D3.1 SOTA Reports and DT models (I)

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DEFINITIONS

A Green Building (GB) (new or retrofit) is a building that, in its design, construction and operation, reduces or eliminates negative impacts, and can create positive impacts, on the climate, social, and natural environment. GBs preserve precious natural resources and improve quality of life[1]. Specifically, this means that GBs should be very energy efficient, use extensively the potential of locally available renewable

[1] https://www.worldgbc.org/what-green-building

energy, use sustainable materials, and aim for a low environmental impact over the entire life cycle. GBs offer their users and residents a healthy climate and a high quality of stay, they are resilient e.g., to environmental change and contribute to social inclusion.

Green Neighbourhoods aligned with the European Green Deal[2], is a set of buildings over a delimited area, at a scale that is smaller than a district, with potential synergies, in particular in the area of energy. A green neighbourhood is a neighbourhood that allows for environmentally friendly, sustainable patterns and behaviours to flourish e.g., bioclimatic architecture, renewable energy, soft and zero-emission mobility etc. Green neighbourhoods are the building blocks of Positive Energy Districts (PEDs)[3] by implementing key elements of PED energy systems. For example, the exchange of energy between buildings increases the share of local self-supply with climate-neutral energy and system efficiency. They also provide the technical conditions to enable Citizen Energy Communities[4] and Renewable Energy Communities[5] to be implemented.

Green Buildings and Neighbourhoods (GBN) in PROBONO are GBs integrated at delimited area or district level with green energy and green mobility management and appropriate infrastructure supported by policies, investments and stakeholders' engagement and behaviours that ensures just transition that maximise the economic and social cobenefits considering a district profile (population size, socio-economic structure, and geographical and climate characteristics). Delivered in the right way, GBN infrastructure is a key enabler of inclusive growth, can improve the accessibility of housing and amenities, reduce poverty and inequality, widen access to jobs and education, make communities more resilient to climate change, and promote public health and wellbeing.

DGNB certification serves as a quality stamp ensuring the state of the building for buyers. The Green Building Council Denmark (2010) established the German certification DGNB meaning 'German Society for Sustainable Buildings'. The Danish version of DGNB was created to obtain a common definition of what sustainability is towards and making it measurable. A consortium of experts was established from all parts of the construction sector. DGNB had to be reshaped for the Danish standards, practice, traditions, and laws but is now available to certify any construction project. They chose DGNB as an innovation-forward and sustainable future guarantee. DGNB diversifies itself by focusing on sustainability and not just the environment. DGNB creates a standardised framework for the construction operations conditions and creates a common language which facilitates communication between professions and helps organize and prioritize the efforts in long and complicated development phases.

Life cycle assessment (LCA)[6] is a tool used for the systematic quantitative assessment of each material used, energy flows and environmental impacts of products or processes. LCA assesses various aspects associated with development of a product and its potential impact throughout a product's life (i.e., cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal. In PROBONO, LCA represents the statement of a building's total energy, resource consumption and environmental impact in the manufacture, transport, and replacement of materials and for its operation over its expected life. Social life cycle assessment (S-LCA)[7] is a method to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle. Life-cycle costing (LCC)[8] considers all the costs incurred during the lifetime of the product, work, or service.

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[2] European_Green_Deal_EN_200710_fin

[3] SET-Plan Action 3.2: https://setis.ec.europa.eu/system/files/setplan_smartcities_implementationplan.pdf

[4] Internal Electricity Market Directive (EU) 2019/944 5 Renewable Energy Directive (EU)

[5] Renewable Energy Directive (EU) 2018/20012018/2001

[6] https://op.europa.eu/en/publication-detail/-/publication/16cd2d1d-2216-11e8-ac73-01aa75ed71a1/language-en

[7] https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/

[8] https://ec.europa.eu/environment/gpp/lcc.htm

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Abbreviations and Acronyms

Acronym	Description
ADFP	Abiotic depletion potential, fossil fuel
ADPE	Abiotic depletion potential, elements
AP	Acidification Potential
AR	Augmented Reality
ATEX	Appréciation Technique d'Expérimentation/ Technical Assessment of Experimentation
BIM	Building Information Model
CA	Consortium Agreement
CBA	Coal Bottom Ash
CDW	Construction & Demolition Waste
DT	Digital Twin
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
FA	Fly Ash
FDES	French Environmental Product Declaration
GA	Grant Agreement
GB	Green Building
GBN	Green Building Neighbourhood
GGBS	Ground Granulated Blast-furnace Slag
GIS	Geographic Information System
GWP	Global Warming Potential
H&S	Health & Safety

Acronym	Description
HDPE	High Density Polyethylene
HEGR	High Evaporative Green Roof
HVAC	Heat Ventilation Air Condition
IBPM	Institut de biologie moléculaire des plantes
ICB	Insulated Concrete Block
IEQ	Indoor Environmental Quality
IoT	Internet of Things
LAI	Leaf Area Index
LCA	Life Cycle Assessment
LCE	Life Cycle Engineering
LDPE/ PE-LD	Low Density Polyethylene
LL	Living Lab
MRA	Mixed Recycled Aggregates
ODP	Ozone Depletion Potential
PET	Potential Evapotranspiration
POCP	Photochemical ozone creation potential
PP	Polypropylene
PS	Polystyrene
PV	Photovoltaic
PVC	Polyvinyl Chloride
RA	Recycled Aggregate
RH	Relative Humidity
SAM	System Advisor Model

Acronym	Description
SCMs	Supplementary Cementitious Materials
SLAM	Simultaneous Localization and Mapping
SOTA	State of the art
SRI	Solar Reflectance Index
TDR	Time Domain Reflectometry
ToC	Table of Contents
TRL	Technology Readiness Level
UAS	Unmanned Arial Systems
UAV	Unmanned Arial Vehicles
UHI	Urban Heat Island
VR	Virtual Reality
WP	Work Package
WPL	Work Package Leader
WUFI	Wärme Und Feuchtetransport Instationär
XPS	Extruded Polystyrene Panel

Executive summary

This document provides an overview of the scope, main activities, and initial findings of PROBONO Task 3.1, entitled "SOTA reports and DT models of Innovations for Smart Green Building Construction and Renovation". Innovations are described in this deliverable as they have been identified across the various tasks in PROBONO Work Package 3, together with the state-of-the-art in each corresponding field. The development of these innovative solutions is part of the research and innovation activities in tasks other than Task 3.1 and a thorough analysis of these development processes is out of the scope of the current deliverable. However, a brief description of each of the innovative solutions currently being investigated in Tasks 3.2, 3.3, 3.4 and 3.5 is presented in D3.1 as required. In this respect, innovations are categorised, and they are collectively referred to as i) insulation and roof-centric innovations, ii) construction and lifecycle blueprints, processes and controls including robots, iii) materials upcycling and iv) social distancing considering epidemiology risks. Moreover, initial concepts of DT models for key innovations are defined to be further advanced, developed and exploited through implementation, validation, and testing in PROBONO LLs.

1. Introduction

The overall objective of WP3 in PROBONO is to provide GBN models of innovations for Smart Green Buildings construction and renovation phases together with state of the art (SOTA) reports. It is foreseen that a focused set of innovative solutions at TRL 6, matching initial LL requirements, will be matured to TRL 8 through application in the Living Labs. These innovative solutions belong to the following categories: (a) GBN Insulation and green and cool roof-centric innovations, (b) GBN related Construction and lifecycle blueprints, processes and controls including robots, (c) GBN Building Materials / upcycling and (d) Social distancing (design for crowds, sensors) considering epidemiology risks. Furthermore, systemic GBN innovations combining initially WP1 and WP2 findings and subsequently knowledge gained from LL operation, will be identified, and exploited in subsequent 'SOTA Reports & DT models' deliverables (D3.2-D3.4).

In this framework, "D3.1 – SOTA Reports and DT models (I)", aims to present the initial scope, activities, and findings of Task 3.1 "SOTA Reports and DT Models of Innovations for Smart Green Building Construction and Renovation" as part of WP3 "PROBONO Smart Green Building Construction and Renovation".

The specific objectives of this report are briefly outlined below:

- Provision of initial SOTA Reports for Innovative Solutions as they are identified in WP3 and categorised above to also expand the initial 1.3.1.4 SOTA section with respect to these technologies. SOTA involved the review and analysis of key scientific publications, identified so far in the project, by partners leading on their corresponding field of expertise. In some cases, evidence from partners' R&D activities is included as appropriate.
- Provision of initial concepts of DT Models of Innovations and mapping (where possible at this early stage) with the selection of Living Lab solutions (*Figure **1***).

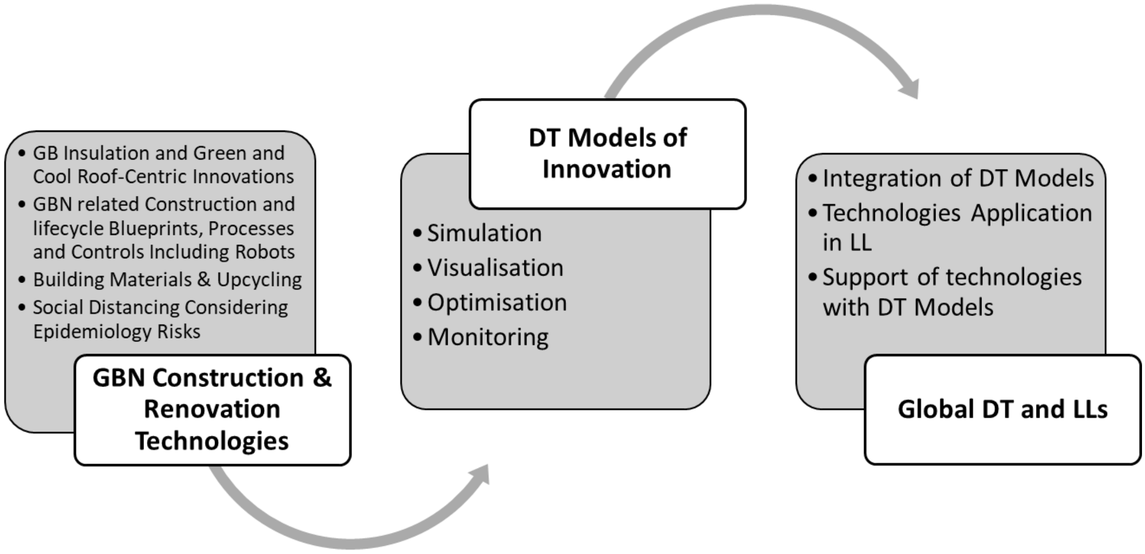

Figure 1: Deliverable Scope

1.1 Mapping of project Outputs

The purpose of this section is to map the research outputs reported in D3.1 according to the PROBONO Grant Agreement Task 3.1 description.

GA Component Title	GA Component Outline	Respective Document Chapter(s)	Justification
TASK			
T3.1 / ST3.1.1	SOTA Reports and DT Models to support the final selection of Living Lab solutions. This will expand SOTA summarised in section 1.3.1.4.	Chapters 3-6	SOTA Reports and DT Models of Innovations for Smart Green Building Construction and Renovation are identified and described.
T3.1/ ST3.1.2	Quarterly reports for the PROBONO Observatory	-	This Subtask will be explored in D3.2: SOTA Reports and DT Models (II), which is due M36 and D3.3: SOTA Reports and DT Models (III), which is due M48. D3.2formulates the findings of T3.1, and explores step/s B, C) Periodic Updates and D3.3 formulates the findings of T3.1 and explores step/s D) Periodic Updates

T3.1/ST3.1.3	Final report on project lessons learned	-	This Subtask will be explored in D3.4: SOTA Reports and DT Models (FINAL) which is due to M58. This report formulates the findings of T3.1, and explores step/s E) Final report.
DELIVERABLE			
D3.1 SOTA Reports and DT Models (I)12] This report formulates the findings of T3.1 and explores step A: Initial SOTA report and DT Models.			

Table 1: Adherence of D3.1 outputs and work performed to the GA commitments

1.2 Interrelationships between T3.1 with WPs and other WP3 Tasks

The most important links of T3.1 with other WPs are summarised below:

- WP1: Macro-Knowledge Base and GBN Framework
  - WP1 provides the overarching macro-knowledge base and GBN Framework regarding sustainability perspectives in GBN strategic planning themes of a) architectural transformation, b) human health and comfort, c) green construction management and productivity and d) management, function, sustainment and operation of buildings and users.
  - WP1 also provides, the scoping for the transition roadmaps from the Target Models detailing the current maturity for each Living Lab, from which innovation testing and evaluation within the Digital Twins can be executed, prior to physical testing and use.
- WP2: Social and Behavioural Innovations
  - WP2 deals with maximising the adoption of the PROBONO approach and innovations beyond the project lifetime by (a) raising awareness of the PROBONO activities, results, and positive impact as well as by (b) iteratively integrating stakeholder needs and requirements from the project onset and finally by (c) validating the project findings against user needs and the market.
- WP5: Digitalisation for data driven GBN human-centred design and construction / renovation

  - In D3.1 initial concepts for DT models of WP3 innovations are defined in order to be aligned with the GBN Digitalisation platform (WP5) designed for implementation and testing in LLs

- WP6: Monitoring and evaluation of the project’s Living Labs
  - The monitoring and evaluation framework developed in WP6 is formulated to include additional KPIs according to the innovations in Task 3.1 / WP3 and the identified concepts of DT models in D3.1.

- WP7: Living Labs GBN Implementation
  - WP7 focuses on the implementation of technologies in PROBONO LLs. As such it provides the overall framework and support for the implementation, validation and testing of innovations and technologies developed in WP3.

Deliverable 3.1 (as the main output of T3.1) is interlinked with other WP3 tasks since it is constituted by the ‘SOTA Reports and DT Models of Innovations’ in T3.2, T3.3, T3.4 and T3.5 and in specific for: i) GB Insulation and green and cool roof-centric innovations, ii) GBN related Construction and lifecycle blueprints, processes and controls including robots, iii) Building Materials / upcycling, and iv) Social distancing (design for crowds, sensors) considering epidemiology risks respectively.

