Professional paper

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PREVENTIVNO ODRŽAVANJE ZASNOVANO NA DIGITALNIM BLIZANCIMA ĆE PROMENITI TRŽIŠTE USLUGA SERVISIRANJA U INDUSTRIJI KGH

Key words: predictive maintenance; automated fault detection and diagnosis; AFDD; digital twins; energy efficiency; performance analytics; trouble shooting; air conditioning; refrigeration; heat pumps; optimisation; machine learning

PREDICTIVE MAINTENANCE BASED ON DIGITAL TWINS WILL CHANGE THE SERVICE MARKET IN RACHP INDUSTRY

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Približava se promena paradigme u industriji KGH. Digitalizacija je dovela do toga da su senzori često fabrički ugrađeni, a sistemi povezani sa sistemima za upravljanje zgradama i cloud platformama. IoT ulazi u industriju KGH, što će promeniti našu industriju. Prakse puštanja u rad i održavanja još nisu unapređene kako bi se iskoristili dostupni podaci i tehnologije.

Industrija KGH koristi 20% globalne potrošnje električne energije, a postoji potencijal za uštedu od 25% na postojećoj opremi, što se može postići po niskoj ceni. Loša operativna efikasnost je uzrokovana nedostatkom optimizacije za stvarne radne uslove i širokim spektrom neotkrivenih „grešaka“. Preovlađujuće prakse puštanja u rad i održavanja ne osiguravaju efikasne i pouzdane sisteme.

Postoji stara oprema koja bi trebalo da se zameni zbog neefikasnosti, ali i nova oprema koja radi daleko od nominalnih performansi. „Uobičajeno poslovanje“ nema zahteve za verifikaciju performansi prilikom puštanja u rad i održavanja. Dobre ocene i standardi proizvoda bi trebalo da obezbede efikasno funkcionisanje, ali često ne uspevaju da to postignu, jer mnogi sistemi hlade zgradu, hladnjaču ili supermarket na određenu temperaturu, ali troše više energije nego što bi trebalo. Povećani fokus na održivost pokreće promenu paradigme koja je omogućena digitalizacijom i novim analitičkim metodama.

Potrebno je izgraditi kapacitete u industriji i podići svest među vlasnicima opreme, kao i ažurirati propise, inače će promena paradigme biti odložena. Klimatske promene doprinose povećanoj potrebi za hlađenjem, što definiše vršna opterećenja u mrežama i naglašava potrebu za osiguravanjem efikasnosti. Postoje dokazane tehnologije za merenje performansi na terenu po niskoj ceni, ali nedostatak svesti odlaže njihovo prihvatanje u industriji.

Rad predstavlja iskustva i rezultate kako se IoT i digitalni blizanci primenjuju sa dobro proverenom metodom za analitiku performansi i optimizaciju. Uvođenje digitalnih blizanaca poboljšava automatsko otkrivanje i dijagnostiku grešaka (AFDD) i drastično smanjuje potrebne inženjerske sate, kao i povećava preciznost ranog otkrivanja. Predstavljeni su rezultati primene digitalnih blizanaca *za AFDD kako bi se izbegli kvarovi kompresora, otkrili curenja rashladnog sredstva i pratilo pogoršanje kondenzatora.*

A paradigm shift is approaching the RACHP industry. Digitalisation has resulted in that sensors are often factory installed and systems are connected to Building Management Systems and cloud platforms. IoT is entering RACHP industry which will change our industry. Commissioning and maintenance practices has not yet been upgraded to make use of the data and technologies available.

The RACHP industry use 20% of the global electrical consumption and there is a saving potential of 25% in existing equipment achievable at low cost. The poor operating efficiency is caused by a lack of optimisation for actual operating conditions and a wide range of undetected "faults". Prevailing commissioning and maintenance practices does not ensure efficient and reliable systems.

There is old equipment that should be replaced due to inefficiency but also newly installed equipment that operates far from rated performance. "Business as usual" lack requirements on verification of performance at commissioning and maintenance. Good ratings and product standards are supposed to deliver efficient operation but often fail to deliver as many systems cool down a building, cold store or a supermarket to specified temperature but consume more energy than they should. The increasing focus on sustainability drives a paradigm shift that is made possible through digitalisation and new analytical methods.

