7th International Conference on Smart Energy Systems
21-22 September 2021
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# Exergy-based performance degradation diagnosis for use in digital twins of thermal systems

**Volodymyr Voloshchuk[a], Oleksandr Pypena[b], Oleksandr Stepanets[c], Anastasiya Zakharchenko[d], Olena Nekrashevych[e]**

[a, c, d, e] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Prosp.Peremohy, 37, Kyiv, Ukraine, 03056
e-mail: vl.volodya@gmail.com

[b] National University of Food Technologies, Volodymyrska str., 68, Kyiv, Ukraine, 01601, pupena_san@ukr.net

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## Agenda

- Introduction
- Scope of the work
- Methodology
- Case study
- Conclusions

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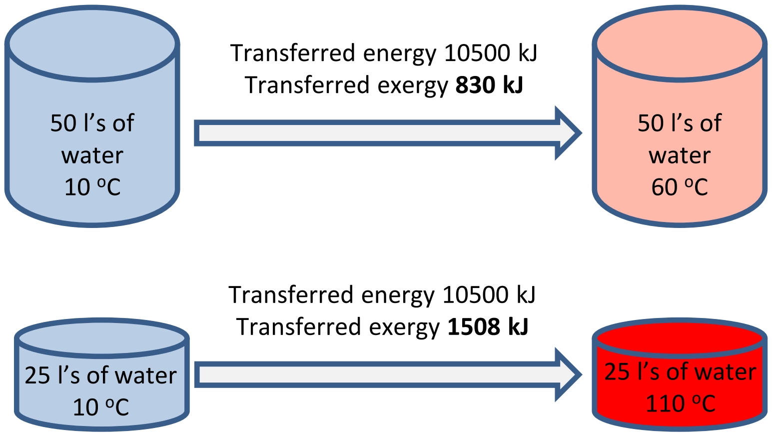
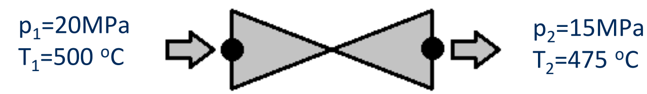
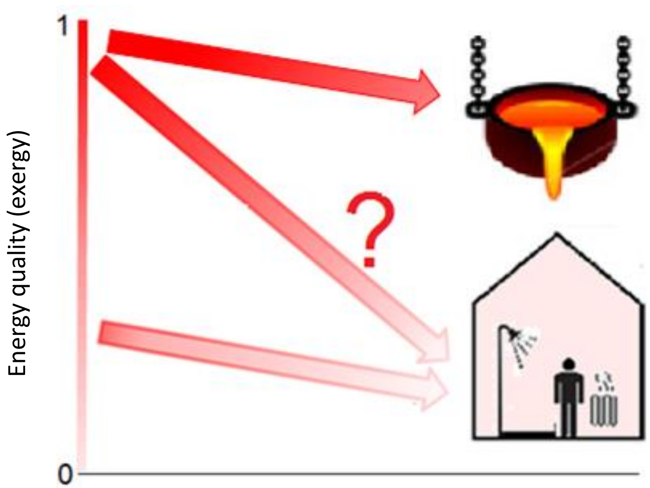


