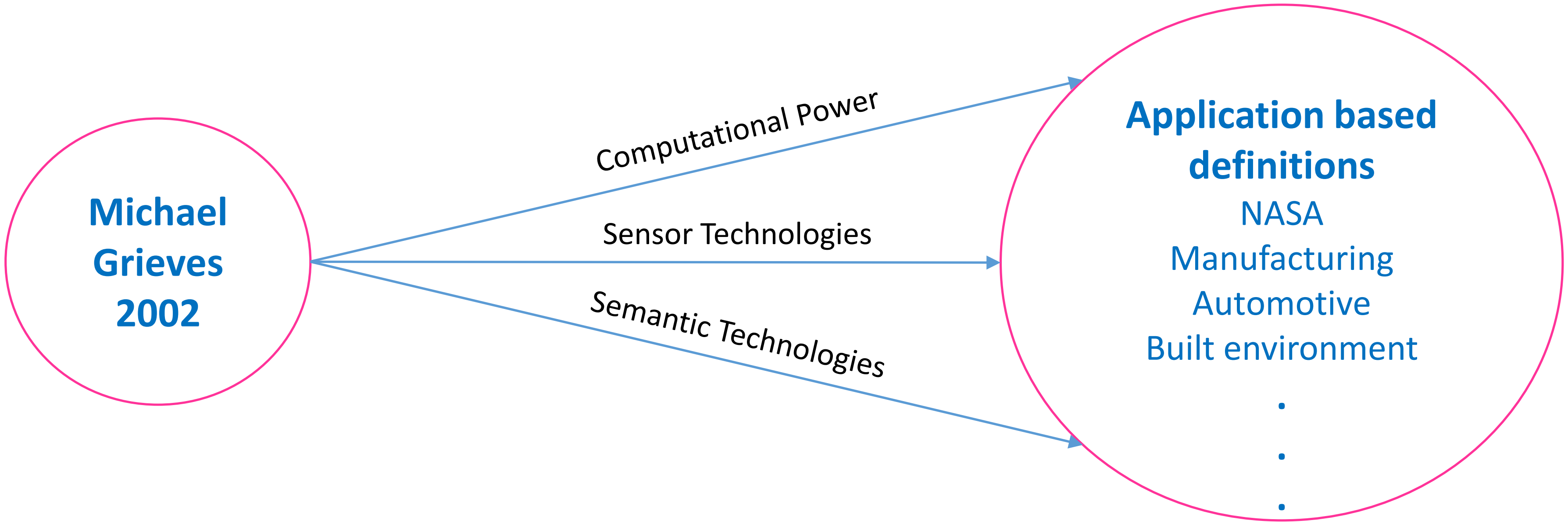
Andrea Iris Joseph Thaddeus

Digital Twins Defined



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Digital Twins of a Residential Building

What is a digital twin of a dwelling?

"A digital twin is a virtual representation of a dwelling that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making."

