SPHERE

BIM DIGITAL TWIN PLATFORM

December 2021

# FROM BIM REPRESENTATION TO FUNCTIONAL SIMULATION AND REAL TIME ADVANCED CONTROL

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## DISCLAIMER



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## ABOUT SPHERE

SPHERE is a 4-yearHorizon 2020 project with 20 partners targeting the improvement and optimization of building's energy design, construction, performance, and management, reducing construction costs and their environmental impacts.

SPHERE seeks to develop a building centered Digital Twin Environment, involving not only the design and construction of the building but also including the manufacturing and the operational phases.

https://sphere-project.eu/

# ABSTRACT

Residential Building Digital Twin functional representation requires a new professional role (BDT Simulation Manager). This functional aspect of the building digital twin covers all phases of the building, from design and concept to commissioning and real time management. It must be well coordinated with BIM and other services of the BDT.

Mathematical simulation can reproduce functionalities of the different systems: passive building, ventilation networks, heating and cooling devices, meteorology and occupancy. Advanced Software in the Loop embedded in supervision and control devices can improve drastically the visibility of health, comfort and energy parameters. Performance contracts (as one economic implication) can make use of dynamic energy evaluations. Maintenance can be carried out effectively thanks to extra parameters derived from simulation, affecting not only equipment but networks and sensors.

Challenges as Trustworthy BDTs and privacy and ethical constraints are considered, describing new aspects and solutions.

The document point out next steps and possible lines of development, and the impact they can have in future EU policies. Especially micrgrids and projection to smart cities is considered.



## KEYWORDS


- Building Digital Twin
- Physical Twin
- BIM
- Real Estate
- Facility Management
- Product Lifecycle
- Management
- PLM
- SCPS
- Internet of Things (IoT)
- Open BIM SPHERE
- Web Ontologies
- Linked Data and Web of Things
- Mathematical Simulation
- Software in the Loop (SIL)
- Hardware in the Loop (HIL)
- SIMBOT
- BMS
- Virtual Commissioning
- Ontology Management
- Human Thermal Model (HTM)
- Human Ventilation Model (HVM)
- Micrgrids
- DERs
- Trustworthy BDT
- Privacy
- Building Ethical Constraints



Figure 1: Conceptualisation of a Building Digital Twin Instance Interoperability Services (sketch by: M.Borràs)

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# 1.-INTRODUCTION

Digital Twins are one of the most relevant trends presently found among digitalization across all the sectors. From health[1] to environment[2], Digital Twinning appears as an unstoppable wave although they are often targeting just one of the most relevant benefits attached to the Digital Twin Environments: the Predictive purpose[3].

In the same way scale models has been used since humanity started to use tools - since they are actually just this -, their evolved Digital counterparts could offer the same benefits and beyond. However, the force that the predictive purpose entails, is by itself more than enough to justify the effort of developing Digital Twins of any connected physical object.

Following the relevance of the behavioral prediction for any stakeholder related to valuable objects in any cycle of its lifespan, this White Paper focuses on the strategies to be considered when the object itself belongs to the AECOO[4] sector.

About value, real estate assets could be products to sell, to rent or to be financed, engineering objects to be developed, construction places to erect or retrofit, energy sources, wells or storages, materials banks, Greenhouse gases emission points…, but after all this, they are also our work or leisure places, and above all this, our homes.

## 1.1.- BDT, Definitions and Roles

In the previous White paper published in 2019[5], three new roles were defined as three necessary facets of a professional person or team to guarantee a proper setting, development, duration, usage, and maintenance of Building Digital Twins across their life scales. Beyond the expected future improvements in standards and automatisms for Data Collection and Integration (e.g. Data Reference Architecture Models[6]), a minimum representative number of datasets have to be gathered to duly represent a building.

Following a functional approach at least we can speak of three new profiles, which respond to the coordination of the whole DT (BDT Manager, or BDTM), the need of interaction during time (BDTConfiguration Manager, or BDTCM), and the need or representing the functionality of the building in a trustable way (BDTSimulation Manager, or BDTSM). These roles are broadly explained in the mentioned white paper. They are abstract roles and they could be organized in different ways.

1 A Novel Cloud-Based Framework for the Elderly Healthcare Services Using Digital Twin. DOI10.1109/ACCESS.2019.2909828
2 https://www.sciencemag.org/news/2020/10/europe-building-digital-twin-earth-revolutionize-climate-forecasts
3 Grieves, M. & Vickers, J. Origins of the Digital Twin Concept. 23, August 8 pages (2016)
4 AECOO: Architecture, Engineering, Construction, Operation & Ownership
5 SPHERE: Digital Twin Definitions for Buildings: https://sphere-project.eu/articles-papers/#
6 https://www.internationaldataspaces.org/wp-content/uploads/2019/03/IDS-Reference-Architecture-Model-3.0.pdf



Whereas BDTM and BDTCM are generic technical profiles the last one (BDTSM) has an advanced engineering concept behind the fact that it must be taking decisions about matters that today may seem too ahead in time. The Simulation Manager "should be responsible for the whole aspects related to the development and maintenance of an evolving simulation model correlated to the physical smart and connected asset system[7].

This means to map or link entities of designed or physical as built elements with simulation components in the mathematical engine used in each case.
This mathematical simulation should not work isolated and will have several interfaces: real time BMS, asset management, outside meteorological and ambient conditions,...

**The Simulation Manager would ultimately be responsible for the certification / validation that the model "responds to reality" to the extent defined**

"Based on the correlation among data coming from both Digital and Physical currents, DTSM shall then establish the validation and even certification methods (depending on the grade of implementation of the Digital Twin) which will allow not only an iterative improvement of the simulation, but opens a wide open window to the optimization of the control operation of any asset".

Following this, these methods are crucial to reduce the gap between simulated and monitored data during the commissioning of the Building Services. This validation between design and operation simulations might hence underpin the future Predictive functions of any BDTI and has a relevant importance in the case of Performance Based Contracts. Since these performance based procurement is based on real measurements, including tolerances, current gap between simulation models and measures have to be significantly reduced. The SimulationManager would ultimately be responsible for the certification / validation that the model "responds to reality" to the extent defined.

## 1.2.- The 'Ontology Management' Problem[8] of BDT´s

What is a Digital Twin and why? Asset management 2.0? Many valid views exist of course but Mark Thomas, CEO of Nextspace, give us his own perspective.

Perhaps most traditionally, DT's are associated with simulation and analytics applications such as predictive maintenance, system I/O simulation, using IoT, AI, FEA, CFD etc. to replicate the inputs, behaviors and outputs of the real world or its devices in some way. My view is that a DT needs 3 critical components to be "valuable"; i.e. able to stated, communicated and optimized (and so then the real world) against chosen goals; e.g. financial, environmental, social.

7 Page 42, " SPHERE: Digital Twin Definitions for Buildings" White Paper.
8 Collaboration of Mark Thomas, CEO of Nextspace

- A data ontology[9] model to store a "state" of a digital world - past, present and predicted.
- A way to represent a data state and ontology to humans - e.g. a visualization is optimal for human cognition and critical to real world action, and lastly
- The tools and methods to work with the DT state model and apply AI, analytics and simulation creating future scenarios for understanding, and so optimize for the future.

In general the challenge we have seen in creating DT's (even before they were so aptly named) over the many years is one of data integration between systems to bring all the disparate data representations of things together. Mark Thomas believes very strongly in the value of a pure ontological approach to this process. Using this approach provides a system independent way to structure and join data.  A good use of ontology for data integration simply asks the question of any incoming data set (static or dynamic):

- Can we find the following information in this data to map to a universal ontology?

- What are the "things" that are referenced in this data? E.g. walls, valves, doors, pipes, supports?

- What are the attributes that are referenced to these things? Size, manufacture, temperature, pressure, date last maintained?

- What are the implied relationships between things?  Parent, child, connected to, supplied by? Links to other data objects (Media, sound, video, documents)

- When and where are these things and their data?  Lat Long, Elev, relationship to another coordinate system, time of creation, destruction date, time to build?

And lastly

- What are the valid visual representations of this thing?  Point, Line, Polygon, 3D model, photo, LIDAR scan, Point cloud? Different resolutions of any of the above?  Different file formats of any of the above?

It is pleasantly surprising how thinking about things and their generic attributes relationships etc. provides a way to systematically connect data from different sources and adds a layer of simplicity and calm to data integration problems.  The reason for this pleasant surprise is that the idea of universal ontology is as old as the Greeks if not older.  The idea of ontology attempts to describe the world in a systematic way that is purely logical and so both computer and hopefully human friendly.  Complexity can be resolved by simply categorizing the world into things we care about and their nature, and the goals we have in managing or interacting with them.

In a practical sense the adoption and availability of open API's between systems allows for such ontological conversations to happen between computers now and not just people, making complex data integrations possible and the amalgamation of vast and varied data into a representation of a "Digital Twin".

9 "An ontology is a formal, explicit specification of a shared conceptualisation" [2] -conceptualisation: classes and types of relations, terminology, describing a domain of knowledge
- formal and explicit specification: applies a machine-readable formal language combined with logics
- shared: result of a collective effort, is shared in a community and is independent of implementations
[2] R. Studer, V. R. Benjamins, and D. Fensel. "Knowledge Engineering: Principles and methods". In: Data & Knowledge Engineering 25.1-2 (1998), pp. 161–197. doi: 10.1016/S0169-023X(97)00056-6.



In addition the Digital Twin should provide a common point of clean, structured and consistent data access for other systems to connect to, especially analytics and simulation systems that can help to optimize the digital world and so on to the actual world.  This data interaction with simulation and analytics systems should be 2 way of course to allow new predicted or possible states to be communicated to the computer and humans.

But as data is collected to form a current picture or "State" of the world in a digital form, the need for humans to be able to see this state - a large collection of different data about the world – becomes a challenge.  It is not enough to get a written report or a 2D plan drawing of the world 1, 2 or even 3 dimension data representations of the current state of the world. These are inefficient for complete human cognition and understanding.

The compelling nature of animated interactive 3D graphics has created a breakthrough how we can visualize the actual world in all its complexity and possibilities, however it is important to remember the place that visualization has in the Digital Twin space.

## Some Problems with "Visual First" Approaches to Digital Twin Implementations

A common problem with many attempts to create Digital Twin Technology in the broader context is the fascination with 3D graphics.  So often the approach has been to take hold of a CAD or BIM or GIS file model and then attempt to force fit the data about the thing this single graphic representing the thing in one state of its lifecycle – usually the engineering design phase.

There are multiple problems with this common approach.  `Things' have a life cycle and the visual representation is NOT the essence of a thing.  It is only as useful as the specific use case at a specific time.

The essence of a thing need, and should be, no more than some kind of unique identifier (GUID – Global Unique ID[10]).  A graphic or 3D model is not a useful consistent GUID but is treated as one by many BIM and Digital Twin models.  GUID management is absolutely essential to Digital Twin data management allowing changes and updates to be processed.  Using a graphic as the absolute definition of "unique" is simply inadequate and fails in too many cases.

CAD files or graphics containers are designed for managing data or data changes over time let alone changes to the very structure of the data – That is what database technology is for. CAD files are typically unable to contain multiple taxonomies (or hierarchies) and so reordering things depending on use case or context is near impossible.  Users get stuck with the engineering hierarchy which is different from the manufacturing hierarchy which is different from the parts ordering structure which is different from the valid configurations hierarchy.

10  In the world of web ontologies and Linked Data, the identifier is often an HTTP URI instead of a GUID. Since the essence of the Web needs to allow different people to start talking about the same physical "thing", they might end up with different URIs. This principle is called the "no-unique name assumption".
E.g. the URI for Barack Obama in DBPedia is http://dbpedia.org/resource/Barack_Obama while in Wikidata the URI is https://www.wikidata.org/entity/Q76
Ideally, there's only one identifier in the network of data storages for each real "thing", but in practice this is often not possible because URIs can be minted by different systems in a network in parallel. Links between URIs that denote the same thing can of course be established, to reduce the semantic heterogeneity.

In short 3D graphics have no business being the basis of Digital Twins they are merely a representation tool that should be driven by a pure ontology model.

In practical terms of BIM meets GIS meets IoT meets finance etc. There can be only one common language. One based on data ontology modeling. Not on pre-structured CAD or GIS file formats or ERP hierarchies with no concept of instance context within larger structures or the world.

A good Digital Twin is more like a dynamic map of connections between things than a static mega structure or 3D visualization. The latter are simply possible representations of the DT which may change depending on use case or the current state of the world that is mirrored, past present or predicted.

And lastly a good Digital Twin platform is one that can be used by anyone (with some training, i.e. not a services contract) and one that can easily and naturally federate multiple separately created digital twins from a machine level to an organization level to a city to a state and a national level.



# 2.-SIMULATION ACROSS BUILDING LIFE CYCLE

Simulation is today a wide set of techniques to reproduce physical behavior using mathematical resources. We can have 0D-1D problems, where the space representation is not considered, or we can simulate complex 3D fluids or solids using FEA analysis. These methods can be combined and we could get sets of models connected exchanging information during time.

In a building a primary analysis is how the structure will be responding to climate, seismic or loads of any kind. For this we can use advanced FEA software to represent the building in 3D and 'simulate' how the building could be responding to loads in different scenarios.

When 3D representation could be too complex or just because we want to simplify the problem we can use mathematical simulation. In this case the 'big' problem can be cut into pieces ('components'), and these pieces connected by 'ports'. This could be the case of energy problems where we have to consider temperatures, fluids, walls,.. In the end I can represent by equations each of this problems without the detailed 3D geometry.

Mathematical simulation gives us a huge flexibility to represent any system as soon as we know its behavior, whether using equations or a graph. Many equipments can be well represented by a performance curve, and using this curve we can create a 'component' with inputs and outputs.

Traditionally these techniques have been used for complex systems, like the ARES MODULE at International Space Station life support system.

Figure 1: International Space Station ISS

A life support system comprise many devices and it would be impossible (or not practical) to represent the fluids interacting with machinery. Instead we used equations, we represent each device and we can connect all of them reproducing the dynamics of the system with great detail.

Figure 2: ESAColumbus module at ISS

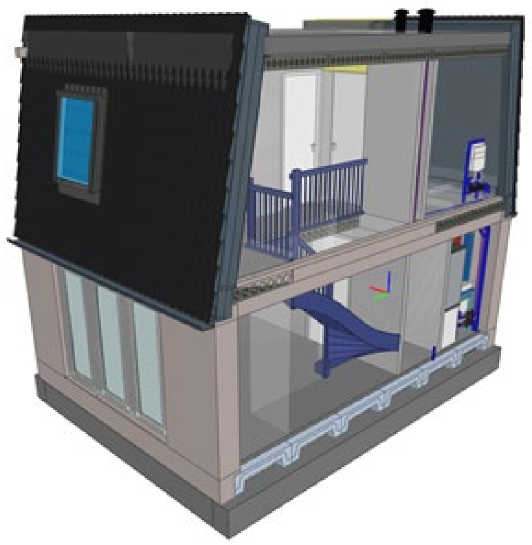


Figure 3:TNO demo pilot SPHERE project

In a building we can do the same. If we consider one of the demo pilots of SPHERE (TNO pilot at Delf, Holland), we can 'extract' all components of discipline ventilation: spaces, doors connecting spaces, home ventilation machine and pipes for the 4 circuits of the network (inlet, air distribution, air extraction and outlet to the roof).




Figure 4: Pilot NERO ZERO, Delf, 2020

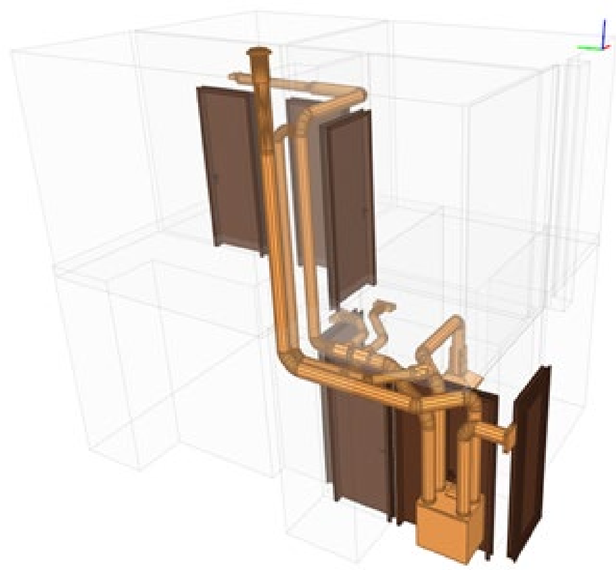


Figure 5: Spaces, doors, diffusers, pipes, and home ventilation machine

We will connect this 'discipline' with others, but we are able to separate these ventilation components from the rest of the building. This capacity of dividing a big problem into smaller ones is essential to solve a big building. We could be creating separate models by discipline and floors as well. There is no limitation.

The simulation model of the system described could be as follows:

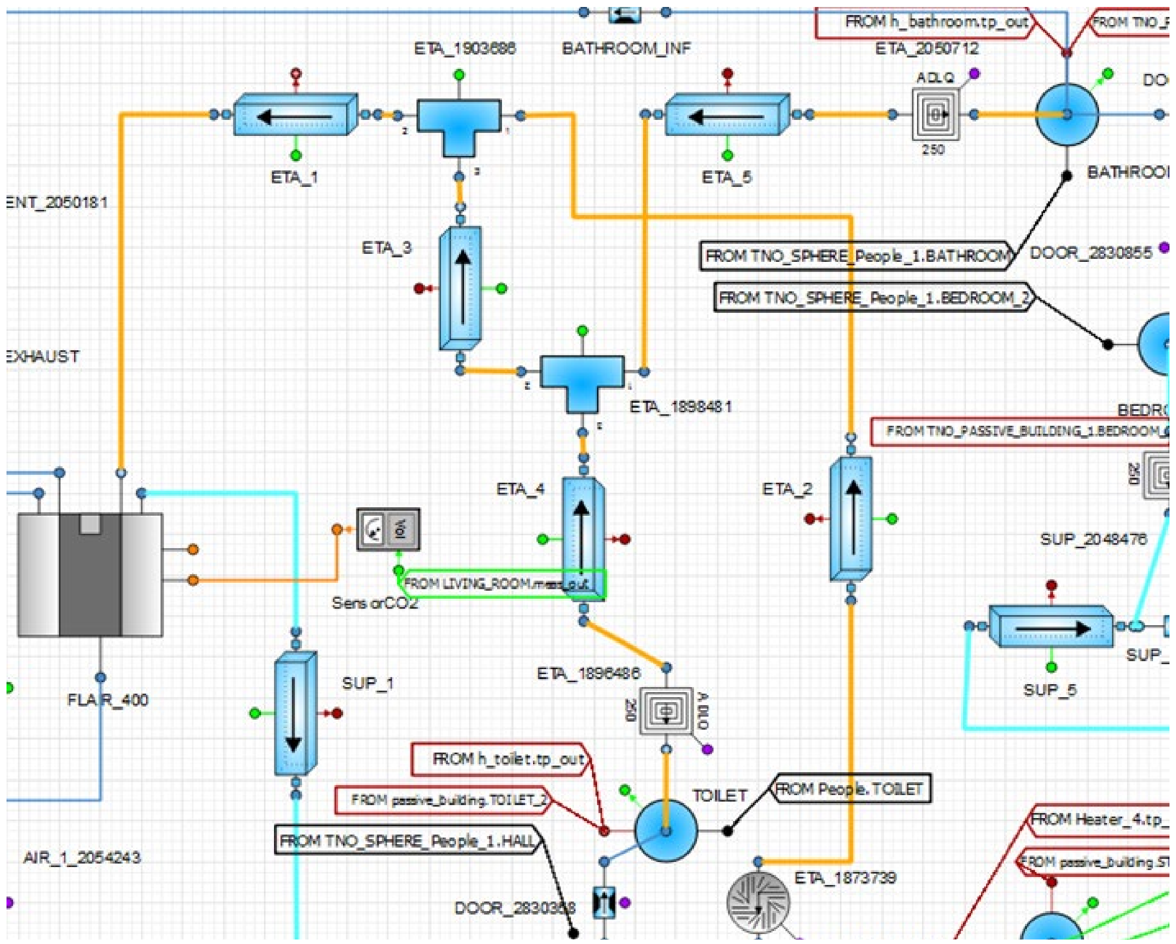
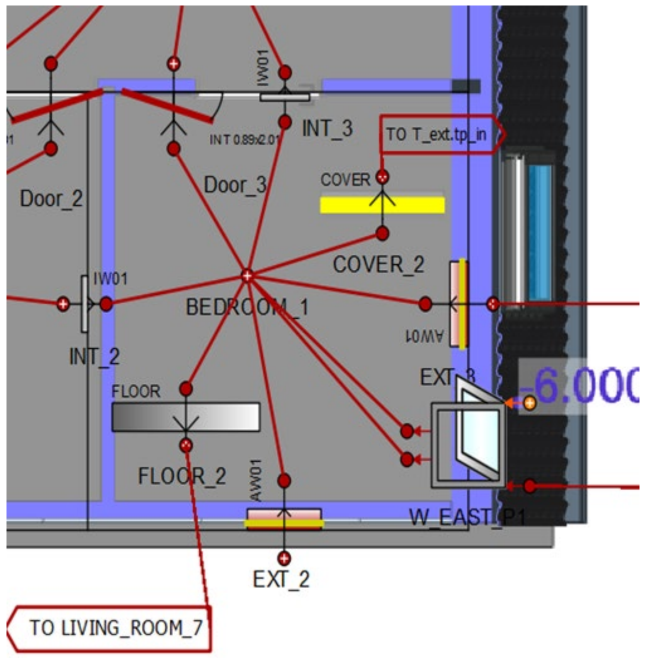



Figure 6: View of components of ventilation simulation




As we see each component is connected with others using 'ports'. There are fluid ports, thermal ports, control ports,... I see big arrows as well connecting ports of different diagrams (in this case we have two diagrams, one for each floor). This model in figure 6 is representing ventilation, but if we represent thermal problems the model would be as follows:

Figure 7: Thermal model of one space for TNO demo pilot



In case of a thermal model the ports are red and we see walls, windows, doors, slabs and cover. And thermal ports can be connected with other floors, rooms and spaces in ventilation.

A single component of a wall is represented graphically by a symbol.

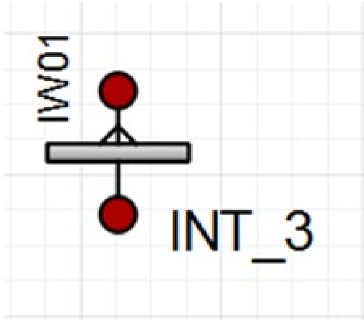



Figure 8: Component of a wall type IW01

This graphical symbol has a mathematical representation behind, which is as follows:

```
COMPONENT Wall_IW01
    PORTS
        IN thermal (n = 1) tp_in  "Thermal inlet port"
        OUT thermal (n = 1) tp_out  "Thermal outlet port"
    DATA
        REAL Area = 1 UNITS u_m2   "Area of the wall"
        REAL To = 20 UNITS u_C "Initial temperature in °C"
    DECLS
        DISCR REAL T_in[5]
        DISCR REAL k
    TOPOLOGY
        BUILDINGS.ExternalWallRC( n=5 ) Wall(
            --Boundary = FALSE,
            mat = {None, None, None, None, None },
            rho = {1600, 875, 40, 875, 1600},
            cp = {1000, 1700, 1000, 1700, 1000},
            To = T_in,
            A = Area,
            d = {0.02, 0.003, 0.02, 0.03, 0.02},
            k = {0.8, 0.2, 0.031, 0.2, 0.8}
            )
        THERMAL.GL(n=1) conv_in(
            cond = k -- We assume h = 7.5 W/m2K
            )
        THERMAL.GL(n=1) conv_out(
            cond = k -- We assume h = 7.5 W/m2K
            )

        CONNECT tp_in TO conv_in.tp_in
        CONNECT conv_in.tp_out TO Wall.tp_in
        CONNECT Wall.tp_out TO  conv_out.tp_in
        CONNECT conv_out.tp_out TO tp_out

    INIT
        T_in[1] = To +273.15
        T_in[2] = To +273.15
        T_in[3] = To +273.15
        T_in[4] = To +273.15
        T_in[5] = To +273.15

        k = 7.5 *Area

END COMPONENT
```

Figure 9: Mathematical description of wall type IW01

We could create new components, increasing the library items available to build the models. These libraries are essential to make all this process economic and fast. Hence it is important to prepare in advance catalogs of equipments to be used in projects. And this is the new concept 'SIMBOT' made up in SPHERE EU project. A SIMBOT would be just a model of one equipment available in the market.

In the case of the ventilation model the home ventilation machine (FLAIR400 of brand BRINKS) is represented by the following component:

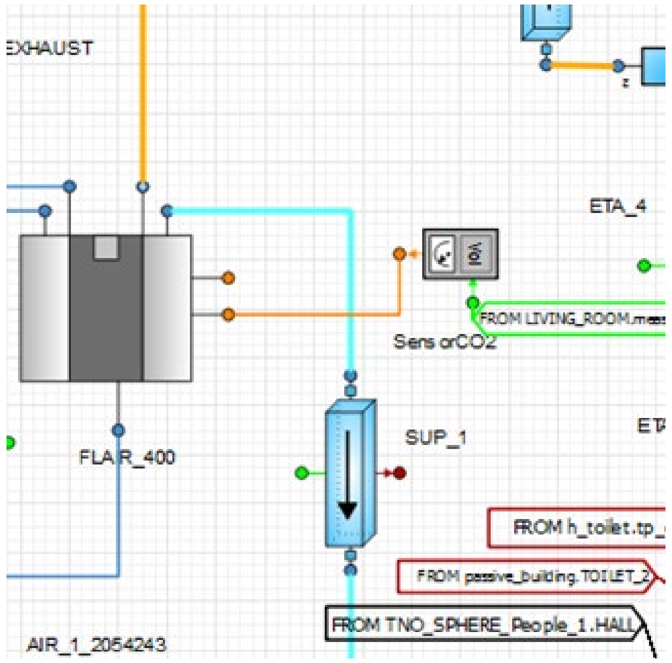



Figure 10: Home ventilation machine component

The component itself (SIMBOT) internally is described by another simulation model:

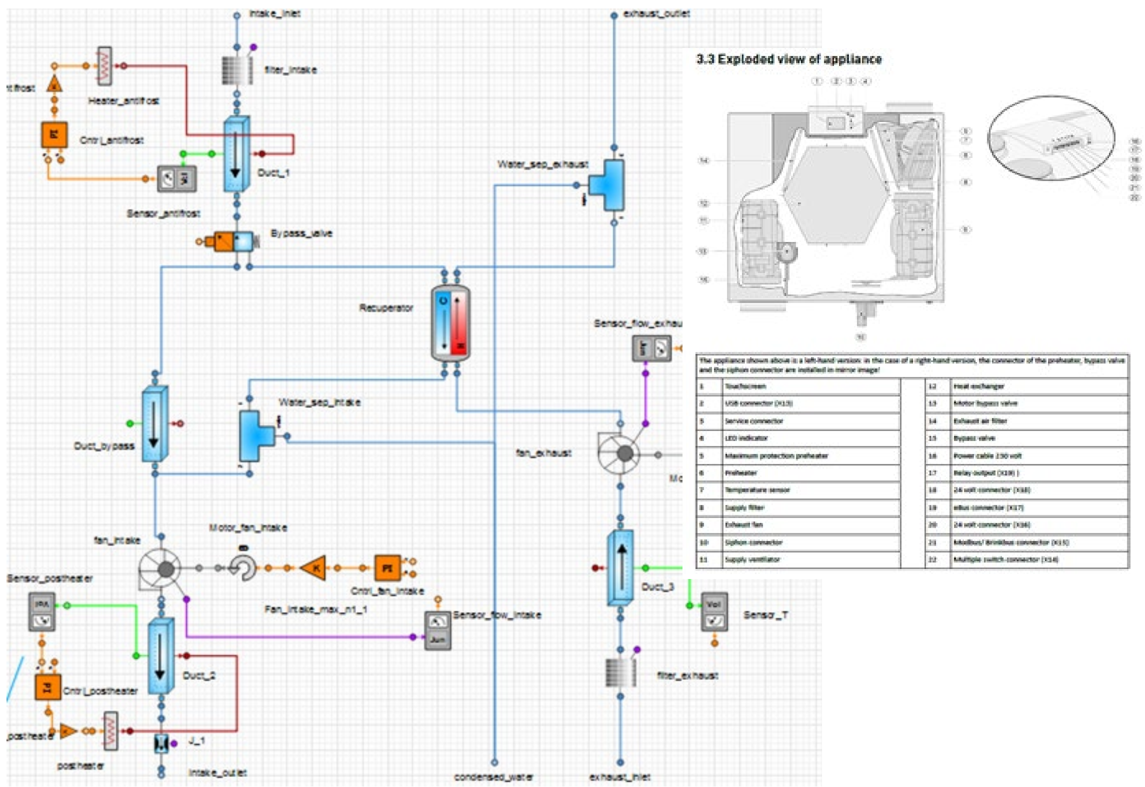



Ilustración11: Flair400 SIMBOT programming



The SIMBOT reproduce how the machine is inside: it has two ventilators, recuperator, bypass, sensors, control signals, filters, ... We would be able to represent the functionality of the Flair400 with high detail. All this components are condensed into a one single symbol and we can play with that symbol is future models.

Implementing standard SIMBOTs to be used massively is posible thanks to standards as FMI, but it is important to define standard ports as well. This task could be performed by the Building Digital Twin Association recently created, providing public connectors to be used with SIMBOTs published by whether fabricators or end users (simulation engineers).

Similar to equipments we can create SIMBOTs representing human models. IN SPHERE EU project human models for ventilation and thermal disciplines have been used interacting with spaces. Using a multiplexor these human models can move around the bulding and they may be specific. This human models will be open and public by the BDTA, in such a way any simulation software could use the models as standard test. More information about these human models will be avilable soon, but in order to be used in real time these models have specific design using the information of a CPX test[11].

## Complexity and Size of the Models

Adding many components and disciplines would create a huge mathematical model. Is such a model affordable? Well, it depends on how the component is created and what is the final use of the model. One single component consuming many equations and convergence problems would make impossible to use that model in real time. So special care must be taken when designing the mathematical complexity of the models. If we want to use the models both for design, commissioning and exploitation of the building components must be designed specifically for real time. This does not mean to lose precision, but simply don´t describe mathematically some of the processes involved internally in the equipment, and in turn to use plots or performance curves. Details about how the equipment performs internally when we want to see the performance of a whole building is a mistake.

In SPHERE project we have tested models of buildings of about 10,000m2 with capacity for being executed in real time (this means they converge in less time that the step used to register the main ambient parameters of the building, which usually are around 600 seconds). But special care must be taken with complex machines with crossed fluid flows.

