BIM SPEED

Methods for surveying and diagnostics of HVAC systems in the existing buildings

Deliverable report 1.2

Deliverable Report: D.1.2, issue date on 13.11.2020

BIM-SPEED

Harmonised Building Information Speedway for Energy-Efficient Renovation

This research project has received funding from the European Union's Programme H2020-NMBP-EEB-2018 under Grant Agreement no 820553.

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Publishable executive summary

Deliverable 1.2 – Methods for surveying and diagnostics of HVAC systems in the existing buildings aim to offer a framework for collecting data of HVAC systems for existing buildings. The report will provide insight into gathering and handling data related to HVAC systems and how they can be used optimally for a renovation project, regardless of its scale. This report is targeted to all stakeholders in the renovation process, from the building owner, contractor, designer, and tenants. Next to a general overview of existing tools, this deliverable will offer an overview of tools that can be used as part of the BIM Speed platform.

Before understanding HVAC data, a short state-of-the-art of the current HVAC systems used in residential applications is presented to give every stakeholder the possibility of identifying and understanding currently installed systems. Next, chapter 2 identifies and presents the technologies that can collect data about HVAC systems. The elements in this deliverable are presented concerning the HVAC data collection, so the perspective is different from Deliverable 1.1, which focuses more on Architectural and Structure data collection. HVAC elements pose different problems in collecting data because they are primarily indoor and can be placed in inaccessible spaces or even hidden; thus, it is essential to understand where technology can be used and how. As every technology has its characteristics, the goal was to present workflows to collect data and choose specific data collection hardware for different systems together with possible on-site issues, financial advantages or disadvantages, and data outcome formats. A specific focus is on providing insights about the relevance of collected data. Through this analysis, the report also constitutes a base for D2.4 – Guidelines for as-built BIM modelling of existing buildings, where multiple sources are considered when creating a 3D model of an existing building.

In Chapter 3, a state-of-the-art probabilistic model and existing software on the market that uses these techniques while showing promising results. The primary outcome of the chapter is an image recognition algorithm developed to identify different types of visible components of HVAC systems.

Despite the types of sources available for information and the technology to reconstruct a 3D model, there are occasions where the 3D model is incomplete. In chapter 4, the deliverable will exemplify the use of the computational design in automatically checking the presence or absence of HVAC components. These possibilities for automated checking are illustrated using Autodesk Dynamo scripts that we developed and illustrated here.

In the end, the deliverable offers a consistent source of information for handling the amount of information that can be extracted from an HVAC system while keeping its focus on optimizing this use to reduce the duration of the time and costs of the project design. The image recognition algorithm and the dynamo scripts are the added value of this report. Besides, it's a comprehensive source of knowledge.

List of acronyms and abbreviations

AC: Air Conditioning

AI: Artificial Intelligence

DoA: Description of Action

BIM: Building Information Model

BMS: Building Management system

BEM: Building Energy Model

Cap/OpEx: Capital / Operational Expenditure

CHP: Combined Heat Power

CPS: Cooperative Positioning System

DHW: Domestic Hot Water

EeB: Energy-efficient Building

EPBD: Energy Performance Buildings Directive

ESCO: Energy Services Company

FPS: frame per second

GIS: Geospatial Information System

GPS: Global positioning system

GLONASS: Global Navigation Satellite System

HP: heat pump

HVAC: Heating Ventilation Air Conditioning

IEQ: Indoor Environment Quality

IP: Ingress Protection

IPR: Intellectual Property Right

LCA: Life Cycle Analysis

LCC: Life Cycle Costing

MEP: Mechanical Electrical Plumbing

NBV: Next based view

nZEB: Nearly Zero-Energy Buildings

PnP: Plug and Play

R&D: Research and Development

RES: Renewable Energy Source

RoI: Return on Investment

SH: Space Heating

SD: Storage device

SLAM: Simultaneous Localization and Mapping
SME: Small and Medium-size Enterprise
TCP: Technology Commercialisation Platform
TRL: Technology Readiness Level
UAV: Unnamed aerial vehicle
VR/AR: Virtual / Augmented Reality

Definitions

3D scanner: A piece of equipment that captures the shape and, sometimes, the colour of real-world physical objects or environments.
3D scanning: The process of using a 3D scanner to capture and convert physical objects into 3D data
As-built: An object's condition and state in real-time
BIM Use Case: Use of BIM to support business processes
Computational Design: Using computer algorithms to generate object geometry in the design process.
Point cloud: A point cloud is the computer visualization of the XYZ coordinates that describe a physical object or environment. Each point represents an actual point on the object or in the environment and collectively describes its shape and measurements.
Drone: Unmanned aircraft that can fly autonomously

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1. Introduction

1.1 HVAC in existing residential buildings

HVAC refers to Heating Ventilation and Air Conditioning, which can be used in buildings to:

- maintain internal air quality,
- regulate internal temperatures and
- regulate internal humidity.

Almost all residential buildings are equipped with heating systems; some have been installed with the new building or incorporated afterwards to improve their thermal capacity or comfort. Differences can appear depending on the country where the building was constructed, the type of fuel used, the efficiency of the system, heating agent, and distribution type. These factors influence the data gathering process since the building envelope or equipment can hide old piping, and no data is available or comprehensible. A few systems are presented below so stakeholders have a general view of heating systems.

In most buildings, ventilation is mostly done naturally, either manually (opening the windows) or organized, using ventilation shafts. Considerating the period of usage of the building, the shafts can present multiple issues such as water infiltration (produced by improper hydro insulation), unintentionally clogged (various waste coming from the roof), or on purpose (grills can be sealed inside the apartments due to lack of knowledge of their purpose). For newer buildings, mechanical ventilation may be present.

Cooling systems may be present or not. Most common cooling systems are represented by split systems or "common air conditioning systems". Data can be gathered relatively easy since the systems are relatively new and equipment and pipes are mounted apparently.

1.2 Space and DHW Heating Technologies

Heating in buildings may be necessary to create comfortable conditions for occupants, prevent condensation, and facilitate activities such as drying and cooking. In residential buildings, heating can be provided by central heating systems in which heat is distributed from a central source or localized heating systems. According to the EC, space heating among European countries is heterogeneous but is mainly dominated by fossil fuel burning technologies[1]. The type of fuel and heating systems are highly dependent on each other. Boilers using oil and natural gas are the leading used technologies in the EU, whilst in recent years coal-fired boilers have primarily been replaced in most European countries. An exception is Poland, where coal technologies still represent 36% of the total installed heating capacity[2]. It is worth mentioning that electric radiators, aerothermal and geothermal HPs, and STS—unglazed, flat-plate, and evacuated

1 https://ec.europa.eu/energy/sites/ener/files/documents/Summary%20WP1%20and%20WP2.pdf
2 https://www.mdpi.com/1996-1073/12/9/1760/pdf

tube collectors are also used, yet not being fuel powered. A minor amount of coal and renewables have driven condensing boilers, and not solely renewables (biomass) powered stoves are operative in Europe.

Based on the above, the following sections describe the mainstream systems for space heating and domestic hot water for residential buildings and their installation scheme. The summary of all the categories described is summarised in Figure 1.

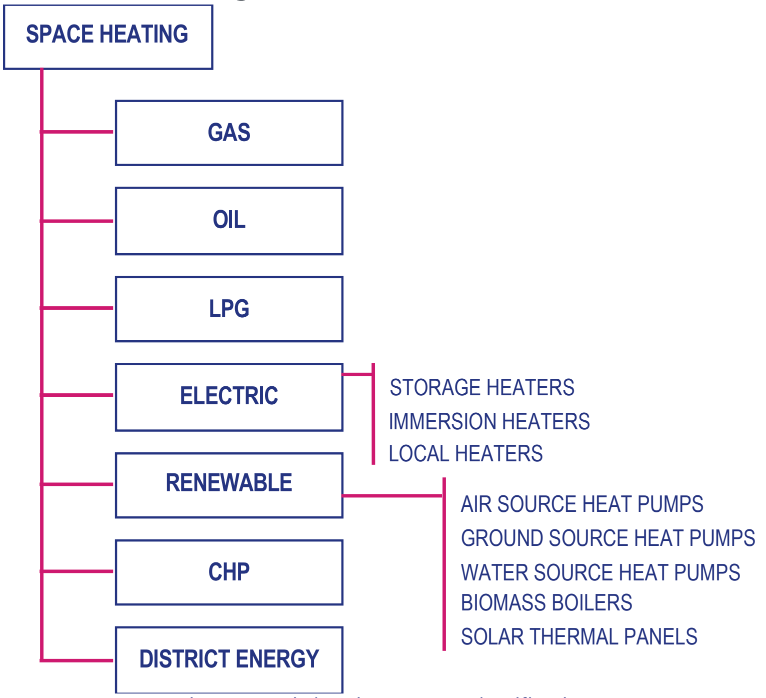


Figure 1 Basic heating systems classification

1.2.1 Gas/Oil and LPG Heating systems

Most households in Europe have mains gas central heating. Gas central heating is a so-called 'wet system', which means a gas-fired boiler heats water to provide central heating through radiators and hot water through the taps in the building (figure 2). Boilers can be condensing or non-condensing. A non-condensing boiler gets rid of waste gases via a flue, whilst a condensing boiler recycles the heat from these gases using a heat exchanger, so it reuses the burnt fuel. The primary difference is the efficiency they achieve; condensing boilers have an efficiency of up to 99%, while non-condensing only reach up to 78%. Based on the EU eco-design requirements, most European countries have adopted legislation for installing gas and oil condensing models. However, in rare cases condensing boilers may not be a viable option, and after specific assessment, it may be possible that the respective legislation allows. Nevertheless, gas is a fossil fuel that produces carbon dioxide when burned and, thus, is not a clean source of energy.

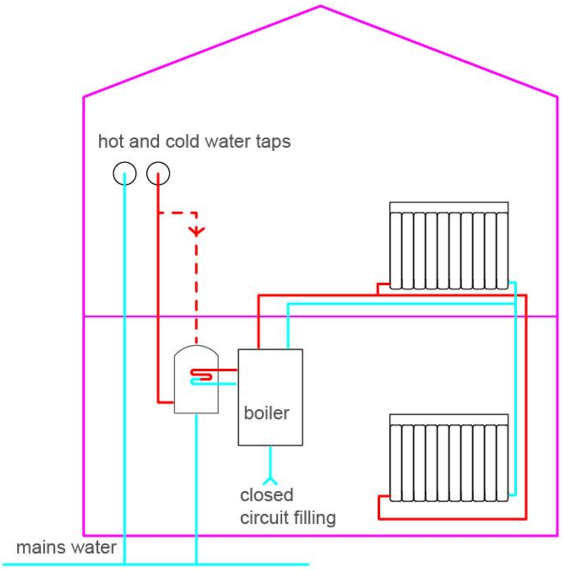


Figure 2 Boiler installation scheme

Some houses not connected to the gas network can use liquid petroleum gas (LPG) or heating oil, which works similarly to central gas heating, yet LPG and oil are delivered by road and stored in a tank.
Heat-only and combination condensing oil-fired boiler types are both available. Most oil-fired combination boilers have an internal hot water store to supply domestic hot water, rather than the instantaneous heating more common in gas combi boilers.
Oil boilers generally limit the hot-water flow rate to ensure the water is as hot as it should be. It means the hot-water flow rate is lower than it would be with a gas combi or hot-water cylinder system, and the temperature will decline as more water is used. Oil is also a fossil fuel and produces carbon dioxide when burned. Therefore, it cannot be considered a clean source of energy. Some governments plan to phase out high-carbon fossil fuel heating systems, such as oil boilers, during the 2020s. (figure 3).

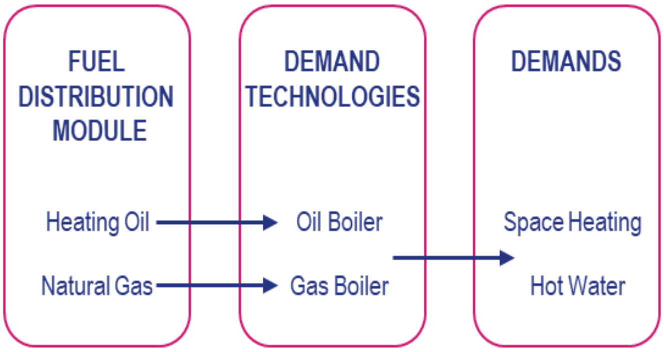


Figure 3 Fuels and boiler technologies

1.2.2 Electric Heating

Electricity is often used as a source of heating as nearly every household has access to the electricity grid, whilst mains gas is not always available. However, electrical heating can be expensive. Below are presented some standard electrical heating options:

Storage heaters: electric heaters that store thermal energy by heating internal ceramic bricks during the night at the cheapest tariff and then release heat from them to keep the home warm during the day. There are two types of storage heaters that differ the output heat is delivered: static storage heaters that give heat through their surface by natural convection and dynamic storage heaters that circulate warmth by blowing air into a room through a fan.

As electricity is more expensive than gas, storage heaters are only cost-effective in cases that gas mains are unavailable, which happens in some European countries where a gas network is still not expanded. A representative image of a storage heater is illustrated in Figure 4. It is worth mentioning that storage heaters are the most cost-effective form of electric heating.

Figure 4 Storage Heater example

Immersion heaters: electric water heaters that sit inside a hot-water cylinder. They act like a kettle, using an electric resistance heater (which looks like a metal loop or coil) to heat the surrounding water. Immersion heaters are connected to their power supply via a cable. They can be easily switched on and off, as there is no need to heat the water in the hot water cylinder constantly. Immersion heaters can either be used as a property's primary water heater or as a backup water heater for combi boilers.

Local space heaters: space heating devices that emit heat by direct heat transfer or by direct heat transfer in combination with heat transfer to a fluid to reach and maintain a certain level of thermal comfort within an enclosed space in which the product is situated. They are often combined with a heat output to other spaces, and they are equipped with one or more heat generators that convert electricity or gaseous, liquid, or solid fuels directly into heat.

Electrical underfloor heating is a type of floor heating that uses wires instead of piping to emit heat through the floor. There are two types of systems that can be used: heating cables or heating mats. They can be the singular heating source or complementary to the primary heating system.

1.2.3 Renewable energy

Most buildings undergoing renovation do not yet use renewable energy technologies, yet it is worth mentioning them as they become more and more popular. Renewable energy is generated from constantly replenished sources, such as the sun, wind, or water. Generating heat or electricity from renewable sources reduces reliance on fossil fuels.

Heat Pumps: Unlike other heating systems that burn fuel to create heat, air-source heat pumps and ground source heat pumps use naturally occurring warm air or heat in the ground to create power and heat the residency. They will need an electricity source to work but can cost less to run than some traditional heating systems (Figure 5).

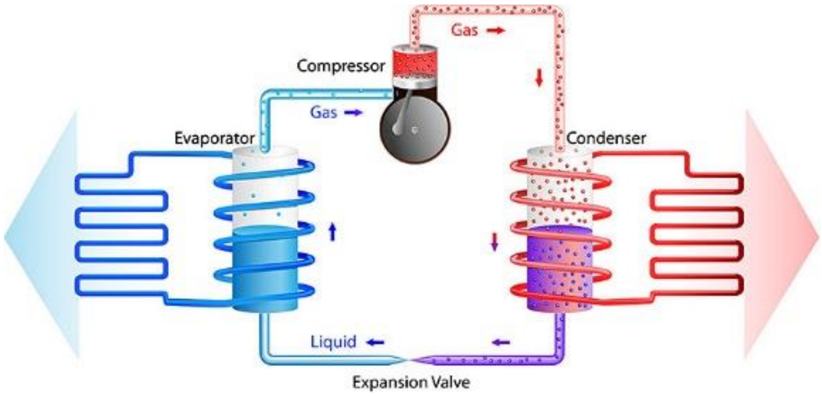


Figure 5 Heat pump basic scheme

Heat pumps can also provide cooling for the summer period, considering that they are reversible. This device can constitute an effective measure to secure thermal comfort, integrating both functions. Depending on the heat-pump type, electrical consumption may differ since the ground temperature is less fluctuating than the air.

Heat pumps can be connected to systems that use either air or water, as thermal agents, inside the residential unit.

Solar thermal systems: There are several types of solar thermal systems, as illustrated in Figure 6, and each technology has its installation scheme. Solar thermal systems harness the power of sunlight to generate electrical energy, thermal energy, or both. Flat-plate collectors and evacuated tube collectors mainly collect heat for SH and DHW or cool with an absorption chiller.

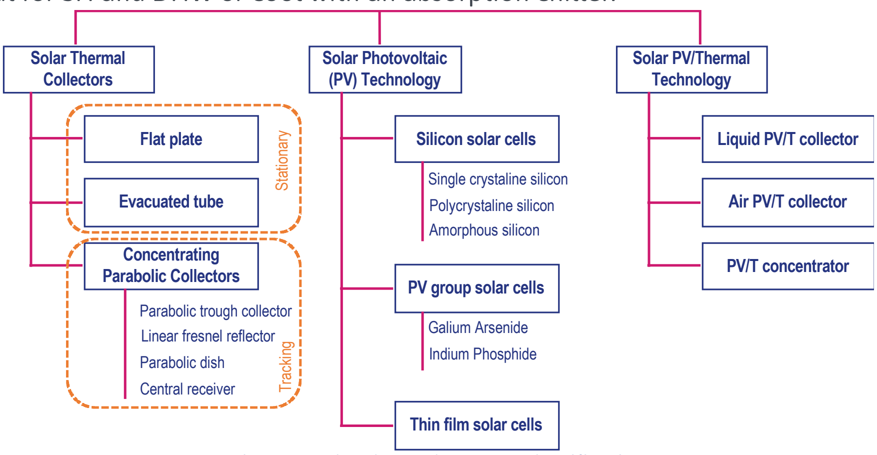


Figure 6 Solar thermal systems classification

In contrast to solar hot water panels, they use circulating fluid to displace heat to a separated reservoir. Flat plate collectors are the most common technology in Europe.

Solar Photovoltaic (PV) is a technology that converts sunlight (solar radiation) into direct current electricity by using semiconductors. When the sun hits the semiconductor within the PV cell, electrons are freed and form an electric current. Unlike solar thermal collectors, solar PV relies on sunlight, which means that electricity is not produced when the sun does not shine. Photovoltaic thermal collectors (PVT) or hybrid solar collectors are power generation technologies that convert solar radiation into usable thermal and electrical energy. By combining electricity and heat generation within the same component, these technologies can reach a higher overall efficiency than solar photovoltaic (PV) or solar thermal (T) collectors alone.

Solar DHW and SH thermal systems can be installed alongside other hot-water heating systems and provide electricity to electrical appliances, thus reducing the electricity cost. Moreover, the option to sell electricity to the grid becomes more and more popular in Europe (Figure 7).