1.3 Deliverable Overview and Report Structure

The deliverable structure is as follows. In chapter 2, the most important aspects pertaining to the conceptual framework of the research and innovation activities in Task 3.1 are defined. Sections 3-6 are devoted to the technical description of the innovative aforementioned technologies and approaches including the key initial concepts of DT models envisioned so far. Finally, section 7 summarises the key findings and proposes next actions.

2. Smart Green Building Neighbourhood Construction and Renovation

In the context of PROBONO, a neighbourhood is defined as a set of buildings in the urban environment, together with the built and the natural surroundings which extend in an area smaller than that of a district. A neighbourhood is considered to be “green”, in the case that environmentally friendly technologies and sustainable development planning arrangements, practices and behaviours coexist to a significant degree. Also, it is crucial that a GBN ensures a just transition and inclusive growth while enabling economic and social value for the neighbourhood community. In this context, an initial GBN definition in PROBONO has been considered, whereby GBNs are comprised by Green Buildings (GBs), integrated within a neighbourhood, together with green energy and green mobility infrastructures and management facilities. Furthermore, the term “smart” is used to characterise GBNs in which artificial intelligence and digital technologies are largely exploited throughout the various life cycles of a GBN, to assess and integrate sustainable solutions. Integrating sustainable solutions, can to some extent be achieved by supporting stakeholders in dealing with the complex nature and multiple criteria of the decision-making processes. In this respect, the concept of a GBN, is closely linked to the role of stakeholders and their engagement through appropriate decision-making mechanisms.

Moreover, the concept of the Digital Twin (DT), is considered as a new technological paradigm that can be exploited to support the processes of planning, designing, constructing, operating and upcycling in a GBN. Provided that the Digital Twin for GBNs is a new concept, various definitions and perspectives can be considered as a starting point together with technologies, processes and tools as well as key enablers and challenges. For the scope of this deliverable, a working DT definition is that of *a tool comprised by components for the digital representation of its physical counterpart (i.e. digital models, data connections and the data management infrastructure etc.) designed to provide digital services such as visualisation and (real-time) monitoring, data analytics, simulation, optimisation and advanced control* (Tao, Zhang, Liu, & Nee, 2019).

In chapters 3-6, the initial concepts associating GBN Construction and Renovation Technologies in WP3 with DT models are presented (*Figure* ***2***).

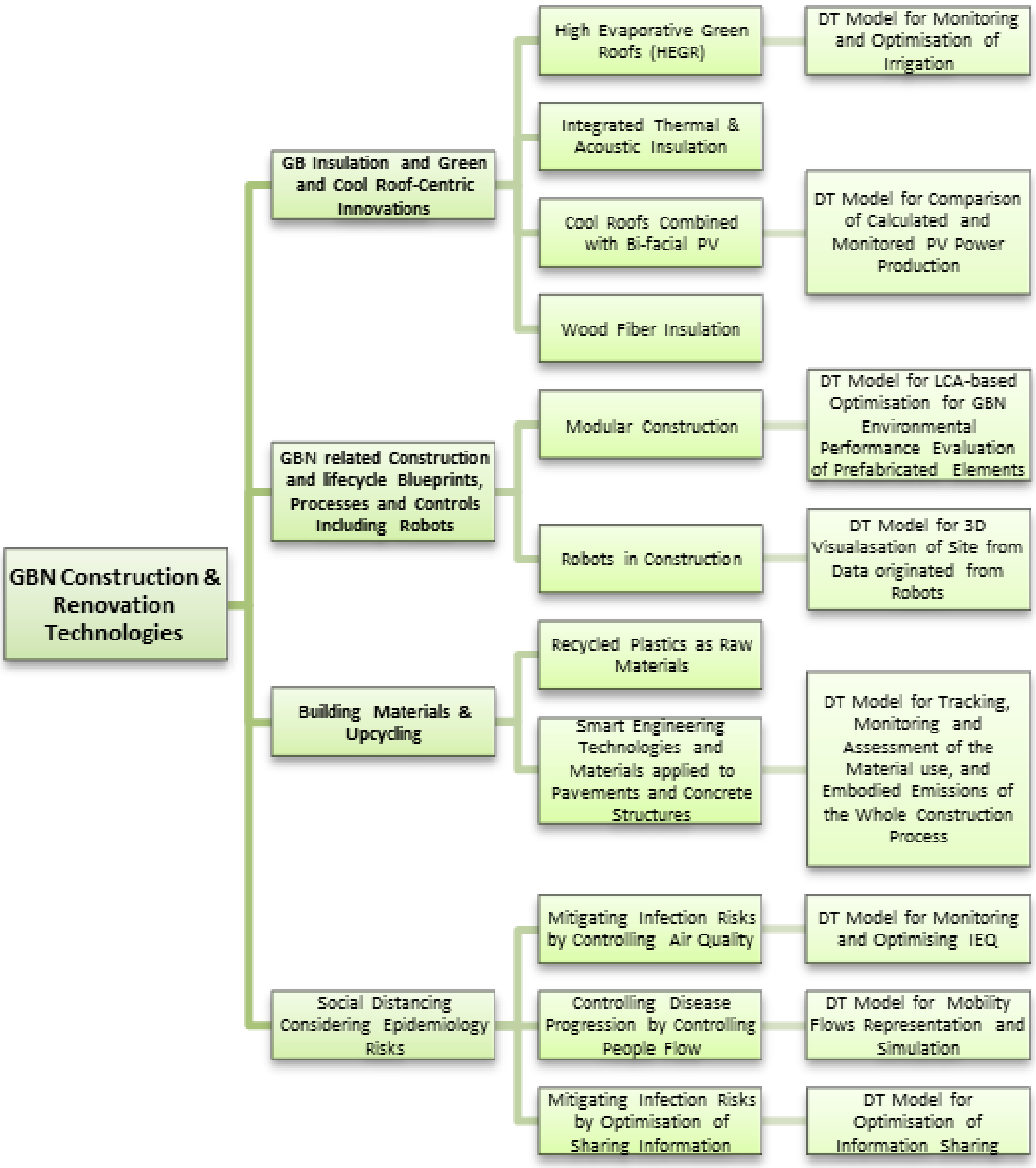

Figure 2: WP3 Technologies & DT Model Concepts

The overall aim, is that the initial concepts of DT models identified in this report, will be further defined, developed, implemented and tested in PROBONO LLs. This is aligned to the requirements concerning the development, exploitation and replication of the specific sustainable technological and methodological solutions. Therefore, it is foreseen that the development of DT models will contribute to the creation of research and innovation prototypes which will promote the engagement of the research and industrial communities in co-creation activities leading to the generation of new knowledge ultimately leading to a higher overall adoption of advanced solutions.

3. SOTA and DT Models of Innovations for GB Insulation and Green and Cool Roof-Centric Innovations

In this section, GB insulation and green and cool roof-centric innovations that are being developed in PROBONO are explored. These innovations are namely, high evaporative green roofs (HEGR), integrated thermal and acoustic insulation, cool roof technology combined with bi-facial PVs and wood fibre insulation. A technology description is given for each one of these innovations and is supported by an initial state-of the-art review. The innovative characteristics of these technologies are explored in the following sections. In addition, initial DT model concepts are discussed for HEGR and cool roof technology combined with bi-facial PVs.

3.1 High Evaporative Green Roofs (HEGR)

In broad terms, a green roof can be beneficial for a building and its environment in many ways such as by reducing the urban heat island effect (Wang, Li, & Sodoudi, 2022), improving air quality (Zhong, Zhang, & Lv, 2021), reducing urban noise (Van Renterghem, 2018), increasing biodiversity (Wooster, Fleck, Torpy, Ramp, & Irga, 2022), increasing the durability of waterproofing roof membrane (El Bachawati, et al., 2016), improving aesthetic value from neighbouring views (Kotzen, 2018), helping greywater treatment (Thomaidi, Petousi, Kotsia, Kalogerakis, & Fountoulakis, 2022) and reducing or delaying rain runoff (Castiglia Feitosa & Wilkinson, 2016; Droz, Coffman, Fulton, & Blackwood, 2021). The combination of choices in plant species, substrates parameters and irrigation systems can be optimized to answer collectively those challenges.

3.1.1 Description of innovation

Highly Evaporative Green Roofs (HEGR) is a new green roof concept that combines:

- Vegetation of high evapotranspiration rate
- An irrigation system to optimize evapotranspiration in hot and dry conditions

HEGR are effective in protecting the building envelope from direct solar irradiance thereby reducing overheating of the roof especially during the cooling period. In addition, by naturally cooling down the air above the roof, a positive impact on outdoor comfort conditions is observed. *Figure **3*** illustrates the evapotranspiration phenomenon due to the physical processes occurring in the plants of a green roof. The water coming from the irrigation system or rain, is stored in the substrate according to its properties and ambient conditions. In the presence of solar radiation, the plant roots absorb the stored water to facilitate photosynthesis while evaporation from the surface layer also takes place. Under high ambient air temperature and increased solar radiation conditions, liquid water is absorbed through the roots, and it is emitted into the air via the plant leaves in the form of water vapour. With the aid of measurements SOPREMA estimated that the phenomenon of evapotranspiration in a HEGR can lead to an ambient air temperature decrease of 4°C.

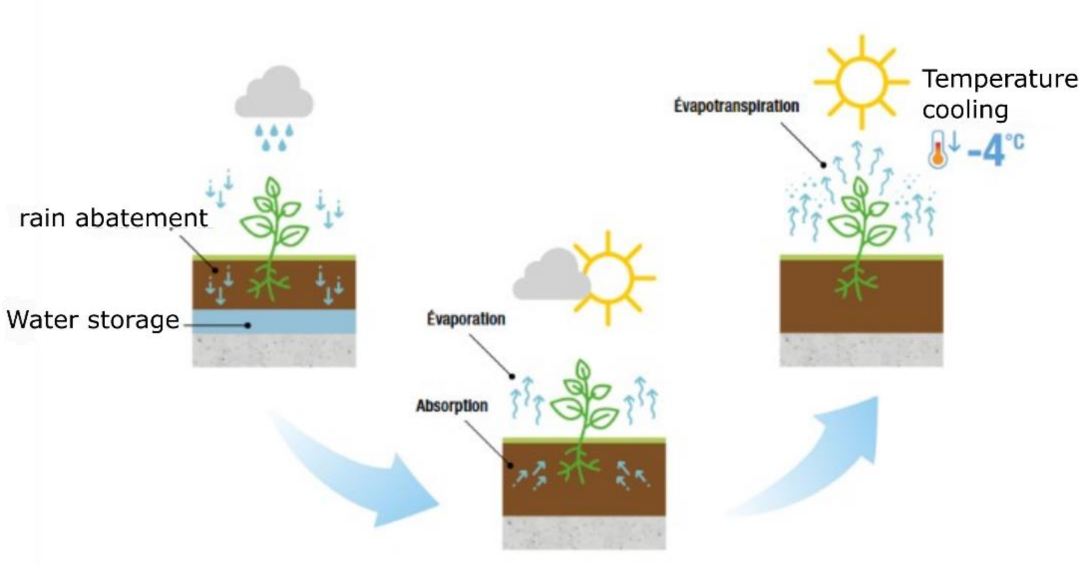

Figure 3: Evapo-transpiration scheme (source: SOPREMA)

Potential evapotranspiration (PET) is the amount of evaporation by a specific system composed of a plant and a soil substrate if sufficient water is available.

Researchers have classified some plants (Stachys, Fuchsia, Jasminum, Hedera, Lonicera, Prunus) according to their potential in evapotranspiration and shading (Blanusa, et al., 2013; Cameron, Taylor, & Emmett, 2014). They suggest that the choice of plant species on green roofs should not be entirely dictated by what survives on shallow substrates of extensive systems, but consideration should be given to supporting those species providing the greatest eco-system service potential. Following those precepts, internal research was led by SOPREMA to identified plants potential in their portfolio. Figure ***4***4 presents the results of experimental measurements performed by SOPREMA in 2018-19 regarding the PET of irrigated gravels, and three typologies of green roofs: sedum, turf and an innovative system called FRESH®.

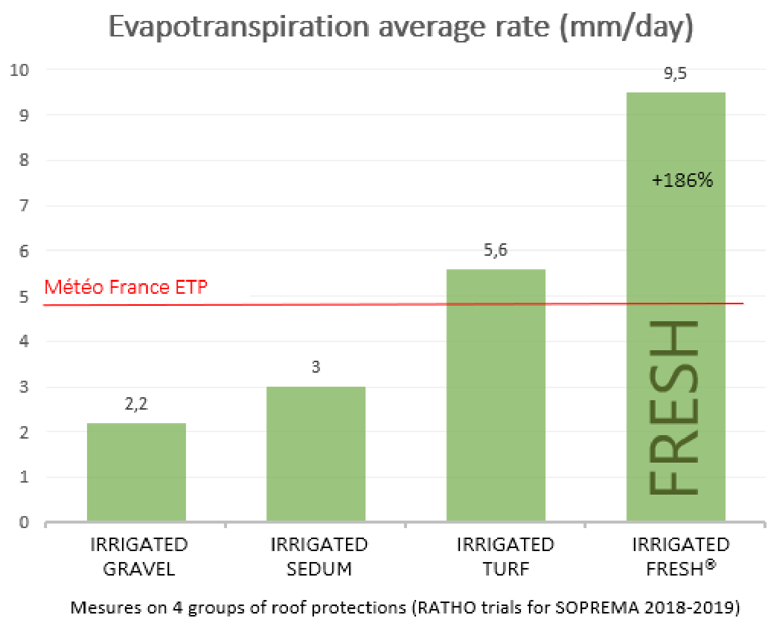

Figure 4: Evapotranspiration rate of different plants / gravel on flat roof (source: SOPREMA)

HEGR can be applied on flat roofs above a root-resistant waterproofing membrane. The complete HEGR system is composed of five layers as shown in *Figure* ***5*** and detailed in *Table* ***2***:

Figure 5: Layers of the HEGR system developed by SOPREMA (source: SOPREMA)

FRESH® consists of a selection of specific vegetal species and roofing products detailed in Table 2.