Capacity building in the industry and awareness among equipment owners is required as well as updated regulations otherwise the paradigm shift will be delayed. The climate change contributes to an increased need of cooling that define the peak loads in the grids which highlight the necessity to ensure efficiency. There are proven technologies to measure performance cost-effectively in the field, but the lack of awareness delays the uptake in industry.

The paper presents experiences and results of how IoT and Digital Twins is applied with a well-proven method for performance analytics and optimisation. Introduction of Digital Twins enhance Automated Fault Detection and Diagnosis (AFDD) and drastically reduce the engineering hours required and enhance the precision of early detection. Results from applying Digital Twins for AFDD to avoid compressor failures, detect refrigerant leaks and monitor condenser degradation are presented.

1. Background

Upgraded methods are required for the future maintenance of Refrigeration, Air Conditioning and Heat Pump (RACHP) systems to reduce the sectors impact on climate-change. Proven methods for field measurements and analyses are available and will be greatly enhanced by Digital Twins based on Machine Learning (ML) which will be described and shown below. The introduction of Digital Twins is drastically improving the capabilities of Automated Fault Detection and Diagnosis (AFDD).

"Predictive maintenance" a crucial part of "Industri 4.0" is well established in production industries. By monitoring the status of machinery, it is possible to drastically reduce failures and avoid down time while repair costs decrease as early warning from e.g. vibration sensors allow for planned actions and avoid downtime and failures. Today's "Preventive" or scheduled maintenance in RACHP systems do not deliver reliable/efficient operation and rarely detect faults before system fail on alarm levels. By measuring or monitoring 24/7 with well proven thermodynamic methods any performance deviations can be detected long before they cause failures. Early Warning for deviation in performance avoid high energy costs and most failures can be avoided - drastically reducing cost of operation.

The “Internal Method” to analyse performance, briefly introduced below, is well proven since more than 35 years is suitable for early detection of performance deviations. The method is used both with portable equipment for inspections and increasingly for 24/7 monitoring, often using sensors installed from factory today.

The uptake is increasing as the conservative industry build competence and start to sell higher quality services to respond to pressure on equipment owners to reduce energy consumption, refrigerant leaks and costly failures. Conventional methods for energy optimisation require many engineering hours which means high cost and uncertain Return-on-Investment (ROI), especially as the number of engineers experienced in optimising dynamic systems is limited.

As the RACHP sector use 20% of the global electricity and today rarely use modern data analytics and AFDD the pressure is rapidly increasing on equipment owners to reduce the energy consumption. There is a saving potential of 10-25% based on ClimaCheck’ s experience from thousands of sites as well as many other reports (1) (2). These savings are likely the most “low hanging fruit” and easy to achieve, for property owners, as they often can be achieved at low cost and reduced failure rates which will more than cover the cost of establishing improved quality of commissioning and Predictive Maintenance in months. The poor efficiency is caused by lack of optimisation for varying operating conditions and a large variety of faults that go undetected for long periods of times.

A paradigm shift is approaching the RACHP industry. Digitalisation has resulted in that many sensors are factory installed and more and more systems are connected to databases and cloud platforms. Data is available but it is still seldom used due to lack of customer awareness.

2. Performance analytics on system and component level

2.1. Key Performance Indicators KPIs for real life systems

Product ratings based on performance indicators such as COP, EER, SCOP, kW/RT and seasonal values for these parameters contribute to push efficiency of products sold on the market but not in the same way to operational efficiency. The requirement on products and test standards has reduced the uncertainty of presented rating data and reduced the installation of equipment with sub-standard performance. To purchase efficient equipment is the first step to ensure efficient systems but it is not enough to have an efficient system operation. Today’s best products are highly efficient and it is very costly to improve today’s products performance with 5 % at the same time energy-consumption after installation is often 25% higher than necessary due poor commissioning and maintenance.