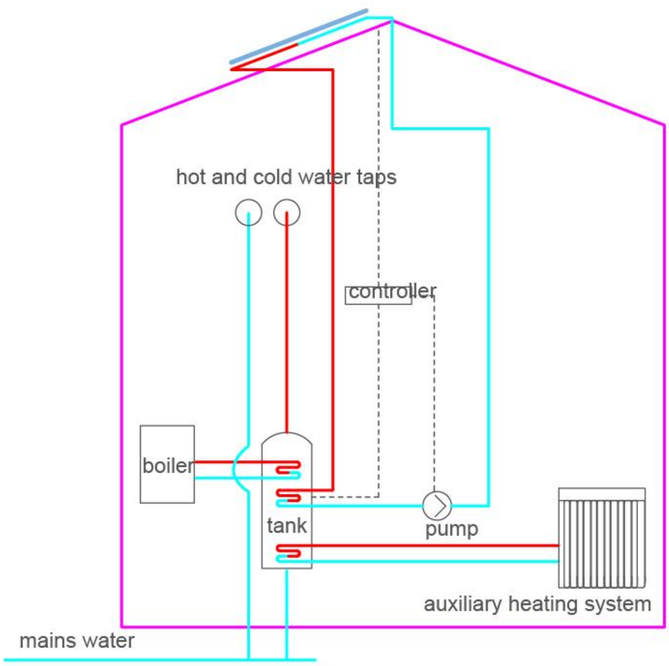


Figure 7 Solar thermal system installation scheme

Biomass: Biomass heating systems burn organic material to provide heat and hot water. They are often used to heat just one room and generate enough heat that central heating is not needed (even though most owners have it and a central heating system). A stove can also be installed with a ‘back boiler’ to use the heat it creates to warm the entire property and heat the DHW. Stoves produce pollutants but are more efficient than open fires and other burnt fuels.

1.2.4 Combined heat and power (CHP) plans with internal combustion (IC)

CHP is a cogeneration plant often added in parallel with the boilers. The system implies that heat and electricity are produced simultaneously in one process. CHP can use the waste heat to produce electricity or district heating and cooling systems (DHC). In principle, a CHP design is independent of the type of heat source, so fossil fuels, organic waste, renewable fuels, and nuclear energy are all technically viable options (Figure 8).

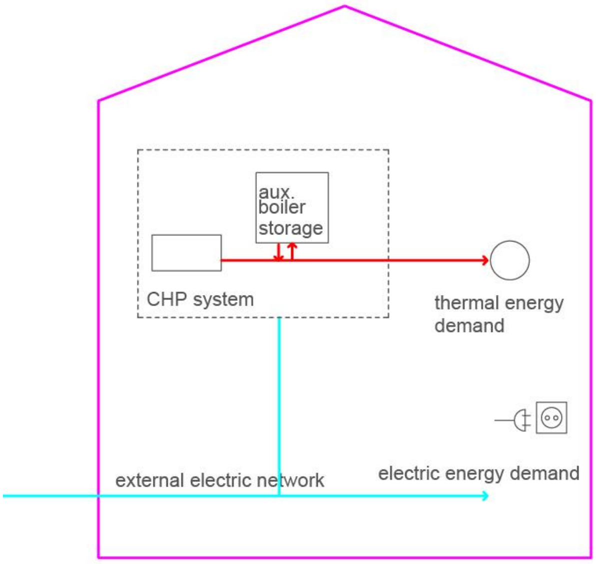


Figure 8 CHP installation scheme

1.2.5 District Heating

District heating (Figure 9 source: Clarke Energy) used to be the primary heating in many Eastern European countries; however, it can be found still in some Northern and Eastern European countries, for example, Iceland (>90% of citizens are being served by district heating), Latvia, Denmark, Estonia, and Romania. The countries with the highest installed thermal capacities are Poland (58 GW), Germany (49 GW), Czech Republic (24 GW), Denmark (23 GW) (Data March 2016). In Iceland, Latvia, and Estonia, the share of district heating in the heat supply is high and has comparably small installed capacities due to the small population size of the countries. The supply source of district heat (fossil/ renewable energy sources) is highly variable between the analyzed countries. For example, in Iceland, the district heat capacity is 100% renewable (geothermal), while the share of renewable capacity in Estonia, Germany, and Romania is meagre. The use of solar thermal collectors and heat pumps is not yet widespread in Europe; it is only used in Denmark, Finland, Germany, Italy, and Spain and provides a small proportion of the installed thermal capacity. Nevertheless, the integration of heat pumps and solar thermal energy has increased in recent years. There are currently several efforts to increase the share of renewables and CHP in district heating systems.

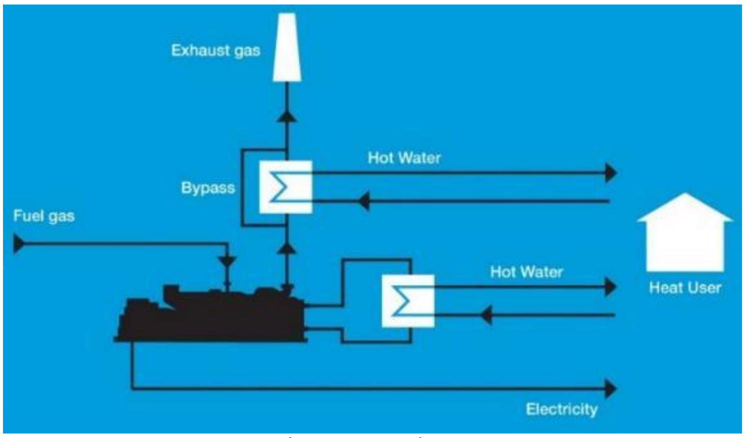


Figure 9 DH scheme

1.3 Natural and Mechanical ventilation

Ventilation can be used to maintain the internal air quality of a building by introducing 'fresh' air into the building, extracting 'stale air', and filtration. For centuries, homes were not ventilated, but ventilation is becoming more and more important nowadays. Building constructed a few decades ago were leaky given the lack of insulation; thus, fresh air could quickly enter through the gaps, crack, and holes in the building envelope. Ventilation can take many different forms; it can be natural, mechanical, or mixed-mode (hybrid systems). Natural ventilation is a common strategy for households, and it can be either single-sided, cross, or stack. In some modern cases, natural ventilation is controllable if, for example, the user wishes to operate the windows using temperature, rain, and wind sensors or it is hard to reach the windows.

In the case of mechanical ventilation, generally, the systems are composed by:

- A motorized fan, whose role is to extract stale air and force air circulation in the house.
- A network of ducts, or two networks in the case of a dual flow.
- Extraction vents, which determine the flow of extracted air.
- Air inlets to allow the arrival of fresh air.
- In the case of a double-flow, the air inlets.

As shown in Figure 10, mechanical ventilation systems can be simple or double flow, each one with various sub-categories.

Simple flow ventilation systems:
- Exhaust ventilation systems
- Supply ventilation systems
- Hygrorregulated ventilation systems

Double flow ventilation systems:
- Balanced ventilation systems
- Balanced, heat-recovery ventilation systems

Figure 10. Controlled mechanical ventilation classification

In the case of simple flow ventilation, the outside air enters through air vents located in the main rooms, crosses the air, and is then rejected outdoors via service areas (bathrooms, kitchens) thanks to a ventilator block, which is usually hidden in the loft.

This technique helps to optimize air renewal and save energy. This configuration, adequate insulation, airtight walls, optimized ventilation produce comfort, energy savings, and reduced CO2 emissions. However, double flow is more complex to mount, expensive and requires more complicated maintenance. (figure 11).

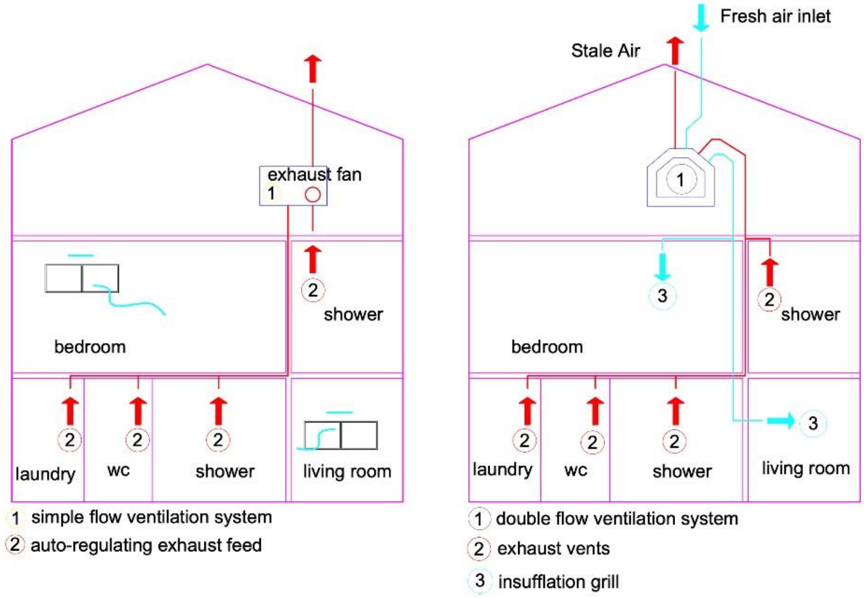


Figure 11 Ventilation (single flow & double flow) installation scheme

1.4 Cooling residential units

Common, when people discuss cooling residential units (apartment, house, an entire residential building), they refer to installing air conditioning. However, the term 'air conditioning In some of the strictest definitions, air conditioning is used to describe systems that control the moisture content of air, that is, its humidity. It can include humidification and dehumidification. However, dehumidification of air is generally achieved by cooling. As a result, humidity control and cooling are often considered together as 'air conditioning'. Both cooling and dehumidification are essential contributors to thermal comfort.

Cooling a residential unit comes in many forms, from massive installations designed to cool an entire building or local units under the form of a portable window-mounted box that can be pulled out and used in cooler climates to handle short summers. The broadest known unit used for cooling is an AC unit composed of internal and external units (Figure 12). Some variations of the internal unit exist in the market, for example, wall-mounted type, cassette type, floor-ceiling type, duct type, console type units, etc. Other solutions include heat pumps that were tackled in chapter 1.2.3.

A newer alternative that can cool an entire building or even an entire complex of buildings is represented by the CCHP system (combined cooling, heating and power). The heating and power-producing part of the system is similar to a district system or a CHP device (in case of using it only for a building). The difference is the addition of an absorption chiller. The chiller recovers the waste heat when producing electricity in the summer and use it for creating a cooling agent.

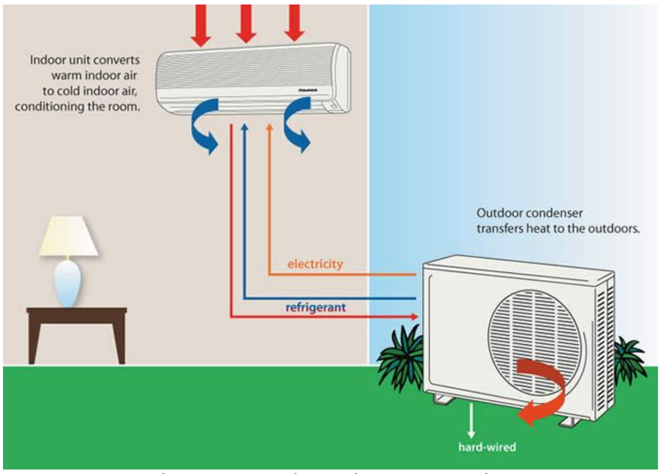


Figure 12 AC schematic representation

2. Data collection from existing buildings HVAC systems

2.1 Introduction

As shown in chapter 1, there are multiple types of heating, cooling and ventilation systems installed in a residential building, leading to a more straightforward or more complex process of gathering data. A lot of data needs to be collected of existing systems, from the position of the equipment until detailed characteristics of each equipment, the system's piping, and the system's electrical components. Gathering and handling the amount of data can be overwhelming if there is no good understanding between the scope of the renovation work and the data required. Additionally, data is available in multiple ways, from manual inspection reports to specification reports to various formats of point clouds. Therefore, it is not surprising that handling and gathering data are usually time-consuming and costly.

All these lead to defining the BIM Use Cases found in the BIM SPEED Methodology Toolkit and are part of the D1.1 – Methods for Architectural, structural, thermal 3D data acquisition of existing buildings. Using that application, one can filter the scope and the Renovation stage (according to BIM SPEED Renovation Process or RIBA). Afterwards, all the Business processes, BIM Use cases, and methods will appear, accompanied by a description.

This chapter will exemplify the types of data collection present in the BIM SPEED Methodology Toolkit. It is divided based on technology that can gather the data and offer insight into whether it is suitable for a specific case.

2.2 3D Scanners

Point clouds are a collection of points, each with its X, Y, Z coordinates, that are put together to form a 3D representation of an object. A 3D scanner creates million of points from one scan, but these scans are limited to the line of sight. So, multiple scans are required for a building with lots of rooms.

Collecting data using a 3D scanner can be divided into three categories:

- Hand-held capture: used for scanning small objects for replication, primarily used in heritage or precise engineering.
- Ground capture: topographic mapping of land or constructed assets, natural features.
- Aerial and satellite: using drones for scanning large surface areas.

Considering that this deliverable focuses more on collecting data related to HVAC systems, the usage of laser scanners will be presented from this point of view.

3D scanners used for building scanning are developed based on several technologies present on the market:

- Time-of-Flight Scanners
- Phase based scanners

Time-of-flight scanners, referred to as infrared scanners, calculate the amount of time it takes for a laser beam to reach and return from contact with a surface. It comprises a transmitter and a detector that sense the beam's return. The parameters for the calculation are the time it takes to go forward and back and the speed of light. The advantages of this type of 3D scanner are that it can be used to capture data on longer distances than phase-based scanners. Time-of-flight scanners are slower than the phase-bases scanned, capturing around 50000 points per second but ranging up to 300 meters. These scanners offer lower quality point clouds than the phase-based scanners but offer an excellent cost-quality ratio when scanning buildings. It needs multiple scans to create the entire building mesh, and it is found in portable devices.

Phase-shift scanners use a beam of laser energy that is transmitted constantly. The scanners measure the phase shift of the return laser energy to calculate distances. These scanners are much faster and collect significantly more measurement points, with values that go over 100 000 points per second. In addition, compared with time-of-flight, the scanners offer a shorter range (around 80 meters). Therefore, these scanners are much more suitable for the interior of buildings.

The market of 3D laser scanners is an emerging market having a yearly increase. Manufacturing the devices, providing 3D scanning services, and software development (processing software of the point clouds, viewing programs, Scan-to-BIM solutions) are just a few of the activities contained in this market. To name a few manufacturers on the market that produce laser scanners:

- FARO Technologies Inc. (figure 13)
- Trimble Inc.
- Carl Zeiss Optotechnik GmbH
- 3D Digital Corp.

- Riegl Laser Measurement Systems GmbH

Considering the life-cycle of a project and the BIM SPEED Renovation phases, laser scanning can be used in the following:

- Existing building data collection: for gathering data from the existing asset. Please refer to table 1 for recommendations on using laser scanners for installation inside the building.
- Renovation design: check the 3D model of the building against a point cloud to see possible deviation and search for clashes against the existing situation.

Figure 13 3D Scanner produced by FARO Technologies Inc[3].

The benefits of creating a point cloud in an industry where saving time and money are essential are many, but if the scope of the usage of the point clouds is not clear, creating a point cloud unnecessarily can lead to extra costs. The benefits of creating a point cloud are:

- Save survey time – creating a point cloud is faster than making a 2D survey of a building.
- Accuracy of the results – the outcome of point clouds (appropriately done) is usually highly accurate and with good precision.
- Allows a pre-analysis of the building – point clouds are a 3D representation of the building. Therefore, they can already be used to pre-assess the current state of the elements inside/outside a building without a 3D model.
- The use of validation – can be used to validate a design. Clash detection between existing and new installations is just one example.
- Reducing costs - if Scan-to-BIM is used, the time required to create a 3D model is less than using traditional methods.
- Avoid errors in modelling – a more precise survey than the traditional way

Point clouds, like any method or technology, have some disadvantages:

- Surfaces that are curved maybe not be represented clearly.

[3] https://www.prnewswire.com/news-releases/faro-launches-new-x-series-laser-scanner-the-focus-3d-x-130-248186641.html

- Point clouds do only include information about the spatial position of points. It only comprised the geometry of the building or part of buildings, in a data format that does not allow easily for further processing (points vs more advanced geometrical presentations of objects).
- The large files may be difficult to manipulate or load into a software application.
- Specific software may be required to transform the point clouds in files that 3D modelling software can import.

The decision to create a point cloud should be considered closely in conjunction with the BIM Use case or a combination of use cases (recommended). In table 1, a few recommendations are made.

Table 1 Using laser scanners for installation inside existing buildings

Reason	3D scanning		
	Not recommended	Optional	Recommended
Point cloud of installations, if the elements are not visible (mounted in construction elements, e.g. pipes mounted in walls or in-floor)	x		
Point cloud of only HVAC systems when installations are visible (for apartments, e.g. pipes mounted on walls)		x	
Point cloud of only HVAC systems of technical rooms			x
Point cloud covering all disciplines (architectural, structural, MEP).			x
Creation of point cloud for deviation analysis		x	
Creation of point cloud for clash detection (in case not all systems will be renovated, and coordination is required)			x

Other characteristics to consider are:

- Technical shafts cannot be 3D scanned with current techniques.
- Level of detail of the scan. For example, since many elements are involved in HVAC systems, the level of detail is higher than for a structural scan.
- RGB colouring or not. The need for colours is another aspect but for HVAC systems is not that required if and only if the information of the material of pipes and ducts can be obtained accurately from some other source.
- The dimension of the building
- The number of scans required.
- Distance to travel.
- Range of device,

- Deliverables,
- Training required for operating the device and software

Depending on the service chosen, one can pay up to 1000-1500 € for one rent of a 3D scanner. For purchasing a scanner, the range of prices is between 32000 € - 66000 €, depending on the scanner's characteristics (estimated costs at the time of writing the report).

2.2.1 Data collection

If an effective laser scanning is to be performed, a few steps are required to ensure this process goes according to plan:

- One must identify the main scope for the data captured using laser scanners.
- Education of stakeholders concerning the advantages and disadvantages of laser scanning will meet expectations.
- One must understand the physical boundaries of the building to be scanned and be familiar with the project scope
- Determine the required deliverable.
- Define the BIM SPEED Use Cases before laser scanning starts.
- Surveyors must be informed about all required data and ensure that these data are collected.
- Assess time deliverables for the final product.
- The experience of the laser scanning team must be adequate according to the complexity of the project.

Choosing the appropriate scanner is not easy and involves planning, as illustrated in figure 14.

After the information is gathered and the suitable 3D scanner is chosen, the next step is to plan the locations where the 3D scanners must be placed. For example, in the case of surveying the MEP of a residential building, some spaces to consider are apartments, corridors, and technical spaces. Some guidelines to follow to better position the scanner is:

- The position must cover the broadest possible area without obstacles in the line of sight and with the least number of shadows.
- The minimum and maximum range of the scanner are to be respected for the scanning to have appropriate accuracy.
- Minimize the number of small angles of intersection.
- Reduce as much as possible the number of positions of the scanner.
- Environment.
- To comply with Health and Safety regulations during the scanning process.

The preparation phase before mounting the 3D scanner involves deciding the location or location of the scanner. It is called registration of the scanner, and it is a crucial step because it defines how the multiple scans will be combined in one point cloud. There are traditional registration techniques or modern techniques. Traditional registration techniques use targets (free-standing spheres, chequerboard surface targets or retro-reflective dots). Appropriate techniques will result in high accuracy registration but will cost a lot of time. Time can be added for the processing part of scans, which can involve a lot of time and a lot of processing time in the case of traditional techniques. The scans need to overlap perfectly, and the software requires a lot of data. Modern techniques imply the use of machine learning and vector analysis. The technique uses the scanner's positional data, which is extrapolated to each point into a directional vector. The vectors can be lifted from their original context, and an entire point cloud is collapsed into a single point. The identity of the scan is retained by the density and directional characteristics of the vector. According to some studies, large projects can obtain a 40-70% reduction in processing time[4].