Real- time data

Models

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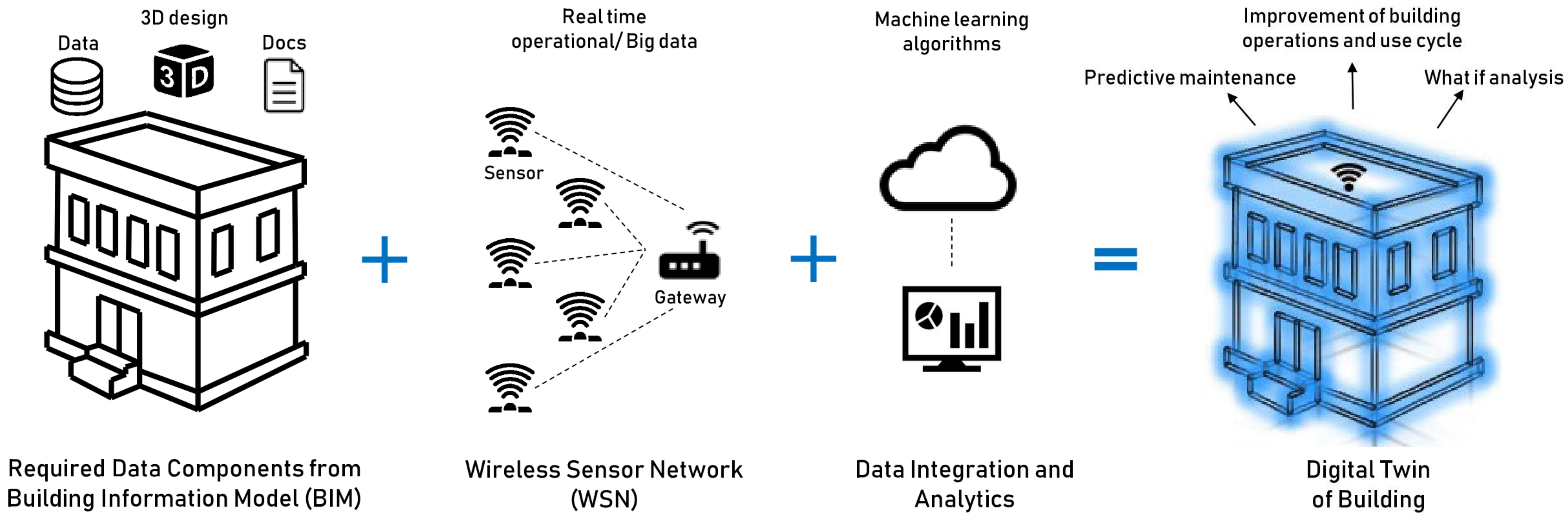
Digital Twins- a vision



Source: Khajavi, Motlagh, Jaribion, Werner, & Holmström, 2019

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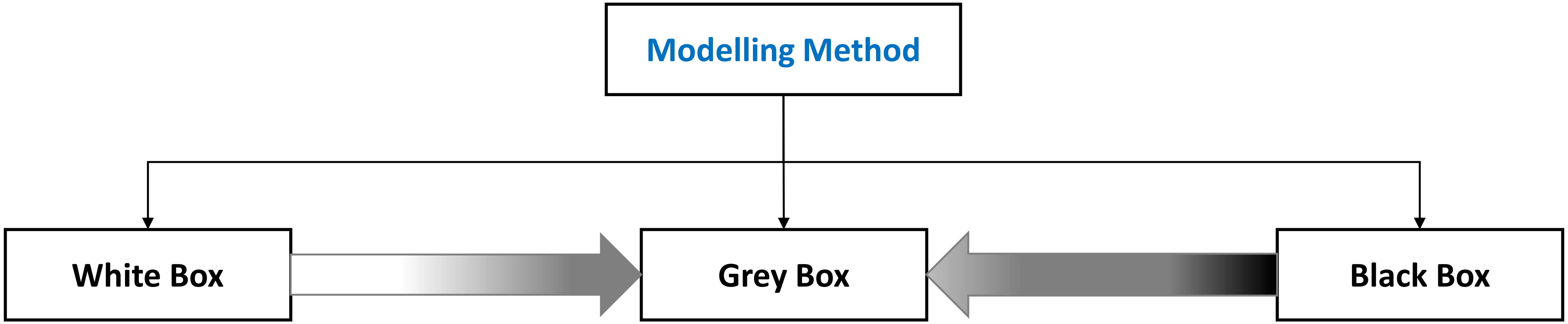
Models Classified Based on Modelling Methods



Models a Basic Understanding

$$y = ax_1 + bx_2 + cx_3 + d$$

y is the dependent variable (the output)

x_1, x_2 and x_3 are the independent variable (the inputs)

a, b, c and d are the parameters (in some cases, also called inputs)

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Models a Basic Understanding

$$y = ax_1 + bx_2 + cx_3 + d$$

$$Q_{heating} = \rho CV \frac{dT}{dt} + (\rho CV + \sum UA)\, T - (\rho CV + \sum UA)\, T_{outdoor} - Q_{sol} - Q_{int}$$

$Q_{heating}$ is the dependent variable (the output)

T $T_{outdoor}$ Q_{int} Q_{sol} are the independent variable (the inputs)

ρCV and $(\rho CV + \sum UA)$ are the parameters (in some cases, also called inputs)