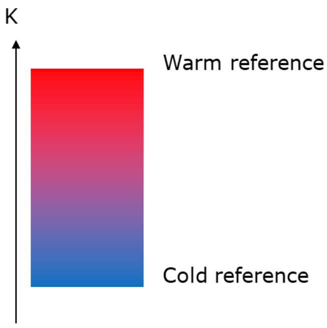
As performance has rarely been measured after installation and few systems operate at rating or design conditions there is a need of new practices and Performance Indicators suitable for use in dynamic system in real applications.

2.1.1. System Efficiency Index, SEI

The introduction of System Efficiency Index (3) (4) serves to address the problem with conventional performance indicators dependence on operating conditions. To measure performance outside a laboratory generally require that system is measured at whatever condition it is operating at and if difference is more than a few degrees from rating points recalculation introduce high risk of making comparison irrelevant and is likely to be challenged. The solution is to use the concept of Carnot Efficiency which is the theoretical COP of a loss-free process between two temperature levels.

This has been taught as apart of thermodynamic studies but then based on evaporation and condensing temperatures to establish the Carnot COP. This has the disadvantage that it does not include the heat exchangers.

System Efficiency Index, SEI, establish “reference temperatures” to calculate the Carnot COP. For a water-cooled chiller or water to water heat pump the reference temperature is the average cooling water temperature and average chilled water temperature. This corresponds to a system with indefinite heat exchanger surface and flow. The SEI then becomes a total efficiency for the unit.



$$SEI = \frac{COPmeasured}{Carnot\ COP}$$

$$Carnot\ COP = \frac{Cold\ ref}{Warm\ ref - Cold\ ref}$$

- *Cold ref = absolute temperature for refence temperature in evaporator (below some examples)*
  - *Water/liquid cooled evaporator = average of return and supply liquid*
  - *Air evaporators = Inlet air -5 K*
- *Warm Ref = absolute temperature for refence temperature in condenser (below some examples)*
  - *Water/liquid cooled condenser = average of return and supply liquid*
  - *Air condenser = Inlet air +5 K*

Figure 1, System Efficiency Index, SEI, is a powerful performance indicator that solves the problem of conventional KPIs that are highly dependent on operating conditions

2.1.2. Sub efficiencies

To know the total SEI of a system is the first step to understand efficiency but to get actionable information for maintenance staff a more detailed information is required, to reduce engineering hours of highly skilled and hard to find engineers. With hundreds of millions of sites, optimisation and early warning when performance deviate requires that AFDD tools are capable to pin-point problems to one fault or at least a limited number of defined faults.

To trigger early warnings when a system leave optimised conditions requires indicators on component level monitored automatically. The “Internal Method” allows efficiencies on component level to be monitored with un-biased Performance Indicators applied on all vapor compression cycles. As there are hundreds of thousands of designs operating at an indefinite variation of conditions it is practically impossible to use manufacturer data to follow systems in the field. The Internal Method defines sub-efficiencies (3) for the components affecting performance in a refrigeration process. The product of sub-efficiencies multiplied with each other result in the total SEI. This means that a change in any of the sub-efficiencies is directly related to the change in efficiency and SEI.

2.1.2.1. Compressor isentropic efficiency

Isentropic compressor efficiency is well established and a part of thermodynamic training but it has not been used as a performance indicator, to benchmark against or for troubleshooting in the field.

2.1.2.2. Condenser Efficiency

Condenser efficiency identify the impact on efficiency of the measured system versus if it had an indefinite condenser surface. This will indicate fouling, flow-issues or over-charge of refrigerant.

2.1.2.3. Evaporator Efficiency

Evaporator efficiency identify how the evaporator operates versus on ideal-indefinite evaporator in the measured and will indicate fouling, issues with refrigerant flow through expansion device or flow on air/liquid side.

2.1.2.4. Cycle Efficiency

The losses in the refrigerant cycle is dependent on operating condition, subcool and superheat but also on if cycle is improved with e.g. an economiser. The measured cycle is compared to a standard cycle thus with an economiser the efficiency can exceed 100%.