Items	Functionality
(1) Shorter plant species	10 to 20 cm, succulents, perennials
(1) Taller plant species	30 to 100 cm, herbaceous, grassy, bulbous, and flowering perennials
(2) Sopraflor I	Substrate conceived for semi-intensive growing potential. It is a mix of porous enough mineral and organic matter chosen for a proper development of plants and rain retention.
(3) Aquatex	The watering solution for semi-intensive green roofs, which ensures the preservation of vegetation and cooling functions. Aquatex is a sub-buried watering system and filter; It provides constant water availability and water savings (60% compared to irrigation sprinkler).
(3) Filter	In a standard green roof, the filter layer prevents clogging of the drainage by substrate particles. It is not needed if Aquatex is used.
(4) Sopralithe Z	Draining system made of light mineral aggregates, with a regular thickness of 5 cm, which provides additional space for vegetation roots.
(5) Insulation and membrane	SOPREMA insulation and waterproofing system with anti-root treatment.

Table 2: Detailed functionalities of layers in HEGR

This system can be adapted to all types of concrete roofs (schools, offices, residential buildings, etc.) provided their specifications support the additional static load of 250 kg/m². All those elements could be adapted as a function of the prioritized objectives and constraints (essentially structural), for example the rain retention capacity of green roofs varies by climate, season, plant type (Droz, Coffman, Fulton, & Blackwood, 2021) and the type and depth of growing media (Zheng, Zou, Lounsbury, Wang, & Wang, 2021).

3.1.2 SOTA for High Evaporative Green Roofs

SOPREMA has conducted experimental & modelling studies on HEGR based on the application of this technology in 3 installation sites in France. The most important findings based on these installations are summarised below:

- The ambient air temperature just above an irrigated green roof can be 4°C lower than the air temperature above a typical (non-green) flat roof
- Vegetation has to be chosen amongst a range of plants with high evapotranspiration rate and well-adapted to the local climate.
- Air conditioning demand into the building can be drastically decreased.

The substrate layer increases the roof thermal resistance by providing an additional thermal layer, given the following remarks:

- The additional thermal resistance of a water-saturated media is not highly significant in reducing the conducted heat flux magnitude through the ceiling
- The additional volumetric specific heat of a water-saturated media brings significant thermal inertia. This can be evaluated as a phase shift between the outdoor surface temperature peak and ceiling surface temperature peak in premises with free-floating temperature condition. More information can be found in Tariku et al (Fitsum Tariku, 2022).

All the aforementioned remarks are extra to the typical benefits of a green roof which are related to biodiversity, rainwater management, aesthetics, and acoustics.[9]

Moreover, Tariku (2022) conducted a study in Vancouver, to find out that that a green roof installed on a highly insulated roof had as a consequence reducing and shifting peak cooling loads. Rainwater retention was measured to range from a maximum of 21% in winter to 100% in summer while a reduction of heat gains of 66% was observed during the cooling months.

[9] The semi-intensive green roofs are not accessible to pedestrian; Therefore, their heat sink potential is entirely dedicated to attenuating the Urban Heat Island effect. In full-roof coverage configuration, they cannot directly contribute to increase the thermal comfort of people. Though roof can be sought as partly covered by the technology and then users could take profit of the decrease in radiant mean temperature and air temperature brought by evaporative plants.

SOPREMA in collaboration with TIPEE have identified the following KPIs to evaluate the impact of a HEGR installation inside the building (summer comfort, air conditioning savings) and outside associated with the UHI impact:

- Indoor KPIs:
    - Cooling demand (kWh/m²/y)
    - Air conditioning cost savings / reference (€/m²/y)
    - Summer comfort (°C.h)
- Outdoor KPIs:
    - Latent heat flux (W/m^2)
    - Sensible heat flux (W/m^2)

The aforementioned KPIs are derived based on a green roof model assessed by TIPEE using TRNSYS software . A parametric study combining 4 building typologies (*Figure 6*), associated with two alternative thermal properties configurations for the building envelope (pre-2000 and post-2020) and 14 different roof systems (8 types of green roofs, 5 types of cool roofs, 1 type of dark bitumen) was conducted in over 13 French regions.

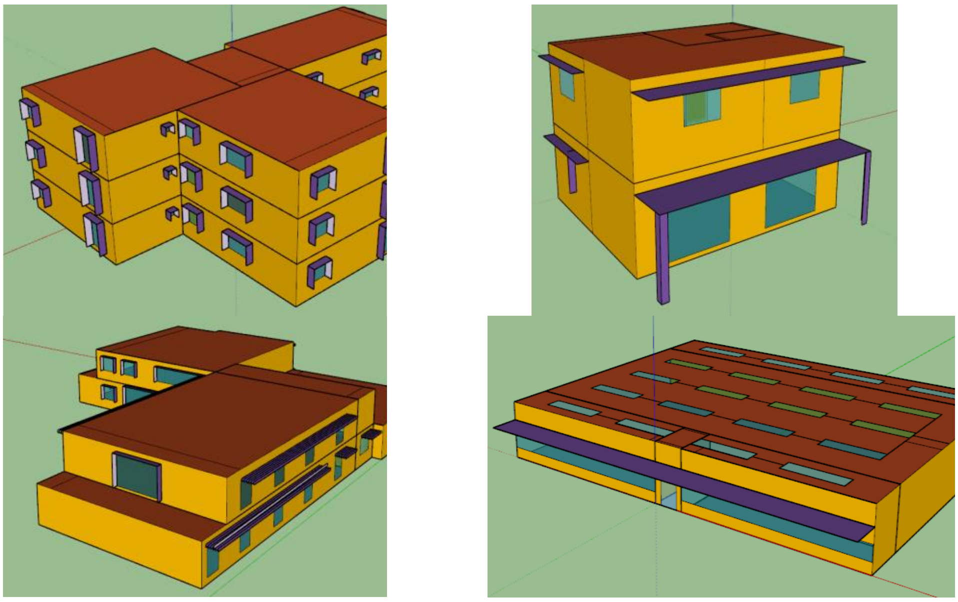

Figure 6: Four building typologies, from top to bottom, left to right: collective housing, detached house, office building and supermarket (source: TIPEE)

The internal gains were estimated based on the French Thermal building rules (RT2012), and the temperature set-points for heating and cooling were set at 21°C and 26°C, respectively.

To evaluate the contribution of different roof typologies to the surrounding urban environment, it was decided that only the sensible heat flux would be considered as the convective transfer is the main determinant of the increased air temperature above the roof. Figure 77 provides a simplified pattern of the three surface heat balances considering a reference roof, a cool roof and two different types of a green roof. Since green roofs cover on average about 90% of the total roof surface as access is needed for maintenance, the green roofs were considered to be covered in 10% by a reference bitumen dark roofing product.

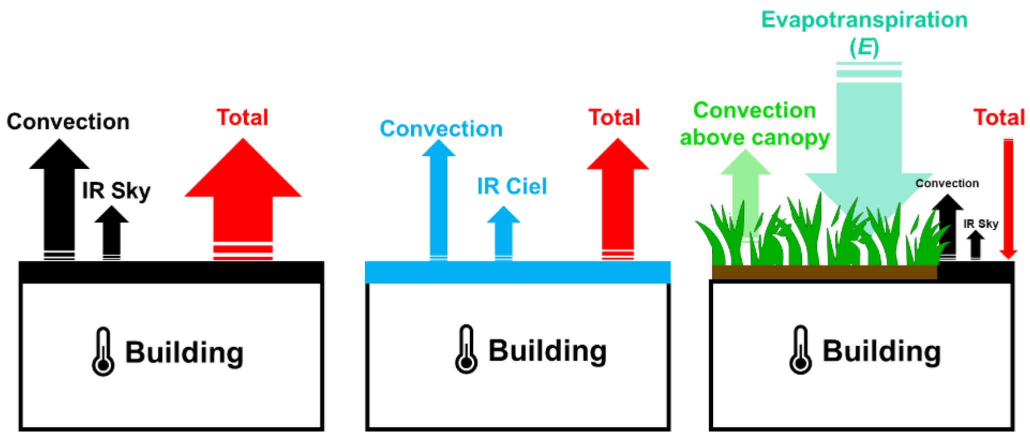

Figure 7: Thermal Surface balances for a reference roof, a cool roof and a green roof (source: TIPEE)

The main characteristics that are parameterized for the reference and cool roof cases are their solar reflectance and infrared emittance. TIPEE identified those optical values through measurements and bibliography. Minimal variations are found on the optical properties of leaves. In this regard, Pisello et al. (Pisello A.L., 2015) searched for light-coloured plants with high short-wave solar reflectance capability on the green roofs, naming the as cool-green roof. The cool-green roof reflects 7% more solar radiation compared to a traditional green grass roof.

For other plant-specific inputs, IBMP (Institut de biologie moléculaire des plantes) collected the following values out of 8 plant species growing on Soliflore® substrate provided by Soprema:

- Height of plants
- Leaf area index (LAI) which is an important parameter in natural ecosystems, representing the seasonal development of vegetation and photosynthetic potential
- Aerodynamic roughness length and bulk sedge leaf area index in a mixed species
- Minimum and maximum leaf stomatal resistances
- Leaf thickness

As for leaf thickness, their apparent density and thermal properties are found to be less sensitive in the model and are mostly found by the bibliography. The substrate characteristics as substrate maximum volumetric water content or substrate apparent density are provided by SOPREMA.

Figure *8*8 illustrates the daily variation of sensible heat flux resulting from modelling of green roofs, a bitumen dark roof and a cool roof.

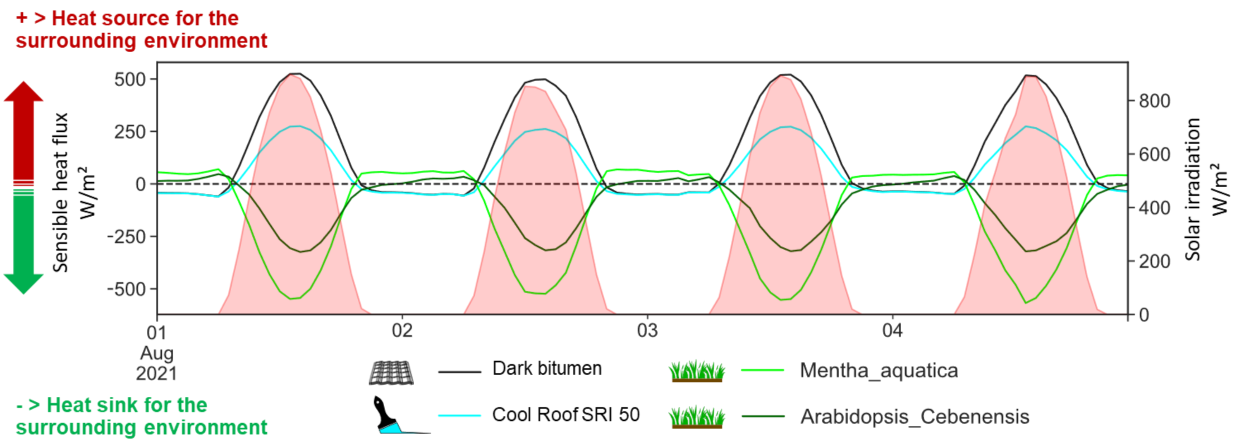

Figure 8 :Comparison of Sensible heat flux for 2 bitumen roofs and two green roofs with different plant species (source: TIPEE)

Green roofs behave like heat sinks during the day thanks to the phenomenon of evapotranspiration. On the other hand, non-vegetated roofs exhibit radiative cooling during the night while the canopy formed by the plants in a HEGR reduces the sky view factor of the substrate thereby minimising the cooling potential by long-wave radiation. Additionally, experimental studies such as (Yang, Davidson, & Zhang, 2021) measured those differences in-situ in terms of temperatures. Their traditional roof had peak surface temperatures exceeding 40 °C and exhibited larger diurnal amplitudes than the green roof.

Nevertheless, yearly results showed a 110% to 130% reduction of sensible heat flux to the urban environment from a vegetated roof surface compared to dark bitumen roofing. The global energy consumption reduction, at an equivalent building typology, range from 6 to 12%, depending on the envelope insulation.

In addition, as stated in Yaghoobian et al (Neda Yaghoobian, 2015), in response to the reduction in building energy use, the amount of discharged anthropogenic heat flux into outdoor air decreases.

3.1.3 DT Models of Innovation for High Evaporative Green Roofs

A DT model for HEGR technology is currently identified to consist of the following main functions, sensors and measurements:

- Visual representation and data monitoring of the HEGR installation
- Weather forecasts and data analysis functions based on historical data
- Irrigation optimisation algorithm and advanced control functionality
- Measurements of air temperature (10, 20 and 50 cm above substrate) and substrate temperature and moisture via connected sensors
- Remote irrigation controller

3.2 Integrated Thermal & Acoustic Insulation

3.2.1 Technology Description

Concerning integrated thermal and acoustic insulation the following technologies are considered:

- Polyurethane (PUR) panels, which present the lowest conductivity value amongst traditional thermal insulation products. (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016) found that the thermal conductivity of a PUR panel ranges from 0.022 to 0.040 W/m K, its density from 15 to 45 kg/m3 and specific heat is between 1.3 and 1.45 kJ/(kg.K). Thermal conductivity in PUR panels is influenced by the cell size and decreases when the cell size decreases (Wu, Sung, & Chu, 1999). Also, PUR panels show no significant acoustic property, because of the closed porosity and low density. Since the material is easily flammable and burning releases dangerous gases, a fire retardant is often added in the manufacturing process.
- Extruded Polystyrene panel (XPS) is produced by melting the polyester grains into an extruder, with the addition of a blowing agent (Vo, Bunge, Duffy, & Hood, 2011). XPS boards shows high compression and its long-term mechanical properties, which are of key importance for thermal insulation placed under foundations, are cited for XPS in (H, 2004). It is also stated that CPS panels are excellent for a foundation application as they absorb less moisture (liquid absorption under 24h < 0.3%) than other insulation products.