## Model for Design, for Commissioning and Model for Real Time Control

One of the great advantages of using mathematical simulation with building digital twins is that they can be useful for design, commissioning and the day by day use of the building. The same mathematical model means equations but we can play with boundary conditions and controls around the same core model.

11Cardiopulmonary Stress Test (CPX)

'Design' phase means that we have to introduce synthetic meteo and occupation, and we can consider many alternative options. There are several resources for historical meteo or TMY files, and occupation may be organize with schedules considering different family configuration or occupants of the house.

The final end point of a simulation 'for design' would be an optimum selection of systems and cost, or comfort expected calculation. We can get this information with detail every 10 or 15 minutes, studying dynamics of the buildings and not only static behavior. We could check how predictive meteo control could improve the energy consumption, or how long does it take to heat the house after a long weekend outside.

Once decisions have been taken and the building is ready for construction we can use 'the model' to test parts of the building. The model would be connected whether as 'software in the loop' (SIL) or 'hardware in the loop' (HIL) with the rest of the installation. With some simplification, SIL could be to have the model as 'virtual building' working against the physical control system implemented in site or in the lab. In this way I can test in advance the controls and train the operators of the control room. Sensors are virtual outputs from the simulated model of the building. Finally simulation can be used for commissioning when construction process has finished, checking that installations work as it is expected.

During the life of the building the simulation model can be used as well, and this may open many new challenges, whether by measuring and increasing comfort or by controlling and reducing the energy consumption. People prefers to pay money to get more comfort, and just paying for less Kwh may be not totally understood. In any case to have both things is not a contradiction.

## Meteo and Occupancy in Real Time

The two key problems to use simulation models for real time is just how to input inside the control system the actual and predicted meteo and occupancy. The control system may be just a monitoring device and a PLC for collecting sensors and digital signals.

Today in most of the countries meteo information is well localized and predictions respond quite well to reality. Instead of looking at the sky we check the phone to see if it is going to rain or not in the next couple of hours, the probability in percentage and how much rain in mm. To get this information (and prediction) from the web is something extremely useful and we can introduce the values in the 'control system', and this control system is connected with our simulation model. This simulation model is an exe file which even may be running locally in the same machine than the house controls, or it may be running in the world wide web. Optimizing the simulation components provide compact executable routines which may be integrated in very small electronics. The exchange of inputs and outputs may be reduced to those values we are interested, which means we don´t speak about hundreds but twenty or thirty values in a house, not more. And we exchange these values every 10-15 min with no stress for even a small Raspberry Pi 4B.



## Less Sensors, More Intelligence

To use technology for life support of the ISS could seem excessive, but there are some interesting points to consider. If we have the behavior model of a building we can have less sensors in the field, and we can detect when a sensor is malfunctioning. Having fewer sensors in a house is desirable as it is not an intensive industrial factory full of engineers. It is not only a problem of cost, it is just that they don´t survive for ever. With simulation we can detect that something is not going well not only based in one temperature sensor, but in the rest of the values of the building.

And we can derive many new magnitudes from sensors. Magnitudes which are not measured. For example euros that are flowing across a wall, money we are recovering at the home ventilation machine, virus risk due to lack of ventilation or thermal comfort of human A, B or C. Simulation can be used as a calculator translating the engineering magnitudes (not understandable for the majority of the humans) into economic magnitudes which may be understood by anyone. I could not understand what means 1.2 W/m2 of transmittance, but for sure I can understand much better that the window is losing 1€ every day. Around this stupid consideration may be a catalysis of many user investments improving the house quality or how to open/close windows.

## Simulation Deck Concept

Once the mathematical model of the system is finished the interface with humans may be simplified. In the same way we can create exe files to run in parallel to the control/monitoring system we can implement a table of input/outputs to be used for testing. This is call a deck and it can be integrated in excel.

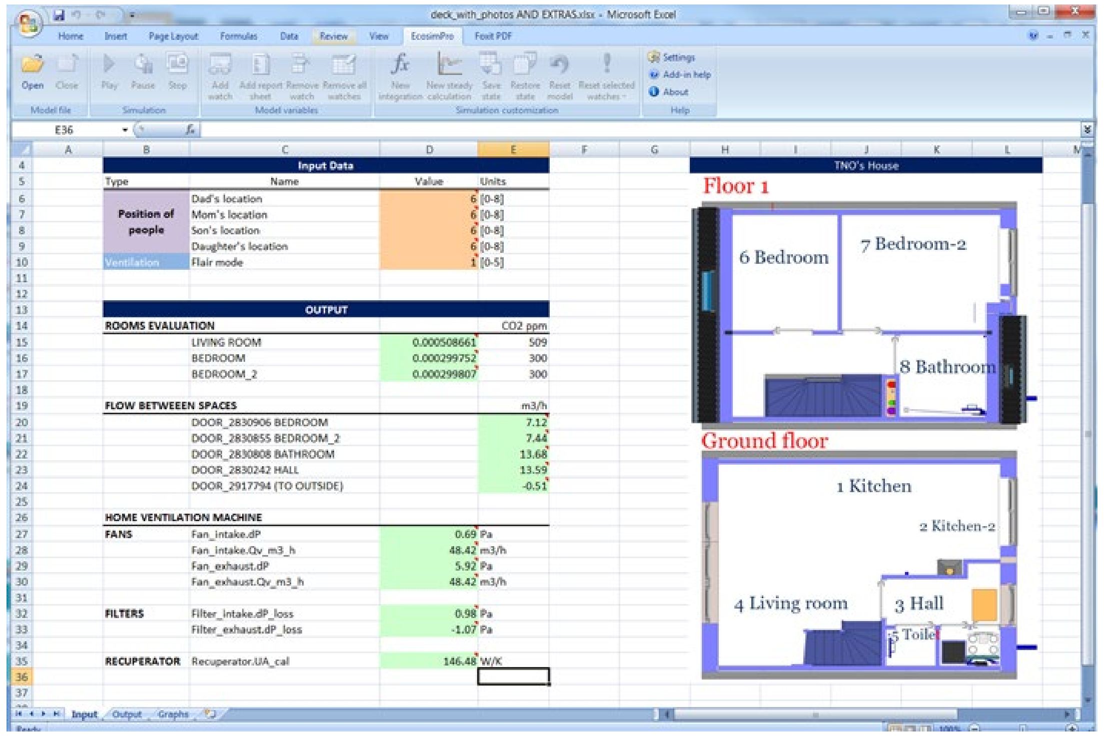



Figure 12: Deck of DEMO pilot TNO ventilation

In the figure we can see the deck generated for the ventilation system of the TNO demo pilot of SPHERE project. Inputs are the manual setup of the Flair400 home ventilation machine and the location of the family ('Value' is the room number). Outputs are CO2 values in the living room and the two bedrooms, flows between spaces (underneath doors), and some parameters of the home ventilation machine (some of them calculated, not measured).

A deck is an excellent way to communicate models before implementing the real time platform and to define which values are necessary to input and output from simulation executable to the control/monitoring system.

## 2.1.- Energy Simulation and BDTs, Reducing the Gap

Energy Performance Certifications were introduced in the framework of European legislation for the first time in 2002. Following the requirements of the first Energy Performance Buildings Directive (EPBD)(2002/91/EC), all the member states had to introduce certification schemes for the energy performance of buildings. The objective of this Directive was to 'promote the improvement of the energy performance of buildings within the community taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. The Energy Performance of Buildings Directive (EPBD 2018/844/EU)[12], has amended Directive 2012/27/EU[13], sending the political signal for modernising the buildings sector using technological improvements in building renovations supporting at least 32.5% energy savings and at least 32% energy from renewable sources by 2030 in line with the Energy Performance of Buildings Directive (EU) 2018/2001[14].

The EPBD was the first EU directive that prescribed that EU Member States should apply a methodology at a national or regional level to certify buildings' energy performance based on a general framework. Although the initial scope was to define a common frame for all the countries, the implementation of the EPBD at the country level has varied significantly in the introduction and performance level. So, the Directive did not contain requirements or guidance related to the ambition level of such conditions. Consequently, building regulations in the various Member States have been developed by using different approaches (influenced by different building traditions, political processes, individual market conditions, and technical limitations for establishing the energy parameters). Additionally, it resulted in different ambition levels where cost optimality principles could justify higher ambitions in many cases. These big differences have made it difficult to get a homogenous vision of implementation at the European and cross-comparisons countries. This problem presents an opportunity for the concept of the digital twin. This multipurpose solution can serve to create a common framework from which to support EPCs.

12 Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency (OJ L 328, 21.12.2018, p. 210)

13 Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (OJ L 315, 14.11.2012, p. 1).

14 Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (OJ L 328, 21.12.2018, p. 82).



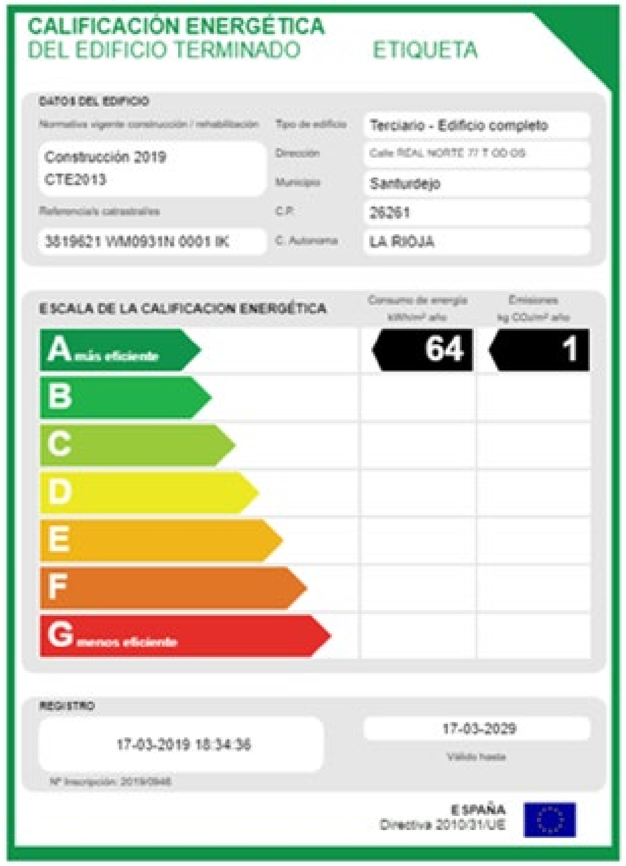



Figure 13: Spanish certification tag

In another way, The EPBD defined that member States have flexibility in the software tool to perform the calculations and in all the related aspects of practical implementation. This flexibility has led to a non-so homogeneous energy certification implementation as it was initially expected. However, some suggestions include operational data, such as actual billing data on EPCs to overcome the performance gap and ensure that the EPC reflects actual building use. However, the use of billing data directly on the EPC, such as the annual energy cost or the annual consumption, would capture the effect of occupant behaviour as well as the performance of the building, and would therefore move away from EPCs comparing building behaviour as such. In addition, there are potential data protection issues with billing data included directly on the EPC as this is more personal to the building occupant.

Next-generation eEPCs shall adopt a single neutral approach that will integrate systematically and accurately information collected and processed under the digital twin to integrate different energy performance approaches, ensuring data quality and avoiding assessment errors highlighted in several papers. Digital Twin will tackle this problem by introducing a methodology that will allow, with building occupant consent, smart meter data to be used in conjunction with other data, such as internal and external temperature, to model the thermal performance of a building. For that, the proposal is coupled the digital with a new concept of direct method of calculation according IEA BESTEST[15]. This option will reduce the

15 International Energy Agency Building Energy Simulation Test and Diagnostic Method, https://www.nrel.gov/docs/fy08osti/43388.pdf

performance gap by allowing ‘as built’ performance data to be used in an EPC rating while also factoring out the effects of occupant behaviour so that the EPC rating remains reflective of the building itself. It could also simplify the process of generating an EPC and improve the repeatability and accuracy of EPCs. Any use of smart meter data would require the householder’s consent, in line with data access and privacy requirements. This methodology will better understand the market demand for these technologies and possible routes for their development and implementation.

The building models used in EPC schemes are quite precise; a more detailed modeling of the archetypes allows for even more accurate simulations, considering for example the real position of the windows, shape of the roof, or real building schedules. However, this information is too complicated to get (LoD 300 or 400). In addition, 3D models simplify the process of obtaining the real geometry of the buildings in a district greatly. The difficulty in producing detailed building models should solve using real measurements of buildings to calibrate or correct simplified building energy models. So, BIM solution. These detailed multi-zone models should be developed in parallel to a building monitoring campaign of the archetype buildings, which would allow model calibration and the development of the energy baselines.

In conclusion, using BIM for geometric and constructive description and measurements integrated in BIM for operational description, the double certificate can be obtained: energy performance certificate with the standard user and real user. Standard user is useful to evaluate the building when it is going to be bought or sold (conventional use of EPCs). Real user requires measurements and it is useful to consider the user behaviour and the final use of the building. This option should be used when the building is going to be renovated (new use of EPCs).

In conclusion, the recommended road map of EPC presents three levels. First, it is the mandatory scheme using the standard user. Second requires the actual energy situation of the building (real user), and it is used when you are going to renovate the building. The third level represents the last step, the smart management of the building. The second and third levels require the use of calibrated energy models or inverse characterisation models. Building energy models need to be calibrated at the second level to reduce the performance gap and consider the actual thermal behaviour. Automatic calibration allows assessing the cost/benefit of improvement measures in rehabilitation interventions. It is interesting to highlight that calibration of a detailed direct model lets to evaluate the potential of complementary or alternative Smartness actions to conventional improvement measures. At the third level, the inverse characterisation model provides the baseline for verifying savings when measures are implemented. The inverse characterisation joined with the direct model provides a new tool that configures the digital twin. Also, the tool allows optimal energy/economic decision-making in the adoption of smartness adoption.



## 2.2.- BDTs During Design and Construction

Digital Twin Construction (DTC) is a paradigm for the construction industry in which production is planned and controlled with the support of extensive data collected from the supply chains and the site which provides comprehensive situational awareness for all[16]. Monitoring technologies of various kinds – including audio, images, RFID and BLE tracking systems, equipment ‘black boxes’, IOT sensors – are applied to supply real-time tracking of the physical conditions on site. The raw data is processed within the context provided by product designs (mainly BIM models) and process plans (production facilities, logistics, schedules, budgets) to generate useful information that describes the status of the project at any time. Comparing the current project status to the project intent information allows one to draw conclusions about current performance, in terms of the quality of production flow, safety performance, quality of the products built, and schedule and budget progress.

But how can that information be leveraged to improve production planning and control? This is a key question, whose answer will determine the value of Digital Twin Construction platforms.

In theory, better situational awareness, i.e. knowing what is happening on and off site with great detail, supports better decisions by people when it comes to making changes to the production system on site. Managers may decide to add or remove a piece of major equipment, such as a crane; to request a subcontractor to work overtime; to change some aspect of a building’s design; etc., all dependent on the scope and time resolution of planning and control cycles. Yet these are highly complex systems, and **good decision making is also dependent on the ability to predict future outcomes for any given intervention**. Construction process simulation provides an effective solution. A good process simulation tool can help determine the range of outcomes expected given any starting scenario and a schedule of changes planned over time. It can provide estimates of the probability of each possible outcome, thus shedding light on the risks involved.

In the DTC context, simulation software can exploit the current project status information to set up the starting conditions – what work in the project has been done, which objects are completed or under construction, what resources are present and what are the trajectories of their production rates so far. It can also exploit archived records of previous DTC records to learn patterns of production, potential bottlenecks, and possible product/process interdependencies that cause fluctuations in production flow. Critical path method simulation tools might simply extrapolate deterministic construction network schedules into the future using distributions of predicted activity durations. Richer, more accurate simulations would apply agent-based simulation to progress construction activities into the future with dynamic assessment of production constraints for each task as work progresses. The latter are far more likely to reflect realistic patterns of behaviour because the underlying model applies concepts of production flow in construction[17].

16 Sacks, R., Brilakis, I., Pikas, E., Xie, H., and Girolami, M. (2020). ‘Construction with Digital Twin Information Systems’, Data-Centric Engineering, Vol. 1, pp. 1-26.

17 Sacks, R., (2016). ‘What constitutes good production flow in construction?’, Construction Management and Economics, Vol. 34, No. 9, pp. 641-656.

With the ability to test 'what-if' scenarios that reflect the range of actionable decisions open to them, construction managers at all levels will have valuable information at hand to aid them in planning and controlling production both at the start and during the execution of their projects. Thus, simulation builds on the first major advantage of DTC, situational awareness, to give construction managers a second significant advantage – a layer of predictability.
The power of predictive simulations of construction processes can be exploited further by wrapping simulations within optimisation routines, such as genetic algorithms. In this way, DTC software systems could not only advise managers on the likely outcomes of interventions they propose, but they could also devise new sets of interventions that are likely to have superior outcomes.

## 2.3.- BIM Models and SIM Models, how to Improve the Linkage

Before performing any simulation a design or at least a basic concept of the building must exists. A BDT Manager (external to the simulation) must define the starting point. And one way we exchange a building 'design' is using an open BIM structure (whether as an IFC file or the IFC data structure in other formats). We could be using more traditional ways to represent the building, form handmade drawings to CAD floor plans, but the power of the IFC standard is to bring together geometry and properties with a great level of definition.
But even having a good graphic definition and lot of properties scope of simulation may need an amount of information and disciplines that the designer is not able to supply. So BIM models many times are not correct, they don´t have the properties we need for simulation, the properties that include are senseless and even they don´t have basic entities we need for the simulation, as spaces, installation networks and similar. They are 'designs', not rigorous 'engineering projects'. The BDT Manager role would be coordinating and correcting this process in order to be as closer as possible to a defined project.

In any case it would not be fair to say that BIM is not bringing an advanced and great communication tool for architects and engineers. Problems are more evident and they are detected in minutes, even for non construction professionals. We are able to get simulation teams of physicians working well with architect´s 3D buildings.

To define how a BIM model must be delivered is a general question in many organizations today. In case of SPHERE project we decided to have a flexible process in which we were receiving IFC models creating components and simulation models based on different ways to design the demo pilots. Attending disciplines we generated several 'checking rules', first for a basic global 'model correctness' and later deeper and rigorous criteria for ventilation installations.

Today it is difficult to find good IFC models with installations. Preventing this problem we were testing synthetic models with detailed installation of ventilations, testing the exchange between IFC and simulation. Even in the case of well calculated and detailed models some problems must be considered. Depending on how library components are generated relationship between IFC entities and simulation components is not 1 to 1. If we consider networks runs as 'one simulation component' the entities in the IFC model may be several straight pipes and elbows. Whereas equipments are easily associated to one single



component, in case of other details of the building (mainly networks) they may be simplified in the simulation model. But this depends on the library created in the simulation scenario, so different libraries could have different mapping tables of entities versus simulation components.

Instead of fully automatic translation from IFC to simulation model we could think on a semiautomatic translation, preparing the IFC models to be translated by disciplines and groups, or just to program 'checking' routines instead of 'translation' ones.

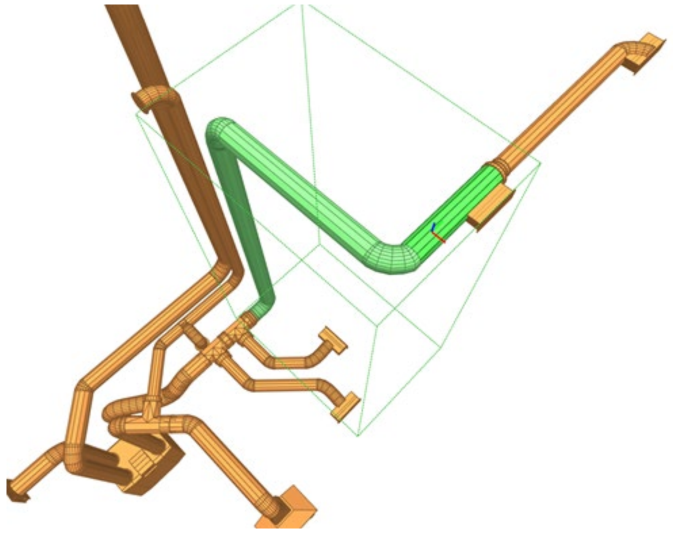


Figure14: IFC model of ventilation network; 'SUP_5' component highlighted

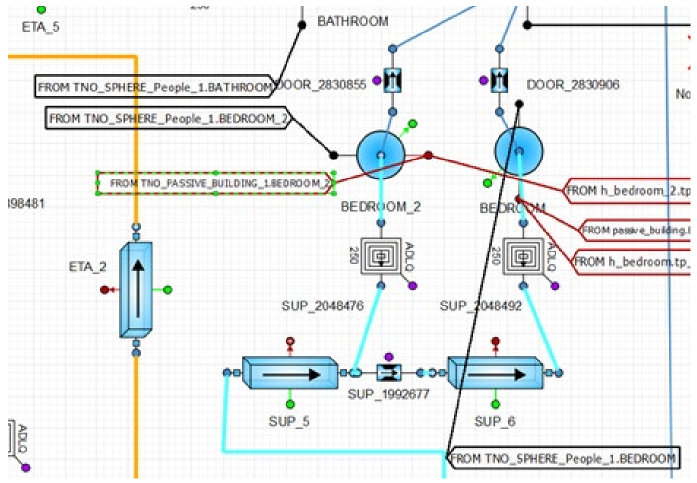



Figure 15: Simulation component SUP_5

As we see in the two images above, the IFC entities highlighted of the network finally are a single simulation component (SUP_5). And it is likely unavailable connectivity between components, as it is not exported in most of the CAD programs. So translation may be a hard route to follow, and probably not given the expected results.

More important than translation is consistency on data. Simulation components must have faithful parameters taken from whether the BIM model or reality. Consistency checks are critical and necessary, and it is not a wonderful activity in which everyone wants to participate. However as important as creation of the model. Checking routines would have much more profitability than translation.

Many software programs tested during the development of SPHERE project were preparing the simulation from inside the CAD. This is the case of ESBO[18] from inside DDS-CAD[19]. Or the case of CypeTherm from inside the Bimserver.center[20] environment. Other programs may be able to create/import the model, but always with great control of details to ensure consistency with calculations (as Simergy[21]). Most of them are conceptual programs and not designed to be used in real time, with full detail of the building and controls. So oriented only to the design phase of the life cycle of a building.

In advanced simulation oriented to real time exploitation of the building we need additional information to what we can extract from IFC models. Re-construction of simulation models need schedules, controls, performance curves, connections, ... We are still far away from defining everything at the IFC model. So where to find this information? Meteorological input and occupancy during design can be represented with historical data (or TMY files) or schedules for human models. But in real time those data must be collected and directed to the simulator, so we need a explicit way for doing it, hardware and software.

And going back to the conversion problem of BIM models into simulation we should consider the way back: using simulation to update or illustrate BIM models. This should be an easier task and more graphical, adding value to the 3D models in real time.

## 2.4.- Monitoring the Real Building

Monitoring a building is a sampling problem and estimation of what we considers 'true'. Buildings with high value per square meter can have attended and sophisticated automatic sensors and equipment, but this does not happen in residential. We face not only a problem of fewer sensors, they may be cheaper and not attended or maintain at all. How could we justify an investment on those sensors?

If we want to control our residential environment monitoring or measuring reality is necessary. We must detect how is exterior temperature to decide whether to switch on the heating or not. It may be done by an automatic device or manually, but the fact is that temperature must be measured. How many sensors or accuracy and precision is another question.
The number of sensors should be adapted to the number of controlled spaces. And residential construction always follows a standard number of rooms and spaces. So we speak of less than 10 ambient sensors and those which are included in equipment as a home ventilation machine. They are not hundreds.

18 https://www.equa.se/en/esbo
19 https://www.dds-cad.net/
20 https://bimserver.center/en
21 https://d-alchemy.com/products/simergy



Precision and accuracy depends on several factors. Accuracy refers to how close measurements are to the "true" value, while precision refers to how close measurements are to each other. A thermal sensor may have plus minus 1 degree C of precision and they are usually accurate. But CO2 sensors may have plus minus 50 ppm precisions (normal values of 400 to 850 ppm) and they are very inaccurate, so we need frequent calibration. What is important is that 'monitoring' is not 'reality', so we must consider statistical errors and deviation for taking (or not) decisions. Many problems arise from over controlled systems.

Measurement may be sampled every second, but finally it is going only to transmit one value every 10 to 15 minutes. Sensors today can perform many low level operations providing treated values at low cost. Transmitting those values can be executed by cable or a series of frequencies and standards, and at the end we will have a hardware and software system, reproducing historical data and tendencies in a human machine interface. And perhaps together with monitoring we may have a controller (PLC) and simulation engine integrated.
Discussion about where and how to locate these systems may have a privacy implication and it will be treated at the chapter of trustworthiness and privacy.

Additionally to resident instrumentation it will be necessary to use some instruments for testing air tightness, flow in diffusers or noise of ventilations systems. As it has been described in detail by TNO[22] , SPHERE partner, for performance contract of ventilation systems.

## 2.5.- Virtual Commissioning

In 2017 the team of PhD Enrique Blanco Vinuela, Control Engineer and Head of the Control Systems Engineering Section at CERN Laboratory, had to take a decission about the LHC (Large Hadron Collider) upgrade. It had been operational since 2008 and for 9 years no major improvement was done on ATLAS and CMS HVAC plants. They had to solve an obsolescence problem (SCADA was not supported anymore) and PLCs were at the end of life. They wanted to migrate control to the CERN UNICOS framework and it would be interesting to take into account all the experience gained during the LHC operation to improve operation and availability. Lot of manual actions were necessary at that time.

Due to very strict conditions to carry out the smooth transition and a limited time for the new installation they decided to go ahead with a "virtual commissioning". It could be done off-line, they could be simulating the installation testing different control strategies and it could be useful for training operators as well. They had to develop a physical model of the building first, in order to use it against the new control system to be implemented.

22 'Commission and performance contracting of ventilationsystems in practice.Determination, analyses and consequences forpractitioners and contractors'. By Wouter Borsboom, Wim Kornaat, Pieter van Beek, Niek-Jan Bink andTimothy Lanooy.

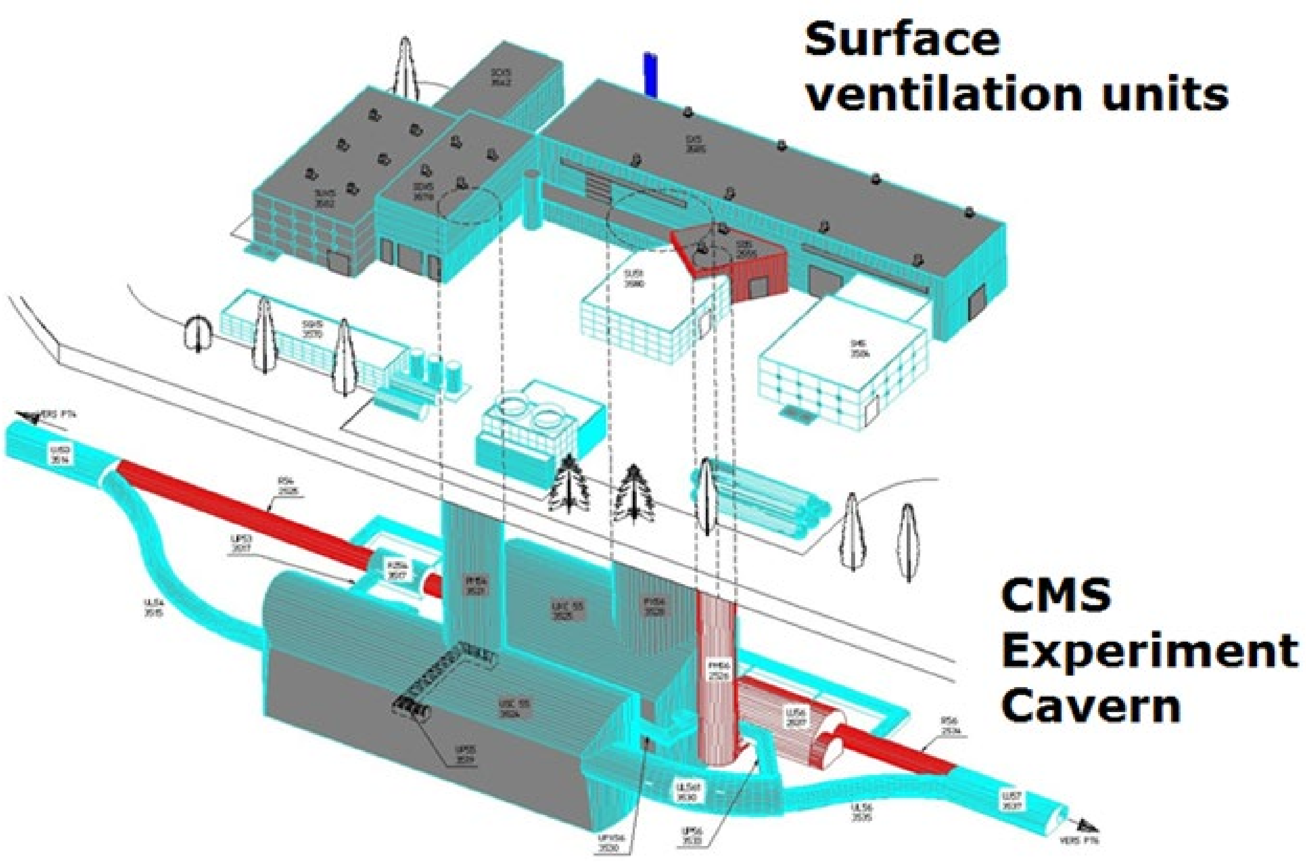



Figure 16: CERN CMS and Cavern

To implement their “artifact replica” they had to review P&IDs, Equipment datasheets, maintenance reports, duct routing, GA drawings, I/O lists, PLC programs, HVAC commissioning reports, and finally of course they discovered inconsistencies, missing data and problems. This is not a task lazy engineers. As Dr. Blanco explains, they had to “use a shovel and pick and dig”[23].

For representing the basic HVAC components they developed a simulation library with the software ECOSIMPRO[24]. Using the right connectors you can simulate mathematically all fluids and ambient conditions, and equipment working in real conditions. They performed many validations of the library even with real historical data they have recorded. Of course not everything was perfect and manual adjustments were necessary due to lack of information, but process model was finally responding as it was expected.