3. Thermodynamic analyses make information out of data.

The "Internal Method" (5) (3) is used for performance analytics of refrigeration processes and offer significant advantages compared to conventional flow-based methods as it does not require installation of costly flow meters. Besides lower costs and the possibility to use already existing sensors or connect all sensors in less than an hour it also offers a much more detailed information as it gives performance on component level. For a standard refrigeration process the following sensors are required:

Refrigerant system to define process performance

1. High pressure (P1)
2. Low Pressure (P2)
3. Discharge temperature (1)
4. Suction gas temperature (2)
5. Liquid line temperature (3)

Secondary media to define heat exchanger performance

1. Water/air return to evaporator
2. Water supply from evaporator (supply air can be informative)
3. Water/air return to condenser
4. Water supply from condenser (supply air can be informative)

Active electrical power

These sensors are often installed in modern equipment of some size but can also be installed without intrusion in system temporarily or permanently.

With these sensors it is possible to analyse the performance of the process as well as efficiency for each component in a system.

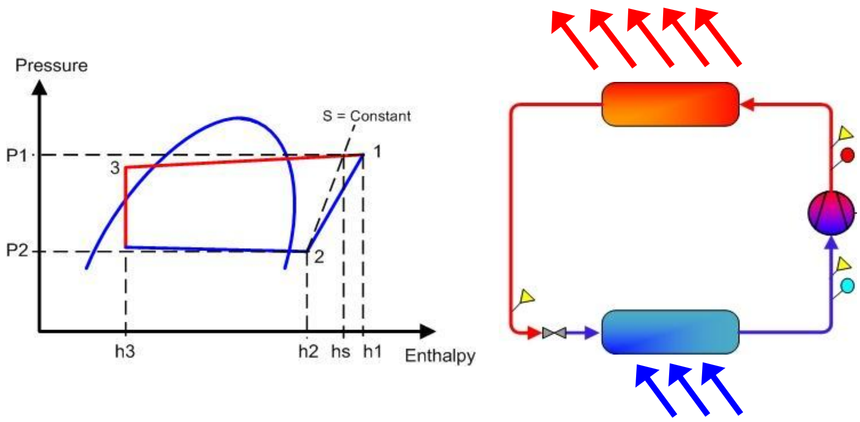


Figure 2, Pressure Enthalpy chart for a standard refrigeration process with the three enthalpy points required to define COP and isentropic compressor efficiency and a flow chart with required sensors marked

This method allows to calculate the COP and cooling capacities with the help of an energy balance over the compressor. Above pressure enthalpy graph show the enthalpies required to calculate the COP without flow measurements. The only factor not taken into account is the heat losses from the compressor that will have an impact on the discharge temperature. The heat losses are small 2-8% and can be introduced as a heat loss factor that in most cases for field use can be set as a default value. The compressor manufacturers organisation has published data that for hermetic and semi-hermetic compressors - the heat losses is between 2% and 8%. This allows that the COP and refrigerant mass-flow of refrigerant can be calculated with good field accuracy. In IEA Annex 52 (6) calculated the uncertainties for the Internal Method and resulted in a total uncertainty of less than 5% which is very good for field methods and actually better than for flow-based methods. Flow-based methods are also in practice limited to use when there is a liquid flow to measure whereas the Internal Method can be used also for direct evaporation systems such as supermarkets and split/VRV air conditioning and heat pump systems. As the Internal method is much cheaper to apply and give detailed information on component level it will be much more efficient for Predictive maintenance and AFDD.

This approach makes it possible that with ten existing or easy to apply sensors establish a complete evaluation of all relevant KPIs on the same level as the development and production test-rigs used by many OEM in real time. The below dashboard show SEI, sub-efficiencies and the relevant KPIS for each component.