- Cellulose bulk or panels are fibrous insulation derived from recycled paper (newspaper, glassine, etc.) and are produced by grounding recycled papers, wood fibers with or without binders, fire retardants and other additives (against rotting and fungal growth) in a mill. The process to manufacture them has a low value of embodied energy (0.95-3.3 MJ/kg) that also combines acoustic and good thermal properties (Lopez Hurtado, Rouilly, & Vandenbossche V, 2016). Cellulose is characterized by a thermal conductivity between 0.037 and 0.042 W/m K, a density between 30 and 80 kg/m3 and a specific heat between 1.3 and 1.6 kJ/(kg.K) (Schiavoni, Alessandro, Bianchi, & Asdrubali, 2016). Regarding the acoustic performance, if panels are used, their elasticity allows the use as resilient materials in floating floors, while porosity and flow resistivity values are adequate for sound absorption and cavity insulation (Asdrubali, F, Schiavoni, & K, 2012).
- Wood fiber panels (Section 3.4). The thermal conductivity of these materials varies from 0.038 to 0.050 W/m K, the density from 50 to 270 kg/m3 and the specific heat from 1.9 to 2.1 kJ/(kg.K). The thermal conductivity increases when increasing the temperature and moisture content (Troppová, Švehlík, Tippner, & Wimmer, 2015). Resilient materials made of wood fibers are characterized by dynamic stiffness between 30 and 50 MN/m3. Wood fibers can be easily recycled. The thermal, acoustic properties and characteristics of insulation technologies proposed by SOPREMA are shown in Table 3.

With this complete portfolio, it becomes possible to cover all thermal & acoustic systems in buildings (new or renovation).

Technology	**Lambda (mW/m²/K)**	**Acoustic insulation**	**Characteristics**
Polyurethane panels	20-27	No	Best lambda value. Recycled polyol used as raw material.
XPS	29-31	No	Up 100% of recycled raw materials Resistant to liquid water. Highest compression resistance.
Cellulose	40-42	Yes	95% based on recycled paper. High thermal inertia. Available in bulk or flexible panels

Wood fiber panels	36-42	Yes	Available in rigid of flexible form.

Table 3: Thermal, acoustic properties and characteristics of insulation technologies proposed by SOPREMA

Depending on the application, technical requirements and specifications for each LL, the following properties and design characteristics of the identified solutions are considered:

- Thermo-acoustic solutions together with moisture and air control
- Prefabricated and waterproofing solutions for flat roofs
- Resistance of insulation to mechanical stress
- Low environmental impact of solutions

Indicative solutions proposed are presented below:

- Bio-based solutions for insulation & waterproofing system for HEGR applications: These are based on prefabricated anti-fungi development wood-based fiber rigid panels combined with partially bio-based waterproofing membrane.
- 100% Biobased flexible thermo-acoustic panel for insulation of walls & pitched roofs combined with vapor & air barrier control layers with the innovative use of recycled glassine raw materials is considered.

3.2.2 SOTA for Integrated Thermal & Acoustic Insulation

In PROBONO, the aim is to achieve a proper balance between properties such as:

- High thermal and acoustic insulation
- Low environmental impact

Despite the fact that the thermal & acoustic insulation technologies are considered to be well established construction products, there is a need for prefabricated components solutions such as Panotec Confort (Figures 9 & 10) (pitch roof panels) integrating into one solution:

- The finishing outdoor ceiling layer
- The insulation layer
- The frame for the installation of the tiles

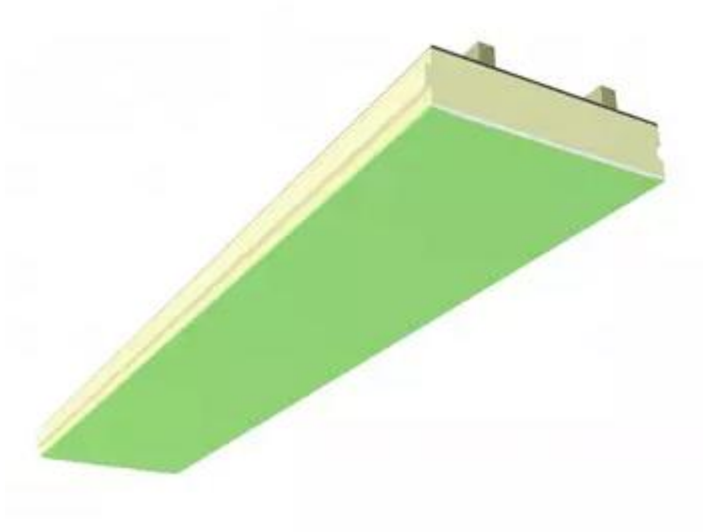

Figure 9: Pannotec Confort sketch (source: SOPREMA)

Figure 10: Typical application of Pannotec Confort (source: SOPREMA)

This type of prefabricated solutions is not widely developed and there is a need to implement new types of solutions to:

- Reduce installation time and effort
- Increase renovation rates

Moreover, Energy Performance Declarations (EPD) provide the means for assessing the Global warming potential (GWP) of insulation technologies. According to EPDs bio-based insulation materials are considered carbon neutral over a reference life cycle of 50 years or even as a carbon sink in the case of cellulose products. For instance, GWP of the cellulose-based insulation technology developed by SOPREMA is evaluated as equal to – 1,29 kg eq CO_2 / m² (145 mm cellulose with R value = 3,45 m².K.W-1).However, it is noted that the GWP is only one of the indicators of the environmental LCA.

3.3 Cool Roof technology combined with bi-facial PVs

3.3.1 Technology Description

Cool roof solutions combined with photovoltaic panels is proposed as a solution that can be exploited to reduce the roof surface temperature and thereby (Figure 11 & 12):

- Reduce the Urban Heat Island (UHI) phenomenon
- Improve comfort conditions inside the building during the cooling period
- Reduce demand for cooling

On the other hand, benefits associated with the use of PV panels are:

- Production of electrical energy
- Shadowing of the roof with a potential decrease of the roof surface temperature

By combining these technologies and in the specific case of the bi-facial PV technology, it is estimated that the electrical energy production can be increased by more than 8%.

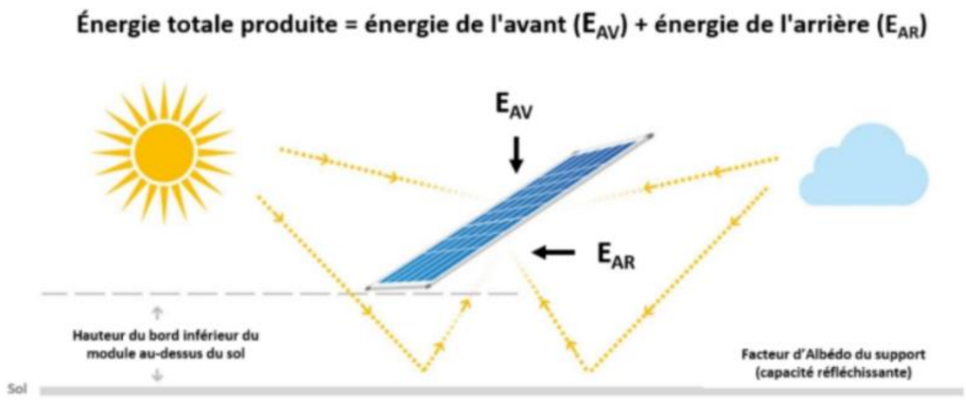

Figure 11: Schematic representation of the cool Roof and bi-facial PV concept (source: SOPREMA)

Furthermore, according to a technology developed by SOPREMA, cool roof waterproofing products can be used with all types of PV panels (rigid or flexible) without having to perforate the waterproofing layer.

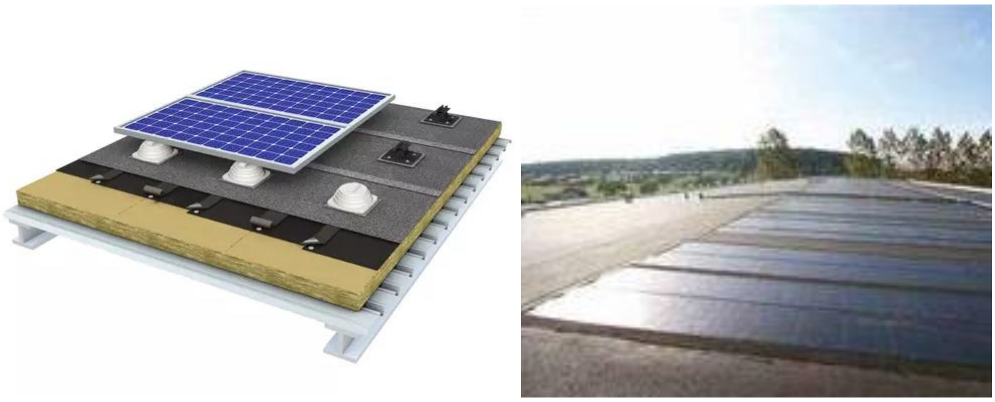

Figure 12: Soprema PV roofs example (source: SOPREMA)

3.3.2 SOTA for combined Cool Roof and PV applications

SOPREMA and LaSIE (UMR CNTS 7356) have conducted modelling studies on cool roofs installed on buildings (Madi Kaboré, 2018), however, there is a need to develop models that investigate the impact of the shadow caused by the PV installation. Another important issue to be considered when such an analysis is performed, concerns the increase of the anthropogenic heating of the building to the local urban environment.

Scherba et al (Scherba, Sailor, Rosenstiel, & Wamser, 2011) have developed methods to model unshaded and PV-shaded roof systems. Models in this case were developed and exploited for five different climatic zones. Across these climates, a black roof and a black-PV roof showed higher daily sensible flux levels compared to cool and green roofs, with average values ranging from 331 to 405 W/m2.

When the unshaded black roof flux levels are used as a reference for comparison, a consistent trend emerges. If a black roof is replaced by either a white roof or a green roof, the peak flux is reduced by approximately 70%, while the total daily flux is reduced by approximately 80% with a white roof and 52% with a green roof.

When PV panels are added to a black roof, the total flux is reduced from unshaded black roof levels by approximately 11%. Compared to the flux for an unshaded black roof, the white-PV roof has a peak flux reduction of approximately 40%, and a total flux reduction of 55%. The green-PV roof has a peak reduction of roughly 45% and a total flux reduction of about 42%.

Cavadini et al. suggested that a cool roof integrated in a rooftop has the potential to increase solar panel radiation yield. However, the influence of this roofing configuration is not yet considered in rooftop photovoltaic (PV) planning models (Cavadini & Cook, 2021).

For multi-crystalline silicon modules, the conversion efficiency is reduced by approximately 0.45% as the cell temperature rises by 1 °C above the reference temperature (usually 25 °C) (Makrides & Georghiou, 2009).

An experimental study in the hot and dry climate of the United Arab Emirates led to the conclusion that integrated PV-cool roof systems increased the annual rooftop PV yield between 5 and 10% (Altan, Alshikh, & Belpoliti, 2019).

Moreover, tools with solar systems' modelling capabilities such as System Advisor Model (System Advisor Model (SAM), n.d.), PVlib (pvlib, n.d.), PVSYST (pvsyst, n.d.) make use of energy and mass transfer equations to simulate a range of PV configurations and climatic systems; however, they do not account for the impact of the rooftop configuration on the surface temperature. In addition, the challenge is to provide a rooftop energy balance model to better quantify the effect of the actual physical components together with the solar energy model to fully and thoroughly quantify the potential effect of cool roof solutions on solar energy generation.

Last, according to Cavadini et al., a representation of the heat fluxes between the panel and the roof considered in the Neises model are depicted in Figure 13 (Cavadini & Cook, 2021).

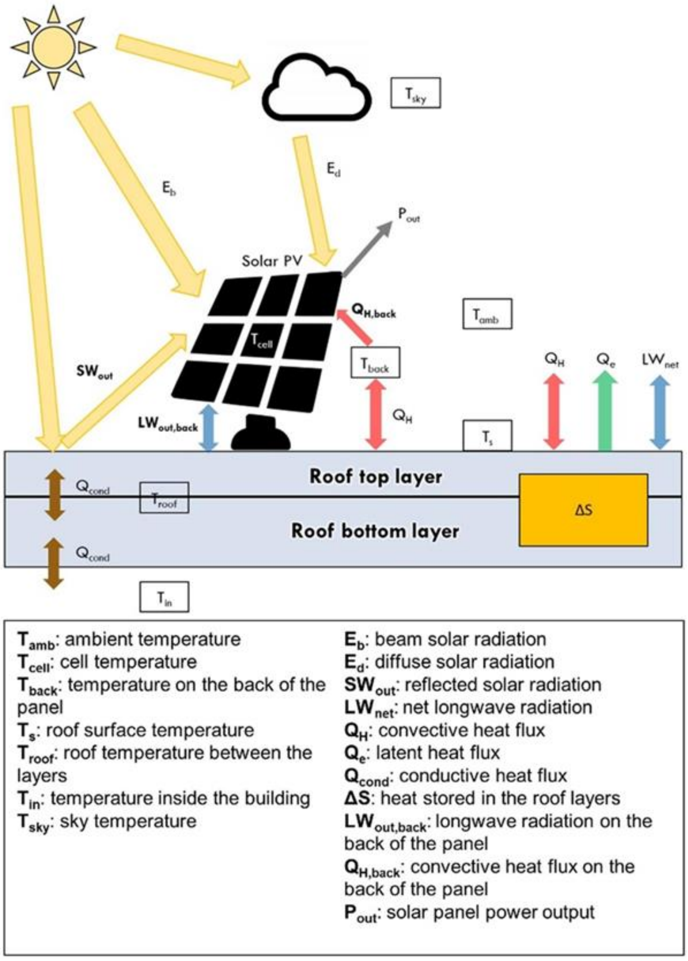

Figure 13: Overview of the heat exchange between a rooftop layer and PV panels (Cavadini & Cook, 2021)

3.3.3 DT Models of Innovation for Cool Roof combined with PV

The vision of for a DT model regarding the combination of bi-facial PV together with cool roof technology has to do with the monitoring of PV electricity production and associated rooftop conditions.