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Modelling methods White Box Models Concept

$$Q_{heating} = \rho CV \frac{dT}{dt} + (\rho CV + \sum UA)\, T - (\rho CV + \sum UA)\, T_{outdoor} - Q_{sol} - Q_{int}$$

Model Structure	Heat balance equation	✓
Output	$Q_{heating}$	✗
Input	T $T_{outdoor}$ Q_{int} Q_{sol}	✓
Parameter	ρCV and $(\rho CV + \sum UA)$	✓

1. Simulation tools like DOE-2, BLAST, EnergyPlus, TRNSYS based on state space equations
2. Lumped parameter modelling- RC Models

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Modelling methods White Box Models

Advantages

1. Accuracy when inputs and parameters are well determined

Disadvantages

1. Almost impossible in real life to determine accurately enough all needed input.

Modelling methods Black Box Models Concept

$$Q_{heating} = \rho CV \frac{dT}{dt} + (\rho CV + \sum UA)\, T - (\rho CV + \sum UA)\, T_{outdoor} - Q_{sol} - Q_{int}$$

Data → Algorithm (correlation) → Model Set Up

Eg: Studying weather and indoor climate data to see which variables influence the occupant behaviour with the ventilation system the most

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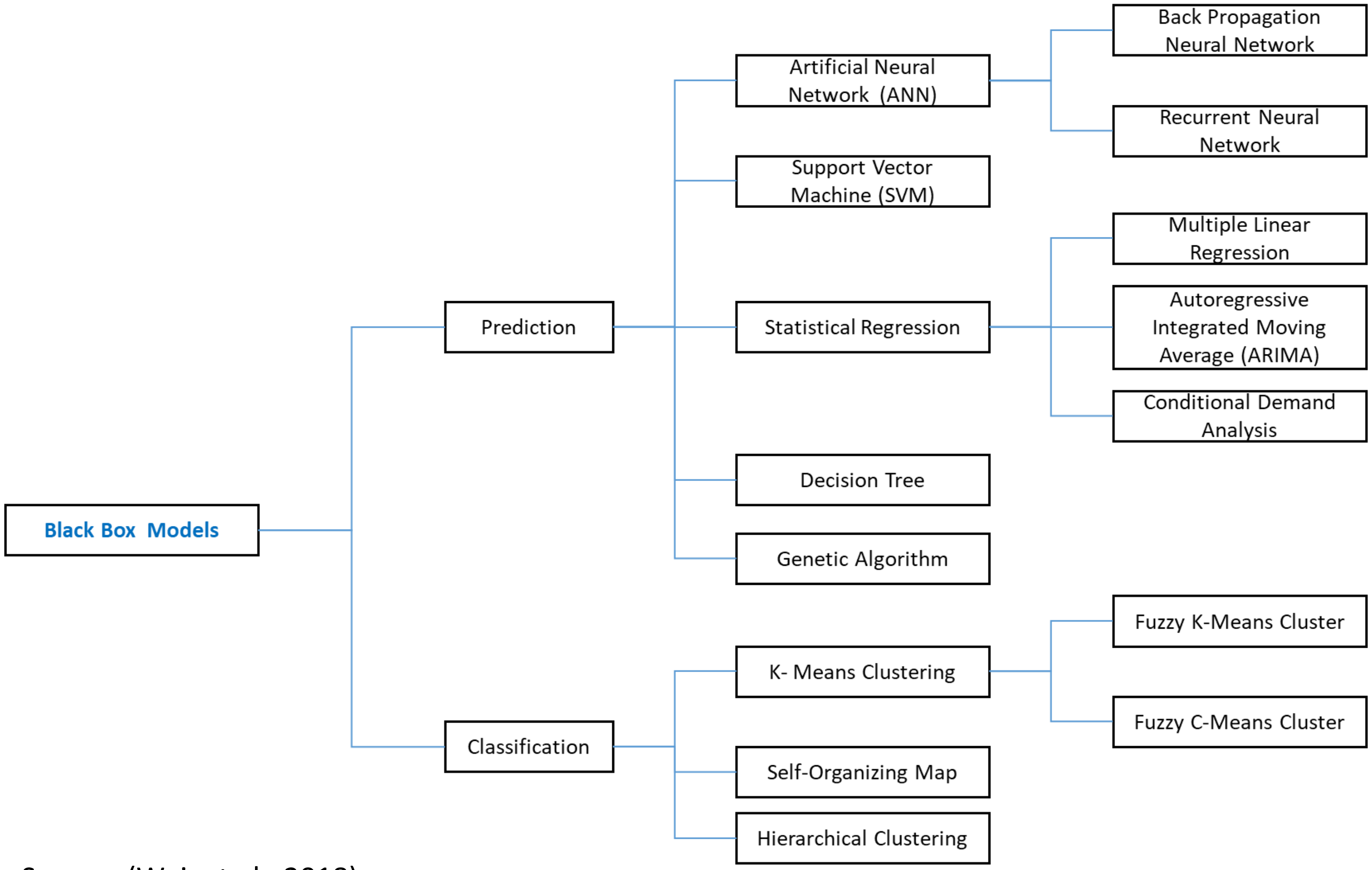
Modelling methods Black Box Models