23 Virtual control commissioning for a large critical ventilation system: The CMS cavern use case, by Booth, William (CERN) ; Blanco Viñuela, Enrique (CERN) ; Bradu, Benjamin (CERN) ; Sourisseau, Samuel (CERN)

24 https://www.ecosimpro.com/



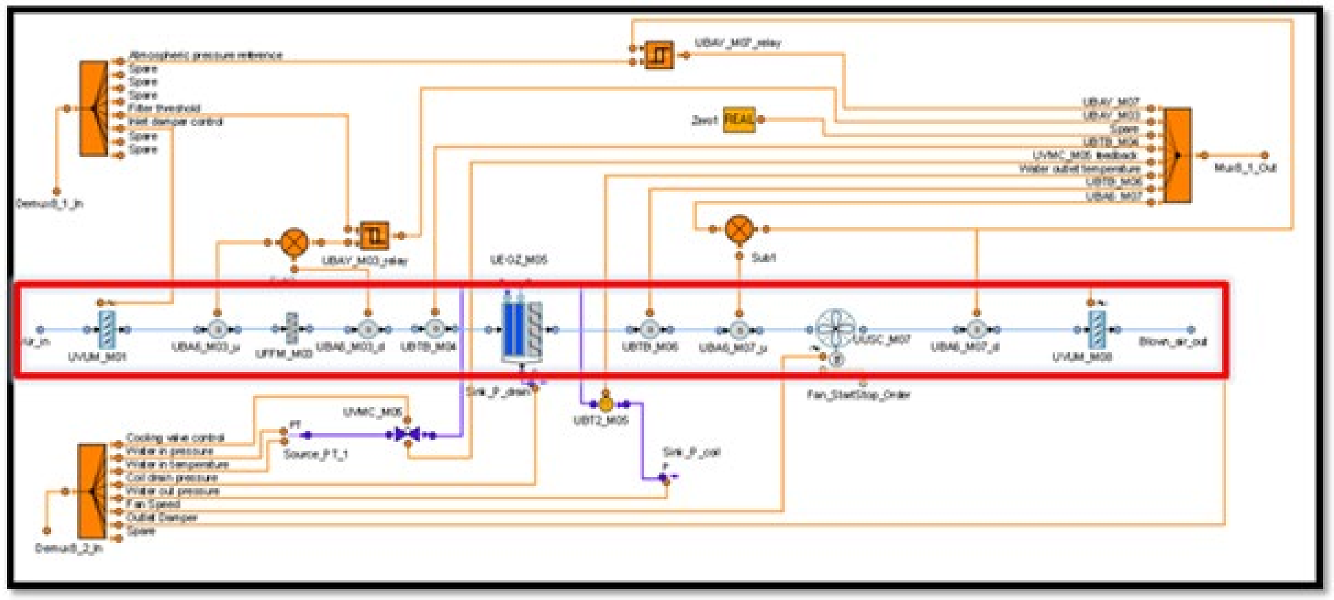


Figure 17: CERN model: in orange control components

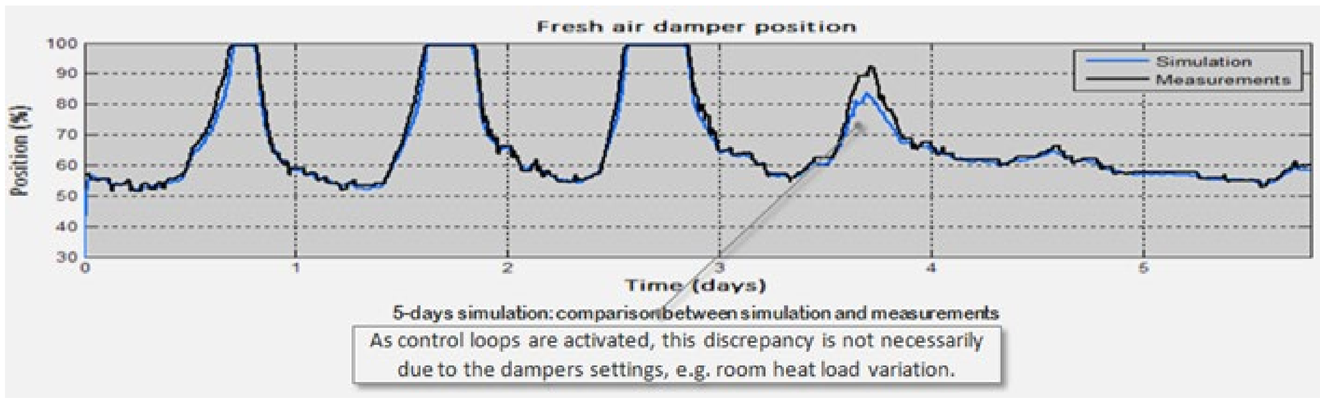



Figure 18: CERN 5 days simulation and validation

The new control system was at the same time developed by the Cooling and Ventilation team at CERN. And more testing with PLCs at the lab was done to test communications and new SCADA system. One day the new control implementation was decided and the new control systems tested against the virtual process model. *“Various operating scenarios were performed over a period of several hours, including different discrete events: a step-by-step start-up, gas detection, cap opening/closing, equipment failure and acknowledgement. These demonstrate the possibility to adapt the control automatically while keeping the regulation loops active”*[25].

25 https://cds.cern.ch/record/2306216/files/modpl02.pdf

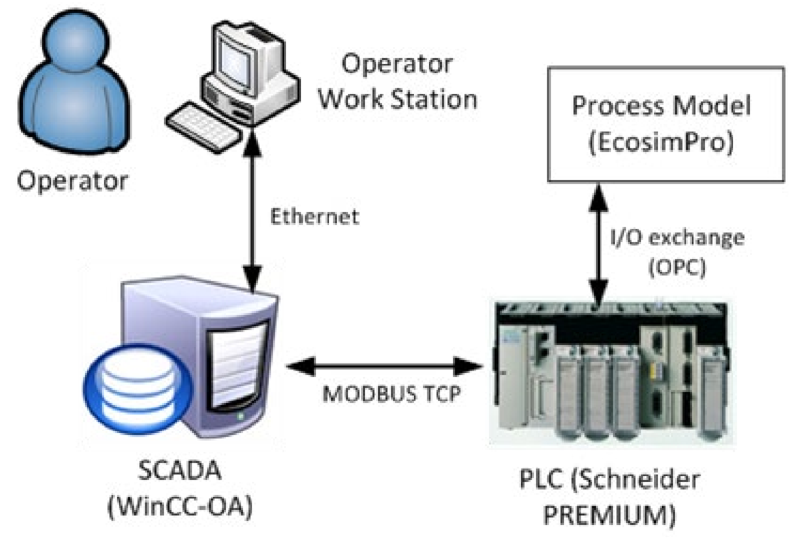



Figure 19: Hardware setup o control system and process model

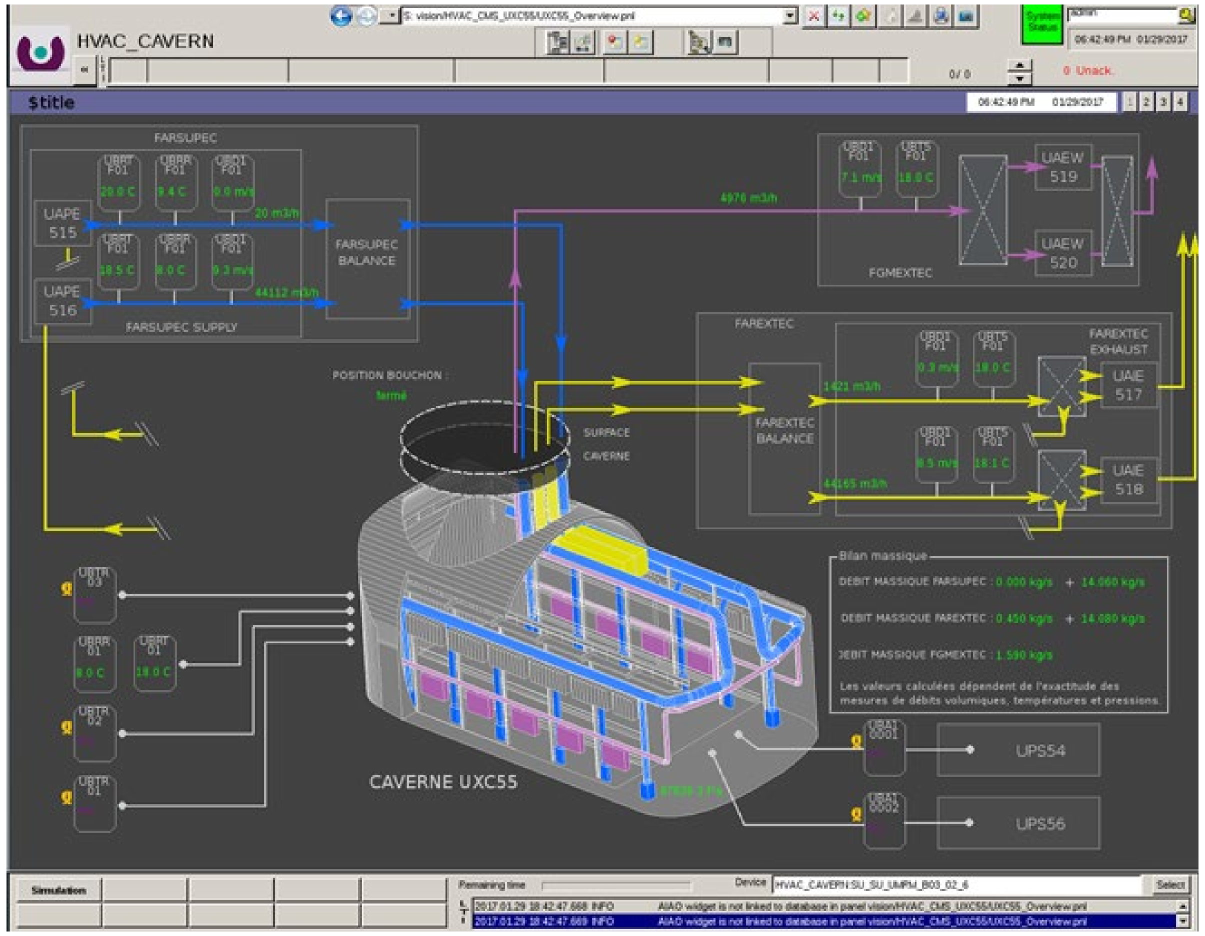



Figure 20: Cavern CMS UXC55 SCADA

Even considering that modeling the process model was essential for the design and concept of the new control algorithms, it is not anecdotic the use for training the operators, as it is common to have a catastrophic event starting up a plant. To be able to train the operators in advance against a simulator should be a common practice in any installation.



## 2.6.- How a Digital Building Logbook Impacts the Digital Twin Uptake

The digital building logbook plays a pivotal role in the digitalization agenda of the construction sector.

There exist a large number of building information databases out there such as public registries, national EPC databases, or other schemes including life cycle assessment or energy and water recordings. The purpose of the digital building logbook is to unify the access to all these data sources by becoming a common gateway. A digital building logbook can also act as a common repository that stores relevant data. According to the “Study on the development of a European Union framework for digital building logbooks” commissioned by the European Commission, a digital building logbook can be defined as a “dynamic tool that allows a variety of data, information and documents to be recorded, accessed, enriched and organized under specific categories. It represents a record of major events and changes over a building’s lifecycle, such as change of ownership, tenure or use, maintenance, refurbishment and other interventions. As such, it can include administrative documents, plans, description of the land, the building and its surrounding, technical systems, traceability and characteristics of construction materials, performance data such as operational energy use, indoor environmental quality, smart building potential and lifecycle emissions, as well as links to building ratings and certificates. As a result, it also enables circularity in the built environment”. In this sense, digital building logbooks have a significant role in facilitating information-sharing within the construction sector and between building owners and tenants, financial institutions, and public authorities. Access and processing of reliable data will foster the roll-out of entirely new business opportunities for design, construction, operation, leasing, financing and real estate transactions.

The diversity of the building data requires nevertheless the development of digital architectures capable to manage the linkage of different databases. Internal linkage processes should respond to manipulation challenges such as data verification, hierarchization of the main linkable keys, deduplication to decrease computational time, or compression to facilitate the exchange. Building digital logbooks have to be capable to deal with static (e.g. building administrative information) and dynamic data that require regular updating (e.g. information coming from smart meters and intelligent devices). Besides, building digital logbooks should enable interoperability between the difference databases, integrate their respective functionalities and facilitate data exchange between different users, while at the same time ensuring legal compliance. Information structures such as the Construction Operation Building Information (COBIe)[26] or the “Formato de intercambio estándar de bases de datos para la construcción” (FIEBDC-BC3)[27] are standards that regulate and oversee the exchange of information in the building sector. The FIEBDC-BC3 is operational since 1996 as a common language to exchange and synchronise building information across the different autonomous regions in Spain. It was developed by seventeen companies looking for a practical method to facilitate the interchange ability of their data. Several Spanish consortia use the FIEBDC-BC3 standard to coordinate international construction. The practice of common language use has been evaluated as very positive and a clear asset for large and complex project developments.

26 https://www.thenbs.com/knowledge/what-is-cobie
27 https://www.fiebdc.es/

A digital building logbook can be a key enabler in the successful uptake of digital twins as it could offer accurate and updated data. Digital twins use artificial intelligence, machine learning and data analysis to process that data and create updatable digital simulation models of building systems (e.g. physical building properties or BACS). With the complexity of the digital twin increasing as the result of the combination of single building elements into systems of interconnected pieces, the value of the digital logbook becomes even more important. The interconnection between the digital building logbook and the digital twin opens up very important applications for system resilience. For instance, in the face of a pandemic outbreak transmitted by airborne agents (such as the COVID-19), digital twin models of the ventilation systems could be massively applied to the database stored at the digital building logbook in order to detect the buildings with the highest chance to transmit the disease. Similarly, building aggregated information made available through the combination of these two technologies could be used to optimize the production and consumption of local energy. “Virtual Singapore”, a digital twin of Singapore is a lead exponent at this level and it uses periodically updated sensor data to monitor energy use, air conditioning and lighting adjustments.

A concrete example of the potential of data access is the use of updated information to run models that allow fighting critical safety situations. The firemen who rush to extinguish a building fire could use the travel time to access critical information (e.g. building plans) from the digital building logbook and even launch some quick models using a digital twin to predict how the fire will spread (Figure 1).

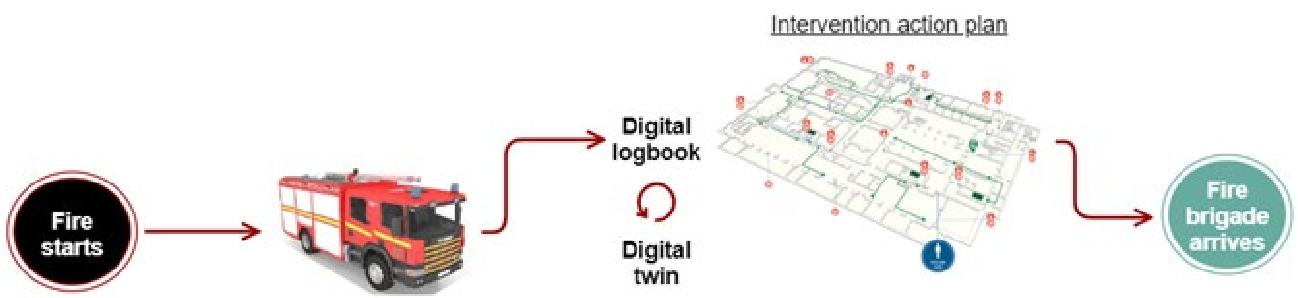



Figure 1: Schematic view of how a fire brigade could use digital information contained in the digital logbook (e.g. building plans) to access relevant data online and anticipate the fire extinction strategy. This and other examples emerged during the Digital Building study commissioned by the EC1

Digital building logbooks are also a promising tool to promote tailored building renovation. The *logbook data quest* within the iBRoadproject (Libório et al., 2018)[28], proposes the use of a continuously updated repository to store building-related information and support the creation of a customized renovation plan that extends over time (10-20 years). The type of information contained in the repository aims at triggering deep renovation and includes a large variety of building inputs such as administrative information, building energy performance of smart technology (see Figure 2a). The logbook database can be used by whole ecosystem of stakeholders (e.g. energy providers, construction industry, research and academia, etc; Figure 2b) although only populated by certified actors (Libório et al., 2018). Some private brands have

*28 Libório, P., Fragoso, R., Sousa Monteiro, C., Fernandes, J., Silva, E., & Casteele, T. Vande. (2018). The logbook data quest - Setting up indicators and other requirements for a renovation passport. IBRoad Project, (July 2018), 54.*



also developed their own digital building logbook version. Such is the case of Schneider Electric and the *‘EcoStruxure Power’* product[29]. Electrical diagrams are sensitive information for the maintenance of the building, and EcoStruxure Power offers digital resources from the design documentation, construction and maintenance phases. The group declares the reduction in the cost of ownership and an optimized maintenance as the main benefits of the approach (poorly maintained switchboards are 62% more likely to fail). Coupling the information contained in digital building logbooks with digital twin models can promote the digitalization of the construction sector, underdeveloped in comparison to other industries. Besides, the existence of common data repositories can contribute to risk reduction, increase innovation and encourage investor confidence.

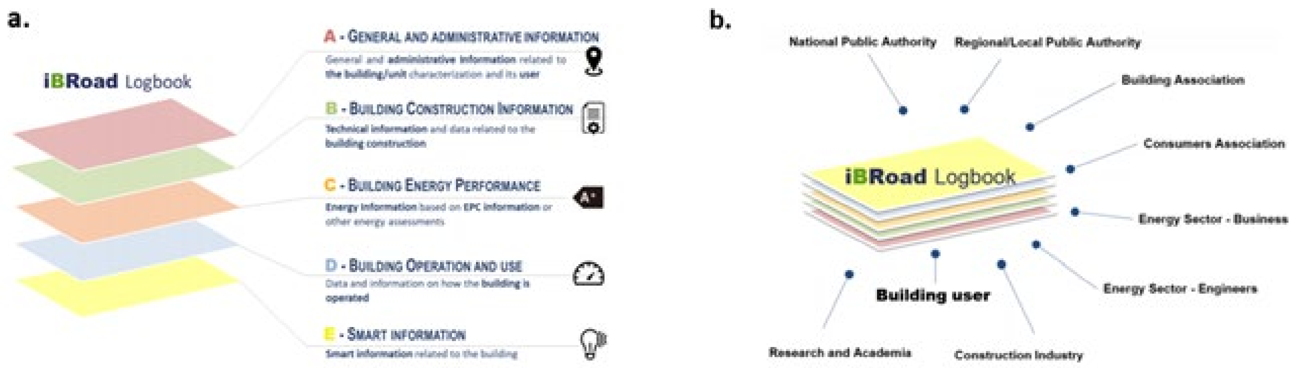



Figure 2: Part of the stake holder ecosystem interacting with the iBRoad scheme. Adapted from Libório et al., 2018

## 2.7.- Kubik Case[30]

KUBIK is an infrastructure born in 2010 to enable the development of new concepts, products and services to improve the energy efficiency of buildings. The main characteristic of KUBIK is the capability **to configure realistic scenarios** to assess the energy efficiency obtained through the optimised interaction of envelope solutions, intelligent management systems (HVAC and lighting) and energy supply from renewable sources.


Figure 21: KUBIK facilities at Derio (Bizcaia, SPAIN)

29 https://download.schneider-electric.com/files?p_Doc_Ref=998-20593900_GMA
30 https://www.tecnalia.com/en/infrastructure/kubik-experimental-building

This R&D infrastructure offers a **full-scale experimental building** which provides up to 550 m2 distributed in an energy systems basement and three storeys for research and demonstration activities. In addition, KUBIK is connected through a smart thermal network to a nearby experimental building, thereby enabling research activities focused on the development of innovative **district heating** solutions.

The supply of energy is based on the combination of conventional and renewable energy systems and active facades. In addition, the building is equipped with a monitoring and control system which provides the necessary information for the R&D activities.

During the last two years KUBIK has gone through an upgrading process to transform it, through a **dedicated Digital Twin solution**, into a completely digitalized infrastructure. This solution, integrated into the legacy BEMS/SCADA system of KUBIK, has been built on top of a 3D model created according to the BIM Methodology. Through this technology real time access to the results of ongoing experimental activities becomes possible from any place in the world.

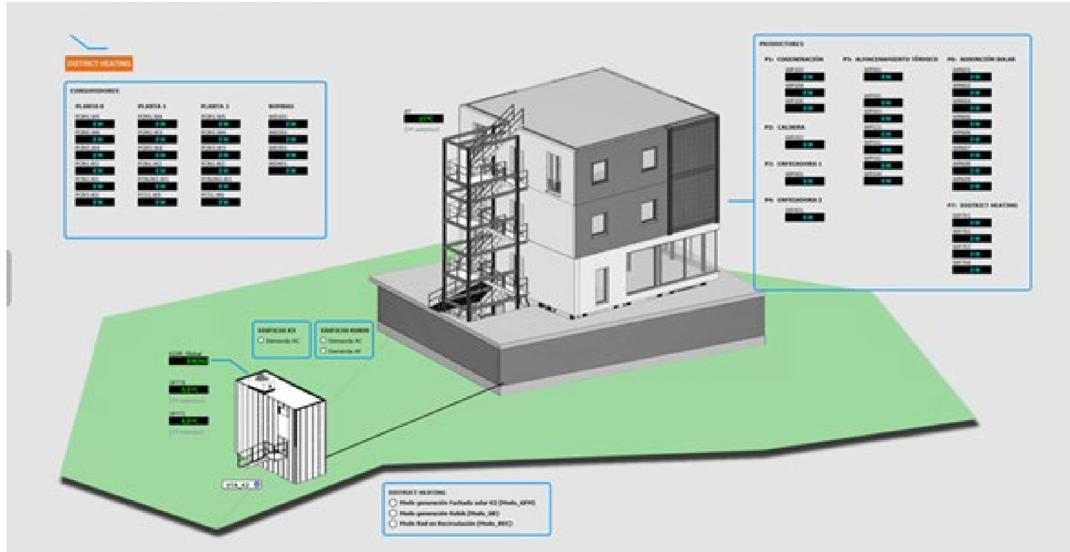


Figure 22: Kubik BIM model and BEMS interface

More specifically, the Digital Twin of KUBIK has been deployed as an additional layer on top of the BEMS of the facility to supervise, without human intervention, the operation of all of the systems existing at KUBIK and the low temperature smart thermal network (with bidirectional heat exchange). This Digital Twin incorporates an energy management optimization service and a predictive maintenance service with diagnosis and prognosis functionalities for the main equipment, thereby allowing the development of new advanced processes in the energy and maintenance domains in the building and district context.

The energy management optimization service based on a Model Predictive control approach provides continuous commissioning and flexible load (thermal and electric) management optimization functionalities to minimize energy consumption and maximize Distributed Energy Resources coverage (solar thermal facade and solar thermal collectors).

The energy management optimization service consists of the **climatic prediction engine, user behaviour prediction engine**, **energy prediction engine** and **optimization engine**



that allow optimizing the operation of the facility according to the forecasted evolution of climatic conditions, energy prices and user behaviour.

The prediction engine incorporates an Energy Digital Twin (co-simulation predictive model) of the infrastructure developed by taking advantage of the potential provided by the Functional Mock-Up Interface standard (FMI) to couple an EnergyPlus model of KUBIK, including all of the locally deployed energy systems(e.g. heating/cooling generation plants solar thermal collectors, etc), with a Modelica model of the smart thermal network consisting of the distribution infrastructure (e.g. thermal network, pumping group, substations) and the solar facade deployed on the nearby building.

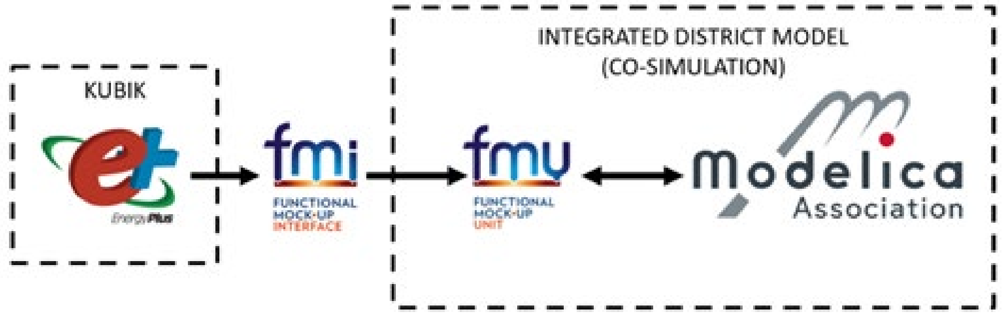



Figure 23: Simulation engine

The Energy Digital Twin can produce predictions for all of the systems of the facility operating according to alternative management strategies. These predictions are exploited by the management optimization service to enable continuous commissioning functionalities, allowing real time optimization, without human intervention, of all of the settings and schedules involved in the orchestration of the operation of the facility (e.g. heating/cooling production and distribution set point temperatures, pump pressure settings, air supply temperature set point of the ventilation system, etc).

According to the results obtained in the testing and validation activities completed at KUBIK, the functionalities provided by this new operation management optimization service, can generate up to 30% savings depending on the use and the energy systems existing in a specific building.

## 2.8.- Other Types and Strategies of Simulations

### Simulation of Ventilation

'Breathing' uses chemical and mechanical processes to bring oxygen to every cell of the body and to get rid of carbon dioxide. Our body needs oxygen to obtain energy to fuel all our living processes. Carbon dioxide is a waste product of that process. The respiratory system, with its conduction and respiratory zones, brings air from the environment to the lungs and facilitates gas exchange both in the lungs and within the cells'[31].

31 Every breath you take: the process of breathing explained - 08 JANUARY, 2018 - Nursing Times

In detailed respiratory human models there are two systems to be consider (external and internal respiration), with the lungs exchanging $O_2$ and $CO_2$ and the circulatory system transporting oxygen to the cells. Such models are complex and may have several nodes to consider trunk and members. Using those models for real time advanced control in residential buildings may be a wrong approach, if we consider that these models typically generate thousands of equations and in site we will have small machines.

On the other hand construction codes about ventilation usually consider concepts as renovations, air quality index, occupancy, or metabolic activity (MET). 'Humans' in this scenario is an abstract concept, represented by a 'standard' human and some degree of security by an extra air volume. And we can say the same for the rest of parameters: they are design parameters, used to dimension ventilation equipments and to calculate spaces, not a set of control parameters in real time.

In advance ventilation we can find $CO_2$ sensors and regulation loops to control ventilation to the occupation of big spaces, increasing ventilation to keep $CO_2$ values under certain values. Even it can be found in modern home ventilation machines as an extra, but reality is that this advanced ventilation is relegated to conference rooms or commercial buildings, not residential homes. Many professionals don´t consider ventilation as a principal comfort criteria and heating or cooling is the main priority. That creates insane spaces and consequences in the human health. They have been dramatically checked during the covid-19 pandemic.

There are several factors to be consider about conventional calculation methods of ventilation. First is that humans are different and they behaves along time in a different way. This means that the ventilation needs (minute ventilation, VE) depends a lot on what human (age, gender, BMI) and what is doing that human (sleeping, running, chatting..). If we consider a 'standardized' human we are calculating with something that does not really exist. Each of us we are specific humans, and our ventilation needs are quite different. For one human VE can increase nearly an order of magnitude (0.5 to 5 liters). So we must keep in mind that many humans together with an increased activity can multiply the $O_2$ need by 10. That is a huge number. It would be great to have a control system regulating ventilation following the human needs (not the 'spaces needs').

In second place classically we consider the term 'renovations'. Considering the space volume, the number of renovations will give a quantity of air flow for that space. But we are moving and mixing air. If that process is not perfect (and it is not) mixing may be inefficient and the air quality poor. Diffusers and its position is very important. It is not just a design question.

Third, calculation of networks is performed between the demanded airflow by each space and the ventilator, AHU or home ventilation machine. The idea is to have that 'sub-network' equilibrated. But what is happening with the air at the space? It needs to go through the door to ventilate the corridor and later cross another door (or several doors) to be extracted in another room. Traditional methods don´t consider the complete circuit of air (and in many cases networks are not equilibrated at all, so some spaces are extra ventilated and some other infra ventilated).



In Fourth place there is a complete lack of control resources. Even the concept of controlled ventilation in residential buildings is totally absent. There are not sensors ($CO_2$) neither dampers for regulating different spaces or zones. Ventilation is in many cases a pure potentiometer with several positions for increased flow.

And finally we have the thermal needs, which in an adverse scenario (cold or hot weather) are working against ventilation. In Southern European countries (Portugal, Spain, Italy and Greece) the majority of designers would consider the so called 'natural ventilation' (opening and closing windows), which is a modern way of fooling yourself. In these countries winter is not long enough to realize that heat recovery is a need if you want to keep ventilation in healthy levels. And Summer can be endured opening windows at night and closing them during the day, using the thermal inertia of the buildings but decreasing again the ventilation rates. How covid-19 pandemic has affected these countries and Northern European countries may have some explanations considering how houses are ventilated.

Ventilation and thermal problems of course can't be separated, but considering in one 'system' the need of air by the humans (human centered ventilation simulation model) and thermal problems in another 'system' (connected with the ventilated spaces by thermal ports) may be a good way of understanding different objectives and priorities. Energy efficiency is a great target but human health should not be neglected.

## The Challenge in Simulation of Ventilation in Residential Buildings

The mathematical simulation of ventilation must take into account the following components: humans, fluids, equipments and networks. We can consider contaminants as well, but the specific model of each contaminant may need special ports and components if this contaminant is affecting the fluid or the state of the components.

**Human models** is the main factor if we want to design and control an installation based on human needs. Human models must be configured to be used in both design and real time scenarios. That means that we must sacrifice the exterior and interior respiratory circuits. In SPHERE project we implemented a specific human model based of the CPX test and the 9-panel plot representation of Wasserman[32]. This plot give us the VE, $CO_2$ and $O_2$ as a function of metabolic activity (in W, not MET), and this as a function of heart rate. This model can be implemented in the future in wearable devices, transmitting to the room the exact respiratory needs of each human in that space. It was out of the scope of this project to model contaminants, but it will be a future development in another project. Contaminants have been grouped in 5 'behavioral' groups. Each group will need special components. In case of viruses the air flow is not affected by the size and concentration of virions, so a combined contamination model for the ventilation system and another one for the human response could be possible[33].

32 The Wasserman 9-Panel Plot, often called a Nine-Panel Plot, is a standard layout for the graphical representation of data produced by a cardiopulmonary exercise test. The layout was updated in 2012. The graphs give an overview of cardiovascular, ventilatory, and gas exchange parameters.

33 Some research has been done regarding this human response using models of PBK and inhalators (see https://www.physpk.com/)

**Models of equipments** (generally home ventilation machines for residential) is another pillar. IN SPHERE several manufacturers have collaborated with documentation and properties of their equipments (S&P, TROX, BRINKs). As a result models of several home ventilation machines have been implemented, integrating ventilators, heat exchanger, controls, mechanics and internal networks. The experience gained with these models have generated the idea of SIMBOTs described in another chapter[34], in order to have an economic way of producing models.

