Examining Model Qualities and Their Impact on Digital Twins

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Motivation

Model Qualities

Impact on DT Services

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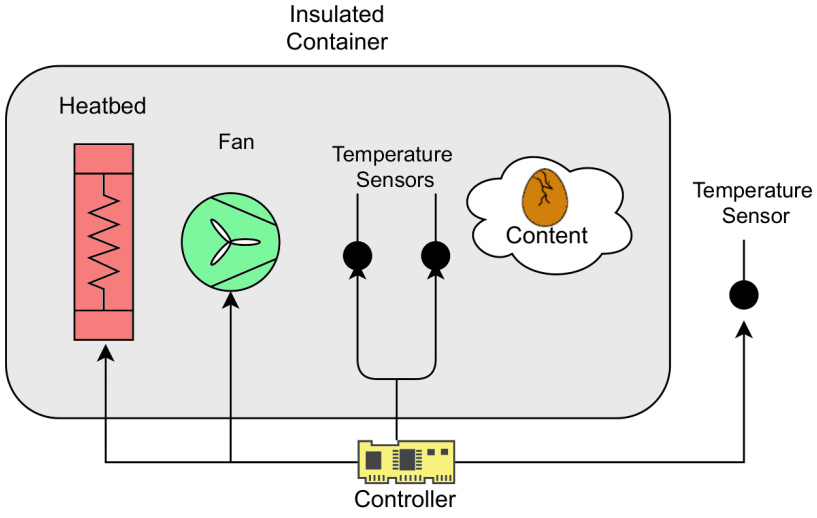
Incubator Running Example

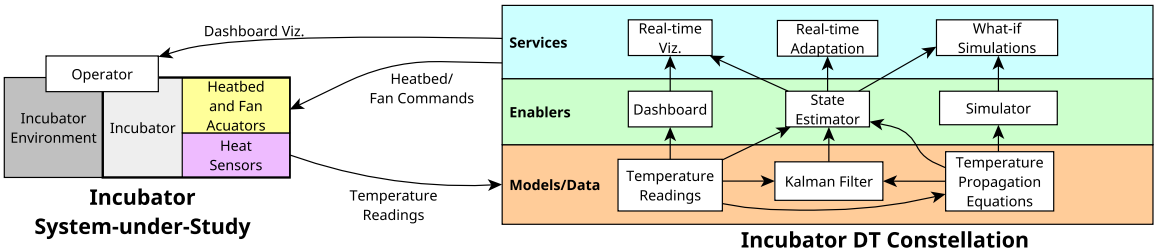
Purpose:
Stable temperature
Egg incubation



Feng *et al.* (2021). *The incubator case study for digital twin engineering*. arXiv preprint arXiv:2102.10390.

Incubator Digital Twin

DTs are a *virtual replica* of a physical system
Offer *services*, to provide *information* or *control*
in *closed-loop* with system



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Challenges and Contributions

Challenges:

- DT services relies on models to capture system behaviour
- DT and physical system evolve over time (*degrade*, *upgrade*)

Objective: Define concepts to *discuss quality of DT services*
Go further than “high-fidelity”

Contributions:

- Formally define four *model qualities*
- Discuss impact on DT services
  - Quality degradation makes services *unreliable*

Motivation

Model Qualities

Impact on DT Services

Term	Example	Details
System	Incubator	Box, object, heating element, controller
Environment	Room around incubator	Temperature, table, . . .
Context	Room $\rightarrow$ incubator influence	Ambient room temp. affects heating rate

Properties

1. Warm up from 20 to 30°C in 10 seconds
2. Remain $<$ 80°C at all times

Created for *purpose*, for certain *properties*

Example: Differential equations for *modelling heat propagation*

$$\dot{T}_{heater} = \frac{1}{C_{heater}} \cdot \left(V \cdot I \cdot \Delta t - G_{heater} \cdot (T_{heater} - T_{boxair})\right)$$

$$\dot{T}_{boxair} = \frac{1}{C_{air}} \left(G_{heater} \cdot (T_{heater} - T_{boxair}) - G_{box} \cdot (T_{boxair} - T_{room})\right)$$

Model created by setting parameters

Property Satisfaction

Satisfaction
In particular context, does system satisfy property?
$[\![S]\!]_{C_S} \vDash p$
"In cold room, does incubator reach $80°C$*?"*

Model Satisfaction
In model's context, does model satisfy property?
$[\![M]\!]_{C_M} \vDash p$
"When simulated, do equations reach $80°C$*?"*

Model Qualities:


Relevancy: Does model's context match the system's context?


Verifiability: Can we check property satisfaction on model?


Substitutability: Does satisfaction result match the system result?


Fidelity: How closely do the results match?