Source: (Wei, et al., 2018)

Identify black box model

~~Not based on that statistical method~~ but based on whether are not there is underlying building model logic

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Modelling methods Black Box Models

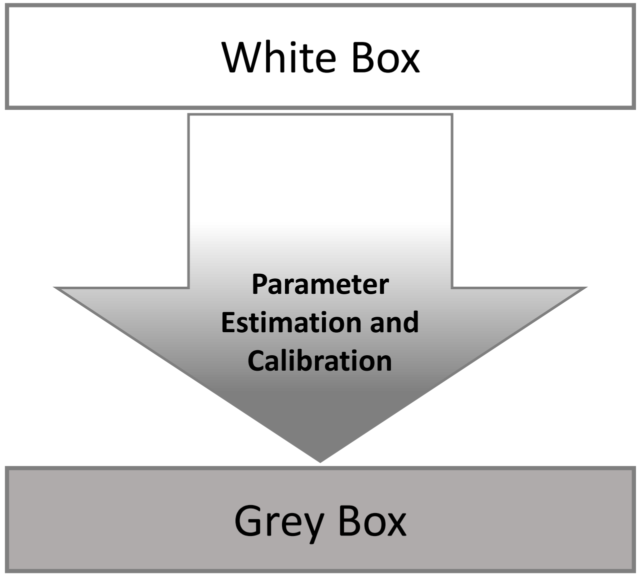
Advantages

1. Purely based on data and do not require a model.
2. Predicting energy use patterns based on occupant behavior.

Disadvantages

1. They offer little possibility to steer and control the systems they are describing and to propose improvements to the system

Modelling methods Grey Box Models



$$Q_{heating} = \rho CV \frac{dT}{dt} + (\rho CV + \sum UA)\,T - (\rho CV + \sum UA)\,T_{outdoor} - Q_{sol} - Q_{int}$$

Model Structure	Heat balance equation	✓
Output	$Q_{heating}$	✓
Input	T $T_{outdoor}$ Q_{int} Q_{sol}	✓
Parameter	ρCV and $(\rho CV + \sum UA)$	✗

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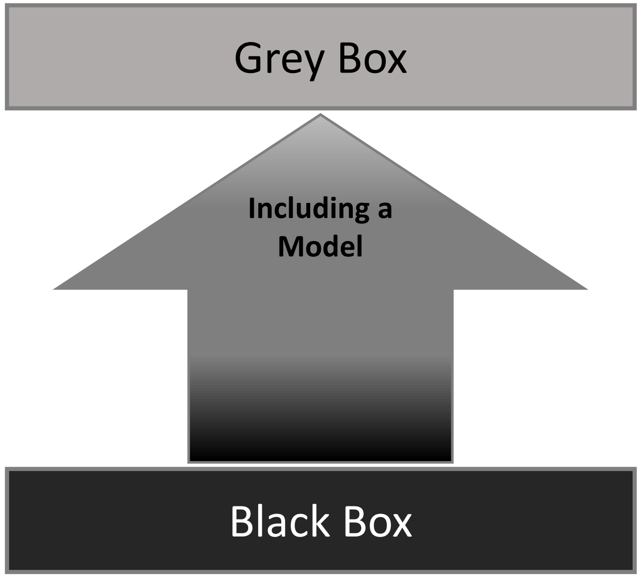
Modelling methods Grey Box Models