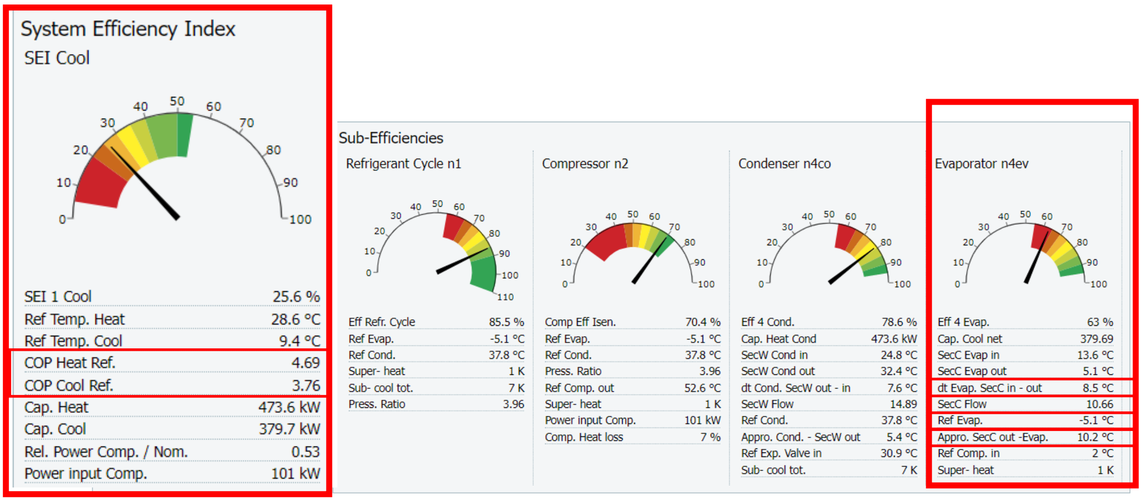


Figure 3, Example of dashboard visualising low SEI caused by low sub-efficiency for evaporator caused by high dT/low flow in evaporator

4. Predictive Maintenance with Automated Fault Detection and Diagnostics (AFDD) will change the industry

How efficient a site operates is dependent on many parties defined in several contracts, outdoor conditions and how the sites are used, which is rarely identical to design. In this situation nobody becomes responsible or is paid to ensure efficient and reliable operation. Profitability in the maintenance sector is not been based on delivering competent services but rather to have the contract when failures occur - this is what the market has adapted to. There have been no incentives to build competence and push predictive maintenance and optimisation to equipment owners that focus on low initial price. There is competition from somebody offering services at lowest cost and challenges for equipment owners to evaluate claims on offered services.

The requirement to reduce energy consumption, refrigerant leaks, failures and downtime now push for new methods. The preventive (scheduled maintenance) methods used today cannot deliver efficiency and reliability as it does not include relevant monitoring. The focus on increased product standards, with the expectations that efficient products and design should automatically result in efficient operation is not sufficient.

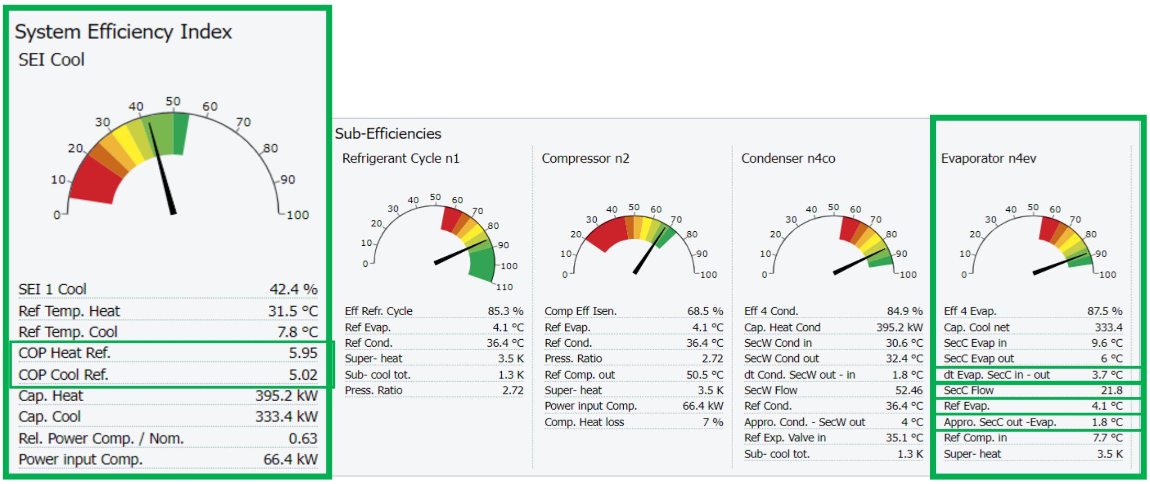


Figure 4, Dashboard showing the same system operating with nearly same supply temperatures but System efficiency has improved from 25.6% (COP 3.76) to 42.4% (COP 5.02) after recommissioning evaporator flows. The system is operating with the same cooling capacity but consume 66.4 kW instead of 101 kW