Auxiliary equipments such as ventilators, dampers and diffusers have been implemented as well, trying to represent directly available equipment from catalogs with less configuration parameters, helping the users in the model implementation and reducing the potential errors. Libraries have then generic components with many parameters and specific components with just a couple of numbers. This implementation catalog-oriented has been a disruptive methodology for software used in other disciplines as aerospace.

In modeling networks the problem is to represent faithfully the BIM design. As commented before relations are not one to one (several pipes and elbows are only one simulation component). A methodology was developed previously grouping the BIM components in an IFC entity, to be translated later generating the simulation component with the properties of the BIM entities.

Finally fluid mix definition has been one of the main problems solved. The final solution considers the moisture content and the composition of air ($N_2$, $O_2$, $CO_2$). But this is a potential challenge for future implementations between different software brands. Hence it is one of the proposed objectives of the simulation workgroups of the BDTA.

## Ventilation and Covid-19 Pandemic

During covid-19 pandemic we have assisted to contradictory messages regarding how this disease is transmitted. At EPA official website we can read[35]: 'COVID-19 is thought to spread mainly through close contact from person-to-person. However, some uncertainty remains about the relative importance of different routes of transmission of SARS-CoV-2, the virus that causes coronavirus disease 2019 (COVID-19). Evidence now confirms that this virus can remain airborne for longer times and further distances than originally thought. In addition to close contact with infected people and contaminated surfaces, spread of COVID-19 may also occur via airborne particles in indoor environments, in some circumstances beyond the 2 m (about 6 ft) range encouraged by some social distancing recommendations'. And of course we can mention the WHO[36]: 'The virus can spread from an infected person's mouth or nose in small liquid particles when they cough, sneeze, speak, sing or breathe. These particles range from larger respiratory droplets to smaller aerosols.' Why some institutions have volatilized their prestige in this way forgetting the knowledge and basic rules of ventilation is something that one day somebody will be able to explain.

34 See chapter 2

35 https://www.epa.gov/coronavirus/indoor-air-and-coronavirus-covid-19

36 https://www.who.int/emergencies/diseases/novel-coronavirus-2019/question-and-answers-hub/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted



On the other hand the CDC[37]: 'SARS-CoV-2 viral particles spread between people more readily indoors than outdoors. Indoors, the concentration of viral particles is often higher than outdoors, where even a light wind can rapidly reduce concentrations. When indoors, ventilation mitigation strategies can help reduce viral particle concentration. The lower the concentration, the less likely viral particles can be inhaled into the lungs (potentially lowering the inhaled dose); contact eyes, nose, and mouth; or fall out of the air to accumulate on surfaces. Protective ventilation practices and interventions can reduce the airborne concentrations and reduce the overall viral dose to occupants.'

And finally the Public Health England[38]: 'When someone with COVID-19 breathes, speaks, coughs or sneezes, they release particles (droplets and aerosols) containing the virus that causes COVID-19. While larger droplets fall quickly to the ground, smaller droplets and aerosols containing the virus can remain suspended in the air. If someone breathes in virus particles that are suspended in the air, they can become infected with COVID-19. This is known as airborne transmission.

In poorly ventilated rooms the amount of virus in the air can build up, increasing the risk of spreading COVID-19, especially if there are lots of infected people in the room. The virus can also remain in the air after an infected person has left.'

In contrast we can refer to the ASHRAE handbook and the list of known 'Pathogens with Potential for Airborne Transmission'. Airborne transmission is nothing new for technicians working in ventilation, and dilution of virions is the most effective technique to reduce inhalated dosis in humans.

What in common all these international references about the covid-19 pandemic? A lack of an advanced technical ventilation culture. A lesson not learned and hopefully a future challenge for a project research. Could this explain the dramatic third wave after Christmas in SPAIN at 2021?

## Ventilation and Initiatives at BDTA

The Building Digital Twin Association (BDTA) in the Simulation Workgroup will target some of the critical developments needed for the ventilation in future residential homes. In particular two important movements as the SIMBOTs and standardization of ports for simulation.

SIMBOTs are manufacturer equipments in FMI format ready to be inserted in a simulation schema in any commercial software. The user can not access the integrity of the manufacturer development but it will contain all the functionality (including controls).

On the other hand ports need to be standardized as well, in order to be able to connect SIMBOTS. The simulation group of BDTA will define the steps to follow in order to get these resources available during the SPHERE project.

37 https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

38 https://www.gov.uk/government/publications/covid-19-ventilation-of-indoor-spaces-to-stop-the-spread-of-coronavirus/ventilation-of-indoor-spaces-to-stop-the-spread-of-coronavirus-covid-19

## Human Models

'Occupant-centric controls (OCC) integrate real-time or model-predicted building occupancy and comfort data with centralized building controls, tuning energy related building services to when and where they are needed by occupants'[39].

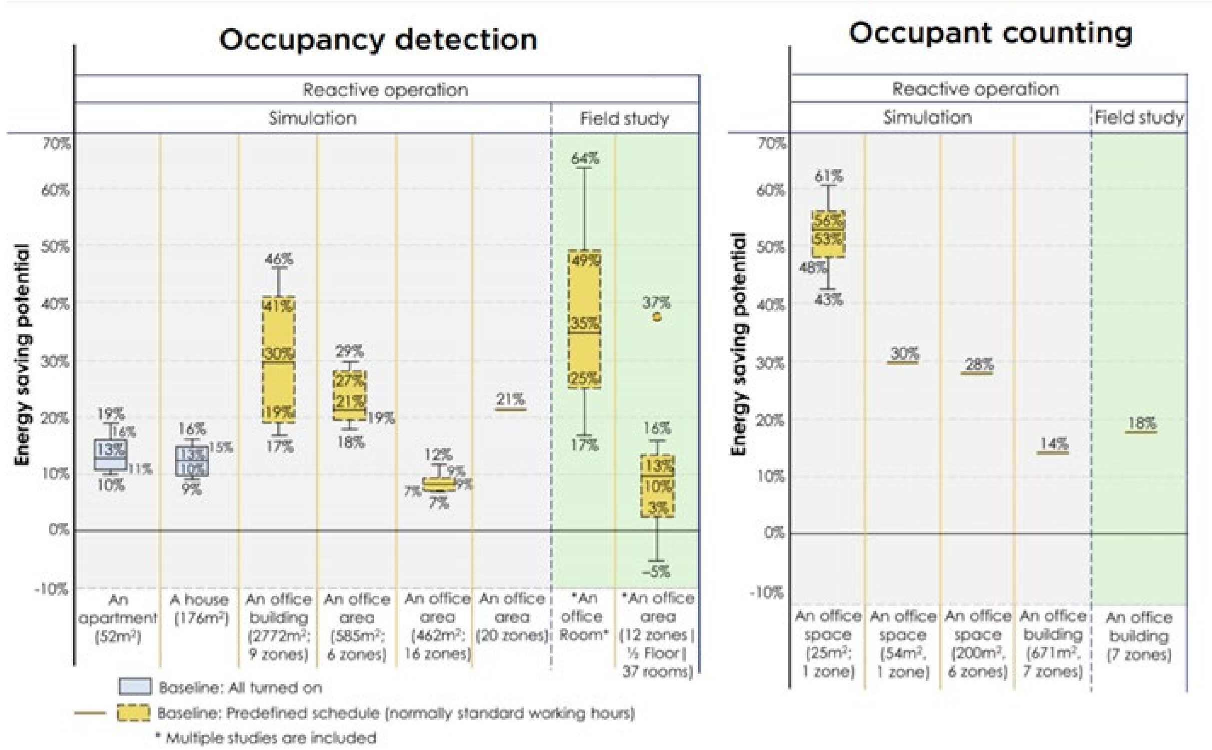



Figure 24: Energy-saving potentials reported by studies using occupancy detection and counting[40]

OCC can incorporate both occupancy and comfort or, in other words, 'human-in-the loop' not only can get information about presence but can introduce into the building specific information of each human and derive multiple comfort estimations. Human-centric means that they are the focus of building control and not only 'one parameter'.

If we want to consider a group of humans a model of comfort must then be set up, as we won´t have a unique thermal comfort temperature and ventilation demand depend a lot on specific age, gender, BMI and metabolic status.

Modern electronics and wearable's make it possible to physically measure real time parameters of individuals, sending presence, human model and activity to the space they occupy. This could be the baseline of a new indoor ambient concept, centered in the human use and not the space itself. This could be done having health and comfort as a target and not energy optimization, which would be a natural result of all the technical effort.

39 Presentation by Jared Langevin, Research Scientist, Lawrence Berkeley National Laboratory: https://arpa-e.energy.gov/sites/default/files/1.%20Langevin_SENSOR_071119_low.pdf, ARPA-E SENSOR Annual Meeting, July 11th, 2019, Denver, CO

40 Energy-saving potentials reported by studies using occupancy detection and counting to control HVAC system reactively. Adapted from: Jung, W. and Jazizadeh, F. (2019). Human-in-the-loop HVAC operations: A quantitative review on occupancy, comfort, and energy-efficiency dimensions. Applied Energy, 239: 1471-1508.



The presence of human models will demand new standards to be able to connect those models with other simulation components, and use of specific and general models oriented to design and real-time scenarios. Anthropometric databases and simplified options tabs would be a useful resource but estimations for specific humans can be a useful way to detect anomalies in respiratory or circulation health habits of subjects.

The economic benefits estimated using these techniques could not be the main goal if we consider the payback of health and comfort, which should be the priority and the main driving force for the big change. To establish the health and comfort reference we will need mathematical simulation, as we are not able to place a sensor of each parameter we want to estimate of the occupancy. These calculations, the integration of humans-in-the-loop and the advance control of the building will set up the baseline to define new and more reliable buildings.

## The Human Factor in Thermal Control

Human thermal comfort varies depending age, gender, BMI, activity and clothing. So they are quite specific of each human and comfort temperature variation may be up to 6 C. To be able to keep a comfortable ambient temperature we must define what that temperature is. A variation of just 3 degrees in temperature means a big energy difference, and even more if there is no human in that room and we can keep a lower (or higher in case of Summer) 'stand by' temperature.
In case of cold winter a lower temperature means less heat flow through the envelope of the building and of course some economic benefit, but the key is that we don´t leave aside comfort.

If we try to control the heating of a building without knowing the thermal demand by humans we will probably use the same temperature for winter and another one for Summer, independently of having children, elderly people, young boys doing some exercise of women reading a book. This undoubtedly goes to the uncomfortable region at some point. The communication between humans and controlled buildings is necessary by the control itself.
Human thermal models may be complex as they need to represent the 'passive' system interaction and the 'active system', as we can see in the image below[41].

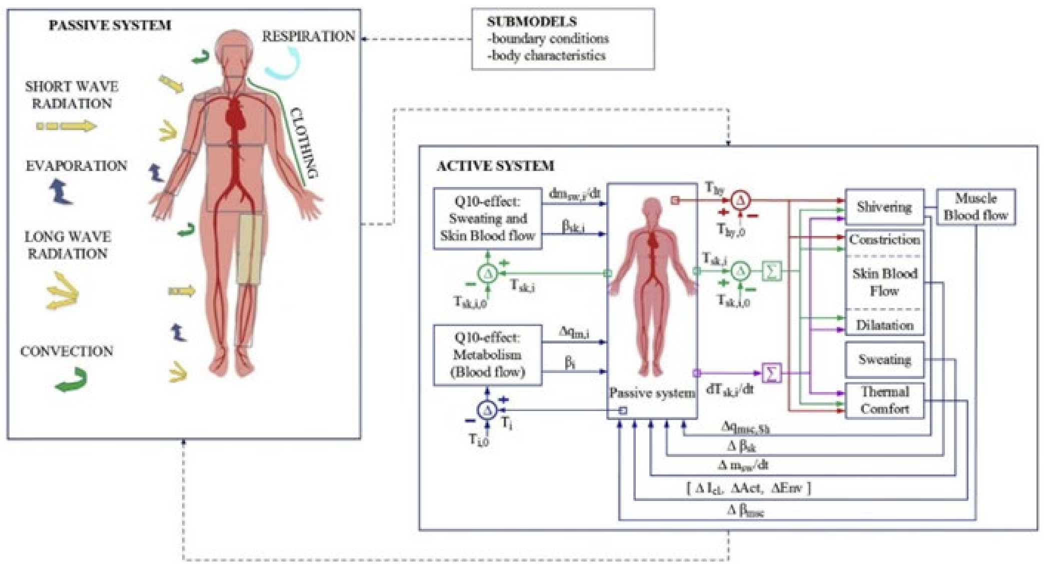



Figure 25: Schematic diagram of the thermophysiological models (modified from Fiala et al).

41 Katarina Katić, Rongling Li, Wim Zeiler,Thermophysiological models and their applications: A review, Building and Environment,Volume 106,2016,Pages 286-300,ISSN 0360-1323

And we can consider a basic single node or several nodes representing the trunk, head and members. A complex model may need thousands of equations and a powerful computer to run it in real time. If we would like to host the human model in a small hardware its representation should be simplified. And we have to take into account the representation of the room itself, because it would have no sense the interaction of a detailed human model of several nodes with a single node room.

## The Human Thermal Models of VTT[42]

When estimating comfort of users in buildings, influencing boundary conditions are commonly divided into two categories as you can see at Figure 26. External (or environmental) parameters are related to surrounding space, and they are air temperature, surface temperatures, air velocity, and humidity. Internal (or personal) parameters are related to human herself/himself, being clothing and metabolic rate. Furthermore, the metabolic rate (i.e., internal heat generated by human body tissues) depends on individual anatomy and activity level.

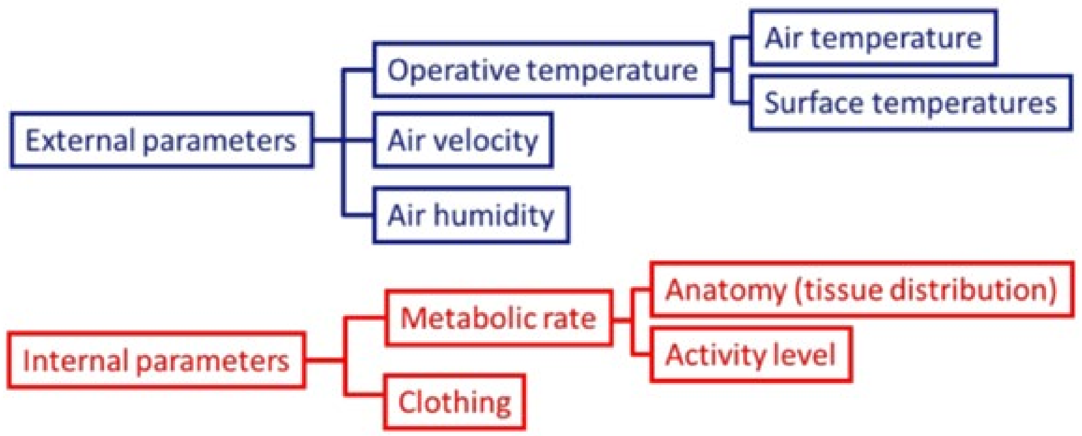



Figure 26: External and internal parameters influencing on human thermal sensation

Thermal comfort in buildings can be estimated with several alternative methods. The widely used international standards ISO 7730 (ISO, 1984) and ASHRAE 55 (ASHRAE, 2003)[43] use Fanger's Predicted Mean Vote (PMV) in method for calculation of thermal comfort (Fanger 1970)[44]. This method is a good starting point for estimation of thermal comfort, and it has been widely utilized when predicting indoor environment conditions. However, the PMV method is applicable only to steady-state, uniform thermal environments. In order to estimate impact of individual characteristics – such as age, gender, body-mass- index (BMI), and muscularity – on human thermal sensation, such human thermal models, which take into account the effect of human thermoregulation system and realistic transient heat transfer phenomena, need to be utilized. There are also other human based methodologies (e.g., Fiala et al. 2001, Huizenga et al. 2001)[45].

42 Models developed in H2020 SPHERE Project by VTT. Tuomaala, P., Holopainen, R. &Piira, K. (2014) A comprehensive Human Thermal Model for evaluating individual thermal sensation. In proceedings of Building Simulation and Optimization: London, UK. June 2014.

43 ASHRAE 2003. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Standard 55P Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, USA.

44 Fanger, P. O. 1970. Thermal Comfort. McGraw-Hill, New York, USA.

45 Fiala, D. et al. 2001. Computer prediction of human thermoregulatory and temperature response to a wide range of environmental conditions, International Journal of Biometeorology, Vol. 45, pp. 143–159.



The development at VTT presents an integrated Human Thermal Model (HTM) method, enabling both the human body and the surrounding space to be described as an integrated thermal nodal network, which consists of node capacitance and inter-nodal conductance. This approach allows both definition of individual body composition, and realistic estimations of thermal interactions between the human body and the surrounding space including convective, radiation, and evaporative heat transfer. Ultimately, the transient node temperatures of both human body tissues and building structures are solved using the finite-difference heat balance method (Tuomaala, 2002)[46].

The HTM is based on true anatomy and physiology of the human body, and it estimates human body tissue and skin temperature levels. The human body is divided into **sixteen different body parts**: head, neck, upper arms, lower arms, hands, chest and back, pelvis, thighs, lower legs and feet. Each body part is further sub-divided typically in **four realistic tissue layers** (bone, muscle, fat, and skin) by concentric cylinders. The functional tissue layers are also connected to adjacent body parts by a blood circulation system, which has been used for physiological thermoregulation of the whole body. (Holopainen 2012).

Simulated human body tissue temperature values offer general level information about thermal indoor environment (Tuomaala et al. 2014). In order to obtain more valuable information, the thermal sensation and thermal comfort estimation methodology by Zhang (2003) has been integrated in HTM, allowing much more detailed thermal sensation and thermal comfort index estimations than e.g. traditional Fanger's commonly utilized methodology. The quantitative analysis of the significance of both external (air and surface temperatures, air velocity, and humidity) and internal (clothing, metabolic rate) boundary conditions on thermal sensation and comfort.

To conclude, individual people may have even 6 degrees difference in perceived thermal conditions in the same space, same time, and same activity level and clothing (Figure 27). This means that different people prefer optimal indoor temperature varying for example from 20.5 °C to 26.5 °C, caused mainly by differences in anatomy (tissue distribution). These alterations in temperature are also caused by gender, age, weight, height, body mass index and fitness.

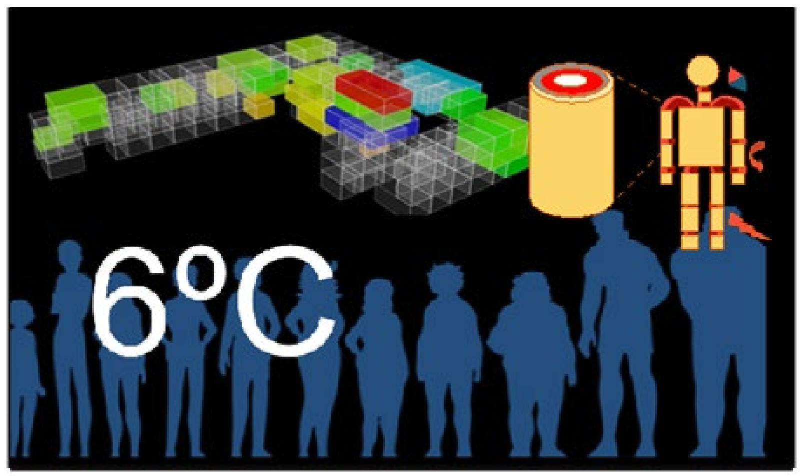



Figure 27: Concept for Human ThermalModel (HTM).

46 Tuomaala P. (2002) Implementation and evaluation of air flow and heat transfer routines for building simulation tools, Doctoral Dissertation, VTT Publications 471, Espoo, Finland.

HTM helps to customize and control thermal conditions for individuals and integrated in a building simulation environment for a more accurate estimation of thermal comfort in transient conditions. The primary benefits and especially savings in energy use are reached at the operation and use period. The Thermal Sensation (TS) determines how comfortably subject persons are feeling the conditions over a period. The Thermal Sensation Index (TSI) is a measure to determine comfortability of thermal conditions, values ranging from -3 (cold) to +3 (hot) with different kind of people as shown in Figure 28.

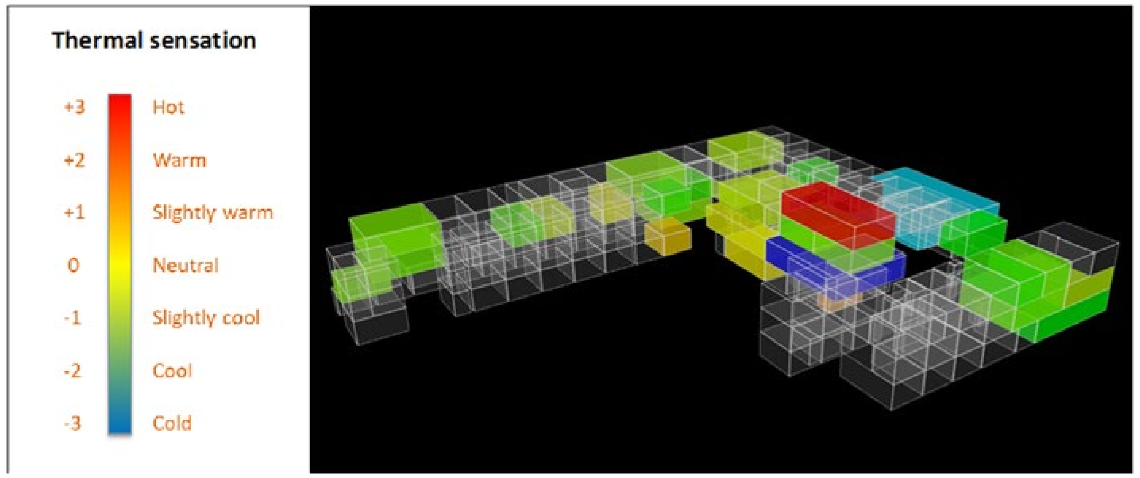



Figure 28: Thermal Sensation Index values visualised for spaces

HTM is a tool that enables personalized indoor conditions, but those can be reached when we know user and have an HVAC system and Building Automation and Control System (BACS) enabling influencing on thermal conditions. In practice this means that HTM needs input from sensors on thermal conditions, temperature and humidity in space in particular. For the designer, it's important to acknowledge this that the technical systems selected to building take these needs of HTM into account. HTM is capable to monitor thermal conditions in spaces, and there is also a control module able to control BACS on how individual spaces are heated and cooled (see Figure 30).

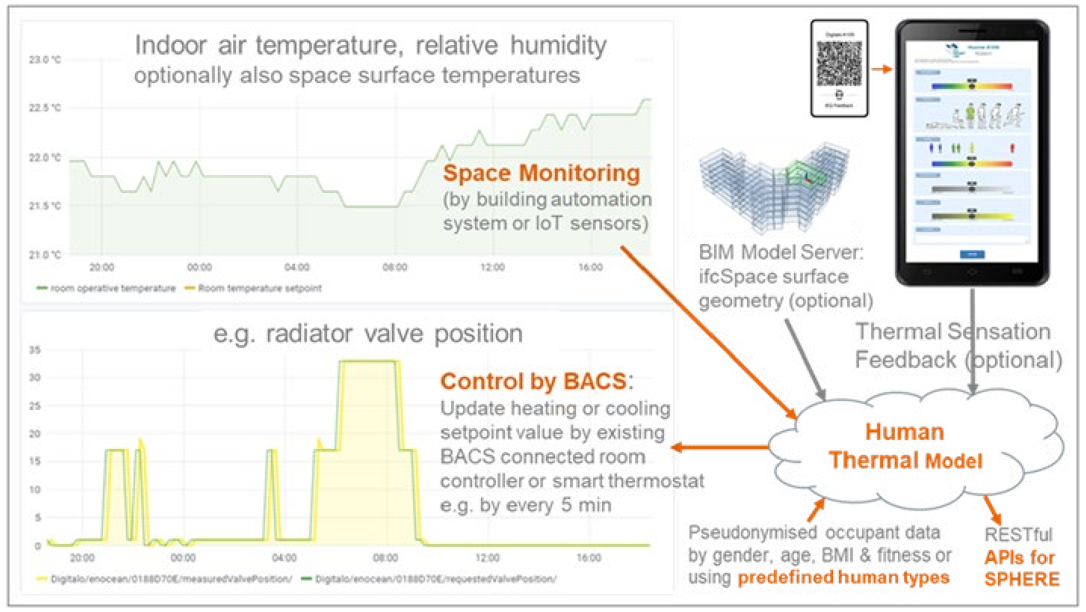



Figure29: Thermal Model bringing together space monitoring, control by BACS and predefined person types



Human Thermal Model (HTM) needs input from user as a prerequisite, including:

1. Temperature in space (External parameters)
2. Humidity in space (External parameters)
3. Selected fictional person type using the space (Internal parameters)

For the indoor temperature and humidity, boundary values for designs are stated usually in country specific classifications and other guiding documents. In Finland, for example, there is an indoor environment classification called FiSIAQ. FiSIAQ states indoor environment classes that include boundary values for both temperature and humidity for different building types, and how these boundary values are met during the year. For temperature, the SPHERE project uses indoor air temperature value because that is easier to monitor in operations and use phase than an operative temperature acknowledging cold surfaces that require complicated measurements. Based on the experiences that VTT has from different buildings, offices, and residential buildings in particular, the difference between operative and indoor air temperature is not usually that extensive. So, for the purpose of the SPHERE project and its varied pilot projects, the indoor air temperature provides a meaningful starting point to estimate thermal conditions.

To overcome possible privacy issues, VTT has developed fictional person types that are a combination of different kind of people. From these fictional person types, the designer should recognize that certain types of people are the extremes and when making design options. (e.g., construction materials and dimensions, capacities of individual heating and cooling devices, and sensor and control solutions). And if the designer considers the most extreme person types, then the thermal satisfaction of all occupants using the building is obtained.

For the designer and facility manager, it's important to notice that different fictional person types mean that the needs for space heating and cooling are different. This needs to be considered in making design alterations and deciding the technical solutions implemented further by the design team, for example an HVAC solutions or Building Automation and Control System (BACS).The most extreme fictional person types for their temperature needs – Thin aged woman who need high temperature and Muscular young man needing low temperature introduced in Figure 30.

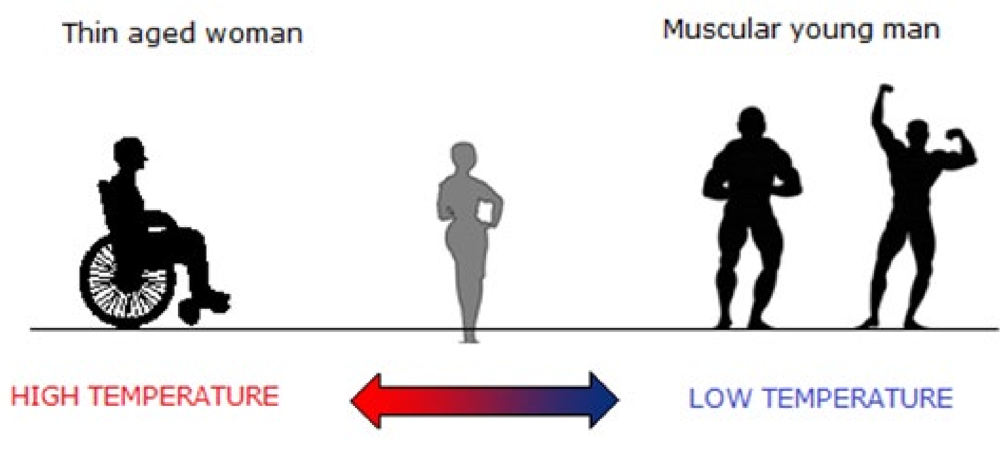



Figure 30: Extremes of different fictional person types concerning temperature needs

To summarize, an aged thin woman usually has less muscular body mass, and therefore, needs higher temperature. Young man who has muscles and usually exercises is in a completely different situation, and they usually ask for low temperature as their optimal indoor condition.

The most beneficial phase for utilizing Human Thermal Model (HTM) is during the operation and use period in the lifecycle.

In SPHERE project VTT has develop several use cases which may use the HTM implementation in a different way. For visualizing Thermal Sensation Index (TSI) for selected person in selected space, designer or facility manager is able to display how different fictional person types feel thermal conditions in chosen space in selected building. This means that user opens HTM dashboard (Figure 31) and selects from dashboard menu 'building', 'space' and 'fictional person type(s)' for thermal sensation consideration.


Figure 31: Screenshot from HTM dashboard

## The Human Factor in Ventilation Control

Human thermal models and respiratory models should be considered as a unified model, unless we want to simulate only the ventilation needs of the human. In case of ventilation differences in ventilation levels (VE, minute ventilation) between humans and levels of activity can be an order of magnitude, and not just a variation of 20 to 23 C as in temperature. In case of ventilation the volume of air (VE, minute ventilation) in absolute rest is ten times smaller than the same human running. If we think that it is common to have a group of people in a room we can imagine how easily we can create a lack of ventilation just moving around, signing or speaking loudly. And in terms of pandemic this is high risk situation.



## The Human Ventilation Models of EAI

Ventilation models try to calculate the amount of air used by the human body, and the exchange of O2 into CO2 which will change the room volume concentration. With that air there could be contaminants that will be treated in different sub models depending on the behavior or impact on comfort or even lungs health.

In the following diagram (taken from a physiology manual) we can see how the total volume of lungs can be described:

FA17 p 630.1

| Lung volumes | Note: a **capacity** is a sum of ≥ 2 physiologic **volumes**. |
|---|---|
| Inspiratory reserve volume | Air that can still be breathed in after normal inspiration |
| Tidal volume | Air that moves into lung with each quiet inspiration, typically 500 mL |
| Expiratory reserve volume | Air that can still be breathed out after normal expiration |
| Residual volume | Air in lung after maximal expiration; RV and any lung capacity that includes RV cannot be measured by spirometry |
| Inspiratory capacity | IRV + TV<br>Air that can be breathed in after normal exhalation |
| Functional residual capacity | RV + ERV<br>Volume of gas in lungs after normal expiration |
| Vital capacity | TV + IRV + ERV<br>Maximum volume of gas that can be expired after a maximal inspiration |
| Total lung capacity | IRV + TV + ERV + RV<br>Volume of gas present in lungs after a maximal inspiration |

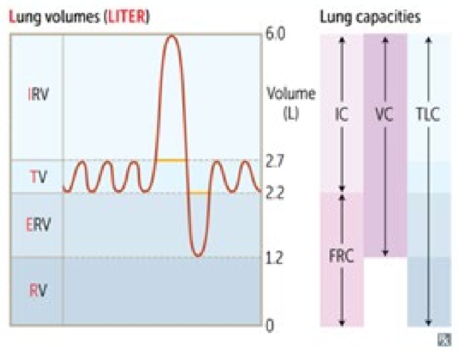



Figure 32: Volumes at Lung

Normal respiration takes place quietly with a typical value of 0.5 liters for inspiration and expiration. It is a repeated process at a rate (again typically) of 12 times per minute. But this may change a lot depending of physical activity.