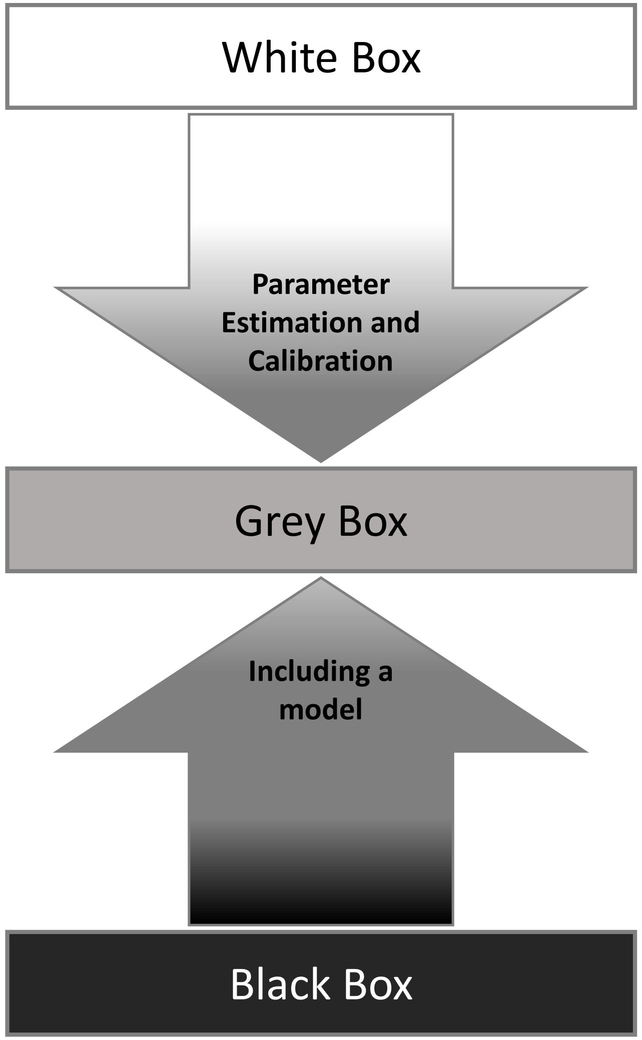
When **data-driven models** (black box models) are (partly) supported by **explicit models** (equations) with a physical meaning

Example

$$\text{simple linear regression}: \quad y = ax + e$$

$$Q = HLC(T_i - T_o) + e$$

Modelling methods Grey Box Models



Advantages

Used for parameter estimation which are otherwise time consuming, intrusive and expensive

Disadvantages

The selection of suitable model structure is still difficult. Lower order models do not reflect the true building and higher order models may be undetermined and lead to multiple solutions.