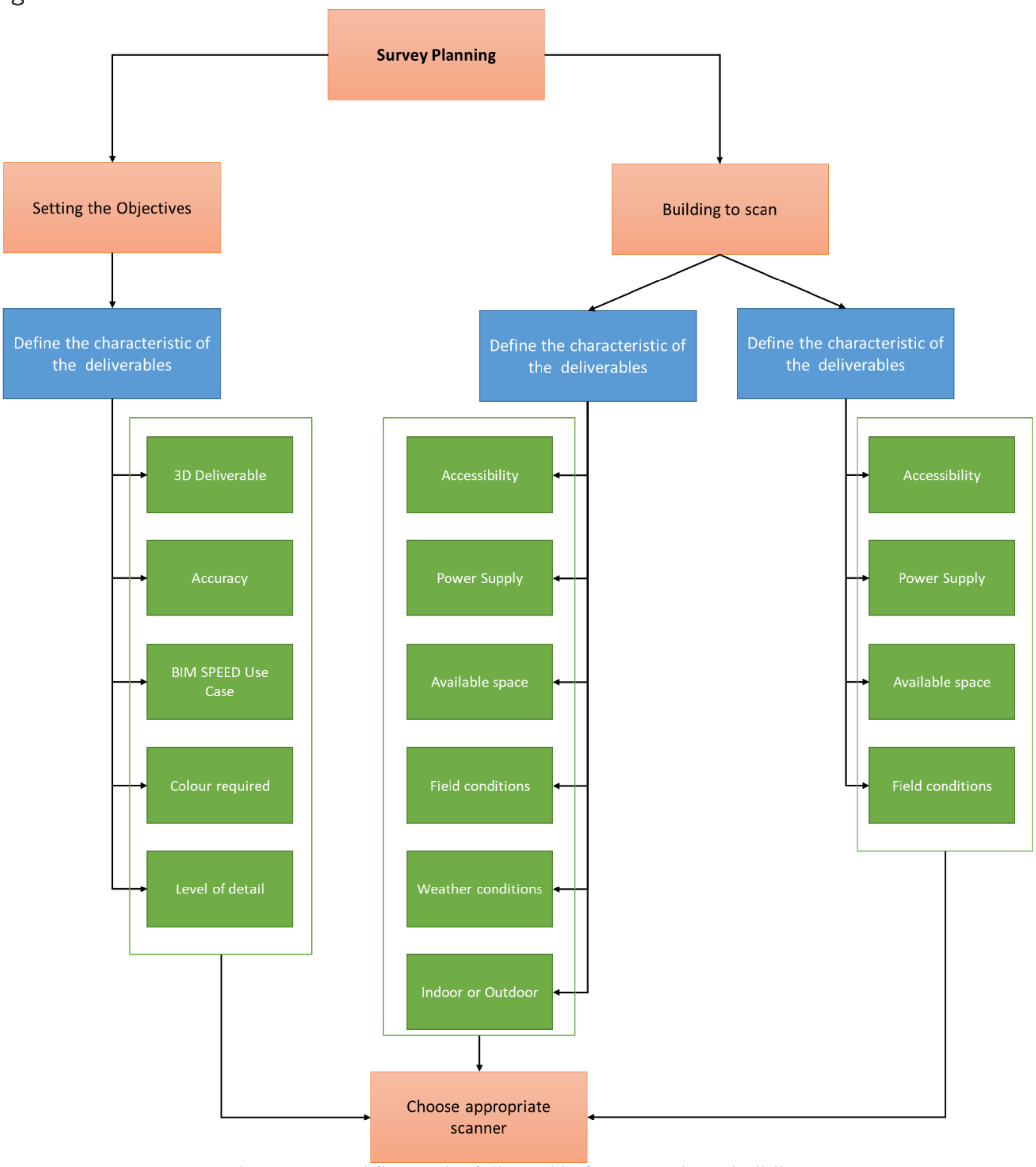


Figure 14 Workflow to be followed before scanning a building

[4] Point Cloud processing has changed – A guide to modernizing your use of laser scanners and 3D modeling

Mounting the 3D scanner is similar to a topographical station. Steps to follow:

- The scanner will be placed at the height of the eyes.
- Place the scanner on the tripod and anchor it.
- Depending on the recording technique, the scanner should be placed on a point is known to reference.
- Level the scanner.

The power supply can either be batteries, the primary connection, or even a generator, depending on the availability of power sources and the time it takes to scan. A regular scan lasts around 4,5 hours. Data storage can be done using SSD cards up to 32 Gb or a connection to a laptop.

After placing the 3D scanner and ensuring enough power and data storage, it is required to define the scan area since most scanners can do 360º scans, but this is not always necessary. Depending on the type of scanners, it is essential to read the manufacturer manual.

Setting the correct resolution represents the final step before starting the scanning process. Resolution is significant since it determines the density of the point clouds and its time to scan. The resolution of a 3D scanner is defined as the distance between two points measured consecutively. Therefore, if points are closer to the scanner, they have a higher resolution than those situated at a longer distance.

After the scanning is done, a good practice is to check if there are unforeseen obstructions. It can be done quickly if the scanner is connected to the laptop (the points are displayed directly) or a laptop where the SSD drive can be inserted into. When artificial or natural points of reference are used to record the point clouds, these points should be labelled and measured very accurately.

2.2.2 Point cloud – processing the data

Point clouds obtained after the 3D scanning process must be analyzed and compared with existing information on site (pictures, notes, drawings). It is advised to use a copy of the original scanned files. After this, the data must be saved in a format recognized by the 3D modelling software. The manufacturers for 3D scanners usually have the software that converts the data into point clouds and usable files. Besides them, software companies developed products in this area. To name a few products made by 3D scanning manufacturing companies: Autodesk Recap, Bentley Context Capture, Pointools, Trimble RealWorks. Open-source programs that can be used are CloudCompare and Meshlab.

Before the point clouds are processed further, unwanted errors must be removed from the data set (human errors, errors caused by the environment, deleting outliers, and cleaning the noise of the neighbouring objects like trees and bushes).

After removing the errors, linking the multiple scans is required since the scanning was performed in multiple locations. This linking process can be done either directly or indirectly. Indirectly means using artificial or natural targets to align the point clouds. For indirect registration, at least three reference points in the two points clouds are required to register, but the more reference points, the better the results. Direct linking is based on georeferencing of the entire data done using GPS. Nowadays, the latest 3D scanners have incorporated GPS and GLONASS devices.

Processing a point refers to the transformation resulting from the final result. The result may be a cleaned point cloud, 2D drawings, 3D models, or animations. Since a lot of time is spent on modelling with point cloud as a reference, the software can automatically model some elements. One example is EdgeWise, which is very good at recreating pipes, ducts, and mechanical equipment. For using point clouds in the modelling process, please read deliverable D2.4, "Guidelines for as-built BIM modelling of existing buildings".

2.2.3 3D scanners

3D scanners are costly, and acquiring such a device or renting it depends highly on business decisions. If the business development involves purchasing such a device, then the decision needs to be weighed carefully since the cost for one device can be double that of others. There are vital features to consider before making such a decision, such as:

Scan speed and image capture

These two features are essential if users take High Dynamic Range (HDR) or capture the point clouds. For example, HDR full high-resolution of a 10-meter scene can be done in three minutes if the speed of the scan is around 2 million points/second and can take 30 seconds if there is no HDR.

Another item to consider is the source of the imagery. There is natural HDR imagery, where the camera is a high-resolution one that collects high-quality source images that are overlapped to be blended. Other cameras use non-HDR imaging with laser intensity values to create more contrast in the point cloud.

Data quality of the scan

Data quality is essential, but it is hard to quantify when a comparison between devices is made. Therefore, the recommendation is to ask for a high-speed demo scan to check the following points:

- Completeness – there should not be any data missing. A fast check is for the areas where the scan was done with a flat incidence angle (figure 15).
- Cleanliness – no invalid points should be present in the scan (figure 16)
- Geometric accuracy – the objects scanned should have the correct geometry in the point cloud. A point of attention is on round surfaces.
- Range noise – Range noise appears due to the speed of the scan and the quality requested. It is recommended to purchase a laser scanner that delivers the quality required without any adjustments and compromises on speed.
- Mixed pixel filtration – refers to how the laser scanner filters out invalid points. For example, in figure 16, the point cloud in the left has low range noise and correct geometry, while the point cloud in the right has high range noise and an incorrect geometry.

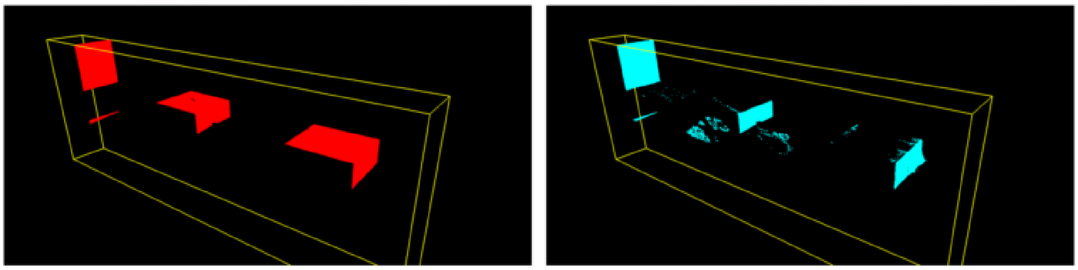


Figure 15 Difference between a complete scan with valid points (left picture) and an incomplete scan with invalid points (right picture)

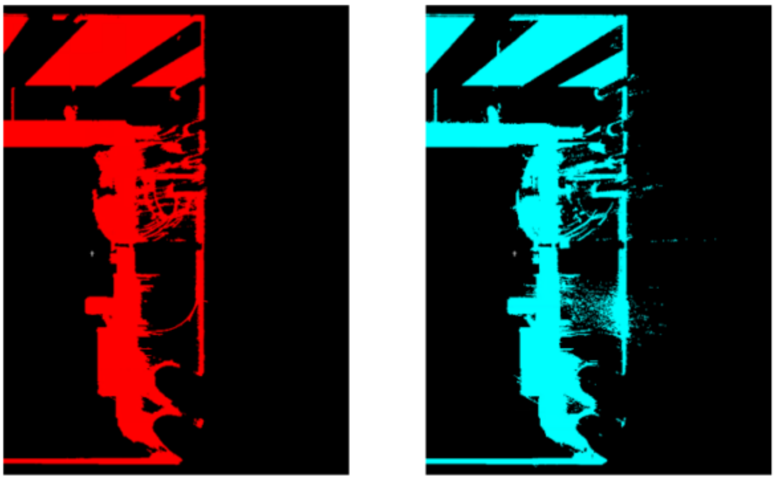


Figure 16 Difference between a sound point cloud (left) and a poor one (right)

Image quality

HDR images made with the scanner should be the same as those made with a high-quality DSLR camera. Therefore, the best practice is to request an HDR image made with the laser scanner and compare it.

Storage and rate of transfer of the data

One must choose devices that enable one to store hundreds of gigabytes of data. If only SD cards are allowed, this may pose an issue since scans take a lot of space. Another aspect to consider is the rate of transfer of the files.

Appendix 1 shows a few laser scanners from FARO Technlogies Inc. and their price and significant differences. The main differences between the most expensive and cheap ones are concerning range, range noise, ranging error, measurement speed, unambiguity interval, and on-site compensation.

2.2.4 Usage of point clouds in BIM SPEED Use cases

Point clouds have a large array of usage in the renovation process. Some BIM SPEED Use Cases were illustrated in the following list, where point clouds immediately impact.

- Design Use Case as part of the Existing Building data collection stage of the project. They are generating the BIM model of the building from the point cloud. A subchapter in deliverable 2.4, "Guidelines for As-built BIM modelling of existing projects", shows the essential steps one must take to construct a BIM model using point cloud as a base. As part of this use case, point clouds can be used for deviation analysis when BIM models are developed based on 2D drawings.

- Definition of Refurbishment strategies Use Case as part of the project's Existing Building data collection stage. It will allow an off-site inspection of the visible MEP elements and define if elements need to be replaced or not.
- Design Quality Management Use Case is part of the Renovation design stage of the project where point clouds can be used for coordination by gathering geometrical information of the current state of the building.
- AS-built documentation Use Case part of the Execution of Renovation works stage of the project. Point clouds can generate the as-built BIM Model after the renovation takes place.
- Construction Quality Management is part of the Execution of the renovation works stage of the renovation project.

2.3 Using photogrammetry in construction work

2.3.1 Collecting good photogrammetry data

Photogrammetry is the technology that extracts data measurements from images to create 3D meshes, point clouds, and images (tiff files) with height value information. Therefore, if one wants accurate and reliable data, it must have high-quality images that contain sufficient information to be processed. Decent outputs can be provided using a smartphone that can take high-resolution pictures (minimal of 2K) with autofocus and capture video with high resolution and a high FPS (30 and above).

When defining a high-quality image for photogrammetry, specific aspects have to be correlated with how the technology works. Therefore, beyond a high-resolution image, here are some factors that contribute to a bad image for photogrammetry:

Highlights and reflective objects – these aspects need to be avoided at all costs because a machine interprets images by placing unique patterns they share. Highlights and reflective objects give a uniform pattern that the technology can't interpret, resulting in a meagre date set that generates inaccurate outputs.

Uniform and consistent colour areas – these areas present little to no difference. As mentioned with the reflective objects, the software will have difficulties interpreting the pattern resulting in low information that generates low-quality outputs.

Overexposed and underexposed images are less than desired data because parts of the image are overcome by bright light or dark shadows. The result will be incomplete or with missing pieces because this generates uniform parts in the image with no specific detail that can be referred to.

Blur and out of focus images –to have clean data, one must have sharp images, meaning that any blur or focus issues need to be adjusted before taking the pictures. Otherwise, this will result in having images with ambiguous patterns that will generate an approximation.

NO camera flashes – this effect of illuminating the subject amplifies highlights and reflections and distorts the overall lighting from picture to picture, resulting in poor correlation and calibration between them and calibration error.

2.3.2 Photogrammetry – photo cameras

Real-life images are required to properly use technology, meaning removing any effects or artistic impressions and effects. Essential characteristics of the devices:

- **Shutter speed** – This setting controls the amount of time the camera lens stays open and allows light to pass. This characteristic contributes to the image's overall exposure and can create motion blur when taking pictures of moving objects. It is measured in a fraction of a second (1s/x). The shutter speed works in conjunction with the Aperture.
- **Aperture** – is the diameter of the shutter opening. It is measured in **F-stop**. A vital aspect of this property is the depth of the field. In simple terms, a brighter image for the closest object will result from mixing a lower F-stop with a wider Aperture. The surrounding will gradually fade into a blur. If the value F-stop is higher, it can create a more focused image with less exposure.
- **ISO** – is the setting that controls how sensitive the camera's light sensor is and, in an artificial way, amplifies or decreases the image's overall exposure. This setting should be used with caution because an improper value can result in grainy images.
- **Camera lens filters** – are handy because they allow compensating in brighter and glossy environments with high reflections. Some of the best are:
  - Polarizing filter - lowers the intensity of the reflections and raises saturation in the images.
  - Neutral-density filter - lowers the brightness in a scene like a pair of sunglasses.
- **Overall lighting:** depending on the picture's environment (interior or exterior), a few methods can be applied to achieve the correct illumination in the right environment.
  - Exterior pictures – One must not schedule in advance the date and time to take pictures if possible since the weather is unpredictable. A sunny day is not recommended because direct sunlight creates hard shadows, amplifying reflections and highlights. Optimal weather for taking exterior pictures is overcast when the sun is behind the clouds and offers an indirect illumination with soft shadows and low contrast. If the schedule can't be flexible, a few camera settings can be changed, but these settings differ from camera to camera.
  - Interior pictures: Same principles apply to the exterior lighting, the only difference being that one has control over
  - interior scenes: the same principles apply to an exterior scene. The only difference is that one has total or partial control over the light.

    In both cases, the critical aspect is to have indirect lighting, and this can be achieved by masking existing source lights whit translucent filters.

- **Framing** – Pictures must be taken of the whole object as much as possible. Background inclusion needs to be minimized.
- **The number of images to shoot** – this variable depends on the size of the site. Generally, one must take pictures that overlap between 50-70 % of them. It is advised to repeat the process at different heights with different inclinations.

2.3.3 Photogrammetry – video cameras

For video data collection, the same principles apply to pictures. Again, characteristics to look for are:

- **FPS** – Minimal values FPS for a video to be considered good quality should be between 24 and 30. In photogrammetry, the values of the FPS are higher from 48 to 60 and can reach 120 FPS.
- **Shutter speed for video** – the shutter speed values directly correlate with the FPS parameter. For photogrammetry, high shutter speed is required for smooth imagery. (ex. 1/2000 of a second).
- **Processing the video**– some photogrammetry software offers the possibility to import the videos directly. If the option is unavailable, this can be resolved by importing it into a video editing software (ex., After Effects) and exporting the video into the desired number of images.

Aerial drone data collection is preferred for exterior and large-scale projects with a lot of metadata embedded in individual images. Examples of metadata are resolution, GPS coordinates, date. Most photogrammetry can interpret it and give a more accurate result.

2.3.4 Using pictures in BIM SPEED use cases

The real-world scale in a photogrammetry project can have a margin of error and is never 100 % exact because this is determined by referencing objects or markers.

- **Reference object** – this method is suitable for objects in the vicinity of the building and where the object's dimensions can be taken. The measurements of the reference object are then placed into the project and a whole model automatically rescaling process starts.
- **Markers** – this is a method best used with an aerial drone. This method implies placing specific markers on the site with known GPS coordinates like ground control points. For good results, a minimum of three markers is required. The data collected from the markers is then added to the project, and the project's rescaling is underway.

The type of output that is generated is one criterion to classify equipment for photogrammetry data collection. For example, a modern-day smartphone is sufficient if the project requires a more volumetric approach with minor detailing in materials and surfaces. On the other hand, if there is a need for a high level of detailing for accurate reconstructions of existing sites, then a professional camera is the best choice. Therefore, when acquiring equipment, one must consider the minimum requirements expressed in table 2.

Table 2 Comparison between smartphone and professional cameras for photogrammetry.

Smartphones	**Professional camera**
the ability to take at least 2k resolution images	8 megapixels min.
the ability to take RAW images(not only JPG)	a camera lens with a focal length from 15 to 35 mm
a good battery 3000 mAh and up	a full-frame camera (this is a specific aspect that helps to capture better light more pixel information. When using ISO, the noise in the picture is highly reduced, and the dynamic range allows capturing more detail in brighter or darker areas)
good storage space or the capability to use cards for 32 GB and up	several batteries and memory cards
accessories in the form of camera stabilizers	accessories in the form of camera stabilizers, tripods, monopods, lens filters, soft-box lights, and light reflectors.

Pictures are used in the Design Use case in the Existing building data collection stage for BIM SPEED Use cases. In addition, they can add value in the Definition of Refurbishment strategy Use Case by making proper documentation in assessing the current status of MEP installations.

2.4 Wall scanners

While Laser scans, 3D scans, and photogrammetric methods can detect objects of an HVAC system that are in clear sight, many components of HVAC systems are hidden within walls and ceilings. Wall scanners can collect the required data about these hidden components. If data to be collected is inside a private apartment, the person that collects the data must request permission from the tenant or owner of the apartment.