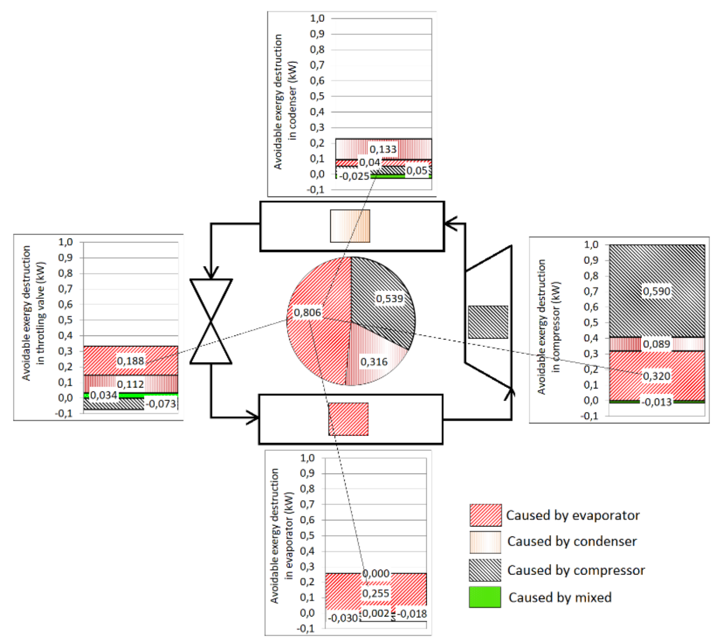

Energy balance:
$h_1=h_2$
3241kJ/kg= 3241kJ/kg

Exergy balance:
$e_D=e_1-e_2$
343kJ/kg= 1443kJ/kg-14100kJ/kg

In the throttling process energy is conserved , but exergy is destroyed.




Energy supply with sources at different quality levels for the space heating and metallurgical processes

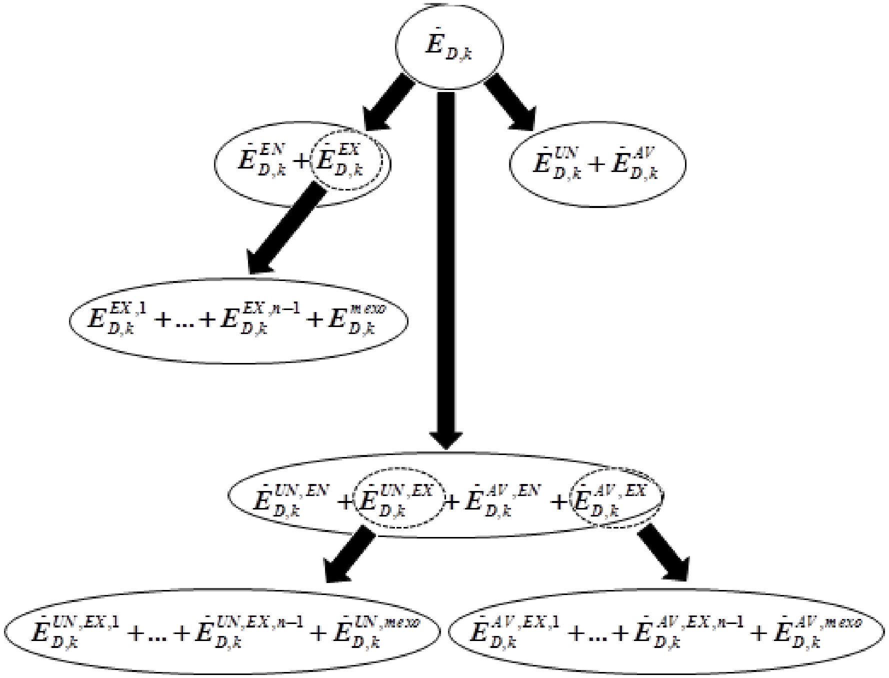



Results of applying of exergy analysis for the heat pump – the evaporator is the main cause of decreasing energy efficiency

## Exergy-based methods for diagnosis:

1. Exergy Cost Theory, thermoeconomic diagnosis (A. Valero and co-workers, University of Zaragoza, Spain).

2. Advanced exergetic analysis (G. Tsatsaronis, T. Morosuk and co-workers, Technische Universität Berlin, Germany, China)



Splitting exergy destruction within the component according to the methodology of the advanced exergetic analysis