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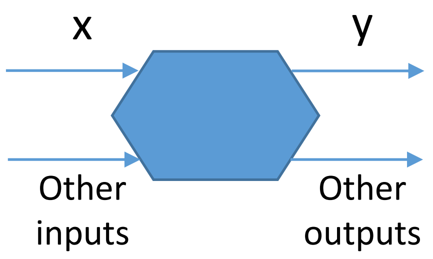
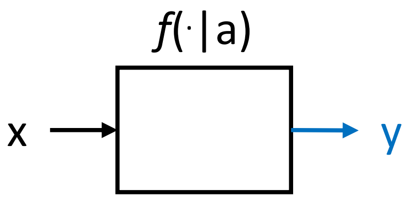
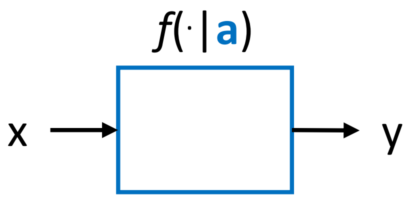
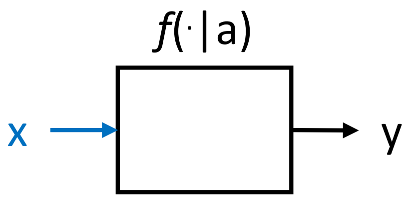
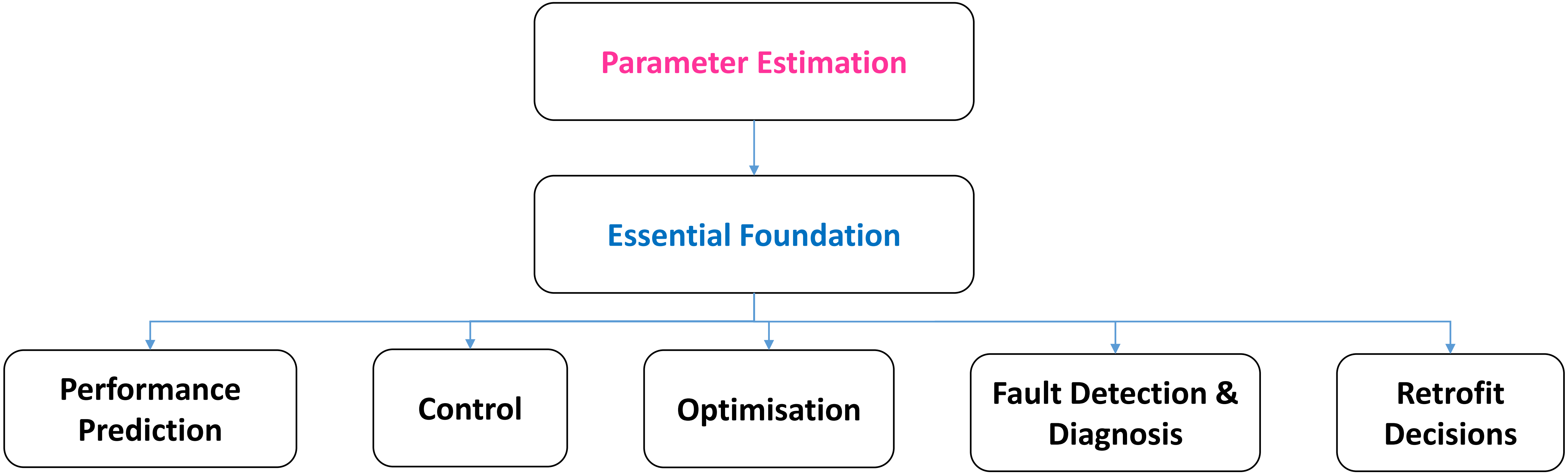
Modelling Approach Forward and Inverse Models

Physical System	Forward	Inverse		
				
	Simulation	**Identification**		**Control**
	White Box	Black Box	Grey Box	
***f*(·|·)** Model structure	Physics	Heuristic	Physics	Feed-back
a Parameters of the model	Known	Output	Output	Known
x Measured inputs of the physical system	Input	Input	Input	Output
y Measured outputs of the physical system	Output	Input	Input	Input

Source: Ghiaus, 2014

Parameter estimation Models Applications



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Parameter estimation Models List of Parameters

Some Parameters That Can Be Estimated

- Infiltration rate,
- Ventilation flow rate,
- Types of glazing,
- Glazing area,
- The resistance of the building envelope to conduct heat between its two surfaces
- The capacitance of the building envelope to store heat

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Parameter estimation Models Grey Box Approach