2.4.1 Devices

Depending on their technology, there are multiple wall scanners types on the market. The most general principles to operate the devices are:

- Magnetic scanners
- Electronic scanners
- Radio-frequency scanners

Magnetic scanners (or studs) rely on a magnet to detect metal objects inside drywall. These devices are inexpensive but not very accurate and can detect only metal objects that are not very deep inside drywall. Electronic scanners can be found with different price ranges. The simple electronic scanners and, less costly, detect objects by measuring electrical capacitance. The presence of a metal object is shown via LED lights (red and green). These devices are more accurate than a magnetic scanner, inexpensive, easy to use, but do not offer much information. The later generation, also called wall scanner, can detect more than studs, including pipes and electrical wire in which current passes. They are using the same principle (with electrical capacitance). However, they cannot detect data cables or control cables.

Radiofrequency (RF) is relatively new to be used in object detection. However, one suitable device in this area is Walabot DIY which requires a smartphone to reconstruct a 3D image of objects behind drywall or concrete. According to the manufacturer, it can detect objects located until 10 cm in-depth in the wall, but it does not work for plaster walls or stucco surfaces.

Objects that can be located using Walabot DIY:

- PVC plumbing pipes
- Metal plumbing pipes
- Metal studs
- Rebar
- Wood studs
- Electrical wires
- Fiberoptic and other cables
- The movement inside walls.

2.4.2 Radiofrequency device – collecting data

These devices are the best items on the market that can go deep and detect so many types of pipes and cables. The output it gives is a picture (screenshots from one's mobile phone). Unfortunately, there are no references to the object's height or other references to other objects in the vicinity. Recognizing different types of pipes is done relatively quickly since the device, and the software has a colour-coding system. It is a tool to use when performing an inspection to determine, check and verify the existence of piping and wiring according to existing drawings.

How to use the device:

- Unpack the device, place the protection surfaces over and on one’s phone and connect it to the phone.
- Download the app and connect the device to the phone, according to instructions from the app.
- Select the type of wall
- Calibrate the device according to the tutorial on the screen. For each type of wall, calibration is required, and it is mandatory to be performed correctly for accurate results.
- Select viewing mode: Image or Expert. Image mode allows the user to see studs, wires, and pipes. Expert mode allows the users to see movement inside the wall or to follow the path of pipes/wires.
- Be sure that the device is pressed firmly on the wall before pushing “Start” and before the calibration process starts.

The device's unique feature is that every user can order the components and create their Walabot. In addition, the manufacturer allows users to develop customized software to see the objects in the wall. There is no direct output to be used with the BIM model, but it serves as a tool to offer accuracy to current data. The number of piping or wires to check can lead to considerable time spent on site.

2.4.3 BIM SPEED Use cases

Wall scanners can be used as support for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Definition of Refurbishment Strategies
- Design
- Cost Calculation

2.5 Drones in building renovation

2.5.1 Drones – advantages and disadvantages

Drones are very suitable for inspection for large areas since they can capture images and be manoeuvred in zones that people may not easily access. However, drones must be controlled by pilots who have drone flight experience. Nevertheless, the construction market has been looking increasingly into using drones in their activities, and opportunities are available (figure 17).

The main advantages of taking into consideration when using drones:

- Speed – drones can scan the exterior of the building much faster than a manual inspection.
- Cost – because of the speed of the inspection and the fact that drones can take pictures or create 3D scans, they represent a cheaper alternative than a manual inspection.
- Safety – drones can be used for building, no matter their heights, not subject the inspector to risks.
- Liability.
- Manoeuvrability – can access areas where a human might not fit and be more accurate in determining defects.
- Visual clarity – high definition or 4k cameras are more accurate than the human eye. In addition, thermal cameras mounted on drones can reveal unwanted heat losses.
- Share-ability – videos and pictures are easy to share with multiple stakeholders.
- Challenges when using drones in inspection:
- Equipment cost: the drones and the type of camera influence the cost of the equipment. Some companies adjust the type of drone and camera based on the scope of the work, which can be more cost-effective. However, the cost can reach a few thousand dollars.
- Human injuries: drones can be harmful in mishandling because the blades are sharp.
- Licensing: drones must be piloted by experienced operators. In some countries, licensing may be required from national flight agencies.

- Special permits: there are restricted areas where drones cannot fly unless a permit is issued. Depending on residential buildings' areas, this permit may be required (airports, government buildings, etc.).

Drones can gather exterior footage for residential buildings and mainly assess the rainwater system on flat roofs. Depending on the type of rain system used, drones can reveal where the water gathers, thus showing if the current rainwater system is designed correctly or areas where a detailed inspection is required.

As mentioned before, drones can fly in areas where people will not fit or are prone to injuries. However, considering that a residential building does not have plenums or crowded areas for building services, there are still issues with inspecting technical shafts. It is where small drones offer the best support via cameras or thermal cameras.

2.5.2 Data collected using drones

Drones collect data in the form of a picture, thermal pictures, videos, and point clouds. Creating an MEP BIM model out of the pictures or point clouds of the shafts can be done using photogrammetry or Scan to BIM. Other added value of this data consists of offering a correct view of the MEP systems that are not reachable, correctly assessing the needs in the renovation process and helping in the decision-making process. For example, in a partial renovation project, items discovered using cameras mounted on drones can help determine what construction work is necessary (changing pipes inside shafts if they are leaking, replacing insulation, etc.).

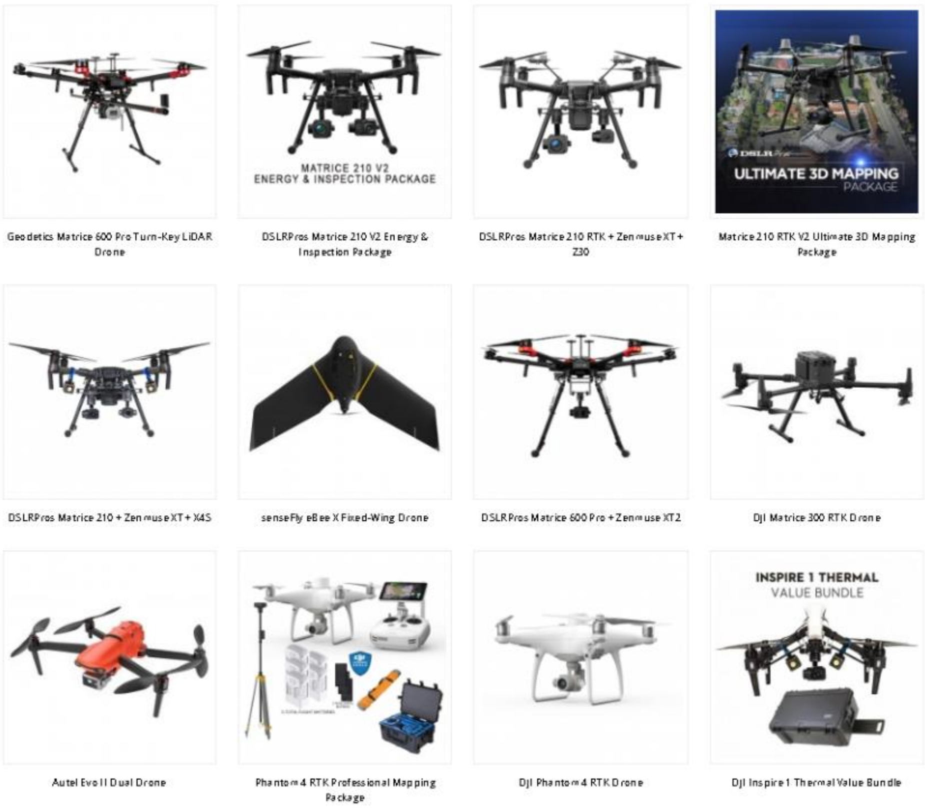


Figure 17 Types of drones used in building survey

2.5.3 BIM SPEED Use cases

Drones can be used as support for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Definition of Refurbishment Strategies
- Design
- Energy performance assessment

As part of the Renovation design stage of the projects, drones can be used for:

- Design Quality Management
- Energy performance Prediction

Part of the Execution of renovation works stage of the projects:

- Construction Quality Management

2.6 Robots in building renovation

2.6.1 Robotics in gathering building data

The use of robotics represents one of the breakthroughs in the construction industry and represents a big emerging market that will have continuous growth until 2025, as per the predictions.

The type of robots used in the construction sector can have different uses. First, an identified robot helps directly the construction process (e.g. EffiBOT, which help workers by bringing the materials tools and avoiding obstacles). Second, a checking robot, e.g. Doxel – a robot with LIDAR sensors and an HD camera, can carry site-inspection, clash detection and compare the current state with 3D models. For the second category, robots are also referred to as Autonomous Scanning platforms (figure 18).

To define a system as entirely autonomous, it will have to perform the following operations:

- To be able to navigate;
- To be able to acquire 3D data;
- To be able to process 3D data;
- Should not have prior knowledge of the environment;
- No human interaction.

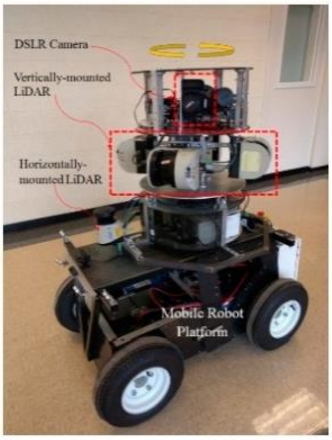


Figure 18 Autonomous scanning platform

Scan to BIM is the most efficient process in gathering data and reconstructing 3D models, but this is primarily outdoor or in big indoor spaces (such as storage, etc.). Creating laser scans indoors will take a lot of scanning points, leading to spending a lot of time on the site.

The use of robotics has paved the way for new technologies to be developed, one of the first being SLAM. However, this technology relies on some primary objectives:

- The ability to return to the starting point – the robot can build a personal map that allows it to return to the initial point. It is done with LIDAR sensors and imagery, and the SLAM algorithm computes the best estimate of the device location and a map of the environment around it.
- Reproduce a human behaviour – when on-site, each person analyzes the surroundings to recognise and determine their speed based on the surrounding movement of other objects
- To measure – SLAM uses all points from the LIDAR point cloud and finds the best position of the sensor by minimizing the difference from frame to frame. With this approach, any environment is easily scanned and quickly merged with other approaches.

SLAM can be seen as a solution in obtaining relevant data, but any technology has its limitations. At its core, one setback stands out since localization is done relative to the surroundings. Therefore, the objects must be spread in the environment and reduce the level of the uncertain position. Furthermore, since SLAM is based on sensors and cameras, there is always the measurement's risk of "noise".

Current literature suggests a combination of two technologies called CPS-SLAM[5]. It consists of a parent robot equipped with a laser scanner and child robots with target markers. Child robots localize the parent robot by taking a stand-still state and acting as a marker. Afterwards, the parent robot stops and is a marker for child robots. In this way, the robot's location is determined with high accuracy. The downfall of this system is that the spaces should be sufficient and not crowded with objects; parent and child robots must easily observe each other.

Another algorithm used for controlling the robots is the "Next best view, " adapted to every mobile platform. Both algorithms (NBV and SLAM) refer to the "sensor placing problem". The robot uses the NBV algorithm to explore the indoor environment and provide a semantic map obtained from coloured point clouds (see figure 19).

Other methods include using a 2D map of the floor and estimating the next scan position concerning the future visibility of the scene. However, 2D information can be outdated, and this can cause non-optimal positions. It is why SLAM and NBV algorithms are more efficient.

The process of obtaining a 3D model from an autonomous platform using NBV is as follows:

- First stage – a coarse model of the scene is obtained by using the 2D map, setting several random scanning locations on the map, and picking an optimal set of positions so that the boundaries of the space are covered.

[5] Kurazume R., Oshima S., Nagakura S., Jeong Y., Iwashita Y – "Automatic large-scale three dimensional modeling using cooperative multiple robots", Computer Vision and Image Understanding, 2017, pages 25-42.

- The second stage – is refining the coarse model. The algorithm assigns three labels for objects (unseen, seen-empty, seen-occupied). The refinement is done by determining the number of "unseen" labelled objects. Based on this, a new scanning position is determined.

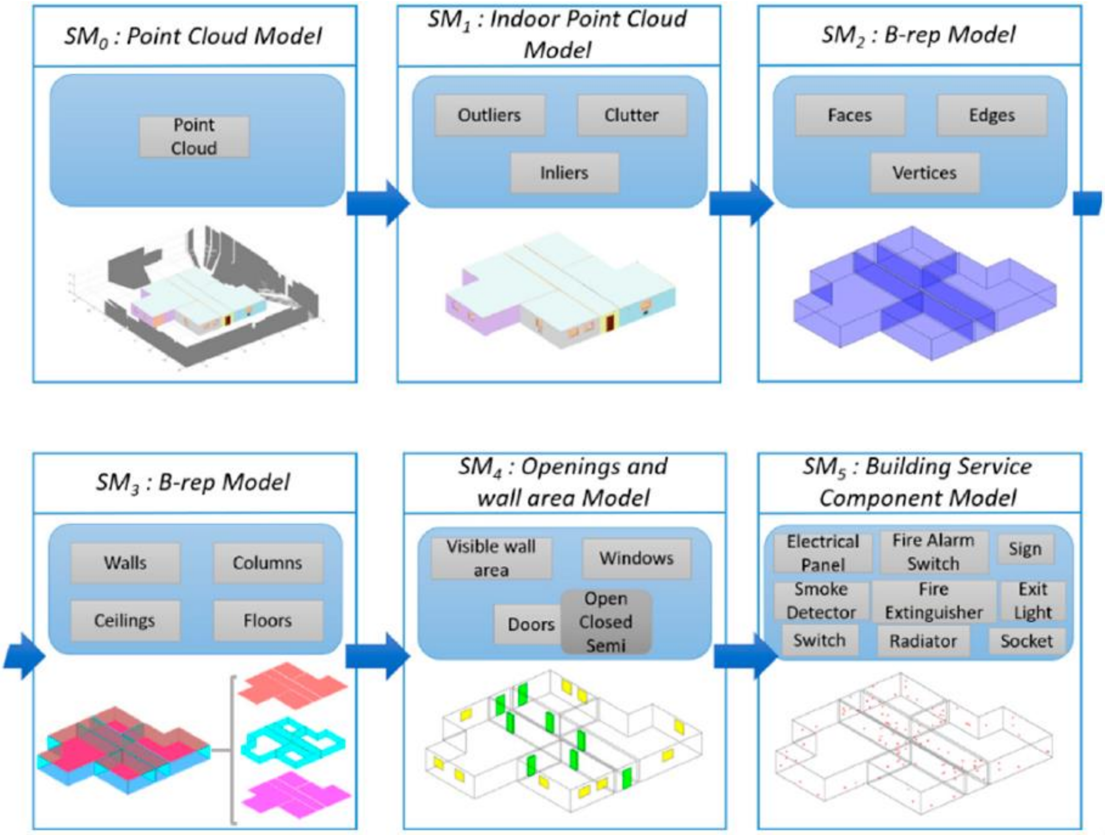


Figure 19 Semantic 3D model levels and the output

There are a few factors that still limit the autonomy of mobile platforms, and this is related to a series of the hypothesis that the systems have incorporated:

- All floors and walls need to be flat;
- All doors must be opened;
- Low level of occlusion.

2.6.2 Data collected using robots

The autonomous scanning platform's data is fundamental since it reduces a lot from collecting the same type of data using other techniques. Two main outputs can be expected from this kind of scanning:

- a point cloud,
- A simple 3D model, where the boundaries are well defined, including architectural elements and openings. The models are floor-based. Until now, autonomous scans were performed on a single floor; the problem of moving the robot to another floor is still pending (about collecting and combining data and not the psychical movement of it). Other issues that may hinder the creation of an excellent 3D model are closed rooms.

2.6.3 BIM SPEED Use cases

Robots can be used as support for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Definition of Refurbishment Strategies
- Design

Part of the Renovation design stage of the projects, robots can be used for:

- Design Quality Management

Part of the Execution of renovation works stage of the projects:

- Construction Quality Management

2.7 Thermal images

2.7.1 Gathering thermal images

Infrared thermography or thermal imaging (how it is often referred to) allows the gathering of data concerning:

- Detection of moisture and water infiltration;
- Detection of thermal bridges;
- Observing voids, cracks, delamination;
- Location heat loss or air leakage for HVAC systems.

This method is non-destructive and non-contact and represents a fast method of identifying the flaws in a vast area.

Thermal images are taken using thermal cameras (figure 20) that operate on long infrared waves. The cameras can take a single picture, time-lapse images, or video formats. Thermal cameras have a resolution of up to 1024x768 pixels. For precise results, the building elements must significantly differ in temperature to the ambient temperature. Thermal imaging can be combined with 3D laser scanning with the scope of producing 3D thermal images.

Thermal images in HVAC have some benefits. Besides identifying where the insulation is faulty, or the current layer is not enough, thermal imaging can be applied to equipment to detect any overheating. In addition, it can have a positive impact Either HVAC equipment or electrical panels can benefit from this preventive maintenance.

Figure 20 Thermal camera from FLIR

2.7.2 Usage of data from thermal imaging.

As mentioned in 2.7.1, the thermal inspection can be under the format of images, videos, or time-lapse. Thermal images can be used to obtain 3D models, but from the HVAC perspective, this has higher value in the residential buildings where there is a technical room or a scan done on an apartment. For hidden pipes inside construction elements, point clouds cannot be obtained. For thermal images, this depends on how deep the pipes are hidden and if they are insulated or not. For shafts, if there are areas to access them, thermal images can be made that will have high relevance in determining the need to replace those HVAC elements.

A process is defined to create a thermal 3D model (figure 21).

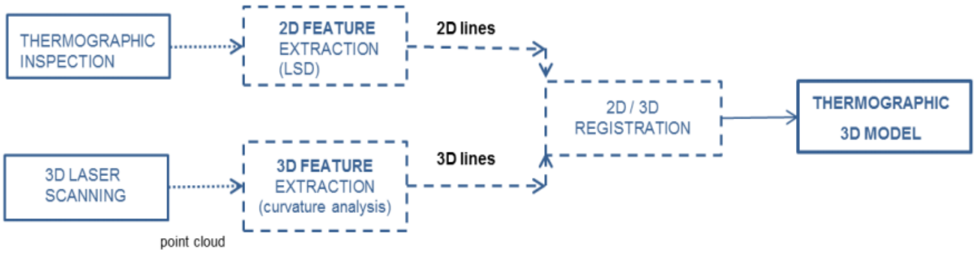


Figure 21 Creating a 3D Thermal model

Thermal images can be used in a BIM model in two ways:

- Suppose the BIM model is intended for visual inspection of the condition of the building and locates defects. In that case, thermographic textures extracted from the 3D model can be applied to the BIM model.
- If the BIM model has the scope of energy analysis, the thermal resistance of the walls can be calculated if quantitative thermography is performed. The values can then be inserted into the BIM model if needed.

2.7.3 BIM SPEED Use cases

Thermal images can be used for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Definition of Refurbishment Strategies
- Energy performance assessment

As part of the Renovation design stage of the projects, drones can be used for:

- Design Quality Management

2.8 Existing drawings

Existing drawings are a set of data that represent the base before starting a renovation project. Depending on the year of the construction, one can find existing drawings in digital format (either pdf, dwg, dgn and other types of files - figure 22), or physical format (figure 23), which are the most common for most of the buildings. Building owners should provide the design team with existing drawings in any format. In some cases, in Eastern European countries, the municipality has the drawings in their archives (if the archives are still available, a situation can occur).