There are estimators of the Vital Capacity (TV+IRV+ERV)[47]:
Male Vital Capacity in L = ((27.63 – 0.112 x Age in years) x Height in cm)/1000
Female Vital Capacity in L = ((21.78 – 0.101 x Age in years) x Height in cm)/1000

In our case we are interested in Tidal Ventilation TV for several scenarios or activities. We can model discontinued processes of seconds (detailed breathing processes of inspiration and expiration). But thinking on a building and time magnitudes of 10-minutes we have to use the Tidal Volume TV and transform that value into a continuous magnitude. That would be Minute Ventilation or VE.

47 https://www.thecalculator.co/health/Normal-Vital-Capacity-Calculator-1101.html - Godfrey MS, Jankowich MD. (2016) The Vital Capacity Is Vital: Epidemiology and Clinical Significance of the Restrictive Spirometry Pattern. Chest; 149(1):238-51.

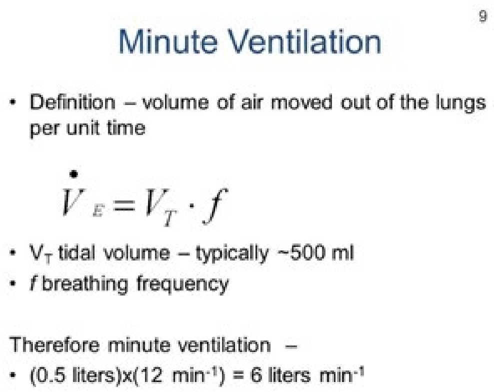



Figure 33: Minute ventilation definition

Respiratory minute volume (or minute ventilation or minute volume) is the volume of gas inhaled (inhaled minute volume) or exhaled (exhaled minute volume) from a person's lungs per minute. It is an important parameter in respiratory medicine due to its relationship with blood carbon dioxide levels.

Alveolar ventilation VA is the gas exchange between external ambient and alveoli. Furthemore there is a death volume VD which is needed to fill spaces and bronchia of the lung, with no exchange of O2 or CO2. Minute Volume VE would be:

VE = VA + VD

In order to represent lung ventilation during time at different metabolic values SPHERE partner EAI was using information from the cardiopulmonary exercise testing CPX. Description of this test can be found in many references[48].

'Modern CPX systems allow for the analysis of gas exchange at rest, during exercise, and during recovery and yield breath-by-breath measures of oxygen uptake (VO2), carbon dioxide output (VCO2), and ventilation (VE)' (Gary J. Balady, 2010). With CPX data we have a big number of tests and different subjects. And some other parameters we could use in the future.

In EAI HVMs metabolic activity is INPUT directly in Watt as Metabolic Working Rate (MWR). The table of MWR for each specific MWR value and the correspondent equivalent activity is then needed[49].

48 Several sources have been used, but with some detail the work of Prof. Karlman Wasserman (https://en.wikipedia.org/wiki/Karlman_Wasserman), who died the 22nd of June of 2020, during the development of our project. RIP.

49 MET values are used for general or standard activities but we used specific humans which may have quite different values of MWR in Watts for similar activities.



There are 4 main processes involved in the cardio pulmonary system:

1. Pulmonary ventilation, or the movement of air into and out of the lungs;
2. Pulmonary diffusion, or the exchange of O2 and CO2 between the lungs and the blood;
3. Transport of O2 and CO2 in the blood;
4. Capillary gas exchange or the exchange of O2 and CO2 between the capillary blood and the working muscle.

The first 2 processes are referred to as **external respiration**. And 4th would be **internal respiration.** We are focused on external respiration only[50].

In normal subjects, minute ventilation (VE) increases in proportion to the increase in work rate WR. Modern CPX techniques uses sensors which can measure oxygen uptake and carbon dioxide output at rest, during exercise, and during recovery, as frequently as breath by breath[51]. EAI was using these 4 parameters to build the HVM dummy: WR Work Rate, VO2 input, VCO2 output, minute ventilation VE and heart frequency HF.

We can use several sources for CPX results, but the most intuitive results can be found at Wasserman graph 9-plot (Daniel Dumitrescu, 2016)[52].

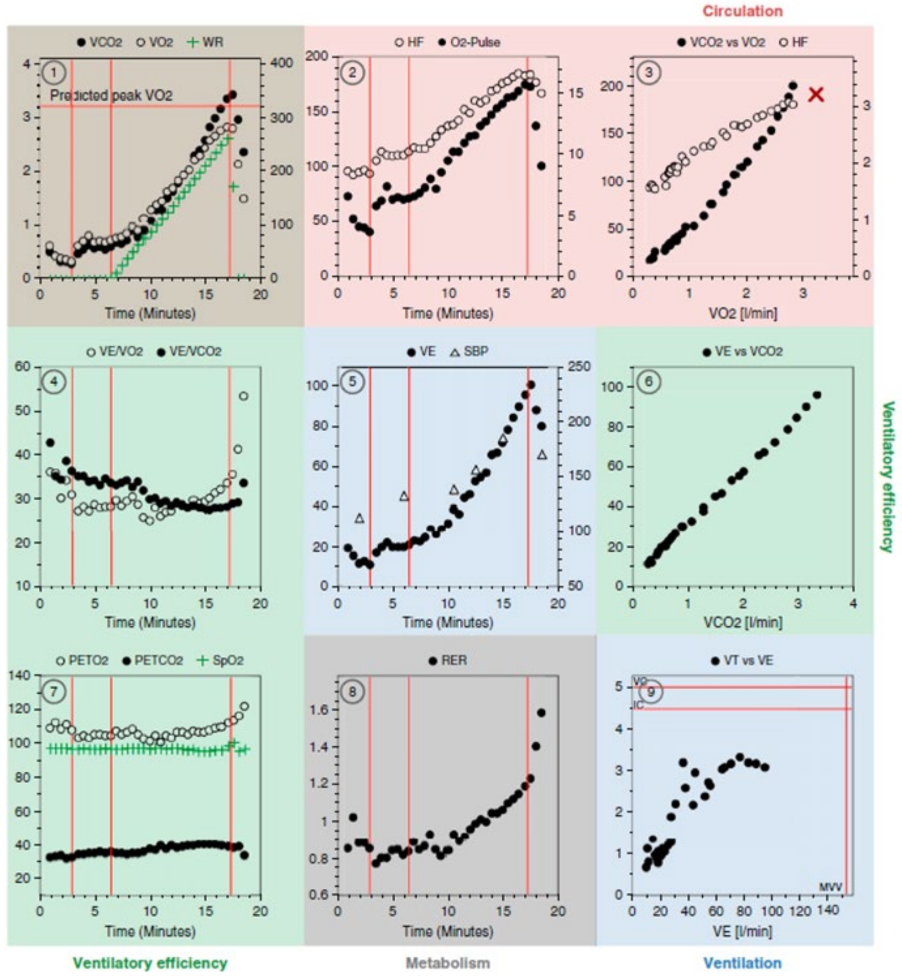



Figure34: CPX test, This is an exercise test of a healthy 28-year-old male subject. Nine-panel plot graphical display with a 30-second averaging of the data

50 It does not mean that it is not possible to simulate detailed transport and internal respiration. But for our objective it could have no sense.

51 But important to note that sensors must be well calibrated, and ambient conditions may affect O2 concentration in air. Ambient temperature, pressure and humidity should be taken into account.

52 Other references may be (Leonard A. Kaminsky, 2015),(T. Takken, 2019) or a text book https://shop.lww.com/Principles-of-Exercise-Testing-and-Interpretation/p/9781609138998

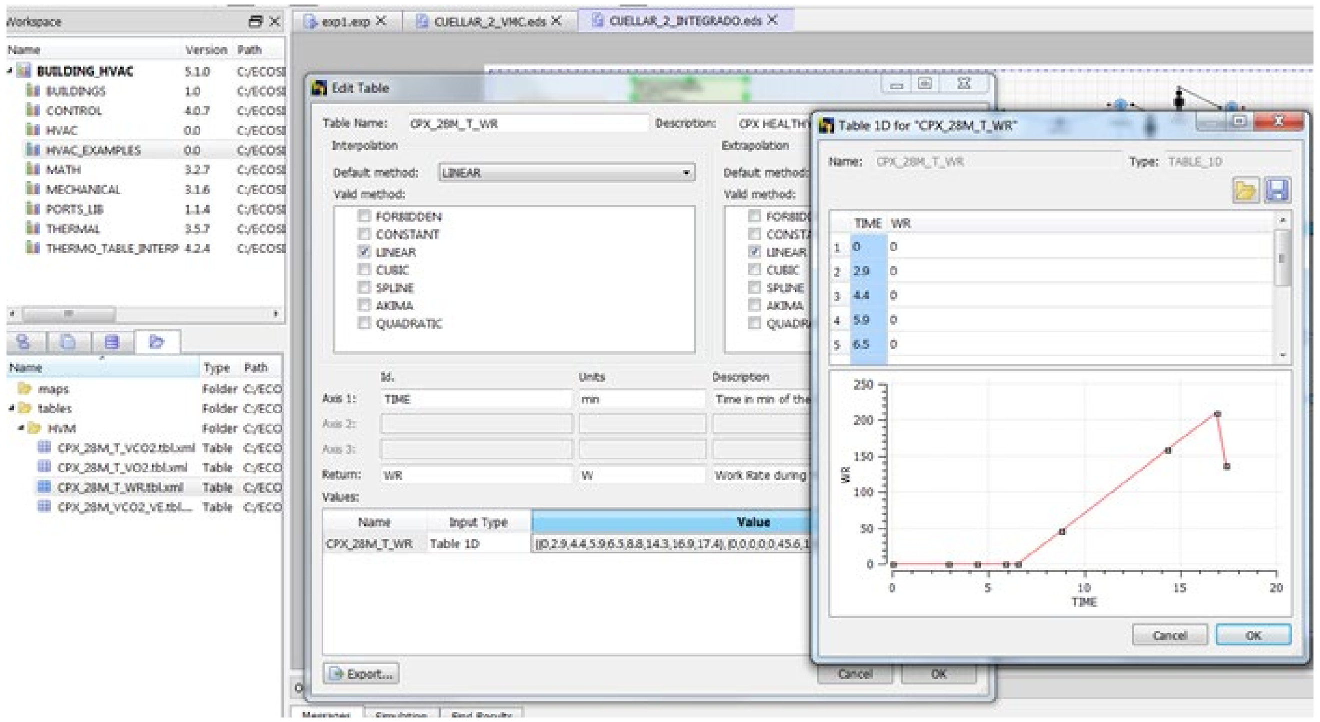
WR Work Rate, VO2 input, VCO2 output, minute ventilation VE and heart frequency HF are measured directly during the experiment, and the estimated precision or limit of variation can be seen below.

**Limits of Variation in Gas-Exchange Variables Obtained by Repeated Study of the Same Subject at a Given Submaximal Work Rate**

| Variable | Variation, % |
|---|---|
| Oxygen uptake | ±5.0 |
| Carbon dioxide output | ±6.0 |
| Minute ventilation | ±5.5 |
| RER | ±3.0 |

Figure 35: Variation in gas measure estimation

The HVM tables are organized under the table's directory of the library of ECOSIMPRO, the software used to prepare the HVM models. Each HVM responds to a specific configuration of a human sample (it is not a standard or general statistic data). With several dummy specimens EAI will try to cover the majority of potential profiles in building ventilation systems. Based on the CPX test values can be extracted to produce the tables used for simulation[53].



53 The table itself is a function or "equation" describing the relationship between two variables.



# 3.-SOFTWARE IN THE LOOP CONCEPT

In industry today, machines and equipment used for production are controlled by software systems and logic devices. Known as control systems, their purpose is to increase productivity, prevent errors, and improve safety in dangerous processes.

The importance of control systems (both software and hardware) has led to new technologies and methodologies aimed at enhancing their design, manufacture, and validation. One of the most notable ones is Software in the Loop (SIL), a technique in which real signals from a system's control hardware and software are connected to a test system that simulates reality. This way, the control system is "fooled" into thinking it is working on the real system or plant rather than on a digitally simulated system.

## Control Problems and Help From SIL/HIL

Building a quality control system requires going through several stages:

- Analyzing the plant or system to be controlled: understanding the operating modes, the system's operating limits, the optimal operating points, etc.
- Designing the control system: defining a system that is able to solve the requirements raised in the analysis stage, taking into account factors such as what technology to use, communications, adaptability, and scalability of the designed system.
- Implementing the control system: using software or hardware to build a solution to the design from the previous stage.
- Testing the system: trying out the control system by connecting it to the plant to be controlled.
- Starting up the system: this is the final stage, when the previous stages have been successfully accomplished, the control system is installed in the plant and production begins.

None of the questions above are easy to answer, especially since the plants to be controlled either have not yet been built, or, to complicate matters even more, they are built up and running but cannot be stopped for testing, analyzing, or optimizing their performance, or to see how they respond to emergency uses.

This is where both software-in-the-loop (SIL) and hardware-in-the-loop (HIL) come in. They offer many different advantages, namely in that the tests and iterations of the stages of creating a control system are done using a simulation or "digital twin" that imitates the building to be controlled. This makes it possible to define and execute thousands of possible scenarios, assessing the feasibility and robustness of the control system without having to carry out any physical tests on the real building.

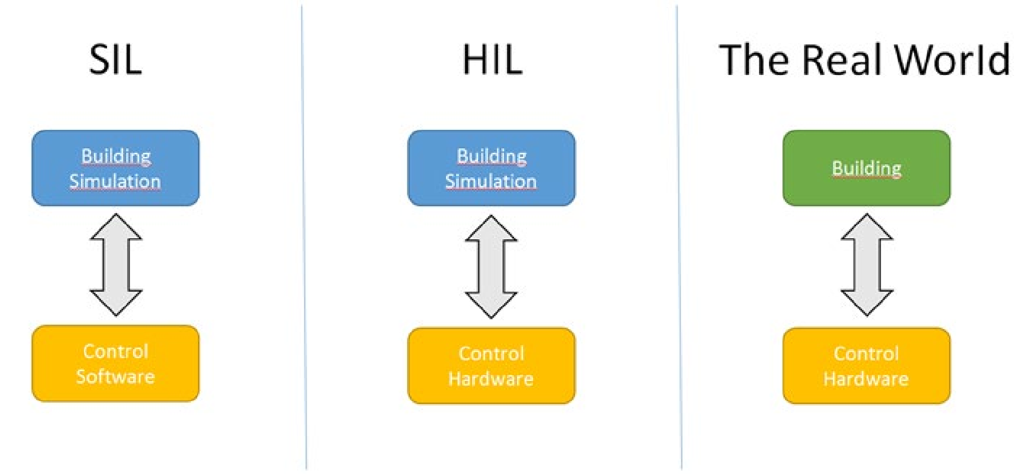



Figure36: HIL SIL and real World

In other words, they help creating better control systems while improving quality and robustness.

## Differences with AI, Expert Systems, Machine Learning, Neural Networks, Big Data

Currently, many industrial and scientific systems are implementing expert control systems based on machine learning, artificial intelligence and big data.
In short, machine learning can be seen as a discipline that is able to create software systems (such as neural networks) able to output correct responses from sets of input data.
Generally, machine learning is a highly useful discipline when it comes to address certain data patterns without having to understand why those system-internal behaviors occur (even detecting relations between data that elude human analysts).

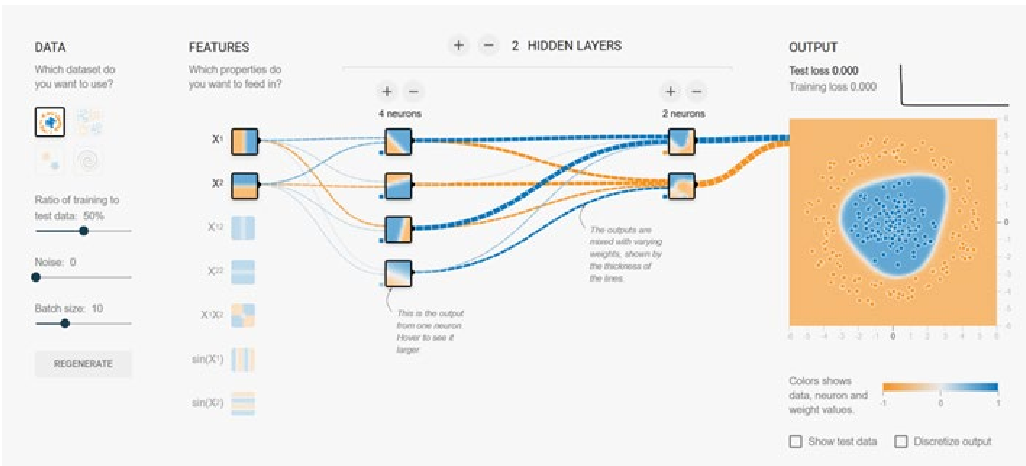



Figure37: Example of a classification problem in Tensorflow (https://playground.tensorflow.org)

These systems have well-known capabilities in problems such as visual pattern analysis of cells to determine cancer, in managing financial resources, or in building experience-based predictive models between many others.



These AI systems can also be used when constructing equipment simulations as well as their control systems (i.e., the systems on either side of the HIL and SIL).

In fact, AI-based control systems act in much the same way as traditional control systems. Both of them receive data from sensors to generate action responses. What makes the AI system different from traditional systems based on programmed implicit rules is that the AI infers those rules as its training is underway.

In the case of AI systems, the results are obtained by training the system with sets of input data, in contrast to traditional simulation in which the results come from solving systems of mathematical and physics equations that explicitly describe each part of the system modeled and therefore the input and output variables may be different in different scenarios.

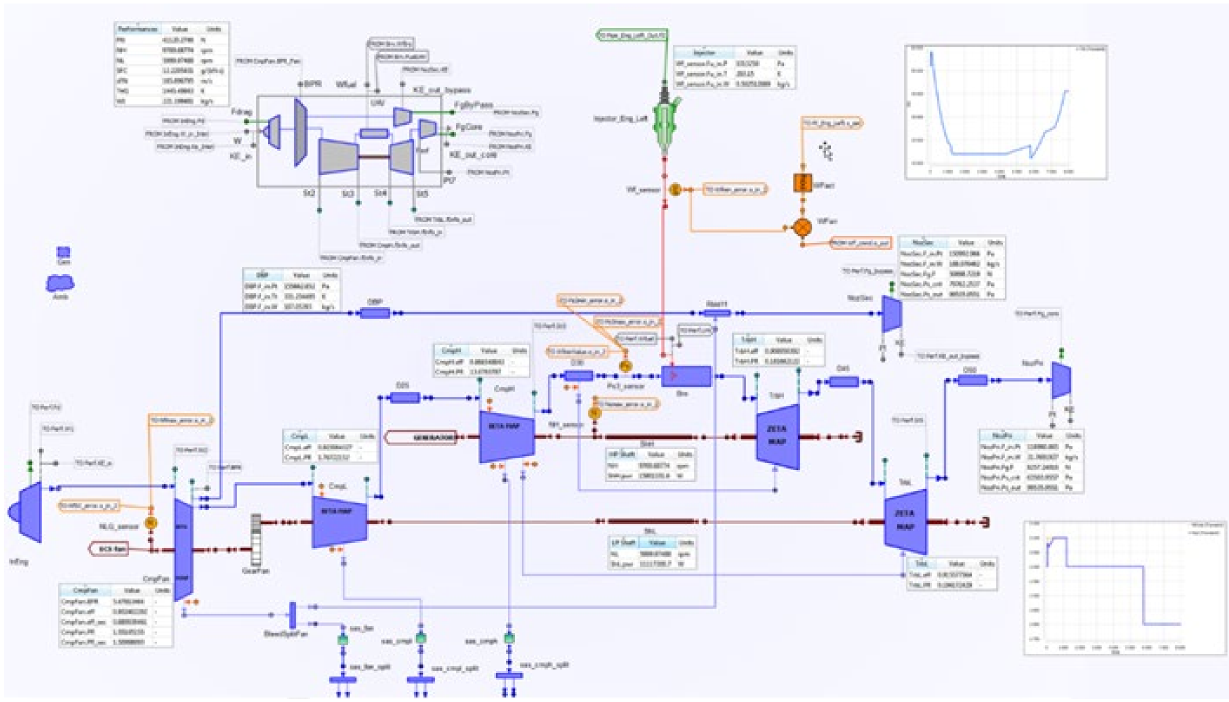


Figure38: Engine simulation in EcosimPro with access to internal variables of a simulated system

The AI systems have a few advantages over traditional control and simulation systems:

- They are relatively simple to develop
- They produce highly accurate results for well-defined problems
- They execute very fast, since their operation is based on calculations that are very simple to compute

However, they also have a number of disadvantages compared to traditional simulation:

- They require strong data collection and a complex analysis of those data.
- They depend heavily on proper training.
- Training the system with partial or unbalanced data makes the rules they infer not valid in all cases of use (especially in strange cases).
- They are not very flexible to structural changes in the systems they represent; they need complete retraining if the system is changed.

Their advantages are very useful in closed systems of processes, with very specific use cases for which there is a lot of well-classified data with which to train the system.

However, their disadvantages come to the forefront when compared with more open systems with multiple use cases (including rare or extreme cases) of scalable size. In these cases, which are very typical in constructing control systems, the efficiency, robustness and reliability of the systems created using simulation-based HIL or SIL is manifest.

Today, the two types of systems may be used to complement each other, offering highly useful redundancies when comparing results obtained by very different methodologies.

### Standards in This Field

The SIL and the HIL are both based on establishing a communication loop between the control system to be tested (hardware or software) and the simulation of the real building or system. That communication and its capabilities determine what type of technique to use. When communication times are extremely critical (on the order of milliseconds), communications and data exchanges between both extremes are done through hardware devices specifically manufactured to that purpose. There are many examples on the market, such as the IPX and RIO industrial equipment from National Instruments, or similar alternatives from other manufacturers such as DSpace, Siemens, and Bosch. All of them are able to execute software very quickly and to send and receive data through direct connections based on the manufacturer's own protocols or on standards that meet the necessary speed requirements. This equipment operates based on integrating software simulations (by using SFunctions in Matlab, for example) in the equipment itself to then connect this specific equipment to the hardware or software to be tested.

If the exchange needs are not that demanding in terms of speed, the simulation software can be integrated into computers with conventional operating systems (Windows or Linux), using devices such as a PC or Raspberry Pi. In these cases, communication can be done over conventional networks using industrial protocols such as:

• OPC UA: An open-source, service-oriented, secure, multi-platform industrial communication technology with rich information models. The technology is maintained by the OPC Foundation (https://opcfoundation.org/). This is a communication protocol between industrial equipment that can be used to exchange industrial data in traditional mode, i.e. between SCADA applications and sensors, and between company applications across every layer of the business. More technically, its architecture is based on client-server services with synchronous or asynchronous communications.

• HTTP: A protocol for transferring information through files (XML, HTTP, JSON, etc). HTTP was developed by the World Wide Web Consortium and the Internet Engineering Task Force, a collaboration that culminated in 1999. This is currently the backbone of most of the internet so there are a large number of software resources, programmers and devices that implement the protocol to facilitate data exchange.

• Modbus: Communication protocol for exchanging data between programmable logic controllers (PLC) and computers. It was developed by Modicon in 1979 for use with their



controllers over serial port or TCP communications. It has now become a de facto industry standard, as it is the most widely available standard for connecting industrial electronic devices (https://www.modbus.org/).

## 3.1.- State of the Art in Other Sectors

### Gaia: The Living Earth[54]

The 8th of June ASME (The American Society of Mechanical Engineers) published an article by Michael Abrams with the title ' A Digital Twin for Mother Earth'[55]. Building a digital twin for Earth would enable global long-range planning to deal with climate change.'

Can the digital twin concept be used to tackle the biggest problems facing the biggest systems of our biggest object? Peter Bauer, deputy director for Research at the European Centre for Medium-Range Weather Forecasts thinks it can'. Bauer, as co-initiator of Destination Earth, plans to create a digital twin of our planet so scientists, climatologists, and governments can better understand, and plan for climate change.

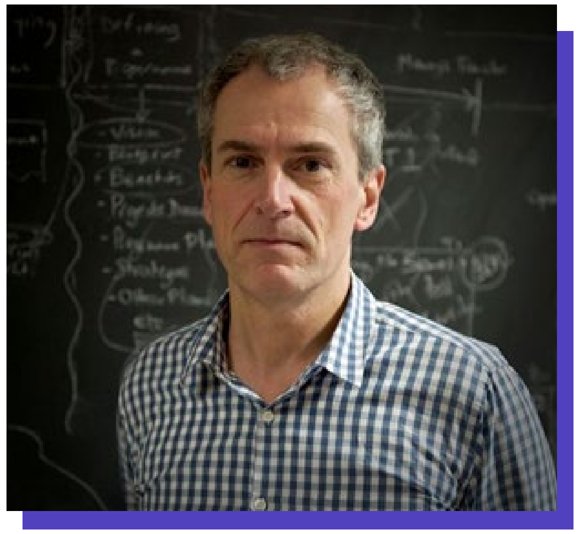


Figure 39: Peter Bauer, Deputy Director of Research at ECMWF (photo: ECMWF).

"It's really important for national or regional decision making. What should a country that has a lot of coastline do if storms increase in the future? Or maybe frequency doesn't change, but intensity does. If certain parts of the coast become more exposed than others, what do I do?" asked Bauer. "For these kinds of thoughts, I need much more reliable information, because that is decision making at the top level; the most costly level, you could argue."

'There are, of course, models already at use today to predict both the weather and the future that climate change will bring, but their resolution is too low for the kind of accuracy Bauer has in mind. "Climate models today run at best at 25 kilometers," said Bauer. "We need to go down to a kilometer at least to have reliable prediction at decision making scale, which is regions and countries. To do that, he plans to use some 20,000 graphic processing units, which will consume twenty megawatts of power."

Resolution isn't the only thing that makes current models less than ideal. "We need to upgrade these systems significantly, because there are so many errors in them," said Bauer.

But with or without errors, models are useless if the people making decisions can't use them. User friendliness is a major goal of the project.

54 Gaia theory reconciles current thinking in evolutionary biology with that in evolutionary geology
55 https://www.asme.org/topics-resources/content/a-digital-twin-for-mother-earth

“Right now, these systems are expert systems[56]. You really do not have access as a non-expert to any of this information,” said Bauer. “We want to make this system a lot more accessible, to upgrade the accessibility and the convenience of dealing with data and models a lot more, so that this enormous threshold that lies between the expert system and the non-expert system gets smaller.”

## Bio Digital Twin[57]

At Forbes Tech Council Kazuhiro Gomi, CEO of NTT Research, afirmed in 2020 that “development of the Bio Digital Twin (of human patients) is informed by a vast array of biological, physiological, genomic, phenotypic, and health records data – as well as data gleaned from wearable devices and sensors. This Bio Digital Twin will employ a collection of high-fidelity AI and physiologically-based computational models”.

Figure 40: Kazuhiro Gomi, Forbes Tech Council, CEO of NTT Research

“With a well-established baseline concept and supportive technologies, the bio-digital twin concept is ripe for more focus and development. Here are three areas that require attention:

• To create a bio-digital twin or alter ego, **you need data, both aggregated and patient-specific.** Data collection in this field can turn into questions of highly advanced technology. Going forward, the digital twin vision will rely on nanoscale electronic sensors that can work with or alongside a targeted organ or tissue, generating reliable, low-noise data from human patients.

• Work on a bio-digital twin **could begin from various points**, but starting with an actual physiological system will make the twin more reasonable and clinician-friendly. Because of comorbidities and diseases that typically affect multiple organs, **other systems will need to be layered over time**, within an overarching model that also allows for medical information services of various types.

• Closely related to the model is the **data processing engine**. This is where you derive value, whether through computing, algorithms, analytics, machine or neural learning, etc. The same point would apply to the simulators at NASA or Formula 1 racing cars. Yet in this case, the process leads to medical decisions that are more precise and finely tuned.

56 In artificial intelligence, an expert system is a computer system emulating the decision-making ability of a human expert.[1] Expert systems are designed to solve complex problems by reasoning through bodies of knowledge, represented mainly as if–then rules rather than through conventional procedural code. https://en.wikipedia.org/wiki/Expert_system

57 ‘How Far Bio-Digital Twins Have Come, And What May Be Next’, by Kazuhiro Gomi, CEO of NTT Research. 8th July 2020, Forbes Tech Council (https://www.forbes.com/sites/forbestechcouncil/2020/07/08/how-far-bio-digital-twins-have-come-and-what-may-be-next/)



## Process Plant

Process digital twin “is becoming a key enabling factor for the new technologies connected to plant operation and optimization, through the integration of the process model, the process optimization engine, and real-time data from the plant. The process optimization engine leverages thermodynamics to simulate the process and optimize its operations as precisely as possible. As further improvement, it is also possible to enhance and reinforce the thermodynamics model with machine learning algorithms to simulate the process and optimize its operations as precisely as possible, integrating production programs and economics in order to maximize the plant margin”[58]. At the blog of Yokowaga Naveen Kumar and Toshihiro Makinouchi it is well described the benefits of process digital twins:

1. Increase in plant margin and productivity: by support operation in day-to-day activities, optimizing the plant operating conditions, fast de-bottlenecking, and reducing the utilities consumption.

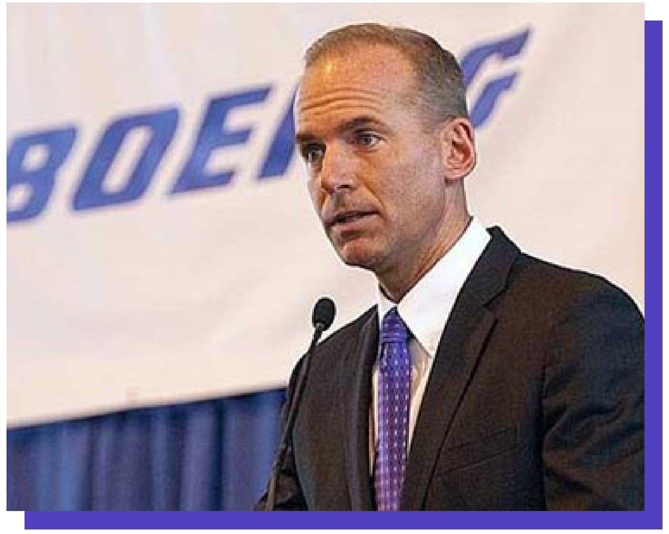
2. Support for operation decision-making: by the application of the Operator Training Simulator.

They comment that “Individual point solutions with digital twins do exist today, serving different purposes such as fit-for-purpose simulation models and individual data sources. But a **future digital twin will be one multi-purpose digital twin**, which aligns the asset life cycle and value chain, a Multi Purpose Dynamic Simulator (MPDS), and ubiquitous data sources. It is unrealistic to assume this future state can be achieved in one step, but it becomes more likely through the connectivity of valuable high-performing individual elements”.