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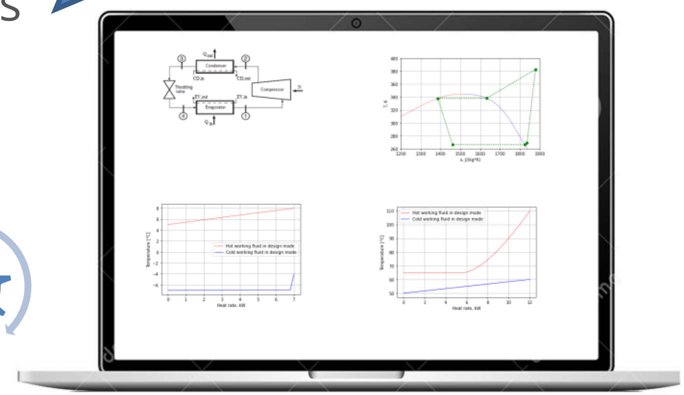
**Physical system**

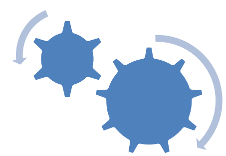
Creating data

Collecting data

Data analysis

**Virtual system**

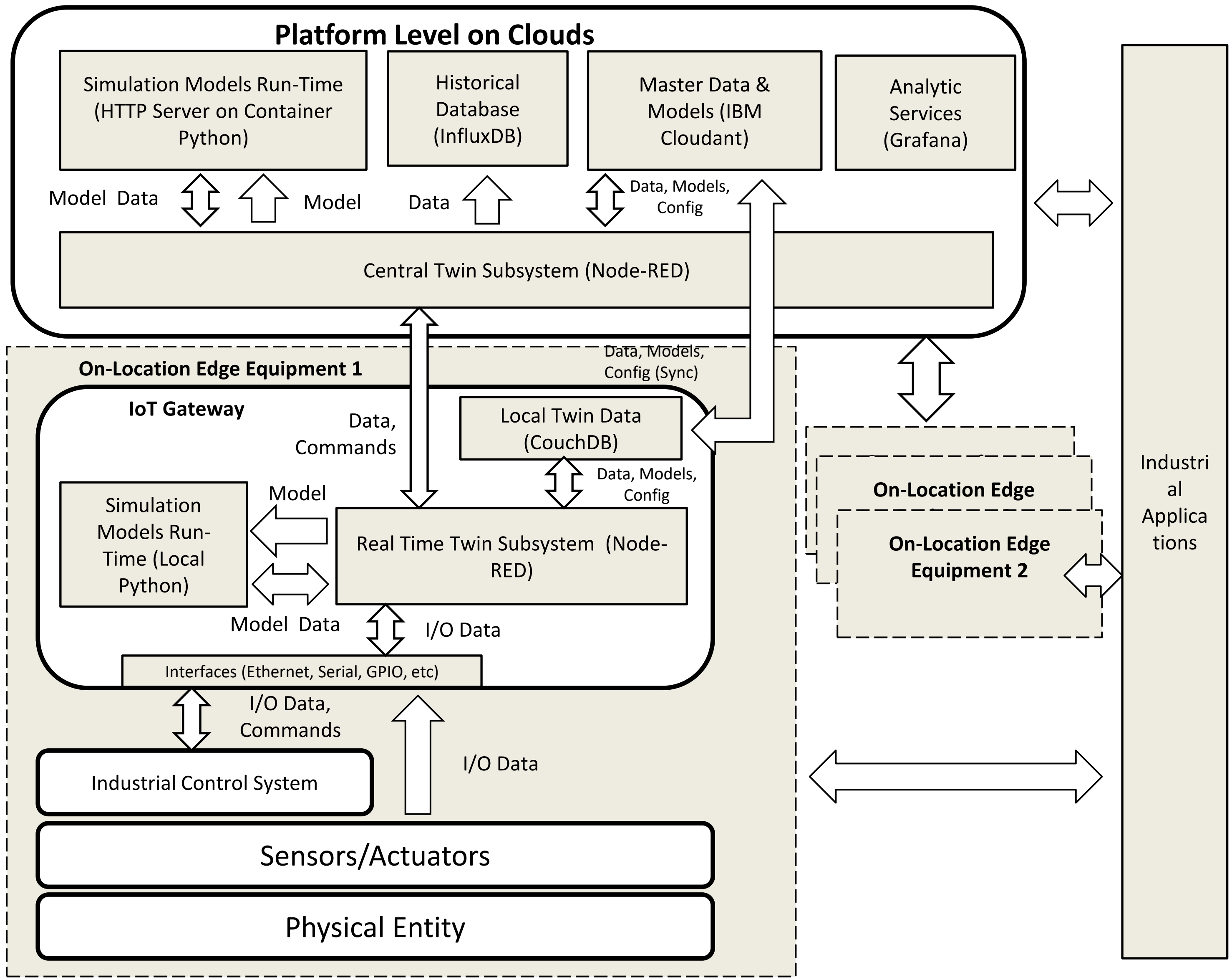


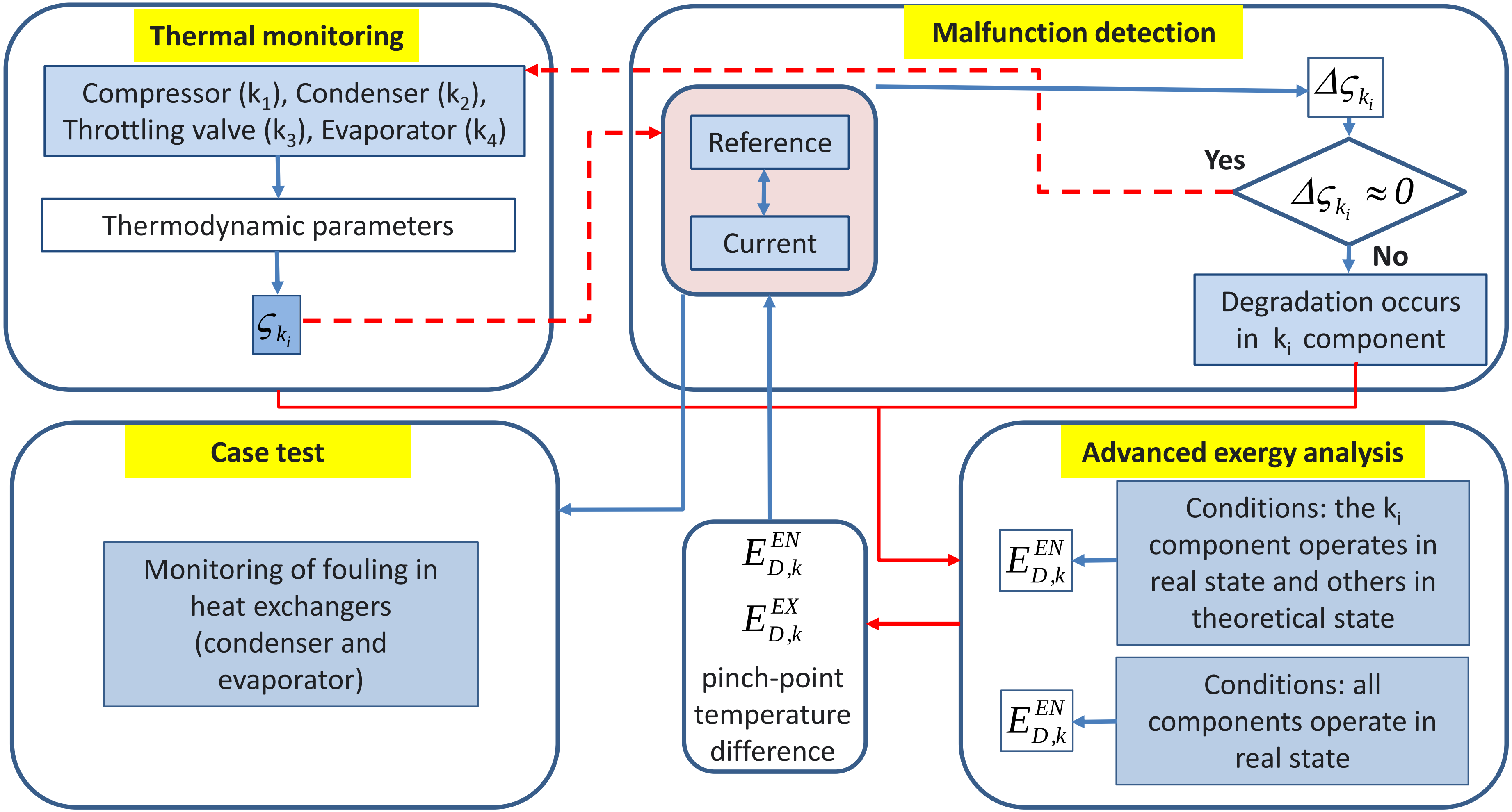


Fault detection and diagnosis

Early stage warning and predictive maintenance

Digital Twin Concept for diagnosis

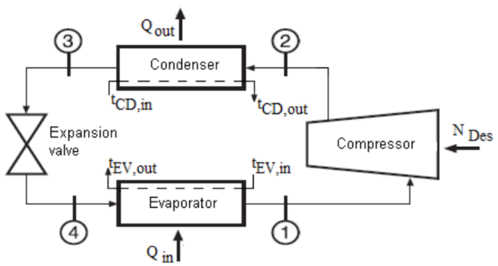

Platform Level on Clouds
Simulation Models Run-Time (HTTP Server on Container Python)