Basic functionality of DT model

The DT model is intended to provide real-time monitoring and analysis of the PV production based on the measured solar radiation and solar reflection by the cool roof.

The envisioned DT model will be accessible via a web-based application which will provide access to data analytic functions based on data from the following system components:

- Inverter of the installed PV system connected to the cloud

- Weather station for measurements including solar irradiance and air temperature
- A camera to detect the deposition of dust or matter on the PV system and roof (optional).

Targeted Stakeholders / Users

Building designers and building operators

DT model associated KPIs

- PV system electrical energy production [kWh]
- PV production efficiency (kWh/kWp).

3.4 Wood Fiber Insulation

3.4.1 Technology Description

Wood-based fiber insulation materials exhibit properties which make them an attractive option in terms of the possible thermal and acoustic insulation applications. The main SOPREMA products considered in PROBONO are distinguished in two types:

- Rigid panels: Density > 100 kg/m3
- Flexible panel: 25 <Density< 70 kg/m3

The value of these materials in building applications is being investigated with respect to their physical characteristics and potential environmental advantages (Figure 14).

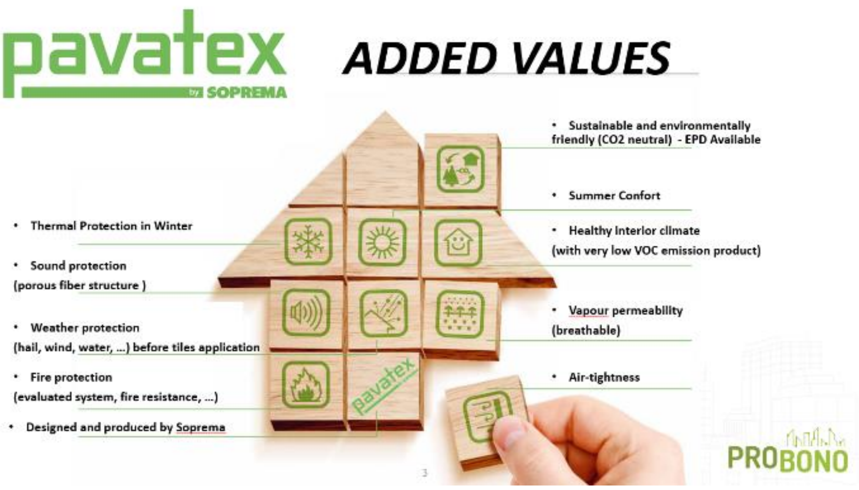

Figure 14: Fiber-based materials values (source: SOPREMA)

In this respect, based on EPD it is considered that wood-based fiber insulation products are CO_2 neutral when accounting for the complete life cycle assessment of such a product.

An Environmental Performance Declaration for specific Pavatex products of densities 110 kg/m² and higher has been issued according to ISO 14025 and EN 15804+A1 standards. Calculations include the emission of 75kg/m_2 of CO_2 during the manufacturing process due to the use of fossil fuels and a storage of 322kg/m^2 of CO_2 over the lifetime of the insulation board[10].

Insulation components used in the built environment must meet specific requirements linked to thermal, acoustic, mechanical properties and other, in a sustainable way. Most of the materials used in the construction of buildings are porous making them permeable to water vapour. In addition, some materials are hygroscopic, i.e., they can bind humidity, which can lead to changes in their physical characteristics, mainly mechanical and thermal.

It is therefore essential to carefully address the potential risks of condensation in the walls or other surfaces as this leads to the deterioration of their performance as well as having a negative impact on occupant comfort and health conditions.

The proposed wood-based fiber panel is not resistant to the development of fungi and hygrothermal calculations (e.g., with WUFI software[11]) are necessary to design proper solutions. It is expected that this technology is effective and reliable in a location with ambient RH levels lower than 85% a threshold that needs to be further investigated. In addition, SOPREMA is developing a new series of wood-based fiber insulation products (flexible & rigid boards) with a bio-based anti-fungi treatment. With such a treatment, it is expected that the use of these materials in many typical applications including thermal insulation below a flat green roof will be made possible.[12]

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[10] https://www.soprema.fr/fr/documentation/search-strict-product?query_type=9

[11] WUFI (Wärme- Und Feuchtetransport Instationär), is one of the most widely used hygrothermal simulation software in Europe. Validated by the Fraunhofer Institute for Building Physics (IBP), this model allows the simultaneous calculation of temperature and humidity transported in a one-dimensional or two-dimensional multilayer structural component of a building.

[12] cold and hot roof configurations. A warm roof is defined as a roof in which the insulation and the waterproofing layer are positioned directly against each other, unlike a cold roof in which an air gap is formed between the two. In the cold roof case, if the ventilation is insufficient, condensation is created, which risks damaging the insulation; strong temperature differences can also lead to cracks in the structures of the roof slab, hence the abandonment of this technique for flat roofs.

3.4.2 SOTA for Wood Fiber Insulation

Wood fiber-based insulation products are considered an attractive alternative option due to their potential environmental benefits and the high availability of recycled raw materials all over Europe. Indicatively, 8,3Mt/y is the estimated quantity based on the sawmill wastes in France associated with a cost for raw dry wood chips between 100 – 250€/t.

Wood-based insulation products might be vowed to landfill or incineration with energy recovery. Incineration is favoured for treated wastes with metals or organochlorinated compounds (Rabbat, Awad, Villot, Rollet, & Andrès, 2022).

Low-density wood boards have a relatively low-embodied energy compared to traditional petroleum-based panels (Pittau, Krause, Lumia, & Habert, 2018). As an example, during the manufacturing process one-third of the energy needed to create polyurethane panels (115 kWh/m²) is used.

Schiavoni et al. made a review and comparative analysis of insulation materials for the building sector using data of EPD available from the manufacturers' websites (Schiavoni, Alessandro, Bianchi, & Asdrubali, 2016). Regarding wood-based fiber insulation, it was claimed that wood harvested from sustainable forestry (forestry chips and cuttings, sawdust of the logging process) as well as waste of the sawmill industry can be used in the production of wood fibres for insulation purposes.

Wood residues are reduced to a fibrous state. Round wood logs may be debarked, chipped, steamed, and then refined through a defibrator to produce wood fibers. Subsequently, the fibers can undergo a "wet" or a "dry" processing, where fibers are washed with water without the use of adhesives, then pressed or hot pressed and dried to form softboards (200–400 kg/m3) and hardboards (>900 kg/m3) (Kallavus, Järv, Kalamees, & Kurik, 2017).

It was argued that a binder can be added or alternatively the lignin of wood can be activated using aluminium sulphate. The latter agent also acts as pesticide and anti-moth. The thermal conductivity of these materials varies from 0.038 to 0.050 W/m K, their density from 50 to 270 kg/m3 and their specific heat from 1.9 to 2.1 kJ/(kg.K). Their thermal conductivity increases with increasing values of temperature and moisture content.

Bio-based insulation materials represent a form of CO_2 storage (Pawelzik, et al., 2013). Furthermore, it is argued that being biodegradable, such materials lead to less pollution when disposed of (Lawrence, 2015).

Wood-based fiber insulation products currently represent less than 5% of all insulation products in constructions. Year after year market shares of wood-based fiber insulation products are increasing but main limitations linked to moisture transfer and rotting continue to exist.

Rabbat et al, reviewed the current status of bio-based insulation materials used in building applications in France (Rabbat, Awad, Villot, Rollet, & Andrès, 2022). The study focuses on their durability and end-of-life management.

Schulte et al. (Schulte, Lewandowski, Pude, & Wagner, 2021) have compared 4 biobased insulation materials (WF, Hemp fibers, Flax, Myscanthus) as well as 2 non-renewable ones. The comparison was conducted following the ISO 14040 and 14044 standards with a focus on the market of Germany. The results indicated that wood fibers insulation materials present the lowest carbon footprint (GW impact) amongst all bio-based insulation materials with a GWP of 2,72 kg CO2eq / functional unit. By the comparison of LCA & LCE, the authors concluded that both wood & miscanthus fibers insulation are the most environmentally friendly materials.

4. SOTA and DT Models of Innovation for GBN related Construction and lifecycle Blueprints, Processes and Controls Including Robots

In the following sections, innovations concerning modular constructions and the use of robots in constructions as defined in PROBONO are described. A state-of-the-art analysis in these areas, is provided based on a selection of publications which are considered essential to demonstrate relevant technological advances and highlight their potential for innovative applications. In this framework, initial concepts of DT models are outlined with reference to the LL requirements currently identified in the project.

4.1 Modular construction

4.1.1 Technology Description

Modular construction is a building process where standardized building components are produced in an off-site factory, transported to the building site, and assembled. The buildings are produced in "modules", but using the same materials, and meeting the same codes and standards in the design as in conventionally built facilities. Modular construction covers a range of methods and varieties of the complexity of the modules being brought together, from single prefabricated elements assembled on-site to fully three-dimensional volumetric units (Figure 15) (Wozniak-Szpakiewicz & Zhao, 2018; Bertram, et al., 2019) .

Subtask 3.3.1 focuses explicitly on modular construction in the context of prefabricated concrete elements. The technologies addressed combine early-stage life cycle assessment and a strategic design process for more sustainable concrete construction design.

4.1.1.1 Using Life Cycle Assessment to Address Environmental Performance and Hotspots of Prefabricated Concrete Buildings

Life Cycle Assessment (LCA) is a methodology used for assessing the environmental impacts of a given product or service, in this case a Building or a GBN. The effects are calculated over the entire life cycle of the building, including the procurement of raw materials, production of building materials, energy and resource consumption during operation and maintenance, as well as disposal and possible recycling of building parts and materials.

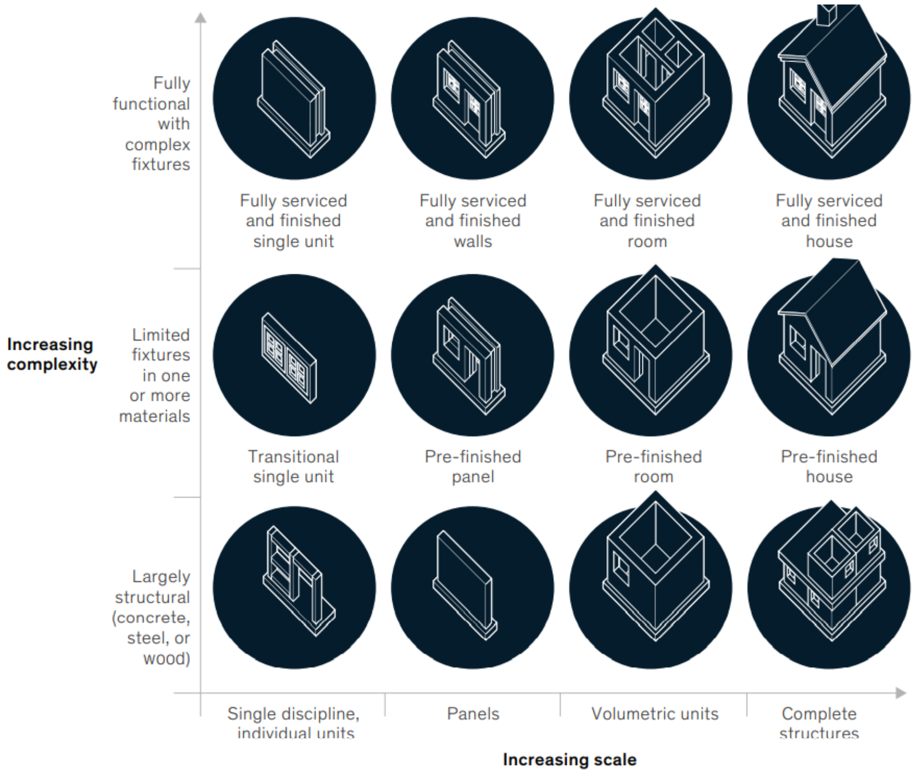

Figure 15: Complexity and scale of modular construction – comparison of approaches. (Bertram et al., 2019)

4.1.1.2 Strategic Design for more Sustainable Concrete Construction Design

When focusing on concrete as a construction material, it becomes clear that cement is a significant climate culprit, as it typically accounts for 90% of the climate impact of a concrete structure. Therefore, it is crucial in a concrete structure to minimize cement consumption, provided. However, the required reinforcement does not increase to such an extent that it offsets the gain.

As a result, the methodology approach to concrete design focus on:

- Sustainable choice of concrete materials among those available.
- Sustainable concrete design - the desired optimum in the CO2 accounts.
- Recycling of entire concrete elements.

4.1.2 SOTA for Modular construction

The production of prefabricated concrete elements is a highly optimized process. The assessment criteria are mainly related to factors such as execution time, manufacturing time, assembly time and the number of units (Wozniak-Szpakiewicz E. , 2016). Subtask 3.3.1 will also focus on improving the environmental performance of prefabricated concrete in the buildings/GBN with respect to the previously mentioned assessment criteria.

4.1.2.1 Using Life Cycle Assessment to Address Environmental Performance and Hotspots of Prefabricated Concrete Buildings

Life cycle assessment is a valuable method for evaluating the environmental impact of buildings and identifying hotspots. LCA is often applied later in the stages of the building industry and is often used more precisely to optimize the building design (Hollberg, Tjäder, Ingelhag, & Wallbaum, 2022). The dilemma is that the accurate information needed for LCA is missing in the early stages. When it becomes available in later stages, it is too late to implement major changes to reduce environmental impact (Hollberg & Ruth, 2016).