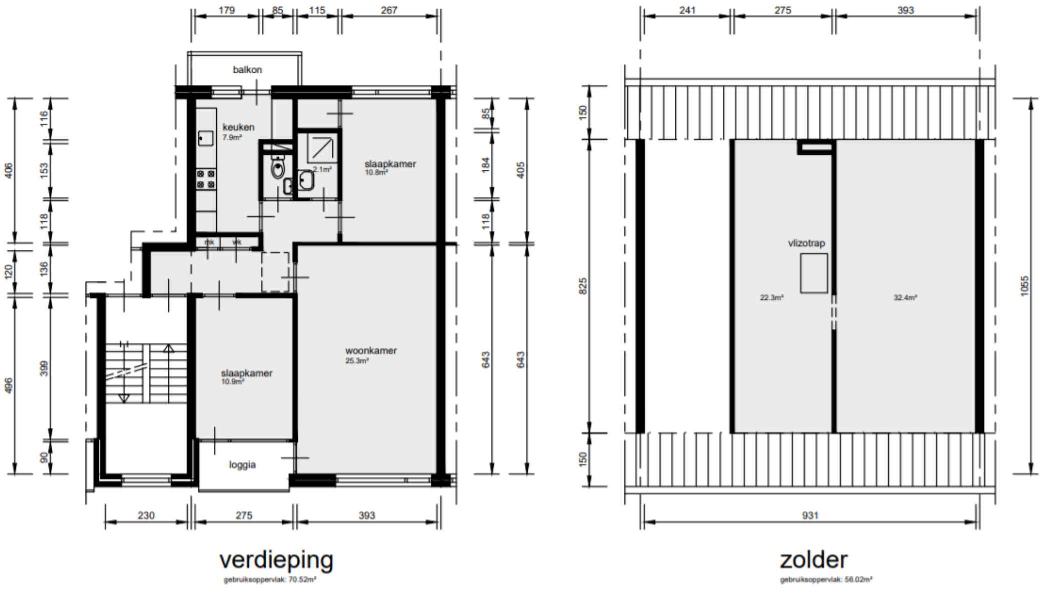


Figure 22 Floor plans in PDF from WARNOCK, The Netherlands BIM SPEED DEMO CASE

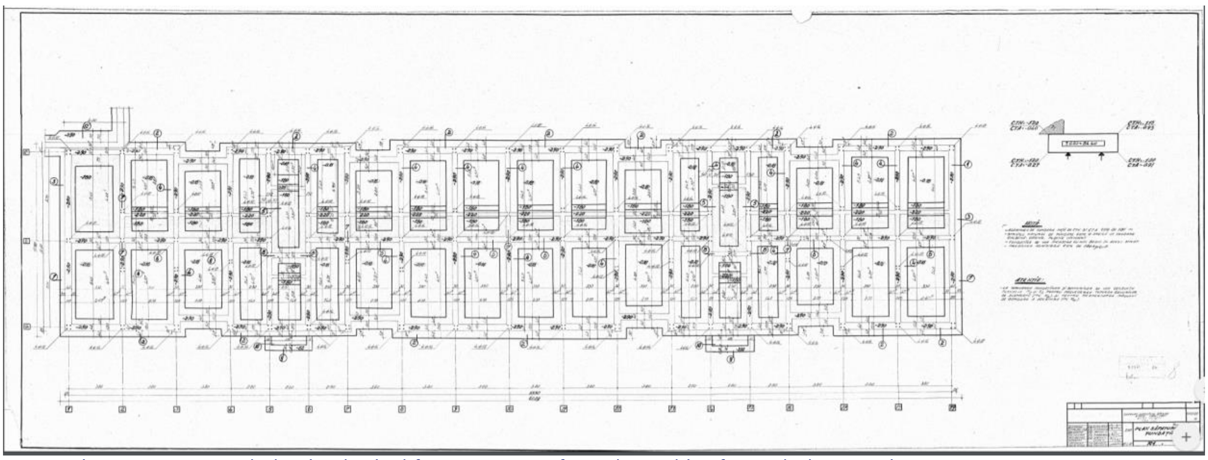


Figure 23 Structural plan in physical format, extract from the archive for Barlad, Romania, BIM SPEED DEMO CASE

As stated above, existing drawings represent the foundation for starting a renovation project. Existing drawings are instrumental in the site visit since much information can be checked and take notes about any deviation. The BIM SPEED Design Use Case benefits from having existing drawings since BIM 3D models can be developed from them. In deliverable 2.4, “Guidelines for As-built BIM modelling of existing projects”, a sub-chapter describes what to consider when creating a BIM Model from existing drawings.

2.8.1 BIM SPEED Use cases

Existing drawings can be used for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Design
- Energy performance assessment – if there is no model available, existing drawings can be used to construct a 3D model in the energy performance tool directly.
- As part of the Renovation design stage of the projects, drones can be used for:
- Energy simulation prediction
- Part of the Development stage of the projects, drones can be used for:
- Cost Calculation

2.9 Manual inspection

2.9.1 Video inspection data

Video inspection devices (figure 24), sometimes referred to as an “endoscope”, are used to assess the condition of HVAC elements, mainly piping, ducts, shafts. The usage is a more in-depth analysis of retrieved data regarding existing cracks or clogs. One can use these devices also to investigate the interiors of some equipment, where the human eye cannot visualize its condition. The length of the endoscope can go until 30 meters, so relatively long routes can be investigated.

These devices have some advantages if one needs to do this kind of assessment. The devices are easy to use, and most do not imply a high investment. The output data can be found in images or video format, and some devices allow the data to be stored on SD cards or internal memory and then downloaded on the PC. The main disadvantage of using these devices is the time spent making the assessment, and the data cannot be used to reproduce anything in 3D.

This data can constitute a solid argument for replacing main piping or ducts systems even though they were not in the initial plans. Of course, the decision to replace piping or duct can be made just by exterior investigation. Still, this method can be used if the installation is not functioning correctly and no external causes have been determined.

Figure 24 Video inspection camera from DeWalt

2.9.2 Working parameters of the installation of the buildings

Depending on the year it was constructed, an HVAC system is designed based on a series of parameters that the installation must fulfil. These parameters should be tracked in time when maintenance work is scheduled. Unfortunately, BMS systems or data analytics systems are almost inexistent in already built residential buildings, so collecting data is left to humans. Unfortunately, this data is not collected in a standardized manner and thus making it hard to have it structured and incomplete (if archives are not available or deteriorated in time). For example, there is no form template for Romania, so every maintenance company gathers it under which format it wants.

The most common parameters refer to the temperature of the heating agent and pressure. Based on calculation software, other parameters can be determined (an example will be if the energy efficiency of a gas boiler has changed). These parameters are read by a maintenance technician and written down in a maintenance report.

Regardless of its form (electrical energy, gas, biomass, etc.), energy consumption represents valuable data that should be available. This information is present on the utility companies' invoices received by building/apartment owners. In addition, data from the last 2-3 years should be available since there are countries that make this recommendation throughout their policies in the energy performance of buildings. Unfortunately, this data is unstructured and under different formats (commonly paper, scanned paper, or pdf version), so extracting data automatically is tricky.

All these types of data are used in the BIM Use Cases energy performances and represent an essential basis for the designer to propose solutions to improve the energy performance of the systems by replacing one or more equipment.

2.9.3 Manual inspection

Traditional inspection is done manually, meaning that a technician checks every part of the installation himself without the help of any pieces of equipment. This process sometimes involves dismantling some portions of the equipment to check the integrity of components or crawling in very tight areas and may present a Health and Safety risk. As mentioned in 2.8.1, an endoscope eases the process, especially for tight areas, but not all technicians have this equipment. Documenting the process is another type of consuming step in this process. Information from manual inspections is relevant when doing a renovation process since it can make the difference in deciding if portions of the installations or just some equipment need urgent replacement or just maintenance work.

A way to digitalize this process is to create mobile forms since technology allows this. Connecting directly to a data storage platform can be done using a mobile phone, and forms can be accessed from there. It will ensure that information is uploaded fast, other people can have access in real-time, and standardised forms to extract data from it.

2.9.4 BIM SPEED Use cases

Maintenance report can be used for the following BIM Use Cases that are part of the Existing Building Data collection stage of the renovation process:

- Design
- Energy performance assessment

3. Digital recreation of HVAC models

Most of the above data collection methods still require a vast amount of manual processing to reconstruct HVAC elements and systems installed in a building and hence allow to support the detailed analysis and improvement of a building's system while designing renovation options. However, machine learning-based classification methods can provide automated methods to extract meaningful information from images, point clouds or other scans. This section provides the first exploration of these possibilities by describing an experiment to detect HVAC components from images and discussing possibilities to extract information from point clouds.

3.1 Detection and classification of HVAC components in images

3.1.1 Introduction

The main objective of this part of deliverable 1.2 is the evaluation of the possibilities offered by deep learning techniques for the detection and classification of visible HVAC components in the photographs taken during the survey of the buildings.

The first phase is proposed to train some of the states of the art convolutional neural networks (Inception, ResNet, InceptionResNet) to detect and generally classify the most common components in different demo sites. And in a second phase, we will study the possibility of identifying the manufacturer and exact model of each component detected.

In both phases, the availability of many correctly labelled images is essential.

3.1.2 Deep Learning

Deep learning is a branch of "machine learning" based on algorithms that attempt to model high-level data abstractions using model architectures composed of multiple nonlinear transformations. Deep learning is based on supervised or unsupervised learning of multiple levels of features or representations of data. The top-level features are derived from lower-level characteristics to form a hierarchical representation. In the last few years, deep convolutional neural networks and, more recently, different variations such as Residual Networks (and others) have become one of the most popular architectures for image recognition tasks. As a result, the field of computer vision has gained a framework for fast and scalable learning, which can provide excellent results in object recognition, object detection, scene recognition, semantic segmentation, action recognition, object tracking, and many other tasks.

A convolutional neural network is an artificial neural network where neurons correspond to receptive fields similarly to neurons in a biological brain's primary visual cortex (V1). Its typical architecture is structured as a series of stages formed by layers. The early stages are composed of convolutional layers and pooling layers. The neurons at the network's end perform the final classification on the extracted features using fully connected layers. These neurons in distant layers are much less sensitive to disturbances in the input data but are also activated by increasingly complex features.

The discrete convolution is a mathematical operator that applies a filter (or kernel) to the input image so that specific characteristics become more dominant in the output image, generating a feature map. The extracted features are determined by the shape of the filter in each layer; for example, edge detection can be performed with filters that highlight the gradient in a particular direction. The output of each layer can be expressed as:

$$\boldsymbol{a}^{l} = \boldsymbol{\sigma}\left(\boldsymbol{w}^{l} * \boldsymbol{a}^{l-1} + \boldsymbol{b}^{l}\right)$$

where l represents the l-th layer and $*$ means a convolution operation (filter or kernel), $\boldsymbol{w}^{l}$ is the weight matrix, $\boldsymbol{b}^{l}$ are the polarization vector (bias), and $\boldsymbol{\sigma}$ is the nonlinear activation function.

After the convolution, non-linear activation functions are applied to the feature maps, the most common being the ReLU: $f(x) = \max(0, x)$. This function avoids the problem of vanishing gradient when there are many layers. It is because it is linear, and there is no saturation in the positive sense of its domain.

However, when the learning rate is too high, there may be up to 40% of non-active neurons. This problem can be reduced with a suitable dynamic adjustment of the learning rate or some variants of the ReLU function, such as Softplus, Leaky, and Noisy ReLU, Maxout.

The feature maps already generated with this methodology could be used for image classification tasks but would still require computing power and be prone to overfitting. Therefore, grouping operations (max-pooling) that find the maximum value of a sample window and pass this value as a summary of characteristics of that area are used. As a result, the data size is reduced by a factor equal to the size of the sample window on which this operation has been applied. Furthermore, these windows (or patches) are applied while moving, thus reducing the data size to be processed and getting invariant to small changes in position and distortions.

Once the convolutional neural network is defined, the next step is to train it, which minimises a global cost (or error) function. This cost function is usually interpreted as an average of the loss functions for each image in the dataset. Therefore, it is intended to evaluate the error between the output obtained from the network and the desired output. The most used loss functions are the mean square error, cross-entropy, and Softmax.

The training requires a series of steps to be completed: firstly, to calculate the network's outputs using feedforward, then to calculate the error in the output (the difference between what is obtained and what is desired). Then the error is backpropagated, and finally, the network's weights and bias are adjusted, usually by the gradient descent method. It is based on an iterative minimization of errors by updating the network parameters opposite to the cost function gradient (since the gradient indicates the direction of growth and we want to minimize the function). There are three variants of this method, which differ in the amount of data used to calculate the gradient of the objective function (batch, stochastic, mini-batch). The batch uses the complete dataset to update the values (this is slow and requires a lot of memory). The stochastic updates the values with each sample taken randomly from the dataset (this is faster but converges with large fluctuations). The mini-batch updates with each random n-samples of the dataset (this is also fast and has a more stable convergence). Depending on the amount of data, a compromise solution is reached between the accuracy of the parameter update and the time taken to perform an update.

3.1.3 Development of the tool

There is much literature on different applications of deep learning in the classification of images and detection of elements, both generic and specific, such as aerial images, medical images, license plate, and vehicle recognition, gait recognition, classification of microorganisms, recognition of the urban environment, fruit recognition and many more. But no references concerning the detection and classification of HVAC elements in images are known using deep learning. Logically, there are no datasets of images in the realm of HVAC elements, which has motivated the creation of our own focused on these kinds of elements. This dataset aims to be the origin of a system helpful in training neural convolutional networks or other classification techniques in this type of task.

Computer vision techniques are increasingly used to facilitate and improve the documentation of the refurbishment process of buildings. For example, the automatic processing of images makes it possible to detect pathologies and deteriorations in buildings. This part of task 1.2 focuses on using images obtained with terrestrial digital cameras (in the visible spectrum), although images of any type may be used (thermal, multispectral). In practice, different image acquisition systems are usually combined, especially in the study of large and complex sites. In our case, the main objective sought is the application of computer vision techniques based on deep learning for the detection and classification of HVAC elements, regardless of the technology used to obtain them, as already mentioned, the specific use of convolutional neural networks for these tasks.

This task focuses on object detection and classification as a priority for convolutional neural networks. Object detection relates to building models that detect different objects in images. These systems involve not only recognizing and classifying every object in an image but localizing each one by drawing the appropriate bounding box around it. These models are constructed by introducing a set of training data for which objects (and corresponding bounding boxes) are pre-labelled for the algorithm to be learned. Then the model is used by introducing a set of different data than previously used, allowing the model to detect objects based on what it has learned using the training data set. In this case, we consider supervised learning, although interesting applications use unsupervised learning.

The Google Tensorflow platform (figure 25 - https://www.tensorflow.org/) is being used to develop the software due to the wide deployment of this tool and because we have previous experiences in its application.

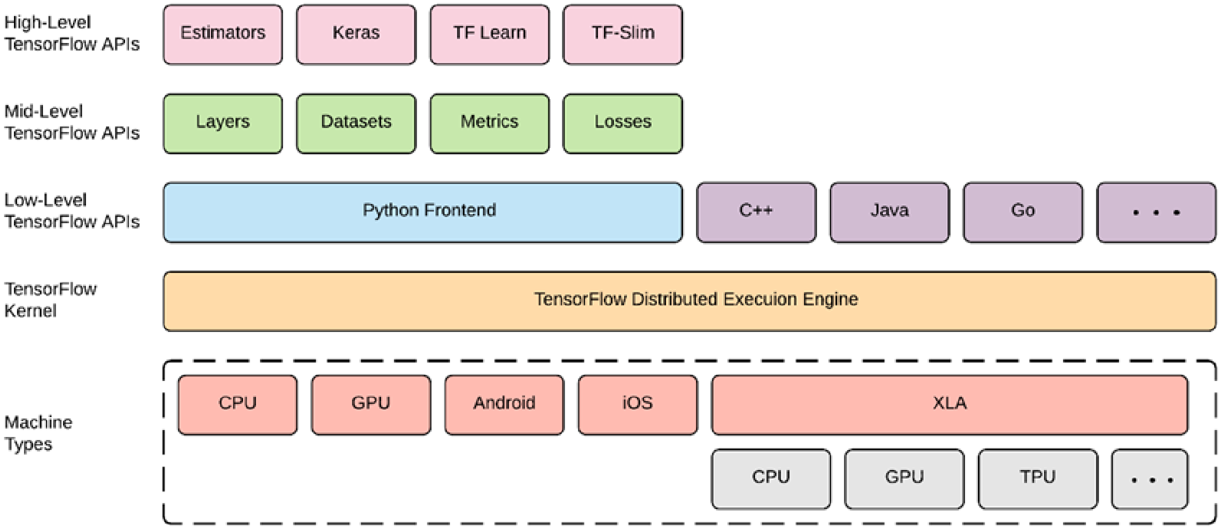


Figure 25 TensorFlow hierarchy

The main programming languages used in the tests are C ++ and C #. The Python language has also been used for some parts of the development. Additionally, the OpenCV library (Intel) has been used. OpenCV (Open Source Computer Vision Library) is an open-source computer vision and machine learning software library. The programming environment used is Visual Studio (versions 2017 and 2019), as it is one of the most common in the development of computer tools.

The procedure followed is as follows:

- Pre-processing of data (image catalogue) and configuration files
- Model construction
- Model training
- Execution or Inference (testing)

There are two main requirements to use these techniques:

- Large amounts of previously labelled images are required to perform training that guarantees good results.
- Deep Learning techniques require significant computing power. High-performance GPUs have a parallel architecture that is efficient for deep learning. Combined with clusters or cloud computing, development teams can reduce the time to train a deep learning network from weeks to hours.

3.1.4 Initial tests carried out

Several pieces of training have been completed using different models: Single Shot Multibox Detector (SSD) with Inception V2, Faster R-CNN with Resnet 101, and Faster R-CNN with Inception Resnet v2. In addition, Google includes some pre-built architectures and weights for a few specific models with the object detection API for Tensorflow.

The best results have been obtained with Faster R-CNN networks (figure 26). Faster R-CNN is composed of two modules. The first module is a deep, fully convolutional network that proposes regions, and the second module is the Fast R-CNN detector that uses the proposed regions. In Faster R-CNN, the image is provided as input to a convolutional network, providing a convolutional feature map. Instead of using a selective search algorithm on the feature map to identify the region proposals, a separate network (Region Proposal Network: RPN) is used to predict the region proposals. The predicted region proposals are then reshaped using an RoI pooling layer to classify the image within the proposed region and predict the offset values for the bounding boxes. Region Proposal Network solves object detection as a regression problem from the objectness perspective. Bounding boxes are predicted by applying learned bounding box deltas to base boxes, namely anchor boxes across different positions in feature maps. The training process directly learns a mapping from raw image intensities to bounding box transformation targets.