Historical Database (InfluxDB)
Master Data & Models (IBM Cloudant)
Analytic Services (Grafana)
Model Data
Model
Data
Data, Models, Config
Central Twin Subsystem (Node-RED)
On-Location Edge Equipment 1
Data, Models, Config (Sync)
IoT Gateway
Data, Commands
Local Twin Data (CouchDB)
Data, Models, Config
Simulation Models Run-Time (Local Python)
Model
Real Time Twin Subsystem (Node-RED)
Model Data
I/O Data
Interfaces (Ethernet, Serial, GPIO, etc)
I/O Data, Commands
Industrial Control System
I/O Data
Sensors/Actuators
Physical Entity
On-Location Edge
On-Location Edge Equipment 2
Industrial Applications




Procedure for malfunction detection, identification and quantification (modified from [Wang L., Fu P., Wang L., et al. ]).

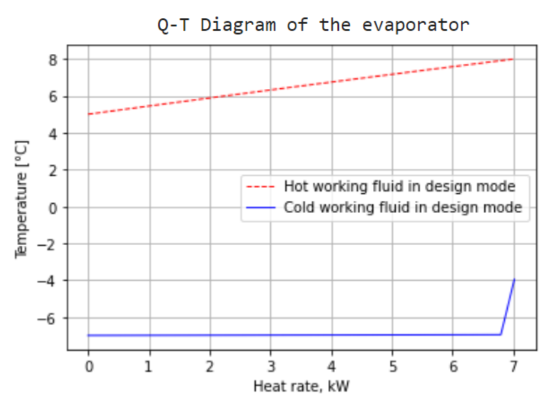
```
pip install CoolProp
```

```
Collecting CoolProp
  Downloading CoolProp-6.4.1-cp37-cp37m-manylinux1_x86_64.whl (4.2 MB)
     |████████████████████████████████| 4.2 MB 5.1 MB/s
Installing collected packages: CoolProp
Successfully installed CoolProp-6.4.1
```