Contractors experience that the purchasing process focus on low initial price for installation and maintenance contracts and must deliver accordingly. There is rarely specified meaningful verification of performance and efficiency of actual operation and Measuring and Verification is not specified in-spite of that most or all sensors are normally installed. Unless it is specified that data should be collected in a structured way with specified sampling rates it is unlikely that the data can be used cost-effectively for performance analytics and AFDD.

To collect data sampled by different systems and use engineering hours to coordinate data and make evaluations tend to be expensive. If method for analytics is defined and "Good practice" for data collection such as discussed in IEA Annex 52 (4) (7) is standardised, system and brand independent analytics can be applied. Annex 52 guidelines are developed for ground source systems but except for the collector they are generally applicable for any system with a refrigeration process.

It is unrealistic that efficient and reliable operation will be achieved by upgrading skills of all local technicians in the industry with competence to optimise all refrigeration, air conditioning and heat pump systems. The operation of a site is changing continuously and systems are complex (increasingly so) which means that optimisation has to be data-driven based on structured data collection and automatic analytics. Automated Fault Detection and Diagnosis can identify when a system deviate from good performance and trigger a call for action. All the KPIs discussed can be monitored and alert set for deviations in performance by a competent engineer. Setting alerts has required time and competence as there are many designs operating at varying conditions. As more and more systems are connected the shortage of competent engineer will be the bottle neck for configuration of AFDD.

4.1. Digital Twin based AFDD is powerful and reduce engineering hours

The Internal method based on thermodynamic analyses and the sub-efficiencies offer a scientifically based and unbiased method to establish performance. It requires no inputs from manufacturer to establish performance although it is obviously beneficial to have good documentation of intended performance and service parameters as benchmark.

Digital Twins makes it possible to predict total efficiency and behaviour of each component in the system with high accuracy. This drastically increase the precision of early warning indicators at the same time as the engineering required to apply AFDD is minimised. Acceptance levels around the predicted value from the digital twin's prediction offer more accurate indication and reduce false alerts. The physical models for the components are well defined and many products follow the same model with limited deviations. The digital twin for e.g. one compressor offers a good prediction for many similar designs. A library of digital twins for components is applied without requiring individual training for each product, which would have required an indefinite number of models for all operating conditions. To train a reliable digital twin can require data for 6-12 months to cover all operating conditions and loads. The figure below shows that the digital twin is capable of predicting condenser efficiency within a few percent during dynamic operating condition where the variation of efficiency is > 20%. To set early warning with conventional methods is time consuming and involves a specialised engineer evaluating the site. Widespread implementation of accurate AFDD cannot be achieved with manual configuration of early warning, due to lack of experienced engineers, even if the savings would be much higher than cost.