## Aviation

At September the 14th, 2018[59], Boeing´s CEO Dennis Muilenburg described the ‘Digital Twin’ Era of Aviation. Boeing had been able to achieve up to a 40% improvement in first-time quality of the parts and systems it uses to manufacture commercial and military airplanes by using the digital twin asset development model. This model would be the biggest driver of production efficiency over the following decade.

Figure 41: Dennis Muilenburg, Boeing´s CEO



“A digital twin is created by using ultra **high-fidelity simulation software** that can create a virtual working model of highly complex systems and components, such as those featured on Boeing’s airplanes. Digital twin replication software is capable of creating a virtual three dimensional model that can go through a simulated lifecycle of the environments and conditions that asset will experience. The lifecycle is created by digitally threading together bits of data about that component’s in-service product lifecycle.”

58 Naveen Kumar / Toshihiro Makinouchi. Advance Solutions Blog, 20th Nov 2020, Yokogawa

59 https://www.aviationtoday.com/2018/09/14/boeing-ceo-talks-digital-twin-era-aviation/

“We’re moving to **model-based engineering** digitizing our entire engineering and development system up front including down into our supply chain and connecting that with the production system and how we service and support to create value for our customers,” said Muilenburg. “That **digital life cycle** — think of it as a digital twin of our airplanes — will unleash incredible value in the future.”

## Automotive

Extensive Software-in-the -loop (SIL) testing is integrated nowadays in automotive development. Testing solutions for PC- and cloud-based simulation lets you simulate and test software functions or complete virtual electronic control units (V-ECU) networks in real-time or even faster. The scenario where this more specific control applications are tested may be simulated as well. Software vendor IPG[60] provides a complete set of tools for testing car or trucks concepts in a virtual environment.

Figure42: Complete car-truck-bike concept and environment simulation by IPG

SIL may be use in a partial control systems of a car or integrations as co-simulation with IPG, from classic automotive mechanical applications, such as powertrain or brake systems, to e-drive applications and functions for autonomous driving. This gives a tremendous capacity of testing saving costs and time.

German company dSPACE, with a global presence in more 14 countries, offers a variety of services from basic ECU generation to complex integrations. These integrations may consider external dynamic factors around the car in 3D, as people closing the street to see the response of safety systems in the car or meteorological influence on the windscreen.

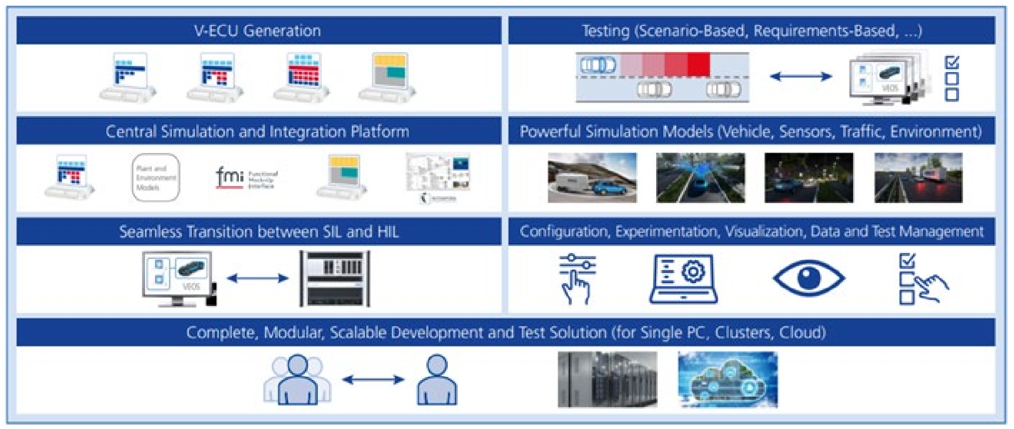



Figure43: dSPACE commercial offer of SIL and integrations

60 https://ipg-automotive.com/products-services/simulation-software/



One of the best and most interesting benefits of SIL is the seamless integration with HIL (Hardware in the Loop) and final physical systems, providing a way to encapsulate knowledge and use it in real time control and maintenance.

As commented in “1.2.- BDT´s implementations in other sectors”, digital twins in automotive are used in factory automation as well. Complex robot movements and production is a strong drive force for development in this case.

## 3.2.- SIL vs HIL

In both SIL and HIL techniques we try to implement and test controls systems. These control systems works against a simulated ambient or process.
In the majority of control scenarios we will have sensors and controlled machines layer (FIELD), and a basic control layer (CONTROL) using specific hardware like PLC´s (Programmable Logic Controller)[61] or ECU´s (Electronic Control Unit)[62].

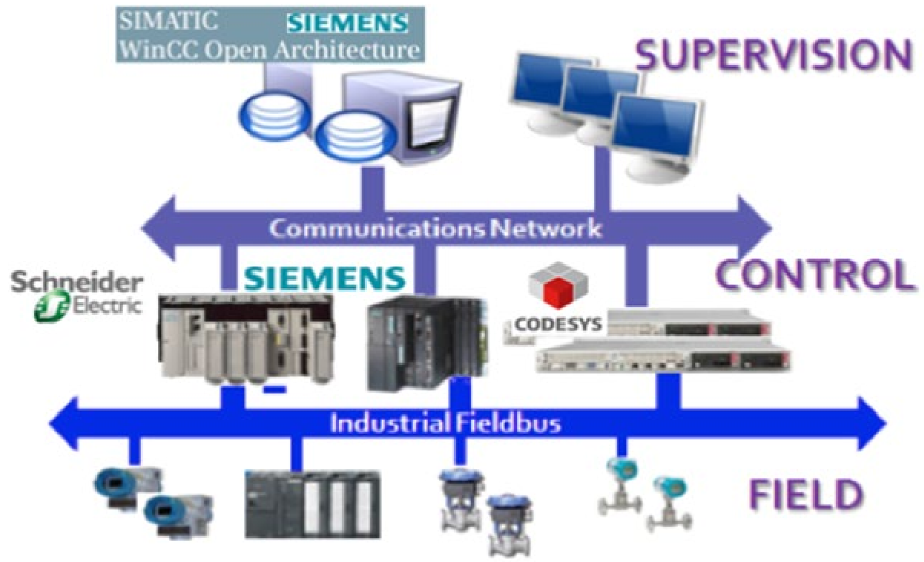



Figure 44: Typical industrial control layer configuration

In this control layer the digital control step time is small (in the order of mili seconds), and functions implemented are low level controls (open a valve, switch on an alarm, to sample an analogical signal, or to send a digital output signal). It may be possible to have complex maneuvers implemented and interlocks, but these controllers are designed to fullfill the basic operations of sensors and automatic machines.

All machines and sensors in factory may be divided in sectors or groups, around a common center of control where we have the PLC and signals concentrated of that area. Modern systems use a field bus to connect the sensors (avoiding a cable from each sensor to the PLC) and the PLC. Near the PLC we may have auxiliary devices to switch on electric motors, calibration systems for the sensors, or even local supervision panels.

61 Typical in chemical process, mining, oil and gas industries
62 In case of automotive industry

These PLC´s (or ECU´s) have a ‘program’ inside, so it may be interesting **to test the physical hardware (with its programming)** before working in real time against the physical system. This process is then called hardware in the loop, as we use physical hardware (physical PLC) in the control loop. *‘A HIL simulation must include **electrical emulation of sensors and actuators**. These electrical emulations act as the interface between the plant simulation and the embedded system under test. The value of each electrically emulated sensor is controlled by the plant simulation and is read by the embedded system under test (feedback). Likewise, the embedded system under test implements its control algorithms by outputting actuator control signals. Changes in the control signals result in changes to variable values in the plant simulation.’*[63]

A most common and popular HIL system may be a physical part of a plane (the cabin) where the pilot sit down to ‘virtually flying’. The hardware surrounding the pilot is reproduced with detail to re-create conditions that pilot may find during the flight. We can find many similar examples with all kinds of machines.

Coming back to an industrial implementation, on top of the network of sensors, PLC´s/ECU´s and controlled machines we will have another higher level layer (SUPERVISION). In this layer we have a communications network (not just a field bus) which may connect several PLCs and PCs. In this case the sampling is not in the order of mili seconds. Depending on the application it may be several seconds or even slower. This is at least three orders of magnitude less than the clock speed of PLC systems.

In this PC level we will have data storage, supervision in real time and high level algorithms to manage the process plant. We may want to simulate the whole system from supervision to actuators and simulated environment. In this case we would be in a pure scenario of software in the loop or SIL.

In case of residential building construction we speak of about 10 ambient sensors in a house or apartment and limited hardware resources (they could be just an ECU concentrating signals and a basic supervision and monitoring hardware and software). We probably won´t have any actuator at all, and control loop applications may be the heating/cooling and ventilation, not more. How can be speaking about SIL or HIL in this so poor scenario?

The answer is not because we have to control complex actuators in blinds or windows. A house is a place to live, to rest and to love. Not a factory neither a spacecraft. The main reason why we need SIL is to help and support monitoring and analyzing what is really happening in our walls, in our air and how the humans interact with the building. We don´t have sensors for all of that, but SIL can be the right tool to supplement the lack of information.

In case of construction pure SIL models can be useful for design, using TMY files for meteorological data and schedules for human behavior. But the real expected value is to use exactly the same models for real time supervision and virtual commissioning. In these cases

63 https://en.wikipedia.org/wiki/Hardware-in-the-loop_simulation



the simulation model may be critical to understand how the building is performing.
Coming back to comparisons between HIL and SIL it is interesting the presentation by dSPACE, a multinational company based in Europe, USA and Japan[64]. In a presentation by Martin Rühl (dSPACEGmbh)[65] he explains the different aspects of real World testing, HIL and SIL (see bellow).

**Options for testing**

- Real World Testing: Test drivers in prototype cars
- HIL Testing: “Hardware in the Loop” tests with real ECUs
- SIL Testing: “Software in the Loop” tests without any hardware

| | Real Word | HIL | SIL |
|---|---|---|---|
| Closeness to reality | ++ | + | o |
| Reproducibility | - | ++ | ++ |
| Scalability and variability | -- | + | ++ |
| Costs, set-up time | -- | o | ++ |
| Test kilometers per day | -- | o | ++ |
| Feedback to function developers | - | o | ++ |
| Debug at code level during run-time | -- | o | ++ |

Figure 45: Real World, HIL and SIL techniques, explain by dSPACE[66]

We see than SIL testing in automation has many advantages over prototypes and HIL, due to the fact that everything is software and we can reproduce it, set up an experiment very quickly, test everything, to have immediate feedback and correct things very quickly.

The SIL models in construction could be setup economically if we get libraries and SIMBOTs (manufacturer’s equipments) ready in advance. They could add a lot of information of non measured quantities. They could transform complex concepts in monetized flows, understandable by everybody. They could detect when a sensor is not working well. The SIL model could be calculating when to switch off the heating because the thermal inertia of the building is enough to keep the comfort temperature. And all of this embedded is a small hardware as we have demonstrated in SPHERE project. HIL applications are possible as well with the same SIL models, testing possible controllers of appliances, but SIL in case of residential construction is a question of smart supervision more than sophisticated control.

64 https://www.dspace.com/en/inc/home.cfm
65 https://youtu.be/Pbau0M7zvAc
66 https://www.dspace.com/en/inc/home/products/systems/sil_testing.cfm

## 3.3.- SRI Indicators

### Concept and Methodology

In 2018 was published an study accomplished under the authority of the European Commission DG Energy[67]. In that study the EC wanted to evaluate the potential and realization of Smart Ready Technologies (SRT) in the building sector. Requires the development of a voluntary European scheme for rating the smart readiness of buildings: the “Smart Readiness Indicator” (SRI). The SRI aims at making the added value of building smartness more tangible for building users, owners, tenants and smart service providers.

The indicator (or indicators) is intended to raise awareness about the benefits of smart technologies and ICT in buildings (from an energy perspective, in particular), motivate consumers to accelerate investments in smart building technologies and support the uptake of technology innovation in the building sector.

The **SRI assessment procedure** is based on an inventory of the smart ready services which are present in a building and an evaluation of the functionalities they can offer. Each of the services can be implemented with various degrees of smartness (referred to as ‘functionality levels’).

The services present in a building cover multiple domains (e.g. heating, lighting, electric vehicle charging, etc.) and can also bring about various impacts (energy savings, comfort improvements, flexibility towards the energy grid, etc.).

In order to cope with this multitude of domains and impact categories, a multi-criteria assessment method was proposed as the underlying methodology for calculating the smart readiness indicator.

In the domain of smart appliances, the European Commission has boosted the development of a common ontology for this domain, called **SAREF** (Smart Appliance Reference) and a standard based on it developed by **ETSI**[68]. These allow matching appliances and systems from different manufacturers, exchanging energy related information and interacting with any other Building Energy Management System. Extensions to the SAREF ontology for smart machine-to-machine communication provide specifications for the energy domain and the building domain. Within the Ecodesign framework of the European Commission, further focus has been given to interoperability in the product and service design of smart appliances and BACS.

### Assessment vs Monitoring, Analysis and Simulation in Real Time

Not many professionals have a clear understanding of what are the possibilities of “calculation software”. As explained in other chapters of this white paper, complex mathematical models can be embedded in the real time monitoring performing a simulation of the building or individual systems. These models can be supported by measured data in different ways, and the derived values and magnitudes that can be extracted are of great interest.

67 European Commission, Directorate-General for Energy, Contract no. ENER/C3/2016-554/SI2.749248. 26th August 2018. Flemish Institute for Technological Research NV (“VITO”), Boeretang 200, BE-2400 Mol, Register of Legal Entities VAT BE 0244.195.916

68 http://www.etsi.org/technologies-clusters/technologies/smart-appliances



Assessment per se is an evaluation at one time. It is a ‘picture’ of the building with more or less ‘pixels’ but not a ‘video’ or a ‘movie’. With a complex procedure we can derive a set of numbers and a total amount. It is more than debatable that policies supported only by ‘assessments’ can get good results in a long term. The EU has already experience in both effort/results with the Energy Performance Certificate EPC, and we cannot consider that it is changing drastically the way construction is responding to the challenge of low carbon economy or climate change.

Measurements on the other hand are trends or historical data, they are the ‘video’ we don´t get in an assessment, but sampling has specific problems and it is impossible or non-economic to fill a house with dozens of sensors.

Simulation in real time (or ‘Software in the Loop’) can be the extra support that measurements need, in such a way that ‘video’ description of the house would be useful for improving health, comfort and efficiency (in this order, taking into account that efficiency is not possible if we don´t have a reference of minimum comfort).

Of course it is always needed a ‘digital decision’ (0/1, good/not good, to go ahead/stop,...) and an assessment must play a role in any policy. But we have to distinguish what means an ‘evaluation’ and what is a ‘description or characterization’ in the future EU policies. This is extremely important for the EU citizens and in SPHERE project we are responsible for introducing new techniques which can be critical in EC decisions.

Characterization is not a ‘digital’ description. It can be standardized but it is not oriented to take any decision (tax, financial investment or grants). Description may be as complex as needed. Assessment is of course based on a description, but always with a ‘digital decision’ with the form of index, letter, number or any other form of evaluation.

On the other hand, assessment or evaluation in a classical approach is oriented to the ‘building’, as the ‘object’ where we apply technology and efficiency. But a building is surrounded by meteorological conditions which change continuously and filled with humans who are changing their demands and comfort targets. Mathematical simulation embedded in real time monitoring systems give us the opportunity to change from the ‘building-object’ concept to the ‘human-dynamic’ approach, understanding that the interaction of humans and building can be technologically solved in the near future thanks to wearable’s and new electronics. Mathematical models of humans can serve as virtual sensors of comfort with historical data, histograms and the best characterization that is possible, and serving as an advanced alternative assessment in real time.

The embedded Mathematical Simulation does not need an expensive hardware platform and may be hosted in-site, in the same hardware providing monitoring and human machine interface HMI. It can generate simple and understandable parameters for the home users or complex evaluations, harmonizing a good user interface and a sophisticated analysis. Simulation can reinforce robustness and estimations provided by the sensors or create new ones. The models itself can have some machine learning capabilities in order to validate thermal inertias or unknown transmittance values.

Perhaps one of the main problems to be settle in future EU policies is not the scope or quality of assessments but the user involvement. Implementing technologies with more potential user involvement means more investment decisions, improvement of humans health, comfort at buildings and real and measurable impact in carbon emissions.

## 3.4.- Use Case TNO

On the Morning of October 5th, 2020, the first brick of the NeroZero houses was unveiled by council members Annette Groot and Monique Stam-de Nijs of the municipality of Heerhugowaard, in the province of North Holland of the Netherlands.


Figure 48: Annette Groot and Monique Stam-de Nijs of the municipality of Heerhugowaard

These NeroZero homes respond to the need for energy-neutral homes, but also affordable, healthy, comfortable homes to live in. For Sphere EU project, these homes are in the spotlight. Project partner TNO is using software to build a Digital Twin, which makes it possible to predict and control the performance for energy and indoor environment in the various building phases, including the use phase. The buyers are cooperating to generate more data in the coming period.

With the energy transition in mind, it is becoming increasingly important to predict energy use and sustainable energy generation. By starting heating homes earlier, the energy demand can be shifted in order to increase the share of sustainable energy and to stay within the available network capacity. And network capacity is becoming increasingly important in the process of sustainability. As an example, these first NeroZero homes are only connected to an electricity network. Artificial intelligence (AI) makes an important contribution to a better estimate of user behavior for a robust prediction and the privacy of the data. That is why TNO is developing scalable building models for energy forecasting applying the latest insights in the field of AI.



The NeroZero house is also equipped with an innovative whisper-quiet cooker hood, a joint development with TNO, ATAG, and Brink Climate Systems BV, which ensures that fine dust production through cooking is minimised. 90% of exposure to fine dust comes from spending time indoors and cooking inside the house. This innovation, not only makes the house energy neutral but also reduces health risks to the people that live in it. Additionally, it responds to the needs of buyers, as they have expressed their consideration toward this cooking extractor, describing its benefits as important. Now, extensive testing is being carried out in the design and commissioning to see whether they are as healthy, comfortable, and energy-efficient as on paper.

A total of 53 NeroZero homes will be built, of which 44 are starter homes, 5 life-course residences, and 4 single-family homes. The construction of the first phase of 18 starter homes was well advanced. There, the festive moment of the unveiling of the NeroZero brick took place. A total of 439 registrations were made for the second phase of 35 NeroZero homes in 10 days.

Figure 49: NeroZero development at North Holland

## 3.5.- Location of Sensors

“Monitoring spatial phenomena as indoor air temperature is a challenging task, especially when applied to large indoor spaces. Large spaces include indoor sport spaces, open space office, entertainment buildings, where the air temperature is not homogeneously distributed, so the monitored values can be different from point to point at a given instant. In particular, phenomena as air stratification and stagnation may be present, causing significant horizontal and vertical temperature gradients”[69]. These phenomena are generally due to large floor area, high height, high percentage of glazing surfaces, incoming direct solar radiation, errors on ventilation system design and heating/cooling sources randomly distributed in the space. The indoor thermal condition are normally monitored using traditional methods as single point temperature sensors, usually located in the return duct of the ventilation system or in a single point of the space, without taking into account air temperature gradients that could occur in the occupied space. Additionally, common practice is to design a monitoring system using criteria based on experience. So, conventional air temperature monitoring techniques could reach a level of measurement uncertainty that prevent accurate thermal comfort evaluation and effective climate control strategies operated by the HVAC (Heating, Ventilating and Air Conditioning) system[70]. Considering that measuring the air temperature inside critical environments, such as large spaces, using a limited number of sensors, is a challenging task to achieve; so the decision making process leading to selection of sensors number and placement is challenging too.

At the “Engineering Building NUI Galway” extensive work has been done in order to estimate the right number of sensors and how differences in temperature may be in the same space. A large space is fully equipped with six thermistors, measuring the air temperature value with accuracy ±0.3 ◦C, in six different points, installed on pillars at breathing level, marked with a green circle in the following figure.

Figure 50: Sensor network design of open space office, Engineer Building

69 P. Rajagopalan and M. B. Luther, “Thermal and ventilation performance of a naturally ventilated sports hall within an aquatic centre,” Energy and Buildings, vol. 58, pp. 111–122, Mar. 2013

70 G. M. Revel and M. Arnesano, “Perception of the thermal environment in sports facilities through subjective approach,” Building and Environment, vol. 77, pp. 12–19, 2014-07



Figure 51: Engineering Building NUI Galway, exterior

The temperature data were downloaded for the entire month of January 2015 with a sampling frequency of 7 minutes, a typical day of temperature distributions is reported in figure 52, where an horizontal gradient of around 2◦C, can be found between the sensors T5 and T6, during the occupancy hours.

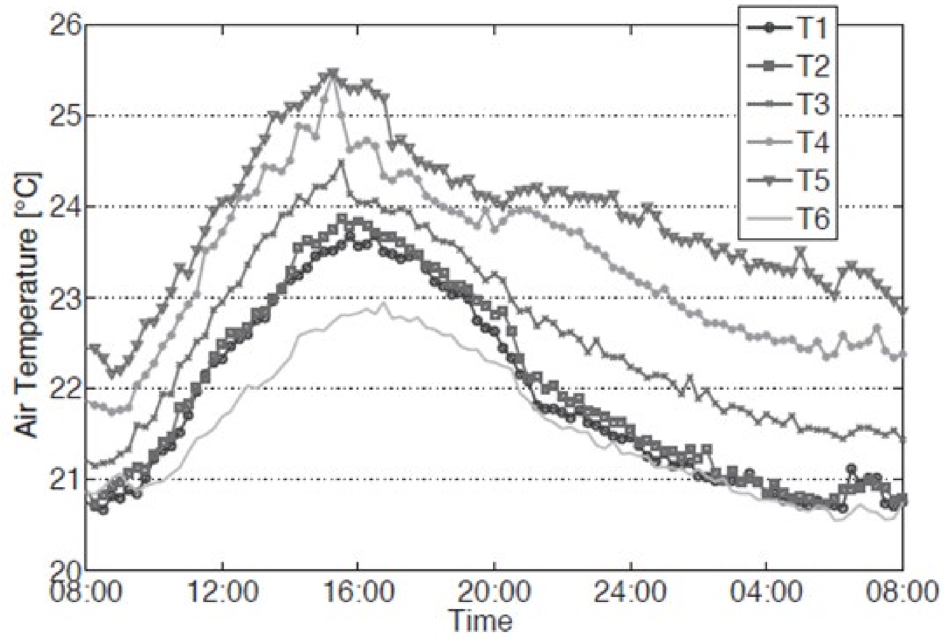



Figure 52: Temperature trends inside the open space office during one day,Engineer Building

This may serve to demonstrate the application of optimization algorithms based on the measurement performance index to the data gathered from the BMS. The sensor selection process calculated as optimal sensors to be kept, in case of sensors reduction, the sensors T1 and T4. The optimization process led to the conclusion that the use of just two sensors for monitoring the temperature inside the space, instead of the initial six (reference temperature), led to measurement performance statistical criteria equal to mean deviation of

0.05◦C, standard deviation equal to 0.25◦C and 21 of sensors working hours with a standard deviation, due to the sensor location, higher than sensor uncertainty, considering the entire January 2015 as time window for the analysis.

In particular, figure above reports the indoor temperature deviance between the reference temperature (calculated as mean value of all 6 temperatures) and the optimal monitoring solution of the two selected sensors during a typical day, inside the open space office.

## 3.6.- Interaction of SIL and BMS

Understanding the exact dimension of resources we need for supervision and control in a residential building can explain the real challenge to be solved. In a family home we will have not more than five spaces to be monitored for ambient quality, and equipment for ventilation or heating/cooling is not a huge installation (perhaps a set of two or three machines of different suppliers). On the other hand the cost of sensors and electronic devices should keep a value in the same order of magnitude than a common appliance (let say 1.5K€).

Networks to connect sensors and monitoring devices must be easy to deploy if we want to play any role in renovation, and user interface must be adapted to a low technical profile. The BMS software (or Scada system, "Supervisory control and data acquisition") should gather sensor data and other simulation outputs in a reliable human machine interface (HMI), taking into account the user who is going to be receiving that information.

In another hardware and software layer this Scada may be using a PLC (programmable logic controller) for high speed sampling, alarms or dedicated control loops. Many people consider PLC´s as part of the Scada system, but in our minimalist scenario a PLC could be reduced to an ECU and some electrical connectors.

The normal observation time for a house may be 10 to 15 min (this could be the Scada refresh) whereas other control loops may have time steps of miliseconds (and so these tasks are supported by the PLC hardware and software).

In this limited scenario, where can we host the advanced simulation engine? Testing this specific problem in SPHERE project we can affirm that small Linux machines as a Raspberry Pi 4 used as a Scada platform can handle a complex simulation deck, which open many possibilities for in-site (not cloud) advanced control. Simulation decks would speak with the Scada system using OPC UA protocol in time steps of 10 to 15 min, permitting a convergence of every simulation step in real time (understanding that real time has a time step of 10-15 min). Underneath this interaction between simulator and scada processes we may have many other tasks oriented to control, alarms or services, but it is important to consider the time frame and how simulation is working.

With simulation we can interact with controls in different ways. We can just compare expected responses versus simulated outputs (differences called "residuals"). Analysis of these residuals give a good and objective measure of validation of our simulation, and how sensors malfunction can be detected. This can be used as feedback to improve some transmittance estimations of individual components of the building or to get thermal inertia values of spaces of the whole building.



Other interesting strategy may be to load meteo predictions from internet services. These predictions may be used to switch on or off heating or cooling systems, using the house as a thermal storage.

Simulation can help to detect sensors malfunction or network problems. Alarms created to detect these problems can help a lot with online maintenance and assistance to end users. Whatever process to be carried out should consider as a priority the final user. Too sophisticated technology is not going to be understood, so a 'translation' of those variables may be a great value of the simulation as well. With simulation we can convert thermal flows in monetized values. This could be a great help to take decisions about windows, doors or envelope, which are the most expensive in a deep renovation.

In summary, simulation can help supervision and control in these cases:

- Residuals, validation
- Improved HMI
- Real time evaluation and SRIs
- Predictive control
- Predictive maintenance

Simulation can be embedded in small machines and in-house, and can have different number of input/outputs, from a black-box concept to explicit mathematical description (white-box).

Combining mathematical simulation with other techniques as expert systems, machine learning, big data or artificial intelligence in general is always possible, but once again the residential scenario may be not suitable for complex data treatment. Simple simulations and some automatic learning may be the best solution, as stated by Mr. Youyang Gu regarding covid-19 predictions[71].

Regarding connectivity between simulator deck and BMS this can be solved in several ways. From web services to embedded simulation in the same hardware that hosts the Scada. In Sphere project we have tested different solutions and implementations with less connections are simply more robust, and provide less privacy problems as well. OPC UA standard has demonstrated its capacity and free applications to test communications from OPC client or server are practical and useful.

## 3.7.- Predictive Maintenance

Maintenance are all actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. These include the combination of all technical and corresponding administrative, managerial, and supervision actions[72] . In our daily lives we are familiar with maintenance tasks such as replacing a bulb when it is burnt out or having the car engine oil changed. The first action is an example of corrective maintenance; the action takes place once the failure has occurred. It causes a service interruption (the light does not work until the bulb is replaced) and some discomfort.

71 https://www.technologyreview.es/s/13425/la-ciencia-es-un-metodo-para-encontrar-la-verdad-no-la-verdad-en-si, by Siobhan Roberts | translated into Spanish by Ana Milutinovic, 3rd June, 2021

72 "European Federation of National Maintenance Societies". EFNMS.org. Retrieved 5 August 2016

However, in some cases we cannot risk a failure because of safety reasons or due to the fact that the failure can cause high economic losses (stop a supply chain or seizing the engine). In those cases, preventive actions are performing such as changing the oil or cleaning or replacing some parts. Those are examples of preventive maintenance. The parts and frequency of replacement is set according to statistical occurrence of failures. This approach leads to replace parts that have still not reached their lifespan or, on the contrary, they failure occurs before the planned preventive action. A third maintenance approach, called predictive maintenance, overcomes these downsides.

Predictive maintenance has become possible using smart technologies that connects digital and physical assets. Historically it has been used in critical systems, especially aerospace, and more recently in industry. The decreasing cost of sensors, computing power, and bandwidth, coupled with increasing technological advancements allows its application in a broad range of use cases, including heating and cooling systems in tertiary buildings[73] . Most work on early Fault Detection and Diagnosis in HVAC systems is focused on air handling units (AHU) monitoring[74] . In the case of gas boilers, some work is being reported at industrial level[75] [76].

Nonetheless, its applicability can be extended to residential dwellings taking advantage of the increasing IoT penetration such as smart thermostats, ambient sensors and energy telemetry provided by smart meters. Nowadays, most of households appliances include an electronic control board and multiple embedded sensors. Furthermore, some appliances are connected appliances (also called smart appliances) that can either be switched on remotely from an app or can automatically order a printer cartridge. The success of this kind of appliances is quite limited so far, either because they are significantly more expensive that non-connected ones or because the functionalities they provide have low interest among the general public.

Either embedded sensors or external IoT sensors can be used to build predictive maintenance tools for at least one (or more) of the following reasons:

- Avoiding failures: taking action before the failure occurs but when first symptoms of deterioration appear
- Increasing safety: minimizing the risks of accidents caused by unobservance of hidden parts such as dirt obstructing a pipe
- Avoiding damages caused by equipment malfunction such as flooding caused by a leakage
- Minimizing downtimes and/or discomfort: early warnings help to plan for parts ordering and workforce scheduling
- Reducing inefficiencies of devices not performing in their best operating conditions and consuming excessive resources

73 Lazarova-Molnar S. , Shaker, H. R, Nader M.and Jorgensen B. N. Fault Detection and Diagnosis for Smart Buildings: State of the Art, Trends and Challenges. Proceedings of the 3rd MEC International Conference on Big Data and Smart City . IEEE, 2016. p. 344-350 7460392

74 Y. Yua, D. Woradechjumroena, D. Yub, A review of fault detection and diagnosis methodologies on air-handling units, Energy and Buildings, Volume 82, October 2014, Pages 550–562

75 Xi Sun, Tongwen Chen, and Horacio J. Marquez, "Boiler Leak Detection using a System Identification Technique",Ind. Eng. Chem. Res. , 41, 5447-5454, 2002

76 M. Addel-Geliel, S. Zakzouk and M. El Sengaby Application of Model based Fault Detection for an Industrial Boiler, 2012 20th Mediterranean Conference on Control & Automation (MED) Barcelona, Spain, July 3-6, 2012



In fact, energy efficiency and resources efficiency, in general, as a mandatory path to follow for a more sustainable building sector and society has become a driver for the research and development of data-driven applications, also for residential building and domestic appliances.