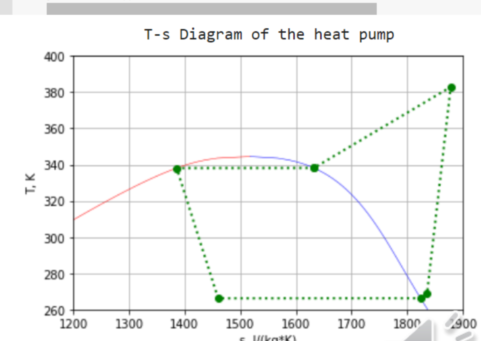



```
e_2_M_Des = T_0 * (s_0 - s_2_Des_0) - (h_0 - h_2_Des_0)
# Specific thermal exergy of the working fluid at the compressor
e_2_T_Des = (h_2_Des - h_2_Des_0) - T_0 * (s_2_Des - s_2_Des_0)
# Heat rejection in the condenser
q_out_Des = h_2_Des - h_3_Des
# Heat addition in the evaporator
q_in_Des = h_1_Des - h_4_Des
# Coefficient of performance of the heat pump
COP_Des = q_out_Des / l_CM_Des
# Mass flow rate of the working fluid
m_wf_Des = Q_HP_Des / q_out_Des
# Total heat addition in the evaporator
Q_in_Des = q_in_Des * m_wf_Des
# Total heat rejection in the condenser
Q_out_Des = q_out_Des * m_wf_Des
# Total power consumption of the compressor
N_Des = l_CM_Des * m_wf_Des
# Mass flow rate heat source fluid
m_EV_h_Des = Q_in_Des / (h_EV_h_in_Des - h_EV_h_out_Des)
# Mass rate heat consumption fluid
m_CD_c_Des = Q_out_Des / (h_CD_c_out_Des - h_CD_c_in_Des)
```

```
#@title Calculation of parameters of low temperature and consumer
if wf_EV_h == 'Air':
    h_EV_h_in_Des = airHTP(T_EV_h_in, p_EV_in, phi_0)
if wf_EV_h == 'Water':
    h_EV_h_in_Des = HPT(p_EV_in, T_EV_h_in, wf_EV_h)

if wf_EV_h == 'Air':
    h_EV_h_in_Des_0 = airHTP(T_0, p_EV_in, phi_0)
if wf_EV_h == 'Water':
    h_EV_h_in_Des_0 = HPT(p_EV_in, T_0, wf_EV_h)

if wf_EV_h == 'Air':
    s_EV_h_in_Des = airSTP(T_EV_h_in, p_EV_in, phi_0)
if wf_EV_h == 'Water':
    s_EV_h_in_Des = SPT(p_EV_in, T_EV_h_in, wf_EV_h)

if wf_EV_h == 'Air':
    s_EV_h_in_Des_0 = airSTP(T_0, p_EV_in, phi_0)
if wf_EV_h == 'Water':
    s_EV_h_in_Des_0 = SPT(p_EV_in, T_0, wf_EV_h)
```




```
#plt.plot(s_2_sv, T_2_sv, 'b--',linewidth=1)

from matplotlib import pyplot as plt
plt.axis([1200, 1900, 260, 400])

plt.show()
```