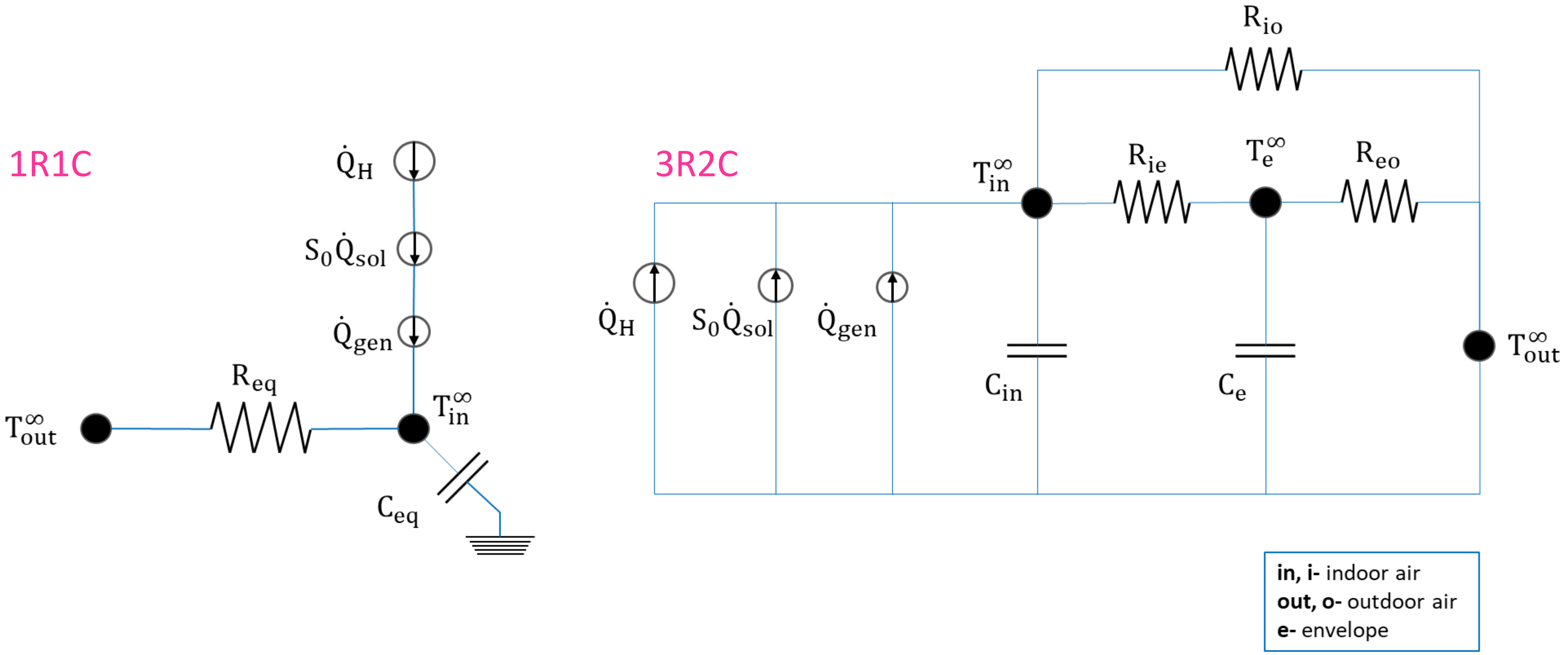
Step 1: Obtain the measured inputs and the outputs of the building

Input Data	Output data	Time Interval	Kind of data
1. Outdoor air temperature 2. Constant Ground temperature **3. Global Irradiance** 4. Internal gains 5. Heat loss due to infiltration 6. Fixed ventilation flow rates 7. Heat gains which included space heating, solar , electrical and metabolism **8. Space heating gas consumption**	Indoor air temperature	5 minutes 10 minutes 30 minutes Hourly	Measured Simulated

"What kind of data is required for parameter estimation?" **Should all inputs and outputs of the heat balance equation be measured or, is it possible to make nearly the same estimates based on logical assumptions?**

Parameter Estimation Models Grey Box Approach

Step 2: Chose a thermal network model



"How to choose an appropriate thermal network configuration based on the available data and without compromising the accuracy of the estimated parameters?"

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Parameter Estimation Models Grey Box Approach

Step 4: Determine the parameters which satisfy the whole set of equations by launching an optimization problem

Define an objective function for the optimisation problem

1. Minimising Root Mean Square Error (RMSE)
2. Maximum likelihood estimation of parameters
3. Minimising the sum of the squares of the residuals

Etc…

Solve the optimization problem with an algorithm that estimates the parameters

1. Gauss Newton
2. Genetic Algorithm
3. Bayesian Approach
4. Generalised Reduced Gradient algorithm

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Parameter Estimation Models Grey Box Approach

Step 4: Determine the parameters which satisfy the whole set of equations by launching an optimization problem

"Can detailed measurements help in improving parameter estimation models and obtain more detailed parameters?" (and can this additional information be kept to a minimum?)

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Conclusion

Can data from the existing sensors and smart meters be sufficient?

Can models feeding a digital twin be improved by including more detailed data?

If so, what kind of data is required in addition to the existing sensor and smart meter data?

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