In summary, these are the steps followed by a Faster R-CNN algorithm to detect objects in an image:

- Take an input image and pass it to the ConvNet, which returns feature maps for the image.
- Apply Region Proposal Network (RPN) on these feature maps and get object proposals.
- Apply the ROI pooling layer to bring all the proposals to the same size.
- Finally, pass these proposals to a fully connected layer to classify any predicted bounding boxes for the image. (Sharma, 2018)

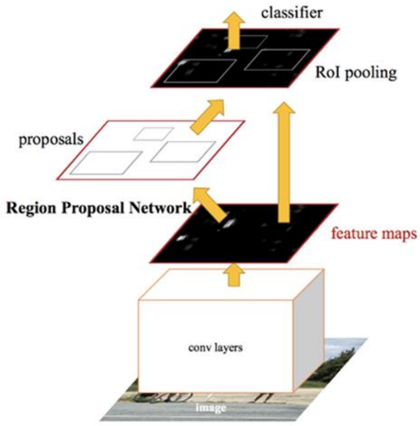


Figure 26 Faster RCNN scheme[6]

The training has been carried out using a dataset created first with the images available from the BIM SPEED Demo Cases and later expanded with images obtained from the Internet. Initially, two types of elements to be detected have been defined: Boiler and Radiator. Of the boiler type, 107 images have been collected, and the radiator type 123 images using the images provided by the partners in BIM SPEED. Although there are few images to get good training, it can be used as a first approximation and evaluate the precision obtained with few training images. The process of data augmentation could be used in this stage. These images have been distributed in 80% of the training phase and 20% for the test phase. The train images are

[6] https://www.analyticsvidhya.com/blog/2018/11/implementation-faster-r-cnn-python-object-detection/

images that we will be using to train the model. We have the classes and the actual bounding boxes for each class in this folder. And the test images are images used to make predictions using the trained model. This set is missing the classes and the bounding boxes for these classes. Additionally, 33 other images (not previously used) have been used to validate the tool.

The following images show some examples of the dataset created for training (figure 27).

Figure 27 Examples of images of the dataset used in training.

The model finally chosen for the precision achieved is the Faster R-CNN ResNet 101. Typically, with neural networks, we seek to minimize the error. As such, the objective function is often referred to as a cost function or a loss function, and the value calculated by the loss function is referred to as simply “loss”. Thirty-two thousand four hundred iterations have been completed to a total loss of 0.01.

The Tensorboard tool has been used to visualize the evolution of the training (figure 28). The following figure shows the evolution of the loss during training.

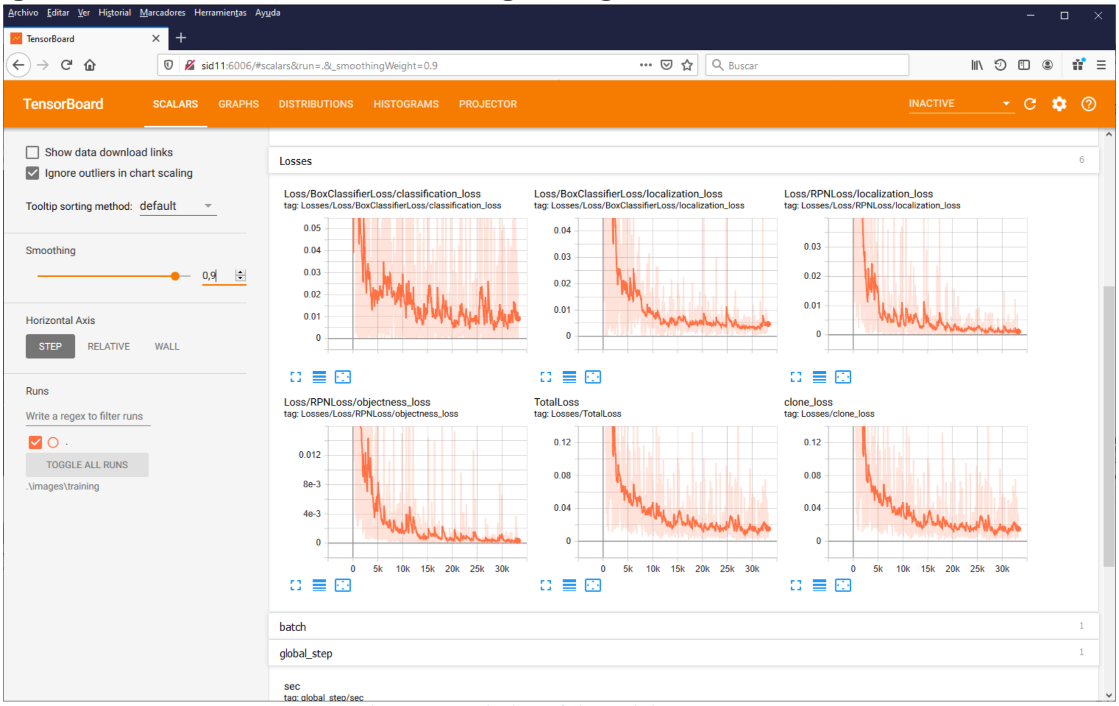


Figure 28 Evolution of the training process.

Also, using the Tensorboard tool, it is possible to view other parameters of the training process carried out (figure 29).

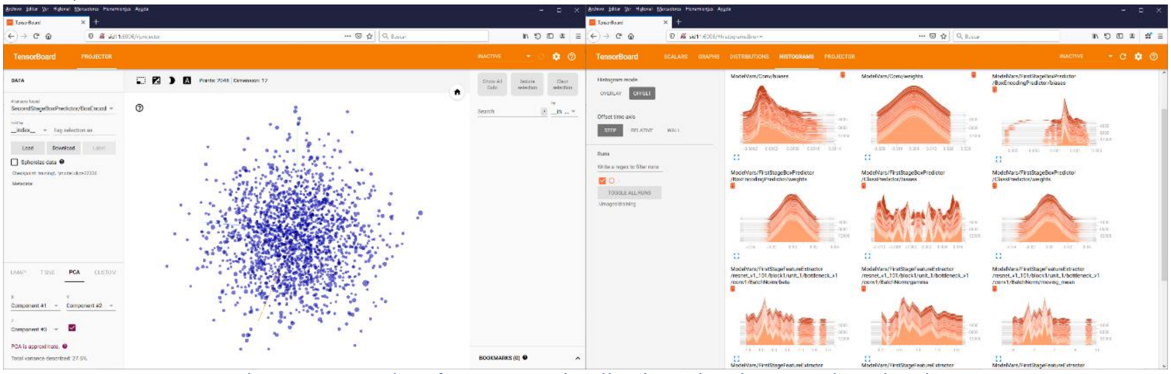


Figure 29 Examples of parameter visualization using the Tensorboard tool.

3.1.5 Software developed

A program that allows inferring predictions has been developed using the Faster R-CNN ResNet 101 model trained with the dataset created for this Project (figure 30).

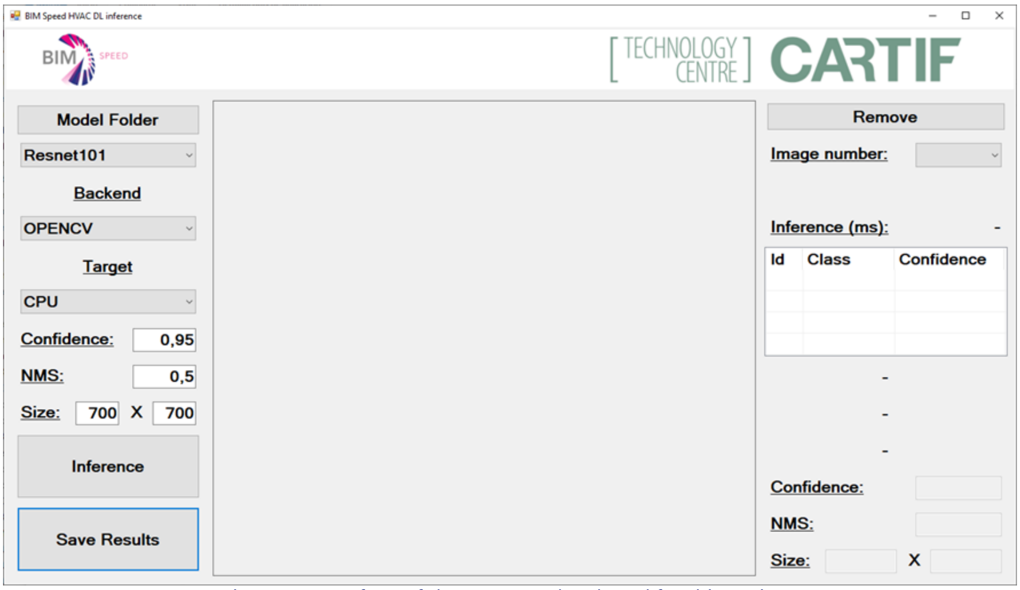


Figure 30 Interface of the program developed for this project.

This program can use the CPU and an Nvidia graphics card with CUDA support to perform the necessary calculations (selecting the corresponding option with the Backend and Target button). Although different neural network models could be loaded using the Model Folder button, the program in principle only uses Faster R-CNN ResNet 101 model. It is allowed to select the minimum acceptable confidence for the prediction, the Non-maximum Suppression (NMS) value, and the image size used in the inference. To infer one or more images, use the Inference button. Multiple images can be selected simultaneously, and the results can be displayed as calculated. Users can also use the arrows to go from one image to another.

A text file is stored in the selected results folder with all the results obtained (image name, detected object, location, size, trust). In addition, all the images with the boxes of the detected object are embedded in the corresponding image (figure 31).

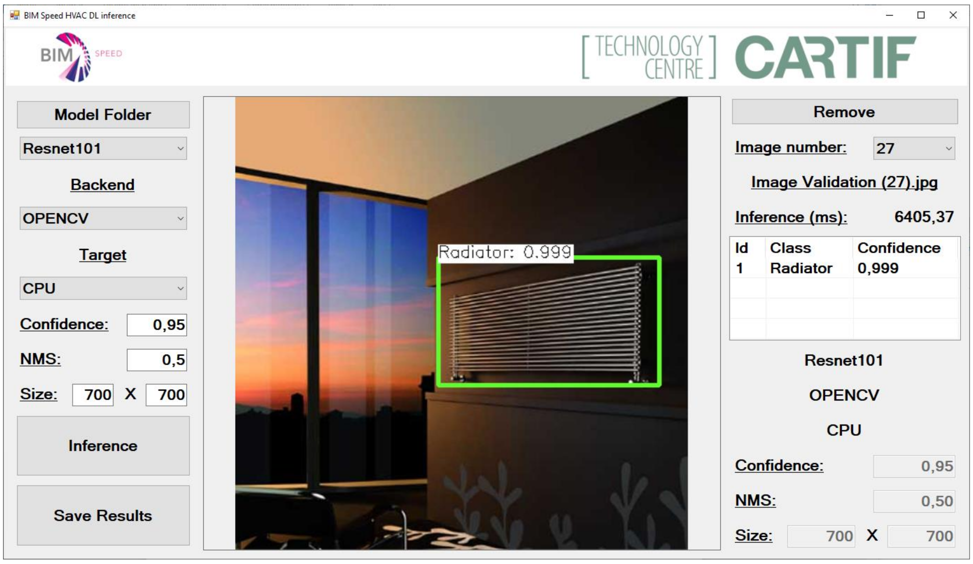


Figure 31 Example of a result obtained (detection of a radiator in this case)

3.1.6 Results

As previously mentioned, 33 validation images have been used with various elements to detect (including several trap images without any element). Inference times (milliseconds) obtained on various platforms are shown below (i5, i7, Xeon, CUDA). (figure 32)

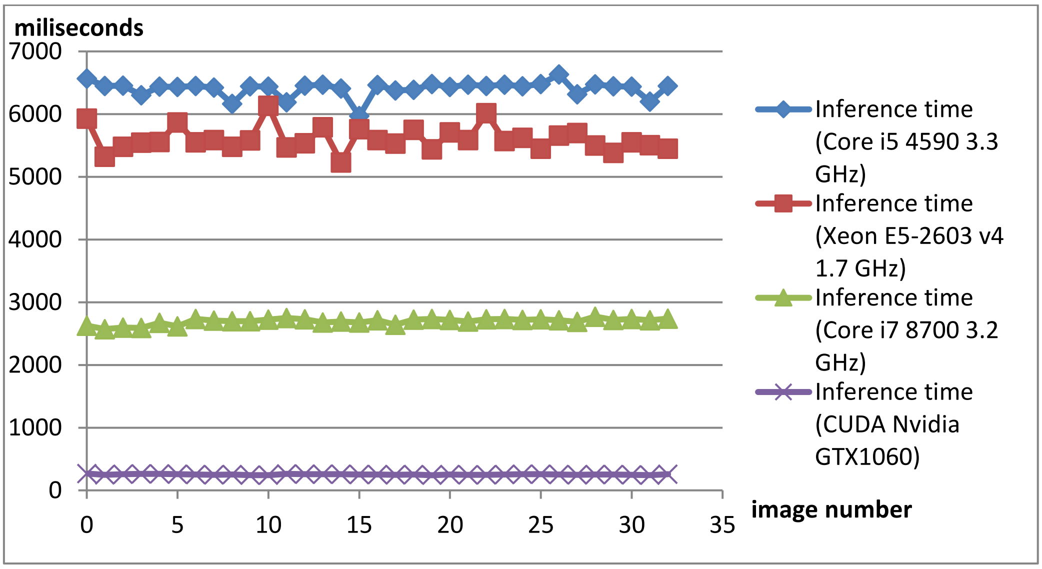


Figure 32 Inference times (in ms) of every validation image.

The image size affects very slightly the time required for inference and also the results obtained (if the image size used in the calculation is reduced, the time required decreases but also the performance obtained). The 33 images in the above graph are of different sizes (from 194x259 pixels to 2121x1414 pixels). It can be seen that the effect of the processor used is more significant than the size of the image to be processed.

Several representative images of the errors that usually appear when using this technology have been selected:

Image Validation (7): Detects the radiator but not the boiler because only a tiny part of it appears. (figure 33)

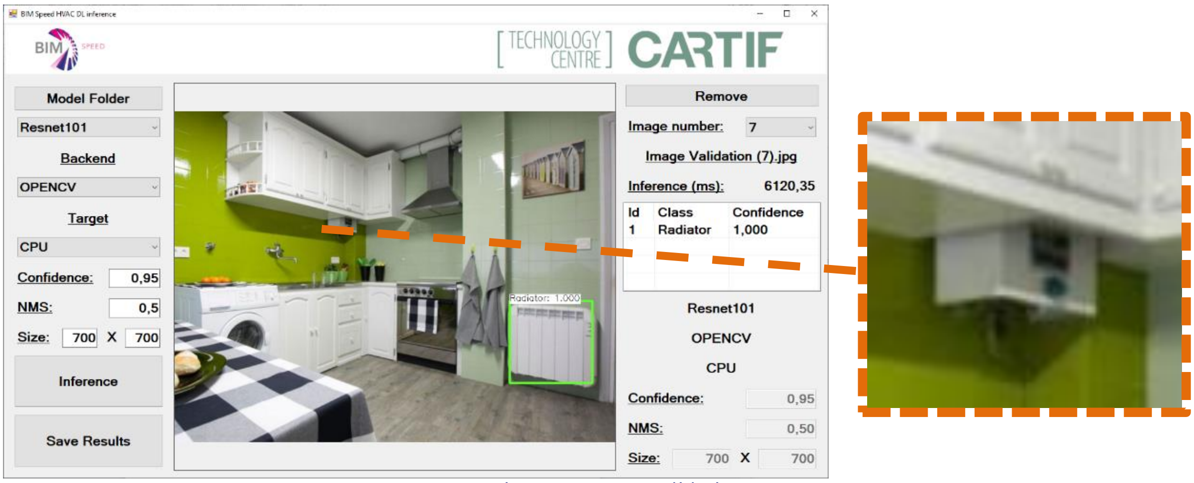


Figure 33 Image validation 7

Image Validation (8): The radiator has not been detected because the network has not been trained with images of radiators in that position. Figure 34 shows some images used in training, with different radiator positions (almost all frontal or slightly tilted). Figure 35 shows validation image 8, where the program could not detect the radiator when it was in a very lateral position.

Figure 34 Examples of images of radiators used in training

Figure 35 Image validation 12

Image Validation (9) and Image Validation (28): It does not detect radiators because no image of those types of radiators has been used in network training.

Image Validation (12): Confuse the bathroom cistern with a boiler; it could be solved by training the cistern class.

Image Validation (17): Detects a plant as a radiator because it has a slight resemblance (vertical lines).

Image Validation (22): It is a low-resolution image (259 x 194 pixels), and therefore it does not detect the radiator well (it does but with shallow confidence) (figure 36).

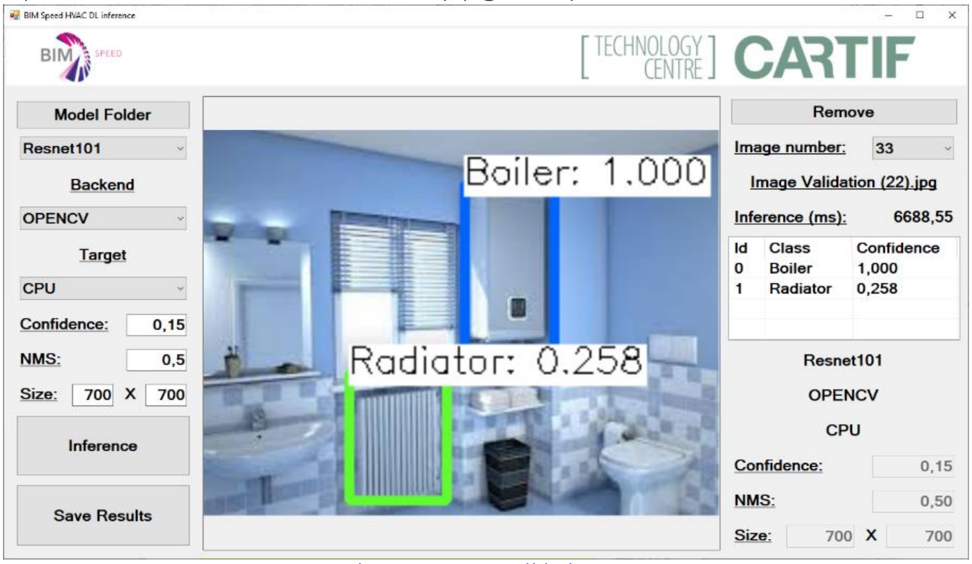


Figure 36 Image validation 22

Image Validation (23): Detects an aerothermal device as a radiator because it has a slight resemblance (horizontal lines).

Image Validation (24): It is a low-resolution image (194 x 259 pixels), and therefore it does not detect the radiator well (it does so but with shallow confidence).

Image Validation (26): Confuses a cabinet with a boiler because it has a certain similarity. There is a hanger at the bottom of the cabinet with a slight resemblance to the boiler tubes (figure 37).

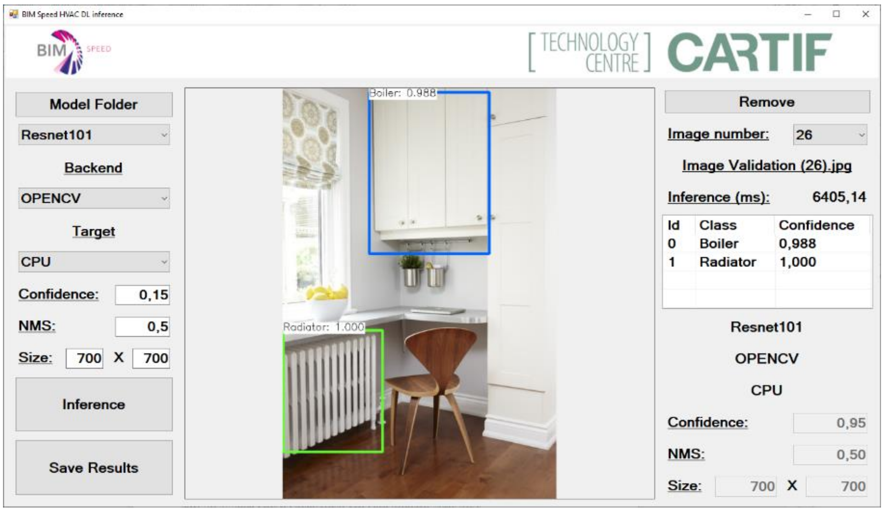


Figure 37 Image validation 26

Image Trap (1): Detects a chair as a radiator because it has a slight resemblance (vertical lines).