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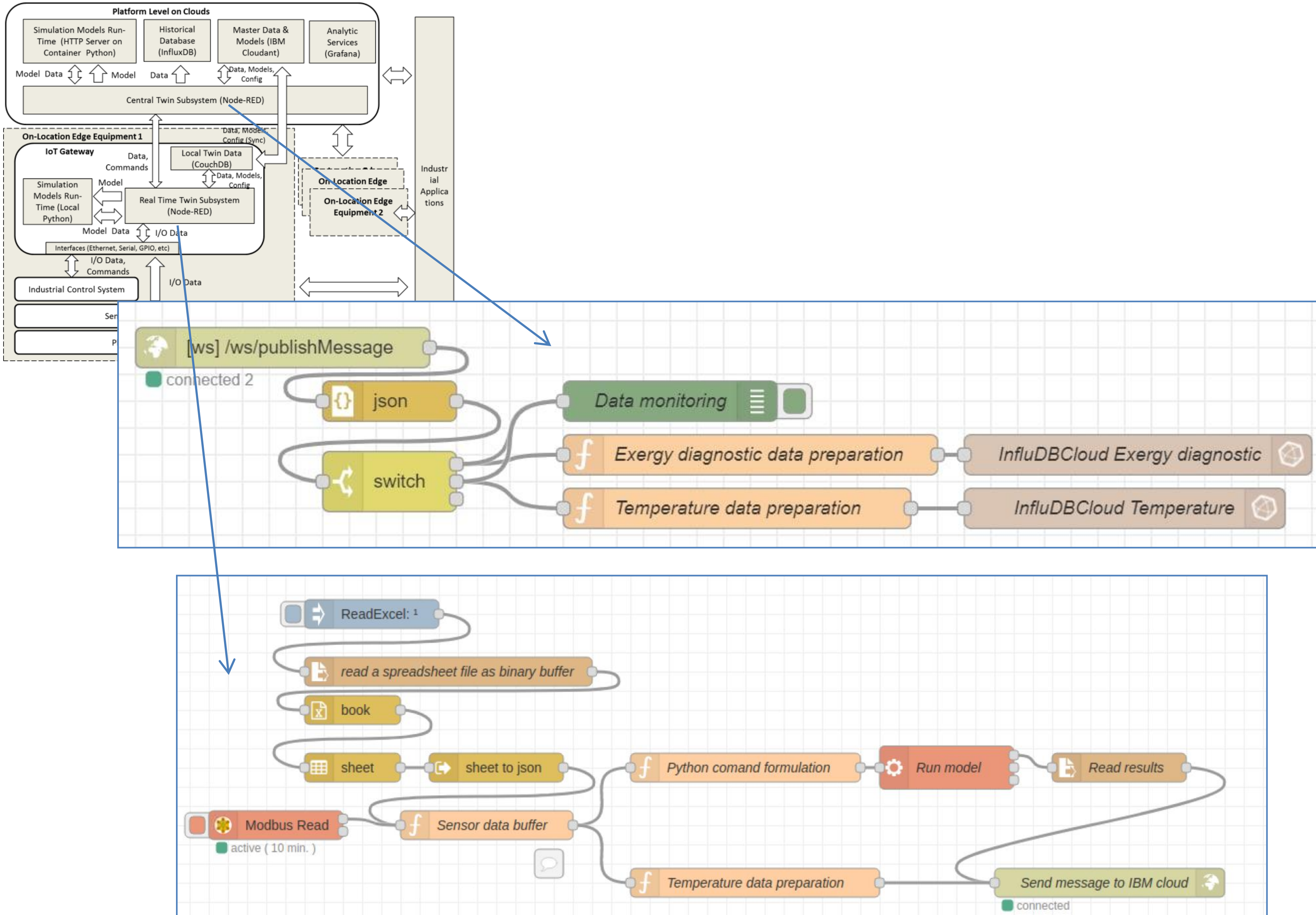
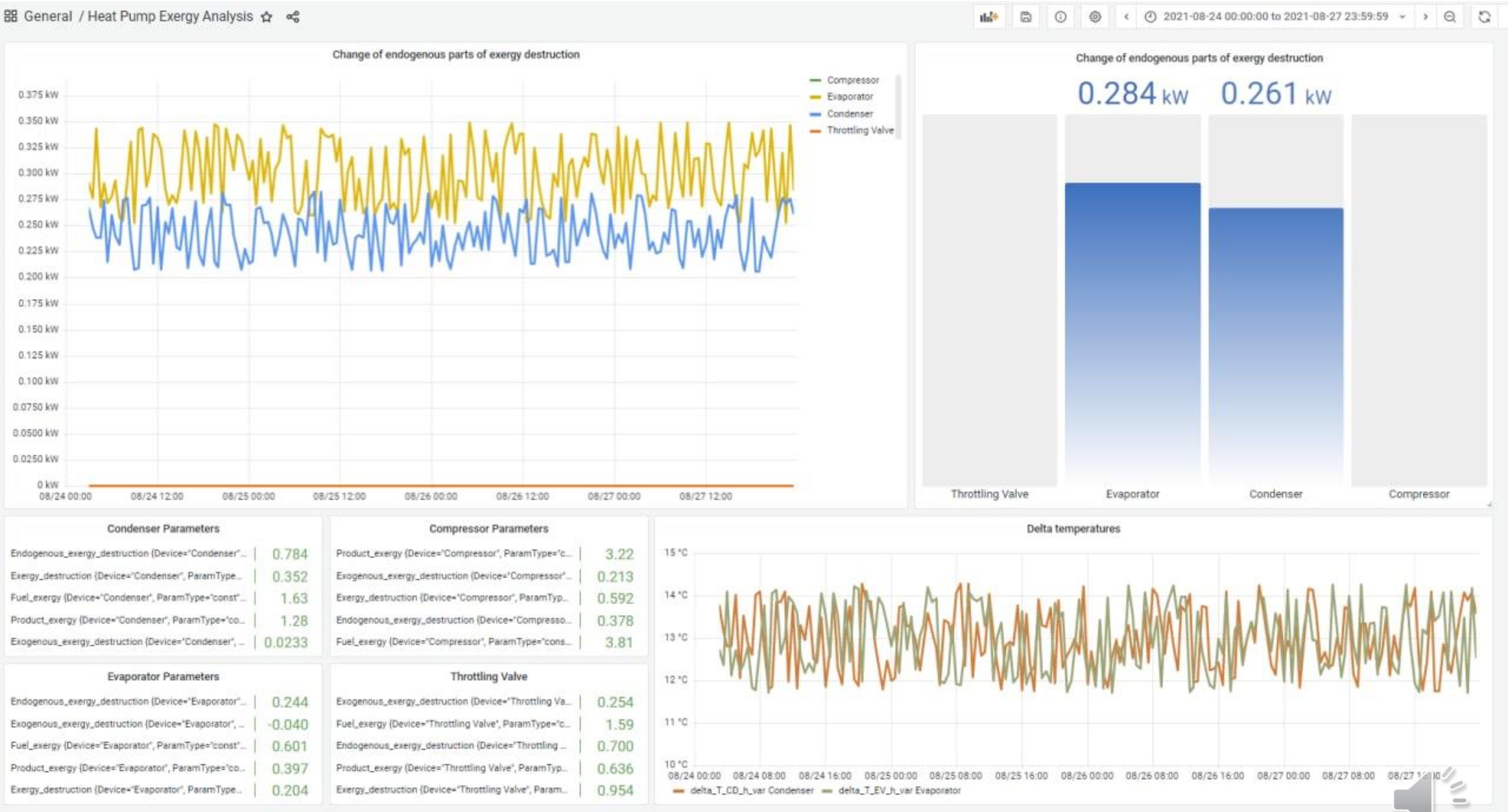


# Results during performance degradation process



**Conclusions:**

1. The work proposes application digital twinning and advanced exergy-based analysis for determining the anomalies and quantifying their negative impacts in thermal systems.
2. A prototype of a digital twin for the thermal system with a structure, contents, programming tools for data processing, storage, transferring, model-based analysis and displaying has been developed.
3. The implementation of a heat pump digital twin is performed. The case of simultaneous malfunctions due to fouling within the both the evaporator and condenser is investigated.
4. On the base of operation conditions of the investigated heat pump it has been shown that in case of fouling providing similar temperature differences within the heat exchangers the evaporator has higher priority for cleaning or replacing compared to the condenser.

# Thank you for your attention