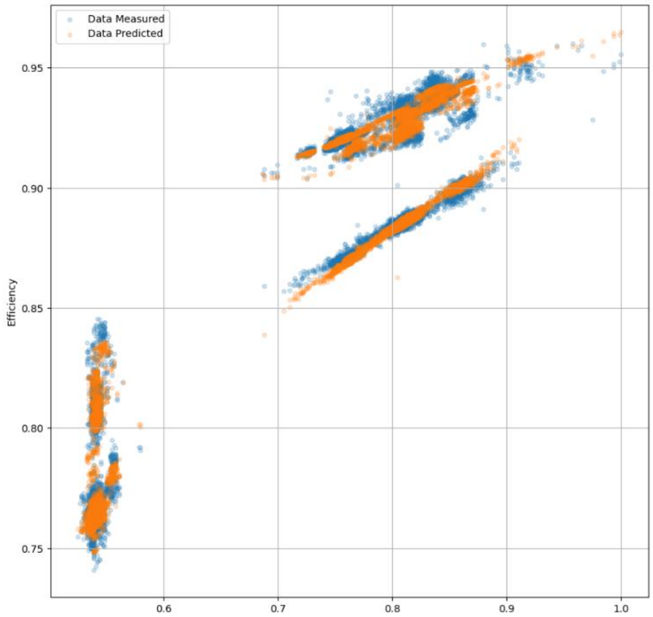


Figure 5, Blue dots represent the measured condenser efficiency and orange dots represents the predicted value from the twin. There are clearly four scatters of data representing different operating conditions. These scatters represent summer and winter operation at 100% and 50% capacity.

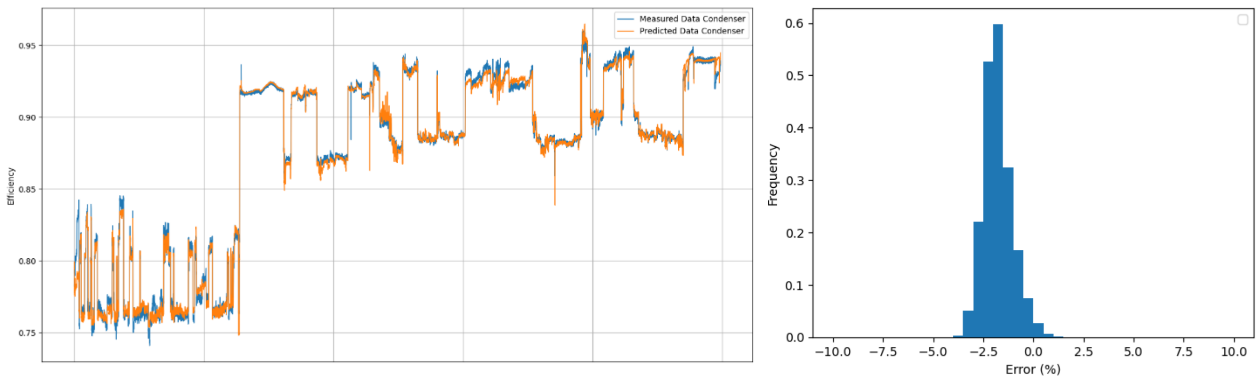


Figure 6, The graph shows the variation between two different units with same type of condenser. The Digital Twin is capable of representing the performance also of the other condenser with high accuracy and show that the trained condenser is 1-2% less efficient than the tested which is well within the acceptable tolerances

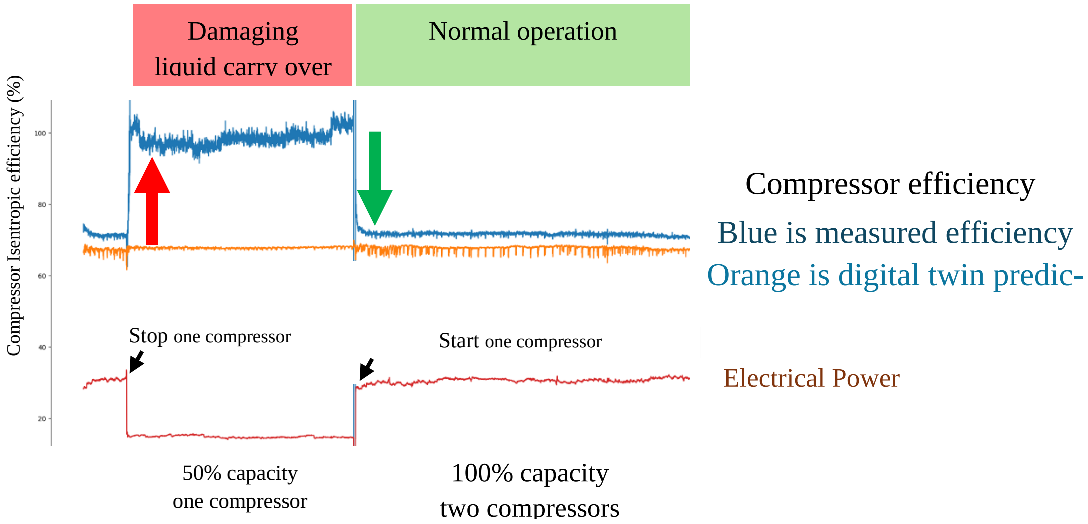


Figure 7, Digital Twin used to detect operation that cause thousands of compressor failures in Europe every year on tandem compressor circuits. There are two different causes for the "fictive" increase of compressor efficiency. Which of these problems that is the cause defined by other measured indicators