Some considerations have to be taken into account regarding data gathering, namely how is retrieved, how and where it is stored and how it is consumed or who has accessed to it.

## Information Retrieval: Sensors

IoT sensors may be low-cost sensors, however, they reliability and accuracy are limited. Despite some applications may not require high accuracy, reliability, easy installation and usage and low maintenance are needed requirements for domestic applications.
Thinking in terms of circular economy, a much smart approach is to use (or re-use) embedded sensors in appliances. The reliability and accuracy of these sensors is higher and they come with the acquisition circuitry in the equipment itself. The challenge in this case is interoperability. In general, the data gathered by these sensors is not accessible for third parties. That links to the topic of where the data is stored and who/how it is consumed that will be discussed later. Although equipment and management systems manufacturers are willing to use proprietary protocols, a shift in the paradigm is observed. An example is the communication protocol created by Opentherm[77] for HVAC systems, which gather over 65 companies across Europe including big players as Siemens, Tado, Vaillant and Bosch among others. The information available through this protocol enables to access over 120 variables and enables a physical-digital-physical loop: gather data from the physical device, clone it in the digital twin for further analysis and feeding back commands to the physical device.

To enable interoperability standard protocols have to be defined, but more importantly manufacturers have to find a reason to open their protocols and data to third parties. This reason may come from regulation, making it mandatory in the interests of more transparent and better products and services for consumers, or it may come from market pull, empowering consumers to request not only efficient appliances but interoperable.

## Data Storage: Edge or Cloud?

Values taken by sensors can be used to take real time decisions (i.e.: if the indoor temperature is higher than the set-point temperature, stop the heater) or to develop AI or machine learning applications that "learn" over time and take complex decisions based on multiple variable analysis. In the latter, measurements have to be stored and processes using one or a combination of machine learning techniques such as Support Vector Machine, Artificial Neural Networks and decision trees, among others.

If this information is stored locally, meaning in the edge, all the decisions (and computations) have to be taken locally. It requires storage and computational resources, making the application/device either more expensive or less powerful, and it cannot take into account the behavior of similar equipment to learn patterns. In order to use context variables such as weather services, calendar, and so on, the user must provide some

77 https://www.opentherm.eu

inputs and communicate with the user support service or service provider. However, users have total control over the data exchange and the application might work no matter how if there is internet connection or not.

On the contrary, if the data is sent to the cloud (or a server outside the household), big data analysis techniques and more powerful data mining algorithms can be applied to increase anomaly detection accuracy and use context variables. This approach requires internet connectivity that might not be always granted, especially for some equipment located in technical rooms, rooftops or inner courtyards. But most importantly, it endangers data protection and privacy.

### Data Access Rights

As a consequence of edge versus cloud data architecture, a new issue arises: who owns the data and who can use it.

This is an on-going debate for social media apps. It is also under discussion for smart metering data and it has to be discussed and, more important, regulated for smart appliances.

Under the humble opinion of the writer, the data belongs to the user of the equipment and must explicitly authorize third parties to access it for a well-defined service and time period. The equipment manufacturers might thing differently and in any case they should find the legal framework and incentives to handle data ownership to the user (and buyer of the equipment).

As mentioned previously, predictive maintenance has been applied in the industrial sector and HVAC systems in tertiary buildings. The concept has also applicability in the residential sector. Following are some examples of application:

- **Ventilation systems:** Detection of obstructed conducts by dirt: air flow patterns in (very) obstructed pipes differ from normal patterns, pressure in the circuit is abnormal, energy consumption to impulse air is higher than expected,…

- **Heating and cooling systems:** performance ratio is lower than expected and causes extra energy consumption, comfort temperature is never reached, abnormal noise or vibrations, hidden water leakage in the pipe, …

- **Water (micro-)leakage:** even if most applications focus on electric equipment, water pipes and systems need repairing and maintenance. As pipes are usually embedded in walls, leakages, if small, are not observable in the short term until they cause humidity in one of the house walls or in the neighbour’s house, and/or the consumer receive the monthly or bi-monthly bill. By continuously monitoring water consumption, leaks can be detected. Water smart metering roll-out is still not as advanced as electricity smart metering, but it is progressing. In addition, there are some non-intrusive alternative sensing solutions that can be deployed for water monitoring. From a perspective of circular economy, there is a tight link between water and energy: water leakage causes a waste of water, that it is and will be a scarce resource, but it also causes a waste of energy, the energy that has been used to sanitize and distribute it. And going beyond, it makes use of energy and materials to repair the damage caused by a leakage or flood. All together increase CO2 emissions.

- **Photovoltaic panels:** Cost of PV panels going down and regulation fostering the installation of local renewable energy sources has lead to an increasing number of small PV installations on rooftops. Those installations need only maintenance to get the most of them. Predictive maintenance can be used to detect a failure in a cell or dirt or dust that reduces power production. Similarly, performance monitoring can be used to detect an abnormal condition in the inverter or a non-optimal operation point.



Predictive maintenance tools can be integrated in a building digital tool to improve management and interaction of a myriad of systems (facades, insulation, ventilation slots, …) and occupants themselves. The results can be provided in the form of alerts, recommendations or commands.

## 3.8.- MPC

Control systems are critical to ensure building efficient operations and occupant comfort. To support building control, real time simulation approaches coupled in real time with building energy monitoring, management and control systems provides the ability to predict thermal loads in buildings and provide guidance on energy - and comfort-optimal control strategies . Energy models fed by real-time building operation data (equipment and systems), predictive weather data, and occupant data, enable the possibility of [near]real-time simulate and assses control strategies across a future time horizon, and optimize the control strategy according to improved energy and comfort outcomes.

This approach is generally known as model predictive control (MPC). Model predictive controllers rely on dynamic models of the process, most often linear empirical models obtained by system identification, allowing the optimization of operation timeslot while simultaneously accounting for future timeslots. Further that, advances approaches are targeting the validation hierarchical, occupancy responsive MPC framework that optimizes the operation of buildings and campuses by controlling lighting levels, HVAC operation, indoor air temperature and humidity, indoor environmental quality, window opening, and shading devices.

The framework takes into account anticipated weather, occupancy, price signals from the electrical grid or district heating/cooling networks and active and passive measures to store energy and reduce peak loads. The proposed occupancy-responsive MPC technology seamlessly integrates building technologies, controls, and human behavior - a substantial need for zero-net-energy and grid-responsive buildings.

Further, or in parallel, real-time simulation provides advanced approach in efficient operation, as is used to detect and diagnose faults (FDD). The framework allows comparison of actual and expected building performance in real time using energy performance simulation working together with EMS and control systems. Here, energy performance model determines and reports the expected performance of a building in real time and a data capturing relevant inputs from the EMS (through common/standard protocol interface), enriching the energy performance simulation as well as a database .

Operational faults are common in existing buildings, leading to decreased energy efficiency and occupant discomfort. It is estimated that poorly maintained and improperly controlled HVAC equipment is responsible for 15% to 30% of energy consumption in commercial buildings. Most buildings, especially those with complex building energy systems, have various degrees and types

### SIL Enabling Automated Assessment and Optimization

The introduction of SIL approach via Digital Twin, enables the automation of assessment, optimization and control abilities by a closed loop, using the two approaches described above. Adding intelligence to the first level of control (or in several levels as well) embedded in the Digital Twin paradigm enables the building to respond in real time without any human intervention. We can configure an intelligent building adding intelligence to each system and appliance present in the smart building, and AI enabled strategies for advanced and automated building operation. This, pave the way for advanced strategies for real time monitoring, load disaggregation and modeling, that together with SIL approaches, including its further synchronization with Digital Twin (Instances) approach, enabled the development of scalable energy performance assessment and optimization algorithms for self-correction and self-optimization based on cutting edge machine learning approaches.

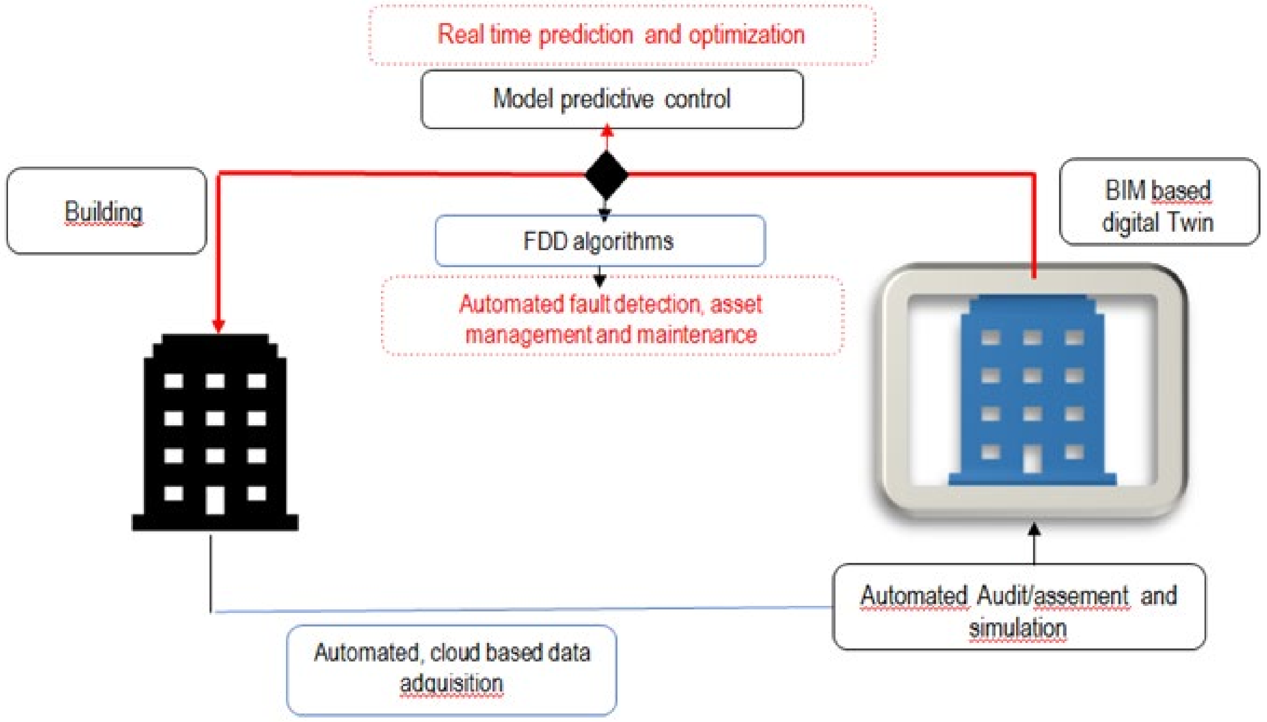



Figure 53: MPC building concept with SIL

# 4.-PERFORMANCE CONTRACTS

The main benefit of mathematical simulation applied to buildings is its capacity of being useful in all phases of construction and life cycle. In conceptual design it makes possible to make quick comparison or even to test virtually the building getting SRIs with synthetic occupancy. Model can be in this phase not made of manufacturer SIMBOTs, but using generic and parametric devices.

During commissioning simulation can reproduce partial testing of systems, adapting boundary conditions to real ambient and hence verifying the performance of passive building, networks and equipments.

Finally during the life and exploitation of the building the same mathematical model can be embedded in control systems in order to perform predictive control, supervision of sensors and networks and predictive maintenance, helping the limited resources we have in-site and letting others to help remotely.

This description which may be common technology in some years is not a reality today, and the EU face a global challenge towards the deep renovation of massive number of existing buildings with the hope of reducing the energy consumption and improve efficiency.

Deep renovation of a building is a costly investment and without a financial instrument in many cases is unaffordable. Banks and other institutions don´t accept operations with a horizon of more than 10 years due to risk evaluation. If deep renovation recover its investment in a similar period of time automatically all operations are denied due to negative risk evaluation. This financial problem can only be solved with a precise technical estimation of profit and exchanging risk by performance, in such a way that banks receive part of the measurable or well estimated profit.

Mathematical simulation in real time with good integration of meteorological conditions and occupancy may produce precise and dynamic analysis of the building, whether in real conditions or simulated, so comparisons between 'how it was' and 'how it is after renovation' can be made with great definition, setting up a dynamic base line which depends on meteo and occupancy. This opens the door to performace contracts and financial tools which may increase exponentially the number of new deep renovation projects.

## 4.1.- 'Stroomversnelling' Case

In the Netherlands, the ´Energiesprong´ network is known as 'Stroomversnelling'. This association originated from an earlier government funded Dutch innovation program called Energiesprong, which aimed to create Net Zero Energy (NZE) buildings on a large scale. In 2013, Energiesprong brokered the "Stroomversnelling" deal between Dutch building contractors and housing associations to refurbish 111,000 homes to NZE. Two years later, Stroomversnelling evolved into a market initiative designed to take NZE to the next level. In other countries the name Energiesprong is still in use[78].

The ´Stroomversnelling´ network consists of contractors, component suppliers, housing providers, local governments, financiers, DSOs (energy system manager) and other parties. Its objectives are to reduce the renovation costs of NZE refurbishments, increase occupants' acceptance of these renovations and increase the pace of growth in the NZE housing market itself.

The Ducth TNO[79] (SPHERE´s partner) is developing a digital twin framework to support these renovations. Using advanced instrumentation techniques and simulation models they can predict the energy consumption, ventilation performance and insulation of the building, even for social houses.

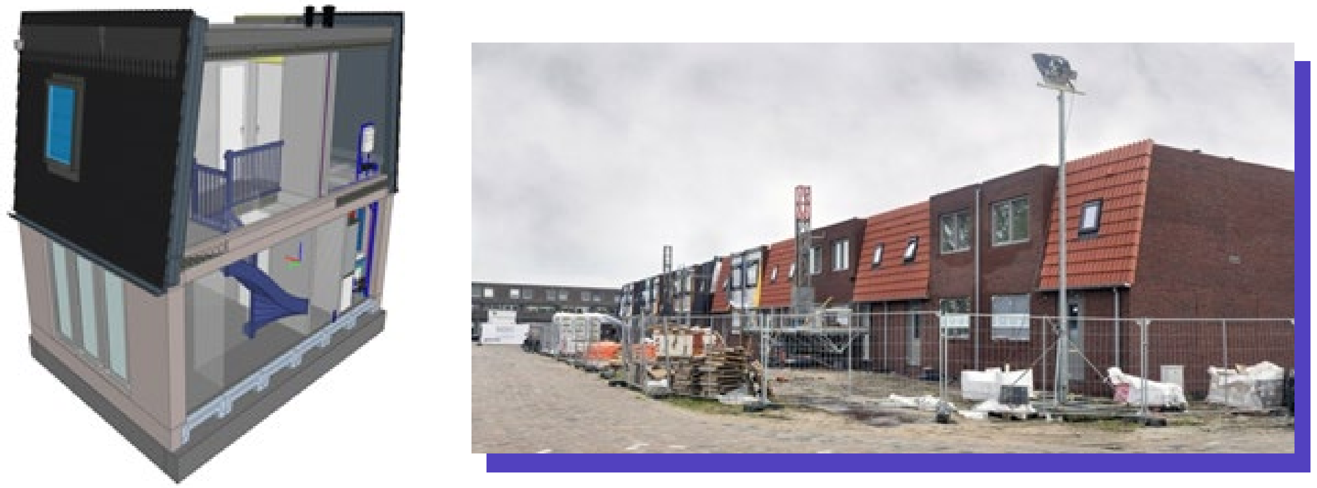


Figure 54: Nero Zero project in Delf (Holland)

The importance of this intensive technological effort will be on providing a platform for performance contracts with third parties. If these contracts are possible and financial risk totally under control development of these advanced renovation or new construction will be able to be covered by credits or other financial models.

Simulation models can provide a lot of information far beyond the sensors of the building and can be integrated with real time systems, in such a way we can have smart readiness indicators (SRI´s) in real time.

78 https://energiesprong.org/country/the-netherlands/

79 https://www.tno.nl/en/



## 4.2.- The Meetscoalition.org

One great example of performance contract may be the MEETS Accelerator Coalition[80]. They explain how historically it has been nearly impossible to make building energy efficient: building owners don´t want to invest because the savings go to the tenants; tenant's don´t want to invest because they don´t own the building; and energy efficiency reduces utility sales, undermining their business model. So utilities only do energy efficiency as much as they are required to do. So MEET would be the "Metered Energy Efficiency Transaction Structure" designed to solve all these problems. They explain how the EnergyTenant(TM) pays a long term rent to the Building Owner. Under that agreement the EnergyTenant pays for the new installations and maintenance in order to improve energy efficiency. Once improvements are carried out the whole building is monitored considering all fuels, generating a dynamic base line and the real building energy use. This monitoring is carried out by an independent third party company. All readings are fully transparent and auditable.

In the payments flow the tenant's don´t see any change other than having a more comfortable home, and they pay the same bill that in the previous situation where the building was not improved.

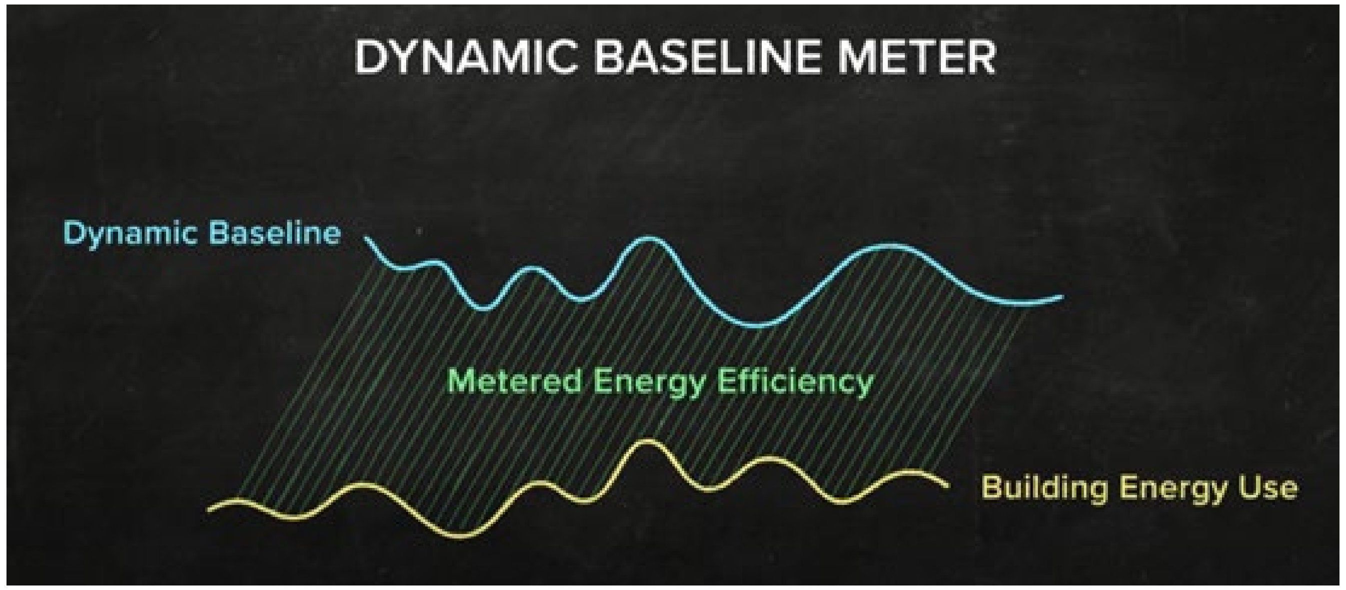



Figure 55: Dynamic baseline

The key aspect of all this methodology is how to define and calculate the dynamic baseline (the real building energy use is available from the smart meters). Mathematical simulation could solve that challenge providing a test period for validation before the deep renovation. In that phase the dynamic baseline should be similar to the energy consumption of the building, providing a way of calculating sampling errors and general contractual aspects.

80 https://www.meetscoalition.org/

There are in Europe similar initiatives than MEET. The LATVIAN BALTIC ENERGY EFFICIENCY FACILITY[81] (LABEEF), founded by a Horizon 2020 project, targets the old soviet buildings for renovation with a similar schema than MEET. Nicholas Stancioff, leader of LABEEF, is working since June 2012 identifying the need for long term capital based on the real estate owner's ability to repay. Mr. Stancioff is currently engaged in the development of an ecosystem for building deep renovation across Eastern Europe and beyond. Currently supporting partners in 10 European countries. He is a co-founder and director of Funding for Future, a Dutch based Fund Management Company and he established the Latvian Building Energy Efficiency Facility (LABEEF), financed by the EBRD, which support ESCOs working with building deep renovation.

Figure 56: Nicholas Stancioff, leader of Funding for Future

81 ttps://ec.europa.eu/energy/sites/ener/files/documents/015_1.2_nicholas_stancioff_seif_warsaw_30-11-17.pdf



# 5.-TRUSTWORTHY BDTS

## 5.1.- BDT and People

A BDT can be conceived as a continuous flow of data from a physical space to a digital system and back. In BDT environments, prediction and prescription are considered the key elements, so that the DT is not only a repository built from sensors and models but also an active element that influences the physical environment of the building through actuators, in a sort of feedback loop.

In consequence BDT environments may impact and influence people either directly via control of the physical conditions (e.g. regulating temperature) or indirectly, e.g. through changes that may affect stakeholders or the global population, as in the case of environmental impact (e.g. if the BDTE actively attempts to optimize global energy consumption). One important impact among others is that BDTs may in some cases have implications in privacy, as the digital replica may directly or indirectly store and process personal data. In general, sensor data can be considered pseudonymous, as it bears a degree of risk of de-identification when combined with other data. This risk can be difficult to identify, e.g. if the sensors of the building track energy consumption at device level, they are implicitly recording personal usage or preferences in the use of those office or home devices. This has regulatory implications, including compliance with the General Data Protection Regulation (GDPR), but goes beyond that since it also potentially affects actuation in the feedback loop from the DT.

The above-mentioned potential impacts on people require an integration of human and societal factors in the design of BDTs, encompassing different aspects of what we can consider a "trustworthy" BDT environment.  That consideration is critical for the adoption and acceptance of BDTs, as it happens in general with cyber-physical systems. Here we approach this starting from concepts borrowed from the field of Trustworthy AI design, and then introduce the roadmap for outlining BDTE-specific guidelines.

## 5.2.- The Concept of a Trustworthy BDT Environment

### 5.2.1.- Background: Trustworthy AI

Concerns with the use of AI tools has led to different initiatives that attempt to develop the concept of a responsible use and application of AI. Here we take as a foundation the work of the EC HLEG AI (High-level expert group on artificial intelligence). Concretely, we depart from the guidelines for “Trustworthy AI systems”[82] that defines them in the following way:

> *“[..] should be met throughout the system’s entire life cycle: (1) lawful, complying with all applicable laws and regulations (2) ethical, [...] (3) robust, both from a technical and social perspective”*

While complying with regulation is a matter of legal assessment, ethical aspects and robustness encompass a consideration of responsible interaction and transparency with people and a consideration of potential threats that make them safe, respectively.

The above mentioned concept of Trustworthy AI applies to a broad definition of an “AI system” that we can extend the concept to any analytical process, simple or complex, as those that take place in a BDTE. This includes components that are actually built with symbolic or sub-symbolic (machine learning) AI, but also other systems that simulate, compute or estimate parameters or aspects that use models of physical systems not falling in the definition of AI.

The just discussed definition emphasizes high level principles that are then realized in more specific ones. Concretely, the requirements stated by EC HLEG AI guidelines are the following:

1. human agency and oversight
2. technical robustness / safety
3. privacy and data governance
4. transparency
5. diversity and fairness
6. environmental and societal well-being
7. accountability

These requirements take a broad perspective of the relationship of a system with their users or stakeholders, some are related to specifics of data protection, but others in general are oriented to considering human and societal factors in the design of the system. It should be noted that all these elements greatly benefit for having shared semantics as provided by an ontology. The ontology approach in SPHERE thus is the basis for building trustworthiness, so that data, and decisions are expressed in terms of a common model, and provenance of data can also be expressed uniformly, e.g. using well-known recommendations as W3C PROV-O[83].

82 European Commission (2019) Ethics Guidelines for Trustworthy AI. Available at: https://ec.europa.eu/digital-single-market/en/news/ethics- guidelines-trustworthy-ai

83 https://www.w3.org/TR/prov-o/



### From Trustworthy AI to Trustworthy BDTE

A BDT environment (BDTE) is an integrated, multi-domain application space for operating on DTs for two purposes: **predictive** and **interrogative**”, as defined in the first version of this white paper. If we take the two purposes in consideration, we can understand the impact on people from two perspectives:

1. A BDTE may collect **personal information**, either *explicity* (e.g. there is a *Personterm* in the *RealEstateCoreontology*[84] and related terms in others), or implicitly, e.g. sensor data, which in the general case can be considered as pseudonymous (capable of being associated to an individual by combining with other information). For example, the *classPrivate office* in *Bricks* 1.2 schema[85] points to BDTEs in which there could be an implicit association of rooms in offices to particular persons, which together with other information, e.g. presence control, may led to re-identification.

2. The **algorithmic decisions** within the BDTE (that in many cases are linked to predictive actions) affect its users. Some may be self-evident, as the regulation of light and temperature, or the behavior of different equipment under particular circumstances. However, some others may be indirect, since those conditions may affect people behavior.

It should be noted that indirectly, the BDTE “performance” (its effective operation) also affects individuals or organizations not physically present. This includes owners and external stakeholders as insurance companies, but it also includes the public and society in general. For example, the algorithms governing energy efficiency are in some respect having an environmental impact.

From the discussion above, we propose a concise definition of a trustworthy BDTE.

> A **trustworthy BDTE** is one that incorporates lawful, ethical and effective mechanisms that make it fair, transparent, accountable, safe and robust to its users. It requires a design approach that make them trustworthy to its stakeholders from inception.

While the definition is inclusive of all the elements that are incorporated in the concept of trustworthy AI systems, here we discuss two more concrete concerns that affect the predictive aspects of those systems. Concretely, accounting for privacy concerns, when acquiring and processing data from the physical environment, and robustness of the actuation and decision-making system, accounting for threats and potential impacts on people, as a result of the predictions made with the data collected.

84 https://www.realestatecore.io

85 https://brickschema.org/ontology/1.2/

## 5.3.- Key Technical Components in Trustworthy BDTEs

Social acceptance of applications and services is strongly depending on the trustworthiness of information and the protection of private data.

If we consider the BDTE as a set of bi-directional data streams with sensors and actuators at the edges, these are two key challenging technical aspects:

- **Robustness:** it reflects in trust that the data used to make descisions has not been forged or tampered with, which would make the BDTE reach wrong (and in some extreme cases even maybe harmful) decisions.

- **Privacy:** the flow of information does not store or reveal personal information as defined by GDPR, or accounts for "privacy by design" minimizing use of data, obtaining consent for its use.

Other elements appearing in the definition of trustworthy systems as human agency, fairness and well-being, depend critically on those two. And accountability and transparency would not be useful if these aspects are not met also.

It should be noted that these two aspects are difficult to characterize as yes/no attributes of the system. They are rather design principles that should be accounted for, and efforts should be maximized to give them the maximum priority.

### 5.3.1.- Security in Data at the Edges

Vulnerability is higher at the edges, i.e. outside the cloud and at the edge of the network, and more specifically in applications where real-time processing of data is required. An advanced BDTE is a predictive system, and this represents also a new attack vector. Malicious manipulation of devices may fool predictive models and cause automated incorrect actuation, with harmful consequences.

The field of "adversarial machine learning"[86] has studied methods to protect against **stealing**, **poisoning** and **evading** models, in turn attempting to make systems more robust. These need to be considered in the design of the particular elements of the BDTE that are to be sources of data for predictive or analytic models, or that will be the receivers of decisions made by those models.

Most adversarial machine learning approaches have been focused on applications as computer vision, for example, finding examples that make these models fail, or interfering in the training process. Examples in IoT devices exist, e.g. Sagduyu et al.[87] which describes jamming and spectrum poisoning attacks. Traditional mitigation approaches include using tamper resistant hardware, anti-spoofing measures and a carefully design failover design. Other solutions (which entail additional computing costs) at the edge that can be cited are blockchain meshes (to get a level of redundancy of sensor data), and active anomaly detection.

86 Wang, X., Li, J., Kuang, X., Tan, Y. A., & Li, J. (2019). The security of machine learning in an adversarial setting: A survey. Journal of Parallel and Distributed Computing, 130, 12-23.

87 Sagduyu, Y. E., Shi, Y. &Erpek, T. (2019). IoT network security from the perspective of adversarial deep learning. In 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON) (pp. 1-9).



It is notable that simulation in a BDTE can help in making systems more robust. Li et al.[88] analyze Cyber-Physical System (CPS) scenarios of data poisoning with respect to the attacker, and point out how having knowledge of the complete system constraints makes the system more robust. For example, if some sensors in a complex network of pipes are compromised, having a simulated replica in the BDTE may detect the anomaly when contrasting to the expected flow properties of the complete system.

### 5.3.2.- Privacy-Preserving Computation

A well-known approach for the training of models or doing analytics is what is usually called Privacy-Preserving Data Publishing (PPDP)[89]. These techniques involve the anonymization of datasets by removing identifiers, and controlling the risk of identification of individuals through quasi-identifiers (attributes that when combined with other data may lead to identification). These techniques have notions of risk buit-in. For example, k-anonymity is a property of anonymized data "if the information for each person contained in the release cannot be distinguished from at least k - 1 individuals whose information also appear in the release." These measures can be used to introduce noise in the data, or just to control when data can be used under some level of risk. The problem with this approach is that it focuses on properties on aggregated data, and it often requires introducing noise. For the interrogative part of the BDTE (i.e. querying systems), the framework of differential privacy can be used. an algorithm is differentially private if an observer seeing its output cannot tell if a particular individual's information was used in the computation. This may be a correct setting in some scenarios and depending on some requirements.

Privacy computation is a complementary approach that addresses computing or training models without actually having access to the date. A number of Privacy-Preserving Machine Learning (PPML) approaches have become popular recently including.:

- **Federated learning** (FL) trains an algorithm across multiple devices holding local data samples, without exchanging them. This is based in sending an initial model to a number of devices, and these devices make a local training, sending the models back to the controller. This process can proceed further until an adequate model is obtained.

- **Split learning** (SL) each device trains a partial network up to a specific layer, in multi-layer neural networks.

These approaches can be combined for IoT settings and there are some reports of systems doing that as EdgeFed[90].

These PPML approaches are based in advances in cryptography, including homomorphic encryption (HE) and multi-party computation. While they have been used in practice and showed results of a quality comparable with non privacy computation models, their use

88 Li, J., Lee, J. Y., Yang, Y., Sun, J. S., &Tomsovic, K. (2020). Conaml: Constrained adversarial machine learning for cyber-physical systems. arXiv preprint arXiv:2003.05631.

89 Fung, B. C., Wang, K., Chen, R., & Yu, P. S. (2010). Privacy-preserving data publishing: A survey of recent developments. ACM Computing Surveys, 42(4), 1-53.