LCA studies can also be conducted to identify hotspots responsible for a large share of the environmental impact related to the building or GBN. A hotspot analysis can be carried out with different levels of detail. It is often applied in buildings to identify the relative impact of building parts e.g. decks, roof and walls, individual materials such as concrete or wood, or simply to identify specific life cycle phases with significant impact (Hollberg, et al., 2021).

The building typology is of high importance to the environmental profile of the building. Studies show significant differences in the environmental impact between single-family houses and higher and more extensive buildings. They also show an obvious shift in relative impact between the different building parts that shift relevant hotspots from one typology to the other. For instance, ground-level decks and roofs would take up a significantly higher percentage of the total impact from a single storey house than from a high-rise building. A range of different parameters related to the building typology influences the environmental impact (Kanafani, Kjær Zimmermann, Birgisdottir, & Nygaard Rasmussen, 2019). These parameters refer to the number of storeys, the floor height, the opening degree of the façade, as well as the compactness of the building.

More and more countries integrate LCA of buildings into national regulations leading to an increasing demand for identifying and reducing the buildings environmental impact especially in the early stages of buildings' construction. The Swedish government introduced mandatory climate declaration in January 2022 focusing on cradle-to-handover (A1-A5), but without threshold values (Hollberg, Tjäder, Ingelhag, & Wallbaum, 2022). In Denmark, from January 2023, it becomes mandatory to conduct an LCA when applying for a building permit. Moreover, for buildings above 1000m^2 the same is accompanied by a threshold value of 12 kgCO_2 eq/m^2/yr and an implementation plan for decreasing the threshold over the coming years (Ministry of the interior and housing, 2021).

Affecting the environmental performance of prefabricated concrete in buildings, the life cycle approach is a valuable measure, especially focusing on the early stages, where an LCA approach can help identify relevant hotspots and support the process forward of addressing these hotspots in the following design process.

4.1.2.2 Sustainable Choice of Concrete Materials Among those Available

There is a range of intervention areas, when aiming at reducing the environmental impact of specific concrete structures, being prefabricated or in-situ.

The Strength and Exposure Class of the Concrete

The reduction of the required concrete strength and exposure class reduces the cement content as well. Therefore, it is most beneficial to keep a close eye on the requirement for concrete strength in the structure. For example, a decrease from C35 to C25 will lead to an average reduction of the concrete's CO_2 contribution of at least 20%.

A Given Concrete Strength can be Produced with Great Variation in Cement Content

Continuing, when specifying concrete strengths for a project, it is important to highlight whether limit values for maximum compressive strength and cement content can be introduced. This should be done on an equal footing with minimum characteristic strength and aggregate size. Concrete strength can result in products with significant variation in cement content, as more cement and higher concrete strengths than required are often used.

Innovative Cement Types

In recent years, cement manufacturers have been working hard to develop CO_2-saving cement types. The innovative cement types, in which calcined clay and lime fillers are used to replace up to 40% of the cement clinker, have now begun to gain ground in the market.

Concrete with Recycled Aggregate

DS/EN 206 DK NA: 2020 accepts that 100% of the stone aggregate can be replaced by crushed concrete, provided the crushed concrete originates from a structure in the same exposure and strength class. However, using crushed concrete as aggregate in new concrete does not lead to a reduction in cement consumption. That is why the reduction of the CO_2 footprint is small, but it plays a role in the reducing consumption of natural resources.

Reinforcement

Finally, it should be mentioned that reinforcement for concrete structures can be purchased within a large range of climate impacts. Here, the CO_2 impact largely depends on the percentage of recycled scrap in the steel production and the use of modern production technology.

4.1.2.3 Sustainable Design of Concrete Structure - The Objective Optimum in CO2 Accounts

In all stages of the design, optimizing the climate impact of the load-bearing concrete structures will be possible. The key concept during the design would be the rough parameter studies of total cement and reinforcement consumption. Many considerations can be made for a static system. The simple, traditional, and robust concrete structure can be twisted in a more sustainable direction. One example can be the reduction of the number of concrete walls and replacing them with beam-column systems. Moreover, smaller deck spans can be used to reduce the thickness of the deck to the degree that outweighs the extra necessary supporting lines, or more use of topology optimization of the concrete elements.

During the project, the design engineer should make rough parameter studies of the resulting material/CO_2 accounts when choosing between static systems. For this purpose, COWI has several programs under development.

4.1.2.4 Recycling of Entire Concrete Elements

The current practice for handling concrete elements from demolished buildings is crushing and recycling the material in unbound substructures under roads or as aggregate in new concrete. Both methods represent a "down-cycling" process that saves resources but does not reduce CO_2 emissions significantly. Demolition of concrete buildings is typically done for cultural needs, and at the time of demolition, the concrete elements will often have a long remaining technical life. They can therefore be reused directly in new buildings, which preserves their value while at the same time significantly reducing both resource consumption and CO_2 emissions. SBI 2019:08 estimates a reduction of CO_2 emission of more than 90% when recycling whole concrete elements, which, compared with a 0.3% CO_2 saving for concrete with recycled aggregate, really emphasizes the potential of this approach.

However, there is a big difference between recycling the elements as load-bearing or as non-load-bearing elements. Reusing whole elements as non-load-bearing elements should already be possible today, including as non-load-bearing partitions. When it comes to recycling whole concrete elements, such as load-bearing or stabilizing elements, there is still a long way to go as new methods and workflows must be developed for carefully removing concrete elements from existing buildings. Also, new design methodologies for designers, new assembly methods for recycled concrete elements, and a paradigm for documenting the technical quality and load-bearing capacity are needed. COWI will, in collaboration with the Danish Technological Institute and several partners throughout the value chain, start a research project under the name (P)RECAST, which will map potentials and opportunities for this in the period early 2022 - mid-2024.

4.1.3 DT Models of Innovations for Modular construction: Improving early-stage decision making concrete use in buildings

DT model vision and scope

The vision of the DT model is to create a simple and more time-adequate basis for evaluating the environmental performance of a building/GBN with a primary focus on prefab elements. This could be used to establish a baseline for future optimization in the design process and identify hotspots and areas of interest for optimization purposes.

Basic functionality / high-level services and needs to be covered

The DT model would automatically or semi-automatically apply relevant LCA dataset to materials, construction parts and annual energy consumption in an already established BIM model. For the operational phase of the LCA, the environmental impact of the energy supply or production should be considered if possible and dynamically be updated.

Phase of building / GBN life cycle the DT services are aimed for

The model is aimed at the design phase.

Targeted Stakeholders / Users

Building designers and building operators

DT model associated KPIs

The relevant KPIs would be different LCA indicators such as, global warming potential (GWP), eutrophication (EP), Acidification (AP), Ozon depletion potential (ODP), Photochemical ozone creation potential (POCP), Abiotic depletion potential, elements (ADPE), Abiotic depletion potential, fossil fuel (ADPF). The indicators should be evaluated based on different detail levels of the building/GBN., i.e., per m2 building part per year (kgCO2eq/m2/yr), for the entire building in its lifetime (i.e., kgCO2eq) or the total building impact per area per year (i.e., kgCO2eq/m2/yr).

4.2 Robots in Construction

4.2.1 Technology Description

4.2.1.1 Drones

Drones contribute to a wide range of applications. A drone is a flying platform that allows for mounting different sensors or other attachments. Drones are technically known as uncrewed aerial vehicles (UAVs) or similar terms such as uncrewed aerial systems (UASs).

Technical Description

Drones come in all kinds of designs depending on the intention of use. They are typically divided into two categories: rotorcoptors and fixed wings. Rotorcopters have propellers (typically 4, 6 or 8), whereas fixed wings resemble more of an airplane. The fixed-wing category, including vertical take-off and landing drones (VTOLs), is most often used for effective mapping and can cover 500+ hectares a day. Rotorcopters drones have the advantage that they can hover in the air, making them suitable for mapping and inspections.

Innovative Characteristics

The innovative characteristic of the drone lies in its multifunctional capabilities. The use cases are most often limited by regulations or safety. Drones have been built for many purposes, and other than the above limitations, another limitation is the drone's allowed load. In recent years more drones are becoming 'intelligent,' meaning that they have the processing capacity to navigate fully autonomously based on inputs from their obstacle sensors.

Applications

The multifunctional capabilities of drones allow for a wide range of applications in the field of construction. The use cases range from mapping to inspection, and details can be customized to fit each specific situation. Some indicative applications of drones in construction are (Frederiksen, Vrincianu, Mette, & Knudsen, 2019; Maghazei, 2022; Merkert & Bushell, 2020):

- Autonomous Site and Progress Mapping using Drones.

- Inspection of Difficult-to-Access Areas.
- Site-surveying.
- Virtual Inspections using 3D-meshes.
- Inventory Scans using Drones.
- Material Recycling and LCA Mapping.
- Mapping of Solar Panel Potential.
- Thermal Inspection of Roofs and Solar Panels.
- Asset Management with Drones.
- Scan-to-BIM.

4.2.1.2 Static Laser scanning

3D laser scanning is considered state-of-the-art regarding 3D registration and documentation. It is highly used for existing conditions documentation due to its high accuracy and efficiency compared to traditional surveying.

Technical Description

For the built and construction environment two methods are widely in use:

- Static laser scanning, where a 3D laser scanner is mounted on a tripod or other fixed object during scanning -can be a robot moving the scanner to the following scan location. This method can be very accurate and is often used in complex and congested areas.
- Mobile scanning, where the laser scanner performs the scanning while in motion, allows for quicker captures. The method is often based on SLAM (Simultaneous Localization and Mapping) algorithm and can be very effective and thus often used to map entire building complexes.

The scanning methods have a typical range of 50-150 m but will most often be used in enclosed environments and within maximum 50 m of relevant objects i.e., facades. The resulting 3D point cloud from laser scanning is best explained as organized voxels -like a 2D image consisting of pixels organized in rows and columns. A point cloud consists of voxels (volumetric pixels) arranged in rows and columns with depth.

A point cloud can have different characteristics, such as being mathematically ordered with normal vectors or unordered (no normal vector information), colorization, density and coverage. All characteristics adhere to what point clouds can be used for.

Innovative Characteristics

The high precision and detailed data sets from static laser scanning creates the base of innovative use cases. The extreme detail of the data sets makes it possible to detect, register, and model small details in a scene. In addition, the characteristics of the mathematically ordered point cloud containing normal vectors offer the possibility of using mathematical modelling principles on the data, paving the way for automated object creation and modelling.

For mobile scanning, the movement allows for quicker data capture, making it possible to cover larger areas as mobile laser scanners are typically carried or pushed around, mounted on a vehicle or drone, but the possibilities are endless. Mobile laser scanners can be mounted to autonomous robots like static laser scanners. In fact, the same laser scanning-based technology is often used to navigate autonomous robots.

Applications

Some indicative applications of static laser scanning in construction are **(Javaid, Haleem, Pratap Singh, & Suman, 2021; Wu, Yuan, & Tian, 2021)**:

- A point cloud of existing conditions on a site is the optimal base for 3D-modelling, whether it is to create a navigation map for autonomous robots, BIM-modelling or registration and documentation.
- Existing conditions documentation.
- Clash check of design.
- Dimensional control during fabrication.
- Autonomous progress mapping and monitoring.
    - Floor flatness.
    - Construction verification.
- Scan-to-BIM.

4.2.1.3 Virtual Reality (VR)

VR immerses the uses in a virtual world. The VR-world is generated in 3D and allows the user to look around and navigate as if it was reality.

Technical Description

VR uses headsets in which the user sees the generated VR world. The user often uses handheld controls to walk around in the VR scene and interact with objects. View angles follow the users own head movement, allowing them to look around in the immersive VR world.

Innovative Characteristics

Letting the user visualize the construction site from e.g., the office creates opportunities such as progress visualization, walking around the construction site remotely, testing workflows, or how inventory will fit in the finished spaces. Some VR sets include multiple senses such as hearing, smelling, and feeling, and can be coupled with different devices for movement, such as stationary training bikes, treadmills, or special build equipment, allowing for the most immersive experiences. VR scenes can also enable the user to manipulate the scene by moving objects around or fulfilling a work routine.

Applications

Some indicative applications of VR in construction are **(Davila Delgado, Oyedele, Demian, & Beach, 2020)**:

- Safety Training using VR.
- Move Around in New Construction.
- Progress Visualization.
- Test of Flows, Wayfinding and Work Processes.
- Light Simulation.
- VR-meetings.

4.2.1.4 Augmented Reality (AR)

Augmentation of reality is possible using augmented reality (AR) tools. In AR, the reality is augmented with an extra layer e.g., by allowing the user to point their tablet's camera at a scene and visualize in real time a new building on what is now just an empty field.

Technical Description

AR tools are typically headsets, tablets, or mobile phones with a camera and GPS. Like VR, there are equipment options that allow the user to interact with and manipulate the scenes. Many VR headsets have different apps, such as Microsoft Teams, to let participants in the Teams call see what the person with the AR headset is seeing. Other apps allow the spectator to manipulate the scenes, such as drawing arrows for direction or adding notes to AR-scene available for the AR-headset user to see in real-time.

Innovative Characteristics

The innovative characteristics resemble the ones for VR, except the user can interact with the real world in combination with virtual assets instead of being entirely virtual.

Applications

Some indicative applications of AR in construction are **(Davila Delgado, Oyedele, Demian, & Beach, 2020)**:

- Support using Mixed Reality.
- Identify Errors Early on when Fitting Prefabricated Elements.
- Visualize Landscaping.
- Remote Inspections.
- Underground Piping Visualization.
- Visualization of Clash Detection.

4.2.1.5 Sensors and Internet of Things (IoT)

Internet of Things (IoT) uses sensors to measure different parameters to know the actual performance of different objects/components (rooms, machines, vehicles, structures, etc.). The obtained data can, through appropriate processing and visualization, provide relevant information to inform decisions.