It can be concluded that although these first results are not bad, they could significantly improve using a more significant number of training images.

3.1.7 Preliminary conclusions

The accuracy results obtained have been satisfactory. Therefore, we consider that deep learning will help detect and classify HVAC visible elements in images. As mentioned, the accuracy achieved has been good, but, logically, it could be improved by considering certain factors. The simplest option would be to increase training times. Still, it is clear that once convergence is achieved, continuing with network training fails to increase accuracy and may decrease it due to overfitting. Some possible solutions to improve accuracy would be to collect more correctly labelled training images or to improve the architecture used (either optimizing the corresponding hyperparameters of the network used or directly implementing a new network). Regarding the datasets used, it is necessary to remember that using datasets of reduced size will suppose a bottleneck in optimising the implemented system. Therefore, progressively building larger, well-labelled datasets is as crucial as developing new algorithms.

One of the most significant difficulties encountered is having a large enough image base of HVAC elements to achieve an adequately trained model. Logically, the images available from the demo sites are not enough. Therefore, many images on the Internet have been used for the necessary training tasks and thus check the technical feasibility of the tool that is being developed.

The possibility of adding new functionality to the tool so that HVAC elements can be manually classified in images is also considered. In this way, the classified images could be automatically stored in a catalogue used for training. Thus, as new sites are inspected with the BIM-Speed project tools, these same tools will "self-learn", classifying the elements seen in previous inspections.

The preliminary conclusion that has been obtained from the tests carried out is that the tool developed for the training and inference of models capable of detecting and classifying HVAC elements in images is technically viable. It has also been verified that the precision achieved was superior to the rest of those elements for which a more significant number of images were available. In any case, it is considered of interest to increase the number of training images and, in general, continue developing these techniques.

The results shown are part of a work in progress, and soon several additional steps are being considered, such as the possibility of identifying the manufacturer and exact model of each component detected.

The final objective of this part of the task is to obtain a valuable tool for professionals to facilitate the automatic detection and classification of HVAC elements in images and help in the refurbishment process of buildings.

3.2 Machine learning in 3D model reconstruction

In chapter 3.1, we have explored deep learning in reconstructing HVAC components based on photographs, which are a 2D representation of objects. As described in chapter 3, the most novel technique to collect data is using cameras to create point clouds. Reduced to some simple sentence, a “point cloud” is a mathematical set, a gathering of data points in space; every point represented by it is XYZ coordinates. Additional information can be added to the points, such as RGB values or surface normal.

AI and point clouds are the novelty in each area of expertise, but little has been done so far to put them together and use AI to collect data from point clouds. Machine learning is an AI technique based on an algorithm that reads data. The algorithm needs to be trained, and the final output will be a machine learning model.

In the following subchapter, this guide will go through some of the challenges of creating a machine learning model for point clouds, methods currently used to create such a model, and some software on the market that use this technique and offer good results.

3.2.1 Machine learning on point clouds - challenges

Point clouds are not easy to manoeuvre. They can create lots of problems in 3D modelling if the scan is not done correctly, and it is easy to understand that they can pose challenges also when one must use them to extract data. Main challenged of applying deep learning on point clouds:

- Irregularity – the points are distributed equally in different parts of the object. For example, it could be that one region has a lot of points and the other only has scattered points.
- Unstructured – the points do not have the exact distance between the neighbouring points, do not follow a grid, and look independently.
- Unorderly – points are stored as a list in the file. The points are in a set that should not change the scene that it represents.

  These challenges pose difficulties when using convolutional neural networks because they work (data should be ordered, regular and structured). Recent developments in this field offer the possibility to work with raw data. The methods used to develop a deep learning algorithm for point clouds are presented in 4.2.2.

3.2.2 Machine learning on point clouds – methods

There are two categories of methods that can be used to develop a deep learning algorithm that can be used in figure 38. This guide will briefly explain how some of the methods function.

PointNet and PointNet++

PointNet was developed in 2017, and this architecture allows the use of point clouds regardless of the challenges mentioned in 3.2.1. The machine learning algorithm performs two tasks: the objects' classification and the objects' segmentation. Classification is determining what type of object it is and labelling it. Segmentation is needed if the point cloud is complex and split into components. PointNet identifies the 3D object and makes a semantic segmentation.

PointNet has two core building blocks: transformation network and symmetric function.

However, being the pioneer in this field of work, PointNet had one major problem: it could not capture local structures. The development of PointNet to solve its issue lead to the proposal of PointNet++. The added feature was a class pyramid aggregation scheme.

PointNet++ has three layers: sampling, grouping, and PointNet. Although PointNet++ can encipher the local feature of point clouds, it fails to use the spatial distribution of the input point cloud.

ConvNets-Based Deep Learning

ConvNets are short for deep convolutional neural networks and are a feed-forward neural network. Seven models use this approach.

PointNet and PointNet ++ inspire dynamic Graph CNN. It is used for classifying and dividing points, and the main difference from the previous method is that it uses an EdgeConv layer. This layer solves the local feature processing problems with PointNet.

PointCNN uses hierarchical convolution and x-Conv operators to capture local information. The benefit of x-Conv is that it considers the shapes of points without focusing on the input order of the data. It has been used in 3D object classification and semantic segmentation. (Weiping Liu, 2019)

RGCNN uses point clouds directly for object classification and semantic segmentation. The features of the point are taken as a node, and, using spectral graph theory, it overcomes the irregularity of the point clouds.

RNN-Based Deep Learning

RNN stands for recurrent neural networks and, while similar to CNN, adds the notion of memory. To explain it, the output of layer 2 is input for layer one, thus creating a base for sequential analysis of data. The traditional NN is not able to do this operation. Another difference is that RNN has no limits in terms of the input length.

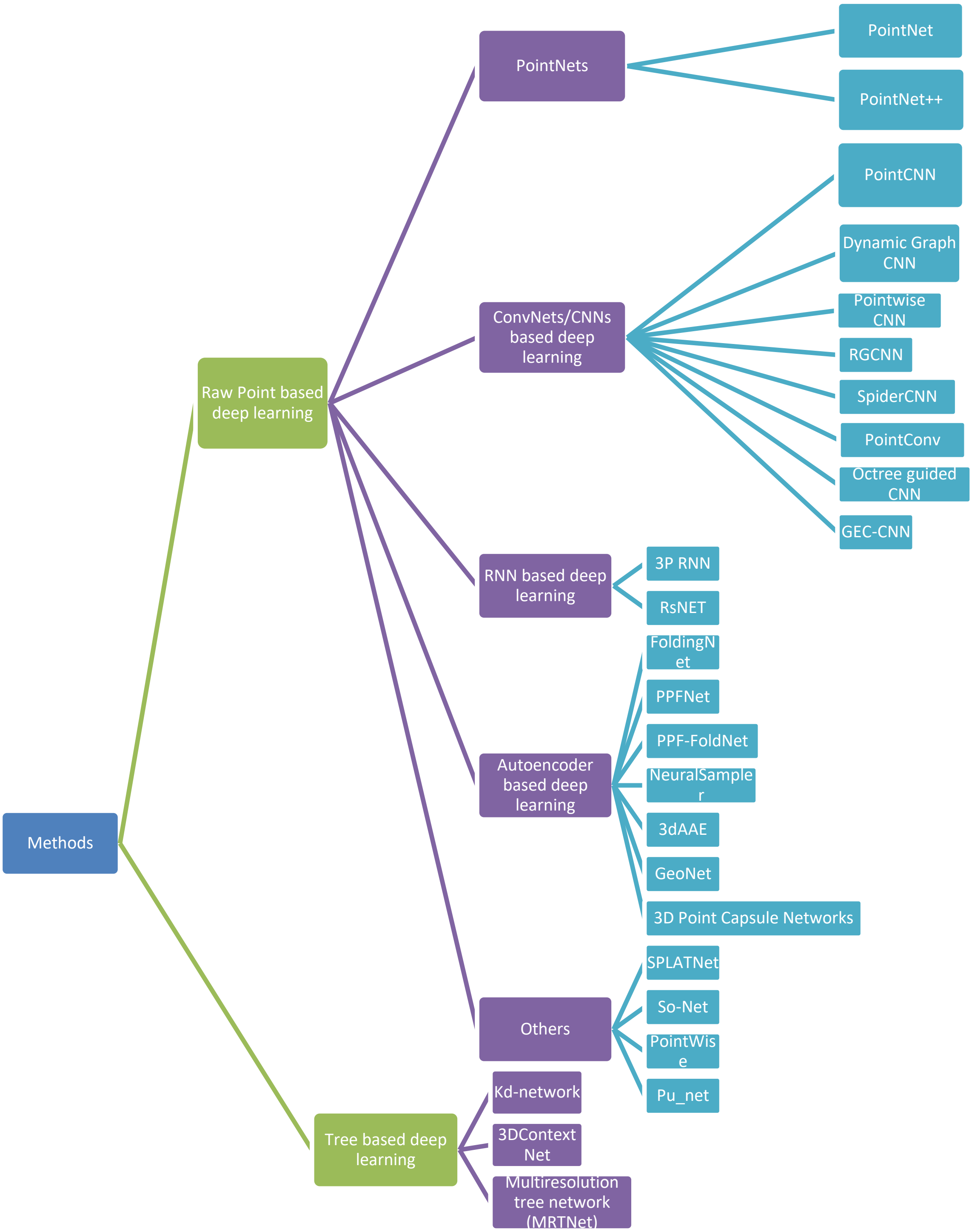


Figure 38 Solution for machine learning algorithms

Autoencoder – Based Deep Learning

Autoencoder methods represent a neural network that encodes its input and decodes it to create the output. It makes a similar representation of the input but filters out unwanted characteristics. It is used primarily on generative models.

Tree-Based Deep Learning

Kd-tree based models take point clouds as regular presentations before feeding information into deep learning models. These methods gradually learn the representation vector of the point cloud along the tree. (Weiping Liu, 2019).

The Kd-network works with an unstructured point cloud designed for 3D model recognition tasks. The architecture performs the multiplication transformation. It shares the transformation parameters according to the subdivision of the point cloud in which the Kd-tree applies. Unlike the main convolution architecture that typically requires rasterization on a uniform two- or three-dimensional grid, the Kd-network does not rely on such a mesh in any way, thus avoiding poor scaling behaviour. (Weiping Liu, 2019)

3DContextNet was proposed to capture the local and global features of the point clouds using a Kd-tree structure. 3DContextNet employs the Kd-tree to represent the 3D point clouds without changing the spatial relationships and can be used for 3D object classification and semantic segmentation. (Weiping Liu, 2019)

3.2.3 Machine learning on point clouds – software

Due to its constant growth in the last 2-3 years, reconstructing a 3D model based on a point cloud can be done using software available on the market. One of the most used software is EdgeWise, produced by ClearEdge 3D. According to the developer, the software can automatically reconstruct structural elements, pipes (and pipe accessories) and ducts, walls, and conduit. Furthermore, according to the developer, it improves the SCAN to BIM workflow by up to 75%. In addition, the software integrates well in Autodesk products such as REVIT and Plant3D.

Another software that can be used is CloudWorx from Leica. It allows as-built piping models and 2D/3D ground surface modelling. It can be integrated with REVIT, Navisworks, Bentley, Solidworks, BricsCAD, etc.

As seen, the first software, EdgeWise, was developed by a software company. The following software is also developed by a laser scanner manufacturer, mainly FARO, with an As-built product. As-built allows the creation of 3D models, clash detection, and deviation check directly in REVIT.

4. Completeness of HVAC BIM 3D Model

Recreating a 3D Model can be done manually, by modelling based on 2D plans or point cloud, or automatically when software uses deep learning algorithms to reconstruct the 3D model. Adopting one or another approach depends on multiple factors. However, no matter how one does this, there is still a risk of misplaying some elements or realising that some data is still missing, especially when constructing an HVAC 3D model. Another common mistake when modelling is sometimes elements are not modelled in the correct space; for example, a radiator is placed in an apartment storage area by mistake.

Checking these mistakes manually is tedious and leads to extra hours on the model. If elements are modelled in wrong enclosures, this can be checked during a coordination process, but that will only add to the number of items to solve during that stage. As per the goals of the BIM Speed project, the proposal automatically checks for the most common mistakes that happen while modelling HVAC components in renovation projects.

4.1 Using visual programming for fast scripting

The goal of these scripts is to perform the desired action but, in the meantime, to be highly customizable since the scripts will refer to objects that may be part of a company library.

The software used to create the scripts is Autodesk Dynamo (referred to as Dynamo from this point forward), an embedded add-in REVIT. Dynamo is a visual programming software; the users can code using code blocks called nodes. The lines that connect the nodes are named wires. For deep learning of the software, check the DynamoPrimer website. The nodes are based on Python code, but what is essential to know is what the node does and not its code. Nodes are divided into libraries, and Dynamo comes with its libraries.

Since nodes rely on Python code, custom nodes and custom libraries can be created.

The usage of Dynamo in BIM projects has increased since it allows automated repetitive processes much faster than with coding. The scripts can be scalable until a certain point, depending on the process inside the companies. The number of custom free libraries on the market is quite significant and thus allows for the fast creation of scripts in less time than before.

4.2 Categorizing MEP elements in REVIT

To better understand the scripts, a few items must be mentioned regarding how the items are categorized in REVIT. As shown in deliverable 2.4, “Guidelines for as-built BIM modelling of existing buildings”, 3D objects in REVIT are called families. These families are grouped under specific REVIT categories to be better identified and distinguished. Figure 39 shows relevant REVIT categories of families for reconstructing HVAC BIM models. The scripts developed in this deliverable are related to them, so one must understand in which category the object will fall and how it will be checked.

Each family has its characteristics in terms of modelling. For example, one will expect valves to be placed on pipes, so any valves found in the middle of the room are incorrect. On the other hand, in the case of water heating systems, BIM modellers will place a radiator in the correct spaces and have pipes going to them. Also, some items have to be accompanied by valves. For example, valves must be modelled before and after a radiator (in strict accordance with the BIM SPEED Use case for which the BIM model is made). The two scripts are created to check these items based on the REVIT categories.

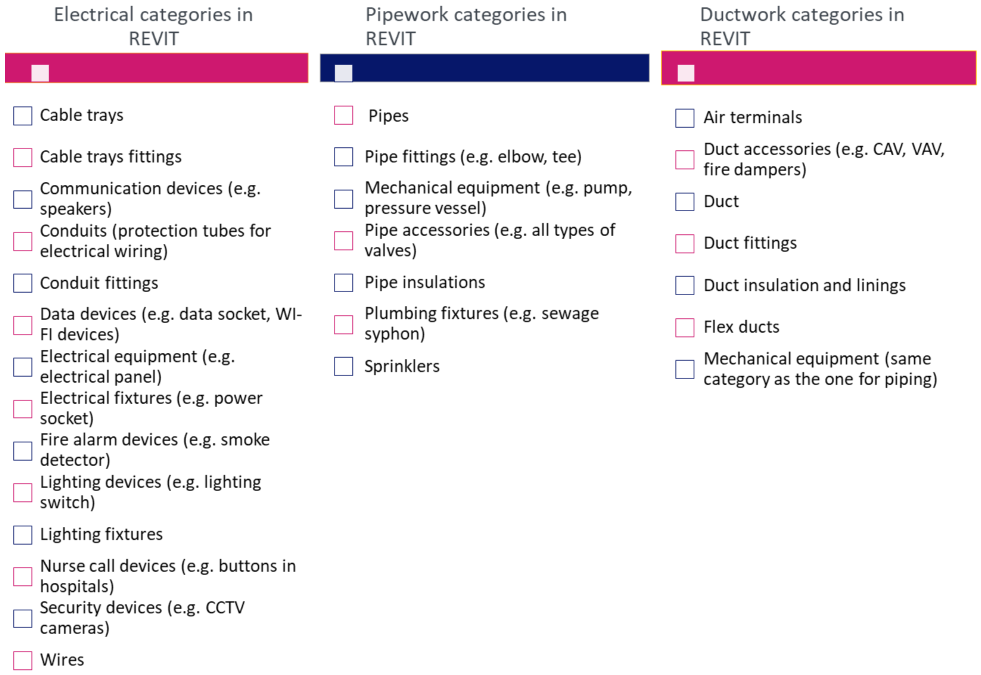


Figure 39 REVIT categorization of families

4.3 Detecting correct placement of objects inside spaces

4.3.1 Scope and application

As mentioned, one of the most common mistakes made by BIM modellers is to place 3D objects in incorrect spaces/enclosures. These mistakes occur when modelling based on a point cloud or just by accident. The issues will sometimes appear in a coordination meeting, but it is strongly recommended to be avoided since they are considered wrong modelling.

The first scrips proposed performs verification of whether an object is modelled or not in an enclosure. In REVIT, enclosures in HVAC models are called spaces, and they must be created. So, for example, the BIM modeller can check to see which spaces have radiators (radiator, in REVIT, is categorized as Mechanical Equipment) placed.

The script allows a second check to be made, this being more of a value requirement. This second check allows the comparison between a technical parameter defined for space (e.g. heat output) is fulfilled by the REVIT element (e.g. radiator). It requires that both data entries be defined and added to both parameters.

Since Dynamo follows the pattern of REVIT versions, one cannot use a script with an older version of the software. To use these scripts, one should have installed Dynamo 2.0 or higher. The scripts work for REVIT 2020 and 2019. Below these versions, no tests have been made.

A few custom libraries have to be installed, which is free and easy to install:

- Archilab v.2020.23.7
- Rhythm v.2020.2.13

The risk of not having these libraries (or packages) is that the script will not run or run incomplete.

One can run the script via Dynamo or Dynamo Player interface for easy work with Dynamo scripts.

4.3.2 Using the script

The first step is to define how the space name filtering must be done. If all spaces must be checked, the default value is"0". If only some spaces have to be checked for some reason, another value from the list will be used. Selecting a different value can be done using either the slider or entering a number in the box. If multiple filtering categories are required, one can add more numbers divided by "," as shown in figure 40.