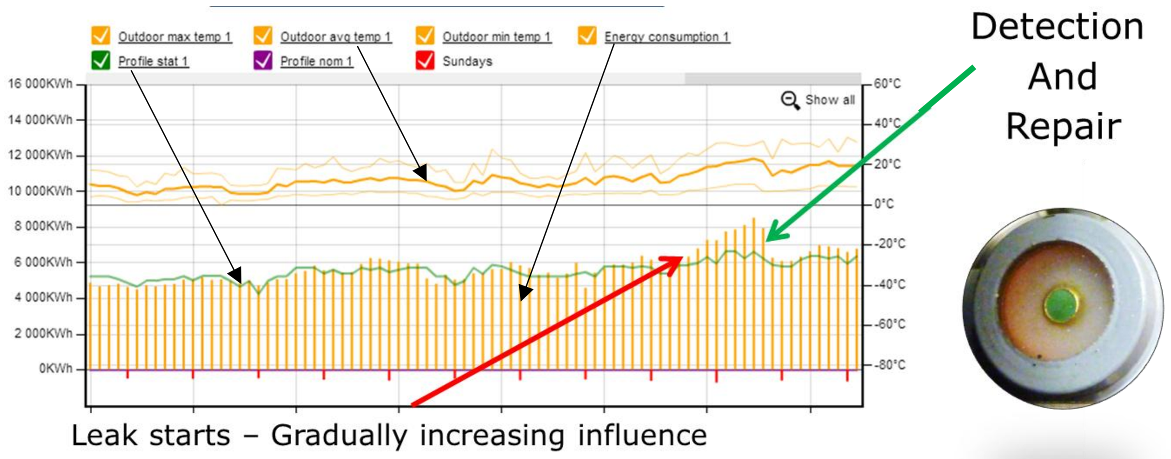


Figure 8, Twin of a supermarket's energy signature used to detect a refrigerant leak one of several indicators to reduce refrigerant leaks and apply "indirect leak detection" that reduce the number of required site-visits for leak detection

5. Conclusions

The requirement on sustainability now include requirements to document and benchmarking how efficient energy is used and digitalisation offer access to data at much lower cost. Often data is available in today's equipment control and buildings monitoring systems, but this has not yet been taken advantage of due to lack of potent performance analytics, established practices and regulations resulting in a lack of competence/experience in industry.

It is a challenge to change Business-as-Usual in a conservative industry where the equipment owners generally are not refrigeration experts and have challenges to balance initial cost versus future operating costs. They are dependent on technicians coming to site to keep their systems in operation and place their trust on them. It is obvious that those visiting the sites tend to conserve Business-as-Usual both based on the legacy experience and Wishful to Project existing business model. To move from scheduled "Preventive Maintenance" based on site-visits to a data driven predictive approach is a challenge but also an opportunity for those that the take the lead in the Paradigm shift.

The increased awareness of the impact on global warming together with introduction of more sensors in Refrigeration, Air Conditioning and Heat Pump (RACHP) systems make the paradigm shift imminent. There are initial costs to set up data collection and analysing but these costs are lower than a compressor failure or most other avoided repairs not to mention loss of perishable goods and downtime.

The cost of data collection and cloud monitoring is also low versus avoided travelling and troubleshooting hours. The challenge is the transition from today's low initial cost for maintenance contracts followed by unspecified future costs for energy, trouble shooting and repairs. The cost of future energy bills and failures are not known making ROI of Predictive Maintenance hard to prove although there is a lot of reports (8), statistics and experience that prove that predictive maintenance is cost effective, reduce failures and downtime.

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