Technical Description

To fulfill the above-mentioned goal, IoT applications consist typically of the following components:

- Sensor devices, used to measure the parameters of interest.
- Communication infrastructure, to transmit data from acquisition to storage and processing locations.
- Data storage infrastructure, to store and access efficiently the collected data.
- Data analytics and presentation to extract information from collected measurements to inform decisions. Data analytics can take place, if need be, in near real-time. Raw or

processed data can be accessed remotely on the internet and displayed in various supports (cell phones, tablets, laptops, etc.).

Innovative Characteristics

The innovative characteristics of IoT solutions are that they enable them to move from assumed performance to actual performance. This paradigm shift allows making decisions based on actual performance, hence opening the door to optimization.

Applications

Some indicative applications of IoT in the construction industry are listed below, categorized in applications during construction phase and during operational phase (Salih, et al., 2022).

During the construction phase:

- Sensors to track and document the impact of construction activities (e.g., vibration levels, noise levels, air quality levels).
- Sensors to track the location of machinery and tools (to optimize construction processes and for traceability of the origin of possible impacts during construction).
- Sensors to measure environmental conditions and performance of materials, as means of quality control (e.g., moisture measurement of wooden/timber elements before installation).
- Verification of performance of components during the construction process (e.g., inclinations and stresses of retaining walls, etc.).

During the operation phase:

- Room Utilization Monitoring using GDPR Compliant Sensors, to assess the flow of people and room/space utilizations.
- Sensors to measure building performance (noise levels, light intensity levels, air flow, air quality, temperatures, power consumption, etc) to optimize building operation and/or CO_2 impact (Home | IC-Meter).
- Sensors to check structural responses (e.g., accelerations in seismic areas, the tilt of structural elements, etc).

4.2.2 SOTA for Robots in construction

The use of robots in construction has had a slow increase compared to the technological advancements of the world. (Carra, 2018) states that robotic technology historically has encountered strong resistance in the construction field due to various barriers. Opposite the barriers, there are drivers who lead the construction field in a more robotic and automated direction.

4.2.2.1 Robots in Construction

Robots in construction is in the case of the PROBONO project defined as the use of robots for construction inspection, particularly matching implementation to design, combined with BIM-aided-smart construction, renovation maintenance and demolition.

In 2017, McKinsey pointed out the efficiency potential which was lacking from construction sites (McKinsey&Company, 2017) and which is still present today (Akinradewo, et al., 2021). In Akinradewo's review article from 2021 they conclude that:

"*construction automation and robotics increase accuracy of components' dimension through the use of lasers for dimension analysis, promote design specifications through the use of computer aided designs, increase quality of construction products by ensuring standards are met, brings cost effectiveness as value for money spent is achieved, eliminate material wastage due to accurate and precise estimate of materials needed, reduce construction accidents due to the usage of machines for dangerous construction activities, improve working condition as workers' are more secure and safety is guaranteed, and reduce labour cost given the fact that machines are deployed for construction activities.*"

4.2.2.2 Robots, Automation, and Digitalization of Construction Sites

(Carra, 2018) describes the construction life cycle in 7 main phases (*Figure 16*). Each of the phases can benefit from the introduction of robots, automation, and digitalization. The following chapters will go through each phase and provide a brief overview of the state-of-the-art within the category.

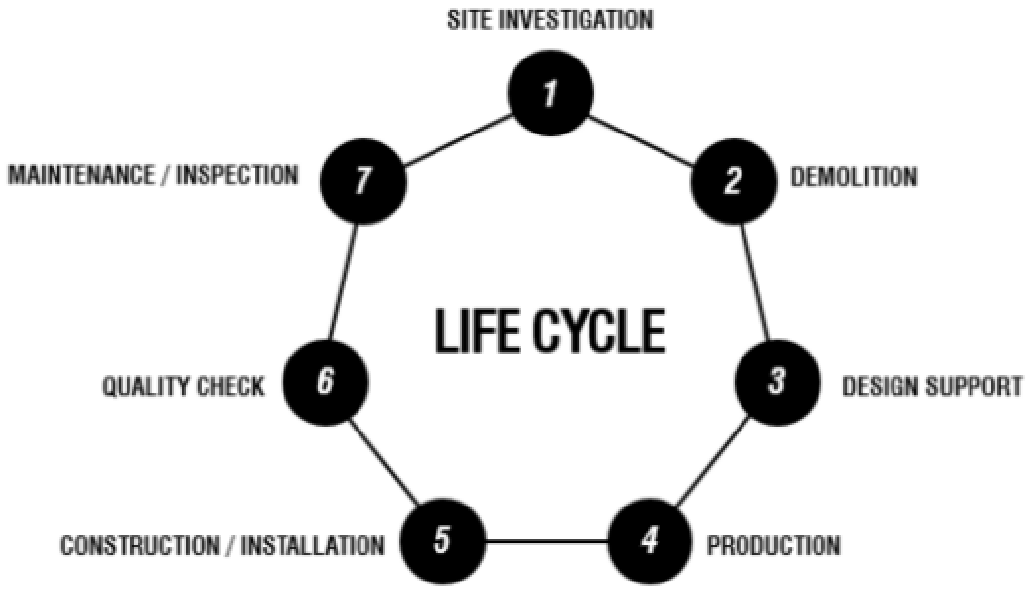

Figure 16: The life cycle of a construction process as proposed by (Carra, 2018)

4.2.2.3 Site Investigation

Site investigation includes all types of assessments before and during construction. Many technologies are available to assist and bring automation into the site investigation. The modern surveyor or geotechnical specialist will have the capabilities in their toolbox to utilize these technologies. The core base of the site investigation tools is that data is georeferenced with a spatial component.

Laser scanning

Laser scanning is a common technology used for existing conditions documentation when doing renovations or extensions on existing buildings. Furthermore, it has established itself as a rapid method for spatial data acquisition with a wide range of applications (Randall, 2011). The output from laser scanning is a point cloud, which can be utilized on its own or as the foundation of BIM modelling.

Prior planning of the data capture is essential to efficiently reduce onsite activity disruptions (Aryan, Bosché, & Tang, 2021). Traditionally, the surveyor will conduct the scanning by placing a tripod with a mounted scanner, wait for it to finish scanning, and then move it to the next position (static laser scanning) or walk around the construction with a handheld mobile laser scanning or mounted to a vehicle/platform.

A method to gain attraction is using a robot carrier to raise the efficiency of data capture. Mounting the laser scanner to a robot allows for an autonomous or robot-assisted workflow. One of the more adapted robots is the SPOT from Boston Dynamics, which enables mounting a wide range of sensors and equipment (Figure ***17***17). It has been adapted into documentation and mapping workflows with several use cases (Knechtel, Klingbeil, Haunert, & Dehbi, 2022).

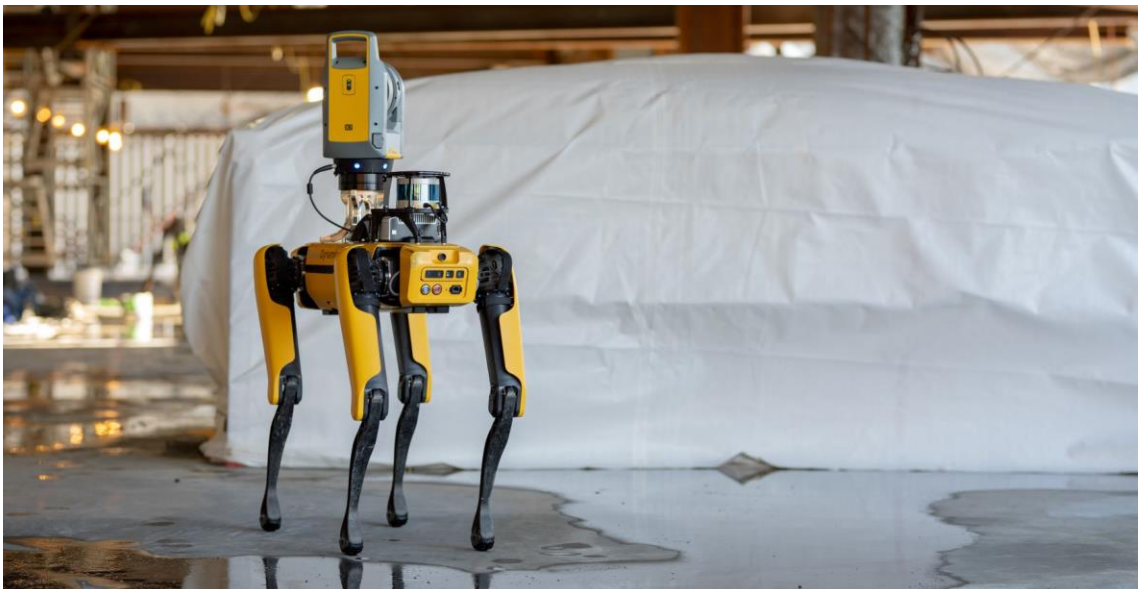

Figure 17: SPOT robot from Boston Dynamics with mounted laser scanner (BostonDynamics, n.d.)

Drones

Another method for site investigation is the use of drones. Drones are mainly able to efficiently collect large amounts of data on the exterior parts of the construction, meaning either the outside of buildings or around the construction site as a whole. Most drones can follow pre-planned paths and capture data autonomously. More drones are getting equipped with intelligent obstacle avoidance sensors, allowing them to plan their flight paths themselves (Figure 18).

Figure 18: The Skydio drone is equipped with intelligent sensors for autonomous navigation and flight planning (Skydio, n.d.)

Demolition

Using robots in demolition or utilizing technologies such as BIM or virtual twins can help a construction contribute positively to a circular economy by planning for demolition (Nikmehr, Hosseini, Wang, Chileshe, & Rameezdeen, 2021). Information about assembly and disassembly can be incorporated into the BIM-model or a virtual twin, together with detailed information about the construction materials which has been used or, if existing, their digital material passports.

Design Support

In a renovation project, details of existing conditions can be modelled from point clouds obtained from laser scanning or photogrammetry. Use 3D-meshes/visual twin for getting the surrounding context of the design.

Computational and parametric design

Using parametric design and BIM-tools can contribute to a more sustainable design concerning LCA (Serda, et al., 2017).

Production, construction, and installation

Production of components or systems used in the construction can utilise assembly robots, on-site manufacturing and UWB tracking.

Quality Check

Digital asset management, like BIM and digital twins can support on quality check, with clash control, simulations, and AR/VR (digital worlds, gamification).

Maintenance and Inspection

Sensors and autonomous data collection support maintenance and inspection

4.2.3 DT Models of Innovations for Robots for Construction Inspection

Digital twins are virtual replicas of a component, an asset, a system, or a process. The aim is to integrate as many relevant elements as needed for a digital twin to reflect the real world. A digital twin can start with a visual twin – mostly a 3D representation of the asset or asset entity. Adding further information to the digital twin such as functionality or performance data from different sensors can help transform it into a full digital twin.

4.2.3.1 Technical Description

Visual twins are either created from 3D models, BIM or can be point clouds or 3D meshes. Visual twins are most often described in 3D to replicate the asset most accurately.

A digital twin for a built environment asset will move from 3D to an at least 4D asset representation. Usually, the foundation is a BIM model with adequate detail/BIM dimensions. BIM dimensions are divided into time, cost, information for facility management, sustainability information, and health and safety. On top of the BIM information, adding real-time data about usage, performance, temperate or weather as examples creates a digital twin.

4.2.3.2 Innovative Characteristics

Digital twins allow for effective planning and operation, and maintenance activities. It can manage all information required during the life cycle of an asset, from design to demolition. Furthermore, it creates the ability to run simulations on different scenarios. Digital twins can be fitting to the need of use, meaning some parts of an asset can be represented as a visual twin, whereas areas of interest can be twinned to contain needed details such as sensors for monitoring temperature, monitoring the number of people in a room, or monitoring electrical issues. The visual or digital twin can be used in VR or as a foundation for AR-use cases.

4.2.3.3 Applications

- Operation and Maintenance
- Input for robot navigation
- Simulations
- Evaluating performance
- Embedded information about building materials, installation, and disassembly guides
- Sustainability evaluation and monitoring
- Demolition and renovation waste estimation and planning
- Design validation
- Clash detections
- Site planning
- Design optimization
- Sharing data

4.2.3.4 Reuse of materials within a GBN

The application of a DT model in relation to GBN and Robots in construction, could as described above be diverse. One application possibility could be using different scanning technologies to map materials and structures in existing buildings coupling them in a DT to enhance the potentials of materials reuse.

DT model vision and scope

The vision of the DT is to create a simple overview of reuse-potentials of materials in existing buildings to improve the basis for and probability of materials being reused as well as enable data inputs to be made to enrich the material data in the DT. It could for instance be based on an ambition of reusing materials from one or more existing buildings for demolition in a new project in a GBN.

Basic functionality/high level services and needs to be covered

The DT model would create an overview of materials or construction parts in the existing building/GBN and couple of visual data on the materials with various materials-specific information.

The first step would be creating a simple overview of the existing materials for reuse. The next step would be a dynamic and easy link to the projects where the materials are expected to be applied in, so material availability can inspire an easier application in the new buildings.

Phase of building / GBN life cycle the DT services are aimed for

Coupling the design phase of new build or retrofit with the demolition/recycling phase of existing buildings.

Targeted Stakeholders / Users

The DT is aimed at the building/GBN designers and Building owners to provide a qualified basis for reusing materials from the existing buildings.

Furthermore, the DT is used to enrich the data created from the building scans. It would require for the user to be able to manually process some of the material data from the scan by visual inspections or other. Or to enrich the data by information from examination of the building with respect to problematic substances or other relevant information.

DT model associated tools

A BIM model with a reality capture mesh based on imagery scans of the existing building, visualizing the building materials in their accurate location and allowing for annotation as well as different analysis across the materials at hand. It would be based on digital scans of the specific buildings and further processing of these data to identify material types and quantities.