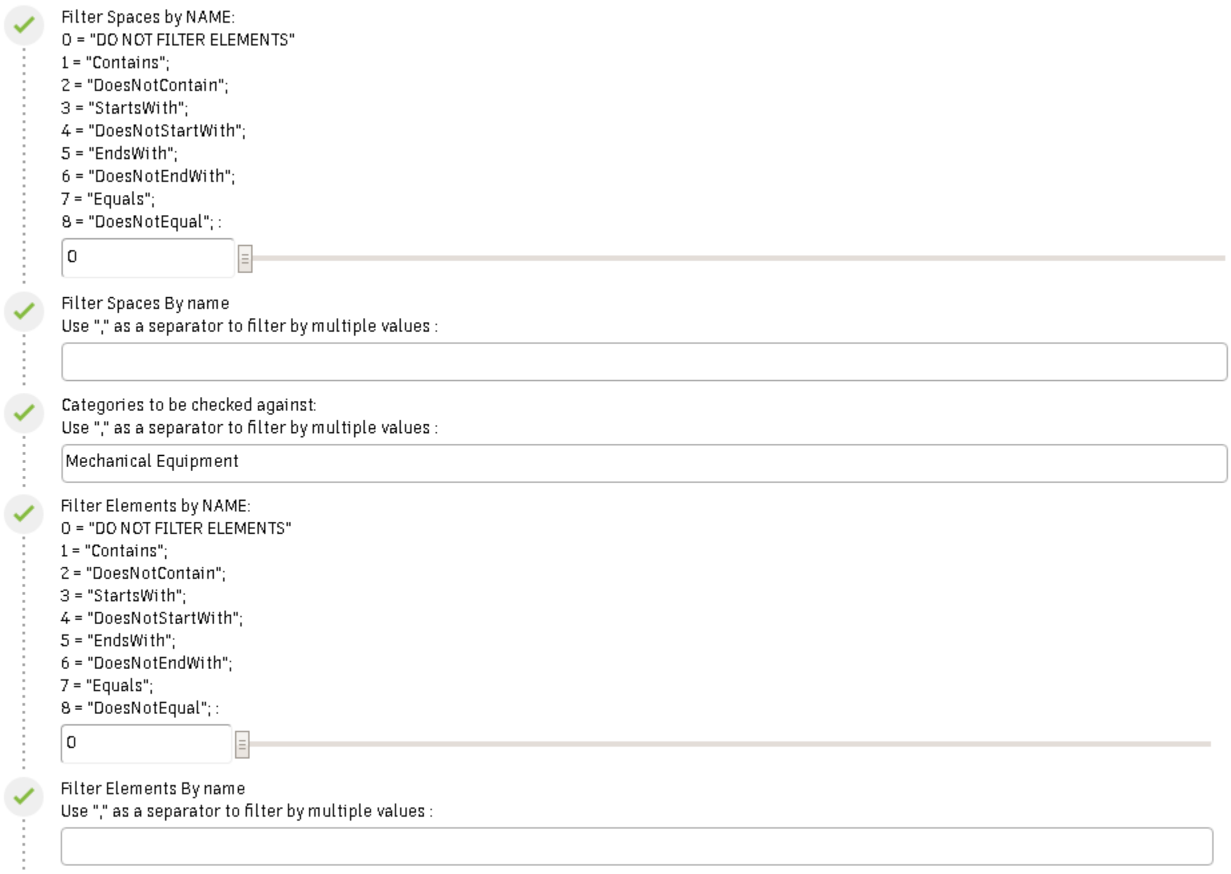


Figure 40 Defining filtering categories

The second step is to define the REVIT family categories to check if they are present in that space. For example, one may choose to check Mechanical Equipment (e.g. radiator) and check lighting fixtures. The same rules as in step 1 are applied for defining the filters.

The third step is to define whether the value comparison takes place or not. One must select the space parameter and the object parameter to compare. (figure 41)

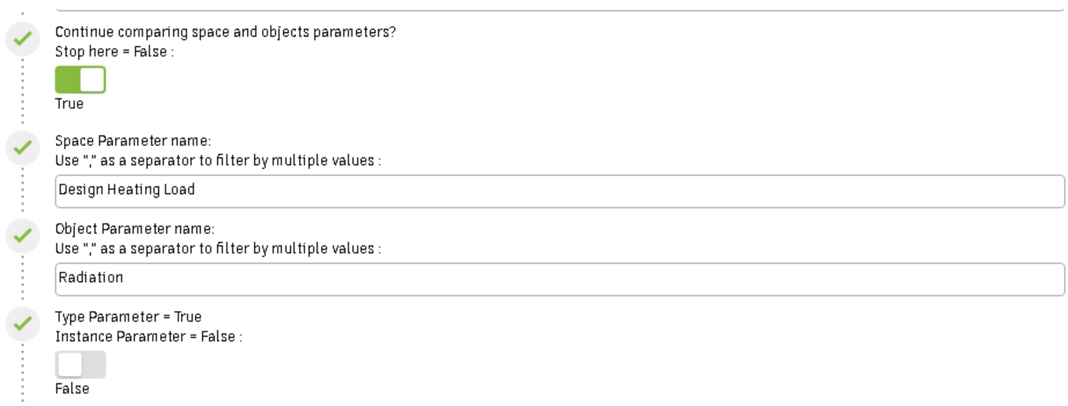


Figure 41 Defining parameters to be checked

4.3.3 Result

The results from the first input part are displayed using Dynamo „watch" nodes. The lists are structured as follows:

- Space Name and Number
- Space ID (a unique number that REVIT gives to all of the items created in the model, either 2D or 3D).
- Elements inside the space & ID

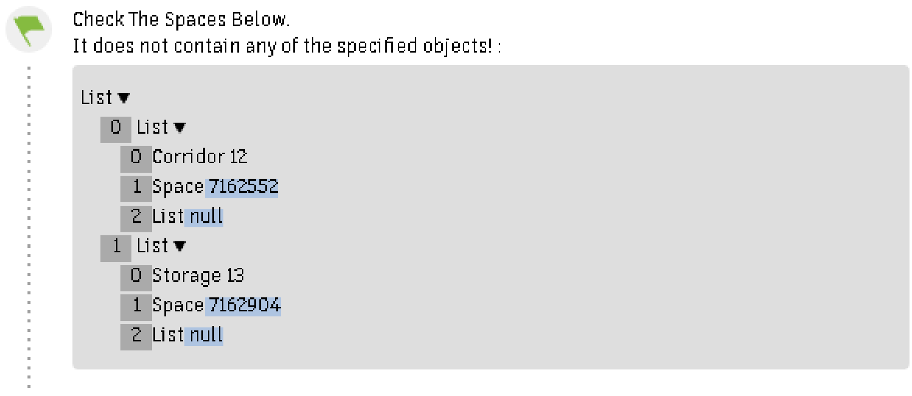
From here, there are three situations:

- The first watch node lists the spaces that don`t have specified elements inside
- The second one shows the spaces and the found elements in it
- The third one shows the elements that are not in an actual space.

The results from the second input part are displayed using „watch" nodes. The lists are structured as follows:

- Space Name and Number
- Space ID
- Elements inside the space & ID
- Space Parameter: VALUE
- Object Parameter: VALUE

Two watch nodes displaying the unsuccessfully and the succeeded checking are displayed, as illustrated in Figures 42 and 43.



Spaces containg objects :

```
List
  0 List
    0 living room 8
    1 Space 7157111
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179575
      1 HC_Radiator_Panel_MEPcontent_Generic 7179698
  1 List
    0 Bathroom 9
    1 Space 7161764
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179917
  2 List
    0 Kitchen 10
    1 Space 7161767
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7180539
  3 List
    0 Bedroom 11
    1 Space 7162549
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179992
      1 HC_Radiator_Panel_MEPcontent_Generic 7180143
  4 List
    0 Bedroom 14
    1 Space 7164816
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179767
      1 HC_Radiator_Panel_MEPcontent_Generic 7179826
```

Elements not inside Space :

```
List null
```

Figure 42 Results for object script

Check The Spaces and objects Below.
The verification process failed! :

```
List
  0 List
    0 living room 8
    1 Space 7157111
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179575
      1 HC_Radiator_Panel_MEPcontent_Generic 7179698
    3 Design Heating Load: 1500.000000
    4 Radiation: 1400.000000
  1 List
    0 Bedroom 11
    1 Space 7162549
    2 List
      0 HC_Radiator_Panel_MEPcontent_Generic 7179992
      1 HC_Radiator_Panel_MEPcontent_Generic 7180143
    3 Design Heating Load: 1500.000000
    4 Radiation: 1400.000000
```

Figure 43 Results parameter check

4.4 Detecting pipe valves and other fittings

4.4.1 Scope and application

Another common issue resulting in incorrect modelling is the missing elements on the piping or ductwork branches. It mainly refers to missing valves or other small items where data is not gathered or cannot be identified correctly in a point cloud. The second script was developed to detect such issues. The script checks to see if certain elements have the necessary valves near where they are placed on the installation branch. For example, the pipes connected to a gas-fired boiler must be equipped with shut-off valves. Running the script will detect if those valves were modelled or not. This principle applies to all types of valves.

The script can be used with Dynamo 2.0 (and above) and was developed using REVIT 2020 and 2019.

A few custom libraries have to be installed, which is free and easy to install:

- MEPover v.2019.12.1
- Spring nodes v.203.2.0
- Rhythm v.2020.2.13

One can run the script via Dynamo or Dynamo Player interface for easy work with Dynamo scripts.

4.4.2 Using the script

The first step requires the user to select the valves or other pipe accessories present in the branch connections. (Figure 44).

The second step instructs the user to select a REVIT category to be checked (Figure 45). For example, valves are associated with the category of Mechanical Equipment (where boilers, radiators and other equipment are included) in REVIT.

Figure 44 Selecting valve types

The script will get all the instances of the input category. If multiple categories are selected, one must make sure that the names are split with a comma only. Space or any other character will generate an error.

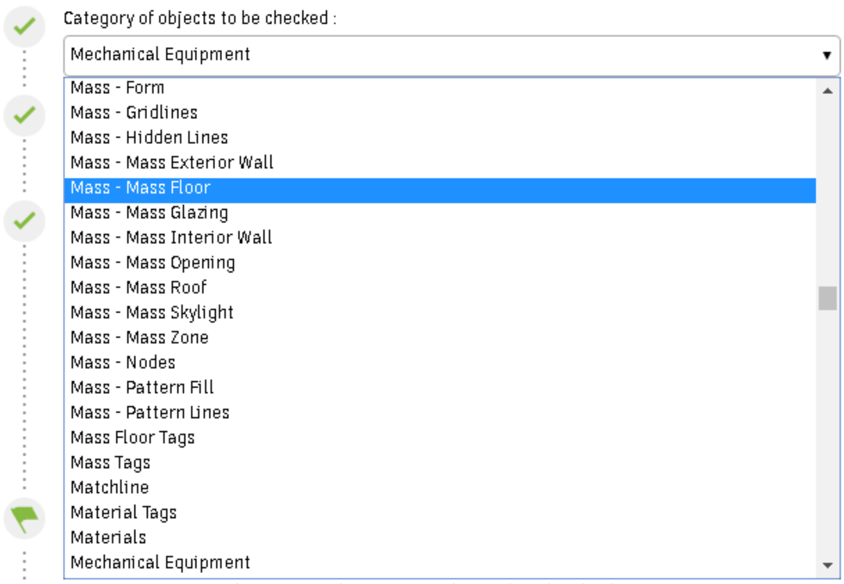


Figure 45 Select categories to be checked

The user can filter the equipment by name (Figure 46). Please select the desired way of filtering by dragging the number slider. Please make sure that the names are split with a comma only if multiple values are needed. Space or any other character will generate an error.

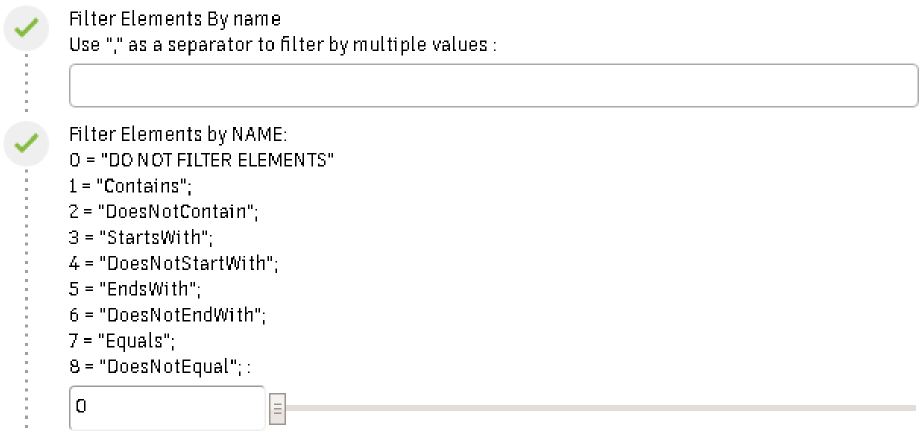


Figure 46 Filtering categories

4.4.3 Results

The results are displayed using „watch" nodes, listing the equipment and ID. They are structured as follows (figure 47).

For the example used to test the script, the user required a check of the shut-off valves if they were present in a heating system for an apartment. Shut off valves are placed before and after each radiator and the boiler. After running the script, the results showed that the boiler and two radiators did not have any shut-off valves. The elements' ID is shown so users can search the elements quickly.

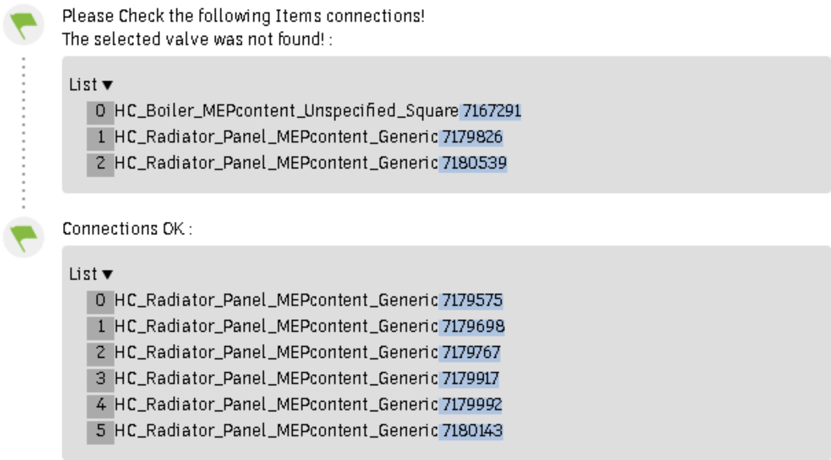


Figure 47 Results for Pipe fitting script

5. Conclusions

Collecting data from existing residential buildings represents a tedious task, considering the number of sources one must look into, incomplete or no information about the building, site visits and numerous methods that can be used to obtain such data. Deliverable 1.2 focused on showing the stakeholders the methods to acquire information from building installations, understand the data collected and how the data can be used further in developing a BIM model. The report considers the types of data that can be collected and how to properly collect the data using the methods available on the market, both hardware and software. The report highlights where the data is relevant and for which BIM SPEED Use Case (detailed in BIM SPEED Methodology Kit v1 developed in Deliverable 1.1) can be used.

As part of the deliverable, research was conducted to establish whether images can automatically identify visible components in building services using image recognition techniques. As mentioned in chapter 3.1.7, the results obtained have been satisfactory and deep learning can be used to detect and classify HVAC visible components. Furthermore, other lines of research can be oriented towards identifying components from point clouds. In this sense, state-of-the-art techniques were made to support further developments in this field.

Additionally, to support BIM modellers in the process of creating a BIM model of an existing building, for this deliverable, two scrips were created to automatically check whether the BIM model is complete and objects are placed correctly. The scripts were created using visual programming software addressed to REVIT users.

6. Result exploitation

The automatic detection and classification of HVAC components in the images tool shown in this deliverable results from developments carried out in task 1.2-Existing HVAC systems surveying and diagnostics in the BIM-SPEED project and is currently in a prototype phase. The validation status of the tool is TRL5 (a feasibility study has been carried out, and images of only two categories have been compiled (radiators and boilers)). The database of images created to validate the tool will be provided upon request to the consortium, Project Officer (PO) and Project Technical Advisor. The commercial exploitation of the software is not explored at the time of writing the report due the actual developments are focused on a research and development phase and will be considered at the end of the BIM-SPEED project.

The scripts presented in chapter 4 are available after a commercial exploration is made. Until the end of the BIM-SPEED project, a decision in this direction will be made.

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APPENDIX 1 – LASER SCANNERS COMPARISON

	FARO Focus M70	FARO Focus S70	FARO Focus S150
			
Price (EUR) inc. VAT	32.242,84	44.438,80	56.162,98
Use	Indoor / Outdoor	Indoor / Outdoor	Outdoor
Size	230 x 183 x 103 mm	230 x 183 x 103 mm	230 x 183 x 103 mm
Weight incl. battery	4.2 kg	4.2 kg	4.2 kg
Range (90% reflectivity (white))	0.6 – 70 m	0.6 – 70 m	0.6 – 150 m
Range (10% reflectivity (dark gray))	0.6 – 70 m	0.6 – 70 m	0.6 – 150 m
Range (2% reflectivity (black))	0.6 – 50 m	0.6 – 50 m	0.6 – 50 m
Range noise (90% reflectivity (white))	0.40 – 0.70 mm	0.15 – 0.30 mm	0.15 – 0.30 mm
Range noise (10% reflectivity (dark gray))	0.40 – 0.80 mm	0.20 – 0.50 mm	0.20 – 0.50 mm
Range noise (2% reflectivity (black))	0.80 – 2.10 mm	0.65 – 1.30 mm	0.65 – 1.30 mm
Ranging Error	± 3 mm	± 1 mm	± 1 mm
Measurement Speed (points / second)	122,000 / 244,000 / 488,000	122,000 / 244,000 / 488,000 / 976,000	122,000 / 244,000 / 488,000 / 976,000
Unambiguity interval	614m for 122 to 488 kpts/s	614m for 122 to 488 kpts/s 307m for 976 kpts/s	614m for 122 to 488 kpts/s 307m for 976 kpts/s
3D position accuracy	no specified	10 m : 2 mm / 25 m : 3.5 mm	10 m : 2 mm / 25 m : 3.5 mm
Camera	A built-in 8 mega-pixel, HDR-camera	A built-in 8 mega-pixel, HDR-camera	A built-in 8 mega-pixel, HDR-camera
Resolution	Up to 165 Megapixels Color	Up to 165 Megapixels Color	Up to 165 Megapixels Color
Field of View (Vertical / Horizontal)	360˚/360˚	360˚/360˚	360˚/360˚
Data storage	SD, SDHC™, SDXC™; 32GB card	SD, SDHC™, SDXC™; 32GB card	SD, SDHC™, SDXC™; 32GB card
Scanner control	Via touchscreen display and WLAN connection Access by mobile devices with HTML5	Via touchscreen display and WLAN connection Access by mobile devices with HTML5	Via touchscreen display and WLAN connection Access by mobile devices with HTML5
WLAN	802.11n (150 Mbit / s), as an access point or	802.11n (150 Mbit / s), as an access point or client in existing networks	802.11n (150 Mbit / s), as an access point or

	client in existing networks		client in existing networks
GNSS	Integrated GPS & GLONASS	Integrated GPS & GLONASS	Integrated GPS & GLONASS
On-site compensation	N/A	Creates a current quality report and provides the option to improve the devices compensation automatically	Creates a current quality report and provides the option to improve the devices compensation automatically
Real-time registration	N/A	Connects to SCENE via WLAN. Processing of scan data, registration, and creation of an overview map in SCENE in real-time	Connects to SCENE via WLAN. Processing of scan data, registration, and creation of an overview map in SCENE in realtime
Power supply voltage	19V (external supply), 14.4V (internal battery)	19V (external supply), 14.4V (internal battery)	19V (external supply), 14.4V (internal battery)
Power consumption	15W idle, 25W scanning, 80W charging	15W idle, 25W scanning, 80W charging	15W idle, 25W scanning, 80W charging
Battery service life	4.5 hours	4.5 hours	4.5 hours
Operating temperature	5 – 40°C	5 – 40°C	5 – 40°C
Extended operating temperature	- 20 – 55°C	- 20 – 55°C	- 20 – 55°C
Storage temperature	- 10 – 60°C	- 10 – 60°C	- 10 – 60°C
(IP) rating class	IP54	IP54	IP54
Humidity Resistance	Non-condensing	Non-condensing	Non-condensing
Maintenance / calibration	Annual	Annual	Annual