90 Ye, Y., Li, S., Liu, F., Tang, Y. & Hu, W. (2020). Edgefed: optimized federated learning based on edge computing. IEEE Access, 8, 209191-209198.

comes with some extra computational burden in some cases[91], or in others they require some extra configuration and deployment steps. They are also vulnerable to adversarial techniques, as data poisoning, so that, while promising, they should be considered together with other approaches.

## 5.4.- Sphere and Trustworthy BDTE Design

BDTEs require the explicit consideration of diverse requirements in its design to become trustworthy to their users and to society at large. Among those requirements, as we have discussed, **robustness** and **privacy** deserve a careful consideration, since the BDT may collect data from people or linked to people, and the actions or decisions on the physical environment may in turn affect people. This last element is a consequence from the fact that operating in the edges poses significant challenges and trade-offs.

In any case, trustworthiness should be included as a critical requirement in the conception, planning, design and construction of every BDTE. The requirements for trustworthiness are more difficult to attain if they are considered after the system is built or deployed.

Privacy-preserving computation is a collection of evolving innovative techniques and methods that are critical to comply with privacy requirements. Differential privacy gives also a framework for introducing privacy when required. However, the design of the BDTE depends on the scope and requirements, and there is a variety of building environments that have accordingly diverse requirements for privacy. SPHERE will develop guidelines for BDTE designers addressing the need to engineer diverse requirements for privacy. Specifically, SPHERE aims at delivering a reference framework for different types of BDT characterizing their types of data flows and how they impact privacy risk. That framework would help in selecting the tools and techniques required preventing overengineering. For example, there are levels of risk that are moderate since there is not direct personal data collected, but still some of the data as power consumption may be disclosing indirectly preferences or consumption habits. In that case, the volume and level of aggregation of the data can be hypothesized to be an indicator of some sort of level of risk, that can inform designers in a direct way, reducing effort and increasing traceability of decisions.

91 Zheng, M., Xu, D., Jiang, L., Gu, C., Tan, R., & Cheng, P. (2019). Challenges of privacy-preserving machine learning in IoT. In Proceedings of the First International Workshop on Challenges in Artificial Intelligence and Machine Learning for Internet of Things (pp. 1-7).



# 6.-NEXT STEPS

Around functional simulation and advanced control of buildings we may find several aspects which potentially will bring developments in the short or medium time period. They are not developments about the digital twin concept but contributors which add value and projection to the concept as a whole.

One of these developments will be **the microgrid concept** applied to buildings and local energy communities, considering small generation of PV installations or other devices to migrate the actual electricity centralized business in a broad transactions system, inside the building and inside smart cities.

Another important development will have **human models and occupancy interaction** with the building as fulcrum, using wearable's and smart sensors to receive the human presence and status and to implement an advance control of the building, not only thinking on energy savings but considering health and comfort implications.

Advanced simulation immersed in real time monitoring systems will be key tools for **performance contracts in the "Deep Renovation Wave"** nowadays in the EU. Simulation provide calculated additional key performance indicators in real time, with a dynamic baseline which may be used as a reference between the stakeholders.

Monitoring and registering statistics gives the opportunity to enrich the **digital logbooks of a building**. This information must be managed and stored, and challenges regarding privacy will be solved in order to have property, security and control over those data collected.

An advance control does not mean more sensors, but **less and more trustable instrumentation**. Simulation will help with the maintenance of smart systems providing an automatic way to detect failures and malfunctioning.

Simulation is a way to connect all phases of the building, beginning with conceptual design, helping in commissioning and assisting the complete life cycle of the building. This could change the "project concept" itself, adding more functional content in contractual processes.

Finally advanced control applied to building will make explicit many privacy threats but solutions as well. **New privacy management tools** will be implemented in order to comply with regulations but making possible data transactions and public reporting in controlled conditions.

## 6.1.- Microgrids and Local Energy Communities

Nowadays, the integration of Distributed Energy Resources (DERs) into buildings or into energy distribution networks is a fact. These resources let the consumers and the grid operators reduce the dependence from a unique power source.

“Thus, current electricity systems are heading towards the “three Ds” goals (“decentralize, decarbonize, and democratize”)[92]. These objectives are driven by the need to rein in electricity costs, replace aging infrastructure, improve resilience and reliability, reduce $CO_2$ emissions to mitigate climate change, and provide reliable electricity to areas lacking electrical infrastructure[93]. This trend is fully aligned with the European Green Deal[94] and the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015. Proof of this is one of its seventeen Sustainable Development Goals (SDGs). The SDG 7 called “Ensure access to affordable, reliable, sustainable and modern energy for all” marks a clear path towards an integration of renewable and sustainable energy.”

However, these systems are based mainly on renewable sources that are strongly dependent on weather conditions. Due to the latter, it is increasingly common to integrate mixed DER topologies that combine different energy sources, seeking the compensation for the weakening of each generation technology. Additionally, DER concept is not only limited to generation systems, to compete this picture, DER also includes Energy Storage Systems (ESSs, which add peak-shifting functions), Demand-Side Management (DSM) systems (which add peak-shifting and peak-shedding functions), and with a special interest, the integration of the electric vehicle (EV, as mobile resource). In this sense, the interconnection and coordination of different DERs conforms microgids[95] which are commonly managed by Distributed Energy Resources Management Systems (DERMSs). DERMSs are responsible of coordinating the energy balance between the different elements within the microgrid, optimizing in each moment its power flows, and controlling when it is the best moment to storage energy or connect specific loads.

However, at any moment, when a building energy balance is positive, it would share or buy this surplus with other nearby buildings. These exchanges can be made using the Distribution System Operators (DSO) facilities through a retailer. However, this market is strongly regulated, limiting the amount of energy sold and setting a price for it. Due to this, to make a free sale possible between individuals, the Local Energy Community (LEC)[96] is a concept that has gained popularity in recent years. Specifically, LECs are legal entities that make possible to share energy resources through the power networks (see figure 57), using the DSO or private networks. Moreover, these exchanges are not limited to the electrical field, also raising the thermal exchanges based on district heating and cooling concept.

92 M. Green, «Community power», Nat. Energy, vol. 1, n.o 3, Art. n.o 3, feb. 2016, doi: 10.1038/nenergy.2016.14.

93 A. Hirsch, Y. Parag, y J. Guerrero, «Microgrids: A review of technologies, key drivers, and outstanding issues», Renew. Sustain. Energy Rev., vol. 90, pp. 402-411, jul. 2018, doi: 10.1016/j.rser.2018.03.040.

94 The European Green Deal (European Commission), «Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions». 2019. [En línea]. Disponible en: https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf

95 D. E. Olivares et al., «Trends in Microgrid Control», IEEE Trans. Smart Grid, vol. 5, n.o 4, pp. 1905-1919, jul. 2014, doi: 10.1109/TSG.2013.2295514.

96 T. van der Schoor y B. Scholtens, «Power to the people: Local community initiatives and the transition to sustainable energy», Renew. Sustain. Energy Rev., vol. 43, pp. 666-675, mar. 2015, doi: 10.1016/j.rser.2014.10.089.



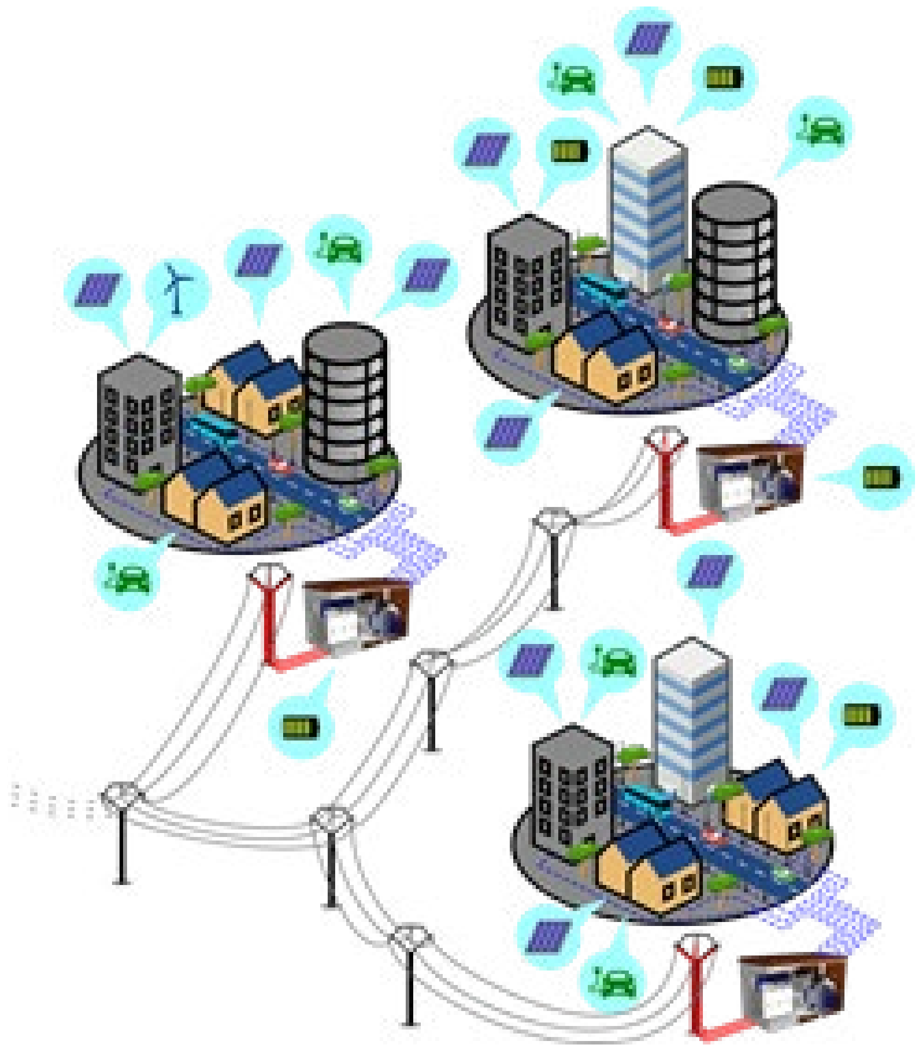


Figure 57: DER deployment in a LEC.

In any case, regardless of aggregation level, to ensure proper operation of all elements, it is essential to have a DERMS that coordinate the energy balance between them but allowing some local self-control. In this sense, a typical control scheme follows a hierarchical architecture (see Figure 58).

This control topology makes it possible to coordinate DERs at different levels, acting each DERMS as an aggregator, exposing each microgrid as a Virtual Power Plant for the rest of its LEC. The same idea occurs in upper level where each LEC would be acting as aggregators for the DSO. In this architecture, each DERMS is responsible to have a perfect knowledge of its DERs behavior and offer its energy capacities at higher levels (as a flexibility service provider, FSP). Thanks to this information, the DERMS responsible for each level can define its control strategy, using the capabilities of lower DERMS as yielded or sold resources. An example of flexibility proof of concept can be found in[97] Guerrero et al. where a demand response (DR) interaction between the DSO and prosumers (or aggregators) is proposed through a day-ahead capacity-bidding program (CBP).

97 J. I. Guerrero et al., «Evaluating Distribution System Operators: Automated Demand Response and Distributed Energy Resources in the Flexibility4Chile Project», IEEE Power Energy Mag., vol. 18, n.o 5, pp. 64-75, sep. 2020, doi: 10.1109/MPE.2020.3000688.

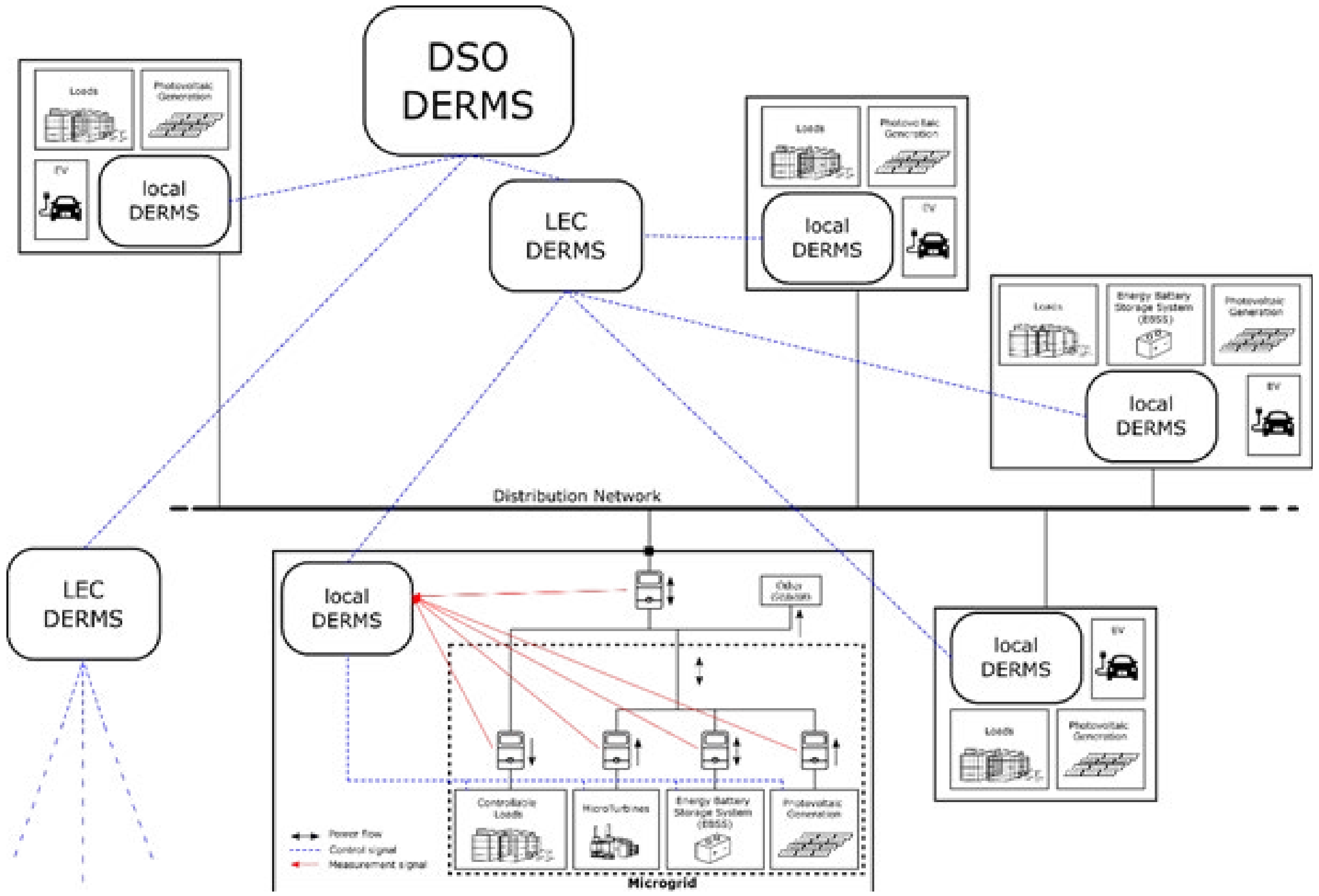



Figure 58: DERMS hierarchical architecture.

To perform such interaction, the local DERMS should internally make forecasting of the DER productions and needs, and later it will balance the resources and establish the control policy of each one for different scenarios. In these scenarios, different levels of offer can be established, balancing comfort level and financial benefit.

As mentioned above, for a proper operation is essential that each DERMS must be fully aware of the behavior of its energy resources as well as being able to forecast its performance in the short and medium term. In this scenario a Building Digital Twin (BDT) can be a powerful tool. As has already been widely discussed in this white paper, beyond the fact of considering the elements of the microgrid as a facility of the building itself, a BDT poses a great usefulness in the design and maintenance process. However, a BDT can also be an excellent operational tool. Since its ability to model and simulate the energy demands of buildings, as well as the behavior of the DERs themselves, its abilities make it possible to increase the forecasting accuracy of the energy needs. Thus, thanks to these more precise forecasts, it is possible to define the control policy with two objectives: on the one hand, more precise forecasts make possible to optimize the energy control strategies (in special for storage systems), and on the other hand, they allow the DERMSs to establish the flexibility offers for the uppers levels (i.e., the LEC).



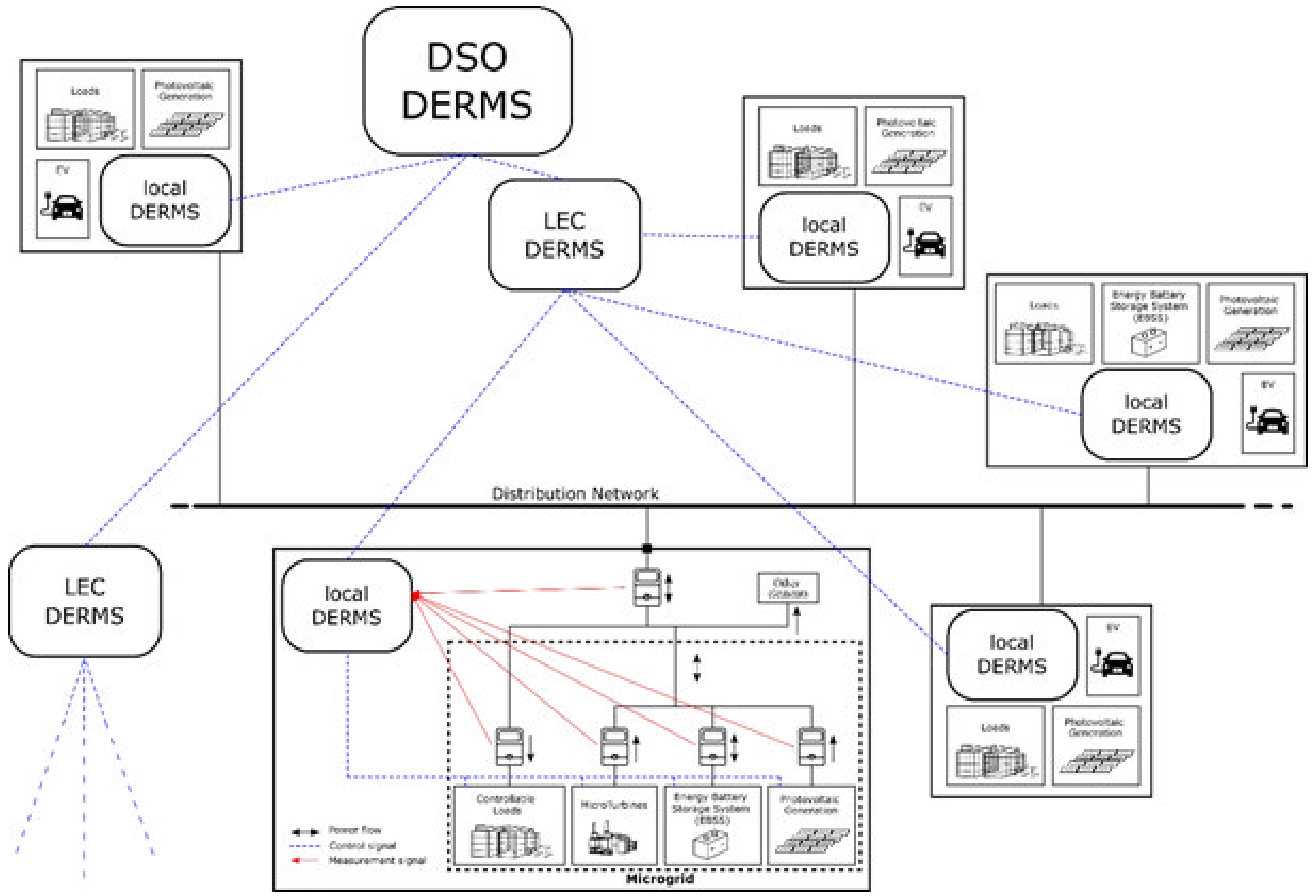



Figure 59: DERMS hierarchical architecture

Specifically, as example, throughout this document, Human-in-the-loop for HVAC operations has been posed. This kind of simulation makes it possible to study the effects of setpoint adjustments over the building room temperatures. This information about the building environments allows the building management system (BMS) to fit HVAC energy demands, improving with it the possible flexibility offers.

In conclusion, the integration of Digital Twins (DTs) into the microgrid (or LEC) control is an excellent option to optimize its performance. Due to this, the DTs can be considered a key element in energy management ecosystem (see Figure 60), where it is responsible for supplying information to complete the energy forecasting.

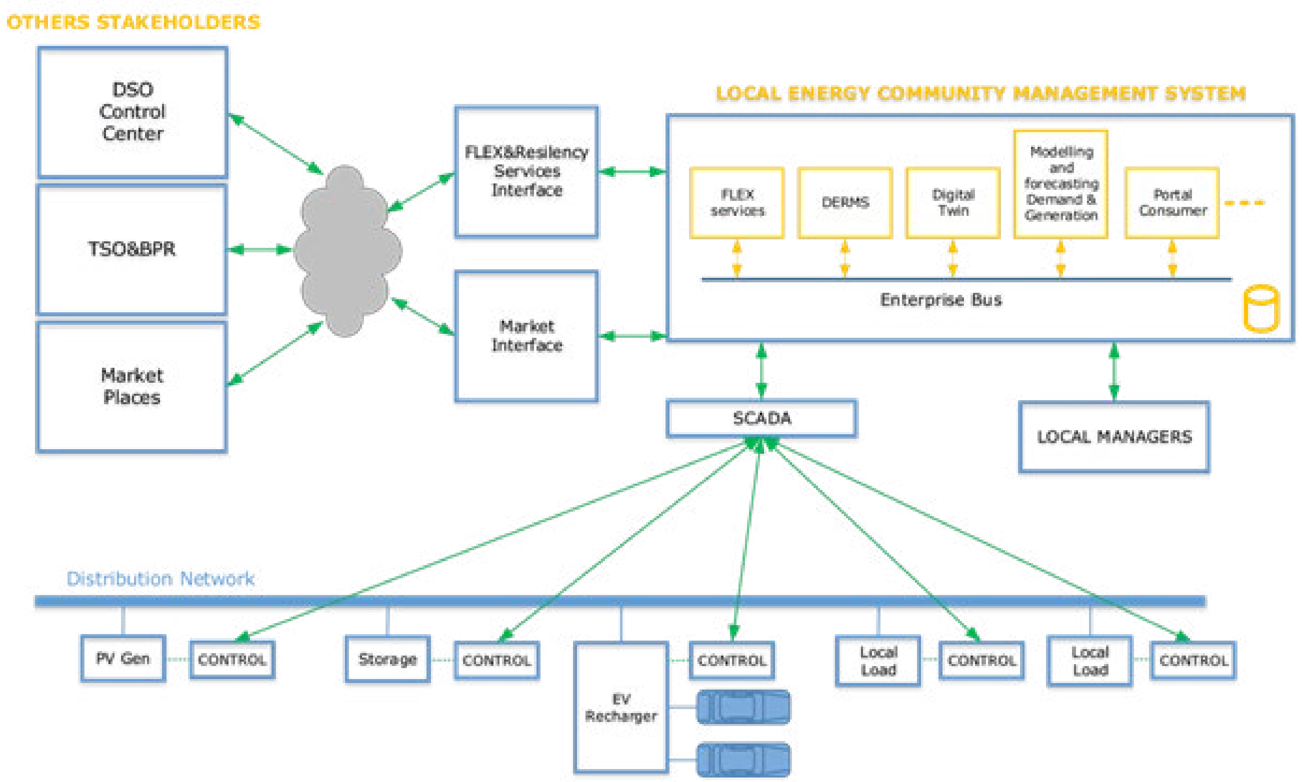



Figure 60: LEC service ecosystem.

## 6.2.- Human Models and Occupancy Interaction

An objective reference of health and comfort level is needed to discuss energy performance, and those levels are impossible to calculate without modeling humans. These human models must be able to be integrated in real time systems and they should consider specific properties of non-standard occupants.

The hardware implementation of human interaction can be supported by wearable's and smart sensors, and simulation will play a key role calculating in real time health and comfort parameters. These parameters are not the same for all humans, so keeping in the loop the differential human factor is critical for the right control of levels of CO2 and room temperature. We can not consider mature the availability of sensors and devices for advanced control regarding occupancy in residential buildings, but this is a constant field of novelties.

## 6.3.- Energy Performance Contracts and Deep Renovation Wave

In despite of the great intentions of the European Commission a deep renovation wave will be supported by single decisions based on metrics: existing versus potential energy performance. For this process simulation provides the perfect tool for validation before implementing any change, and the base for decisions regarding benefits to be shared between ESCOs, financial institutions and stakeholders in general.



Without a trustable technical solution these agreements will be weak or impossible, as it has been for many years using tools as the energy certification. Mathematical simulation can be the framework for the previous agreement (validation of an existing building as it is) and a dynamic baseline for the renovation.

The implementation at the level of residential buildings of monitoring tools and simulation is far to be available today, but it could be implemented in a few years and this could change drastically the way how deep renovation is understood.

## 6.4.- Digital Logbooks, Monitoring and Statistics

Digital logbooks are an old concept and it must have a convergence in some aspects of digital twins, especially those regarding storage of past historical data and statistics. Monitoring of ambient parameters add a new information resource, but how it is stored and which information is worthy to keep in the logbook must be discussed and tested, and it has political implications in all countries of the EU. In the next years we will be able to see how this convergence takes place and how logbooks are extracting information from the digital twin.

## 6.5.- Less Sensors, More Intelligence

Many people think that a smart house must have a great number of sensors everywhere. A sensor for many means "information". But in reality sensors means maintenance, costs and potential problems. So solutions with less sensors but better quality and reliability may be an optimum solution.

Simulation add mathematical models to the sensors. Magnitudes are connected and they must be consistent. So potentially we can detect malfunction thanks to a change in behavior, even in complex situations, networks or thermal inertias.

Sensors itself must solve their connectivity and data treatment in short time scale. They could be not physically connected thanks to low energy protocols, working with batteries and a great flexibility (even with deployments in short time periods of weeks just to demonstrate or calculate the general performance of the building in specific situations).

New sensors will be developed towards the occupancy integration with the building and in parallel with human models, wearable's and smart home tracking and presence detection.

## 6.6.- Functional Simulation of All Building Phases, a New Project Concept?

Mathematical simulation can be present since the first concept until the entire life of the building. The functional representation adds an additional specification to geometric description or architectural design, with great relationship with materials to be used in the construction. Simulation of the building could be prescribed in the future as legal bodies ask today for cost estimation or plan drawings.

Mathematical simulation immersed in control systems could be very useful as commissioning tools. Buildings could be tested before the end of the construction, gaining time and detecting potential problems in advance. This testing should be done with partial installations, so it is critical to know how the system would respond in those conditions.

As it happens with structural analysis simulation models can be implemented in short times if previous libraries of equipments (SIMBOTs) have been developed. This could be useful for dimensioning and for testing special dynamics of the house with humans living inside. Energy certifications comfort and health values would be possible to have them in advance and as a reference for final delivery of the construction or for sales processes.

## 6.7.- New Privacy Management Tools

Data stored in digital twins are useful internally but at one point the digital twin (or logbook) must send information to others. Whether due to administrative reasons or legal purposes the information must be packed, anonymized and sent to others. Packing information may be done in several levels (from sampled date to complex statistics). In general size of data should be kept in reasonable size taking into account that all information can be controlled locally by the stakeholders.

In order to send data to others privacy must be estimated in detail taking into account all the steps and categories of those steps (for example, the entity which data are representing, what magnitudes, the statistic we are using to describe the data, the sampling frequency, how data are going to be used and how data are controlled). We may use a differential analysis for each category in order to get metrics for comparing different processes. In Sphere project this approach has been presented as an innovation and will be developed in the next years.



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# ACRONYMS

0D-1D, zero (geometric) dimension – one dimension mathematical problems
3D, Three geometrical dimensions
AECCO, Architecture, Engineering, Construction, Owner Operator
AI, Artificial Intelligence
BACS, Building Automation and Control System
BDT, Building Digital Twin
BDTA, Building Digital Twin Association
BDTCM, Building Digital Twin Construction Manager
BDTE, Building Digital Twin Environtment
BDTI, Building Digital Twin Instrumentation
BDTM, Building Digital Twin Manager
BDTSM, Building Digital Twin Simulation Manager
BEMS, Building Energy Management System
BIM, Building information modeling
BLE, Bluetooth Low Energy
BMS, Building Management System
CBP, capacity-bidding program
CEO, Chief Executive Officer
CERN, Conseil Européen pour la Recherche Nucléaire
CFD, Computer Fluid Dynamics
CMS, Compact Muon Solenoid (CMS), general-purpose detector at the CERN LHC
COBIe, Construction Operation Building Information
CPX, cardiopulmonary exercise test
DERS, physical and virtual assets that are deployed across the distribution grid
DERMS, Distributed Energy Resources Management Systems
DR, Demand Response
DSM, Demand-Side Management
DSO, Distribution System Operators
DT, Digital Twin
DTC, Digital Twin Construction
EAI, Empresarios Agrupados Internacional
EBRD, European Bank for Reconstruction and Development
ECU, Electronic Control Unit
EMS, Energy Management System
EPBD, Energy Performance Buildings Directive (EU) 2018/2001
EPC, Energy Performance Certificate
ESCO, Energy Service Company
ESS, Energy Storage Systems
EV, Electric Vehicle
FIEBDC, Formato de intercambio estándar de bases de datos para la construcción
FEA, Finite Element Analysis
FDD, Faults Diagnose and Detection
FMI, Functional Mock-up interface (standard)
GA, General Arrangement (drawings)
HIL, Hardware-in-the-loop
HMI, Human Machine Interface
HTM, Human Thermal model
HVAC, Heating Ventilation Air Conditioning
HVM, Human Ventilation Model
ICT, Information and Communication Technology
IFC, Industry Foundation Classes
IoT, Internet of Things
ISS, International Space Station
LEC, Local Energy Community
LHC, Large Hadron Collider
MEET, Metered Energy Efficiency Transaction
MPDS, Multi Purpose Dynamic Simulator
MPC, Model Predictive Control
NZE, Net Zero Energy
OCC, Occupant-centric Controls
OPCUA, Open Platform Communications Unified Architecture
P&IDs, Process and Instrumentation Diagrams
PLC, Programmable Logic Controller
PPDP, Privacy-Preserving Data Publishing
PPML, Privacy-Preserving Machine Learning
RFID, Radio Frequency Identification
SAREF, Smart Appliance Reference
SCADA, Supervisory control and data acquisition
SIL, Software in the Loop
SRI, Smart Readiness Indicator
SRT, Smart Ready Technologies
TBM, Technical Building Management
TCP, Transmission Control Protocol
TMY, Typical Meteorological Year
TNO, Netherlands Organisation for applied scientific research
TSI, Thermal Sensation Index
V-ECU, Virtual Electronic Control Units
VTT, Technical Research Centre of Finland

SPHERE

BIM DIGITAL TWIN PLATFORM

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