Model Quality Consequences

Consider safety property *"does the incubator reach* $80°C$*?"*

Non-relevant model **could** produce **incorrect answer**

Non-verifiable model **can't answer** this question

Non-substitutable model provides **wrong answer**

Non-faithful model provides **erroneous answer**

Model without these qualities is **invalid**

Later: DT services using **invalid** models are **invalid**/**useless**

Relevancy

Model created for particular context

Relevant *only within that context*

Outside context, property satisfaction *may* be unreliable

Example: Temperature propagation equations

Relevant In	**Not Relevant In**
Summer	Winter (below freezing)
Normal room	Mountain-top (low-pressure), space (no air)

$$relevant(M, S) \stackrel{def}{=} \forall i_S \in C_S|_{C_M}, \exists i_M \in C_M \text{ such that } i_M \supseteq i_S$$

Capture relevancy with *validity frames* - Denil *et al.*

Can we **verify** whether a model satisfies a property?

$$\mathit{verifiable}(M) \stackrel{def}{=} \forall p_i \in P_M, [\![M]\!]_{C_M} \stackrel{?}{\models} p_i$$

Example:
Can temperature equations model **provide answer for** "is temperature always $< 80°$C"?

Depends on *model formalism*, *checking methods*, computational resources

- Simulating differential equations can provide an answer
- Formal model-checking may require *more-appropriate* formalism

Can the model **substitute for** the system for property satisfaction?

$$substitutability(S, M) \stackrel{def}{=} \forall p \in P_M, \; (\llbracket M \rrbracket_{C_M} \vDash p) \Leftrightarrow (\llbracket S \rrbracket_{C_S} \vDash p)$$

Example:
If temperature model reports that the temperature is always $< 80°C$,
is this true for the system?

How **faithful** is the model to the system?

Example:
How closely do temperature equations match the system's actual temperature?

$$g_{p_i}(\llbracket M \rrbracket_{C_M}, \llbracket S \rrbracket_{C_S}) < \epsilon_i \implies (\llbracket M \rrbracket_{C_M} \vDash p_i) \Leftrightarrow (\llbracket S \rrbracket_{C_S} \vDash p_i)$$

Note: Distance function g **per property**, and error ϵ **per property**

Measure fidelity: Muñoz *et al.*, Biglari and Denil

Model Quality Recap

Relevancy: Does model's context match the system's context?

Verifiability: Can we check property satisfaction on model?

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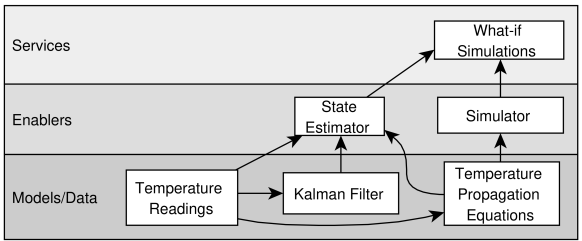
DT Services



Incubator DT Slice

- Data flows “up” through the DT
- Services rely on enablers
- Enablers rely on models
- *Assumption:* Computation is in the enablers, services just report

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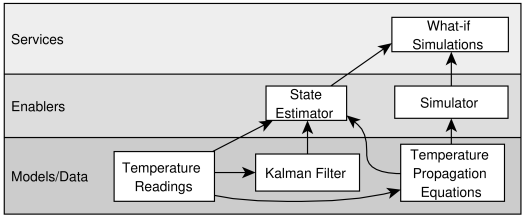
Quality Consequences for DT Services

Property: Is incubator always $< 80°C$?



Incubator DT Slice

Relevancy: Relevant service $\leftarrow$ all models relevant

Verifiability: Property must be verifiable for ≥ 1 model

Substitutability: Property must be satisfied by ≥ 1 model

Fidelity: Faithful service $\leftarrow$ all models faithful

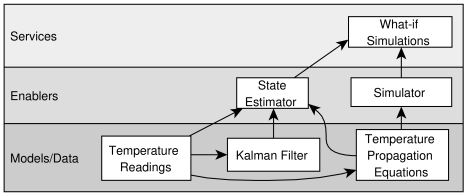
Quality Priority

If the DT or system evolves, order for checking qualities?
Limited time for *safety property*: "temperature $< 80°$C"

1.	**Verifiability**	Model appropriate for property?
2.	**Substitutability**	Satisfaction result? Approximation first?
3.	**Relevancy**	Non-relevant models could be useful
4.	**Fidelity**	Low fidelity results could be useful

Adaptations: Model *switching* or *re-calibration*

Conclusion



Incubator DT Slice

Relevancy: Does DT service's context match the system's context?

Verifiability: Can we check property satisfaction on service?

Substitutability: Does satisfaction result match the system result?

Fidelity: How closely do the results match?

Future work: Integrate into DT framework(s), deepen formalization

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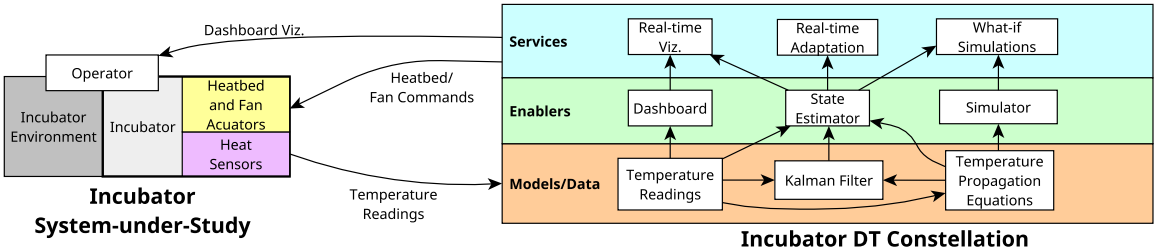

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