DT model desired features

The DT should allow for annotations and quantification of the individual materials.

User interface requirements

The building designers using the DT for assessing the reusability of materials into new projects, should be able to evaluate the different material information from different angles, search across the different material types, locations, conditions, expected remaining lifetimes, colour, reusability or other parameters that might be relevant in terms of trying to locate new ways of application.

5. SOTA and DT Models of Innovation for Building Materials / Upcycling

5.1 Recycled Plastics as Raw Materials

5.1.1 Technology Description

The plastic waste is modified to obtain new raw materials for construction applications. The modification technology consists of a chemical modification carried out in a semi-industrial extruder. In this process, the plastic waste (after separation and grinding) is fed into a process in which the materials are mixed, homogenised and functionalised.

CIDAUT is committed to the modification of complex and challenging to recycle polymers to obtain construction elements with high added value. These wastes may or may not come from construction, and they can enter LLs in two ways:

i. Low density foam from plastic waste

Another polymer with low recyclability is LDPE (Figure 19). CIDAUT has worked on the modification of this material to transform it into flexible and low-density foams (100kg/m^3). These foams contain 40% of recycled materials and have excellent thermal and acoustic insulation capacity (Saiz-Arroyo C., 2012).

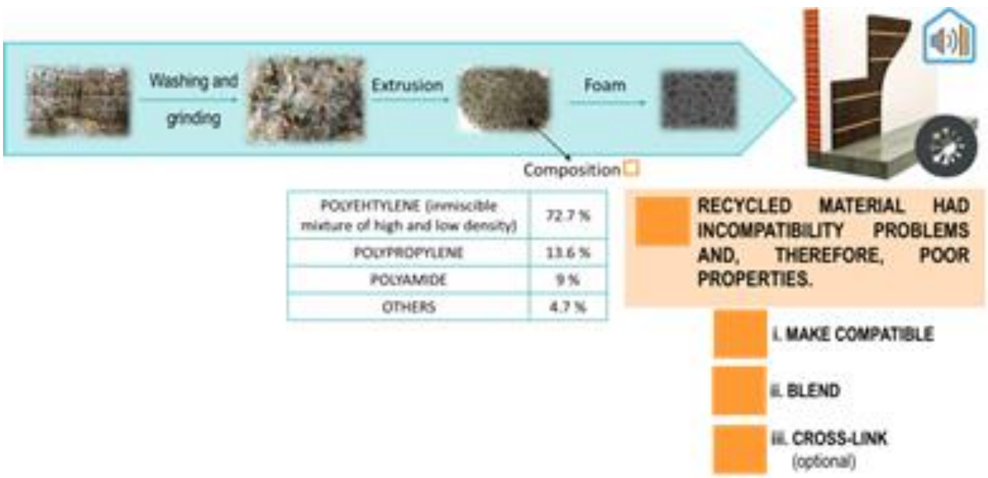

Figure 19: Low density foam from plastic waste (source CIDAUT)

The properties of the achieved profiles are shown in Figure 20.

▪ Insulation properties were determined by dynamic stiffness test (According to UNE-EN 29052-1:1994).

Dynamic rigidity is associated with damping capacity of a product.

▪ Only **most favorable foams** were tested. According to: **density, cellular structure and content of recycled material**.

			RECYCLED MAT./PE/COMP.	RECYCLED MAT.LEVA
CROSS-LINKED	CBA	COMPRESSION MOULDING	189.5–225.9 MN/m3	101.9-176.7 MN/m3
CROSS-LINKED	PBA	GAS SOLUTION	134.2-139.0 MN/m3	95 MN/m3
NON – CROSS-LINKED	PBA	GAS SOLUTION	57.1 MN/m3	-
COMMERCIAL PRODUCT			27 kg/m3	173.2 MN/m3

Figure 20: Properties of the achieved profiles of Low-density foam from plastic waste (source CIDAUT)

ii. Thermoplastic composites from recycled matrices

All sectors are looking for the introduction of thermoplastic composites to replace metals or thermoset composites together with the need to improve the sustainability of products. In this sense, CIDAUT has worked on the modification of multilayer and coloured polymeric materials (Asensio M, 2020) such as PET from food packaging, in order to achieve the appropriate properties to form part of the composites (Figure 21).

These matrices together with long glass fiber were processed by pultrusion to obtain profiles with mechanical properties on a par with aluminum (Asensio, et al., 2020). The content of fiber in these composites is 55% vol. These materials can be used in different LLs to replace metallic structures, e.g., supports for the installation of plasterboard. The properties of the achieved profiles are shown in Figure 22.

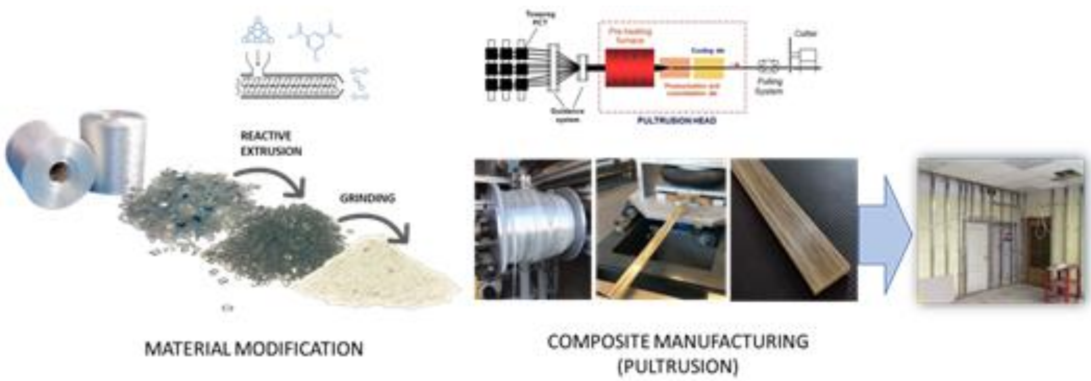

Figure 21: Thermoplastic composites from recycled matrices (source CIDAUT)

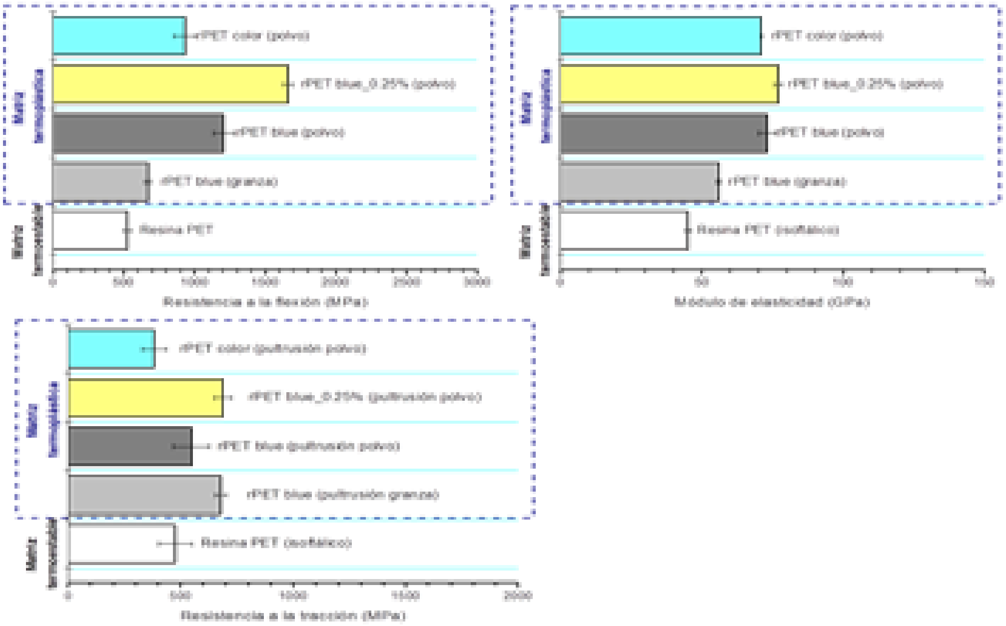

Figure 22: Properties of the achieved profiles of thermoplastic composites from recycled matrices (source: CIDAUT)

The innovation of the two technologies proposed by CIDAUT is based on the revaluation of plastic waste that is currently not profitable to recycle by transforming it into products with high added value: composites and foams.

The proposed applications could be:

- Low density foam from plastic waste: acoustic and thermal insulation for buildings.
- Thermoplastic composites from recycled matrices: Structural elements with similar requirements to current aluminum structures in buildings or street furniture.

5.1.2 SOTA for Recycled Plastics as Raw Materials

Plastic is undoubtedly a wonderful human invention that makes our lives easier every day. However, due to its non-biodegradable properties and its insufficient recyclability ratio, it has a major impact on the environment. The accumulation of plastic waste has become the most important threat to modern civilization, as it is affecting not only the environment but also the economy (Geyer, 2017). The high volume of accumulated plastic waste in the environment has endangered many marine lives and the sustainability of the environment (Wong, 2020).

Plastic waste is generated by many sectors. Figure 23 shows the waste generated in Europe in 2019 (PlasticsEurope, 2019).

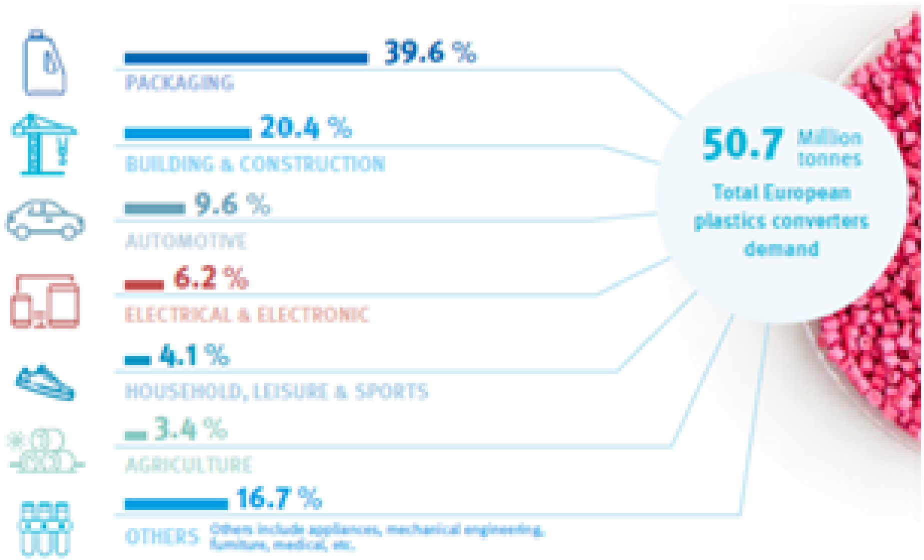

Figure 23: Waste generated in Europe in 2019 (PlasticsEurope, 2019)

Figure 23 also shows that construction is one of the main waste streams in Europe. In fact, more than 10 million tons were produced in 2018, of which more than 1.7mton was plastic waste and of which only 26% was recycled. Of these recycled polymers, PVC has the highest recycling rate (51.7%), followed by HD PE (12.8%0), EPS (8%), PP (7.4%), PS (1.7%) and PE -LD (5.1%) (Eurostat, 2018). Other plastics end up in landfills or are incinerated because their recycling process is inefficient (economically and environmentally). The main problem is that polymers from construction are often highly contaminated or a mixture of polymers that is very expensive to separate.

This sector, in addition to producing plastic waste, is heavily involved in the introduction of recycled materials from within and outside the sector. In recent decades, the use of plastic waste in civil construction has been widely studied (Kamaruddin, 2017). In fact, in 2018, approximately 4 million tons of recycled plastic were used in new products. The building products sector used 46% of the total recycled plastic put on the market (PlasticsEurope, 2019). In most cases, plastic waste has been used in concrete or mortars, either as fine or coarse aggregate, where the maximum that is introduced is 20-30% (Bindra, 2003). Properties such as durability, light weight, strength, toughness, and high heat insulation make waste plastics suitable for use and recycling in the construction industry.

Mainly, there are two forms in which waste plastics are being reintroduced: plastic aggregates and commonly plastic fiber (Gu, 2016).

On the one hand, plastic aggregates are used to replace coarse aggregates and fine aggregates (Babafemi, 2018), (Mercante, 2018). An advantage of them is that they usually have a lower bulk density than granite, limestone, or basalt. For this reason, they are preferably used for lightweight concrete. In order to obtain these plastic aggregates, they are mechanically recycled and, in some cases, the material is chemically modified to improve some properties in concrete (Lee Z. H., 2019), (Mashaan, 2021).

On the other hand, plastic fibers are used as reinforcement and can replace ordinary steel fiber to improve durability and mechanical strength (Yin, 2015). The main drawback of ordinary steel fiber as concrete reinforcement is its susceptibility to corrosion, especially on the surface of concrete when exposed to seawater or salt water without adequate protection. The use of waste plastics as reinforcement allows properties such as durability, lightness, strength, toughness, and high heat insulation suitable for use in construction to be achieved (Azmi, 2018).

Therefore, the use of waste plastics in the manufacturing process of building materials or cement composites would allow the recycling of these wastes in place of aggregate materials. Although the use of plastic waste in building materials seems to be environmentally advantageous, the reuse of waste is not encouraged along the lines of the circular economy.

These materials, thanks to their flowability, have other options to be taken into account when considering plastic recycling, like street furniture, ceilings and floors, batteries, PVC windows, acoustic barriers, cable ducts and pipes, panels, cladding and insulating foam (Coventry, Woolveridge, & Hillier, 1999). These applications allow for the reuse of waste and a possible recycling cycle. In this sense, CIDAUT is committed to the modification of complex and difficult to recycle polymers to obtain construction elements with high added value.

Currently, there are numerous scientific works that have been demonstrated at the laboratory level. In addition, in a relevant industrial environment (TRL 4-5), various techniques of chemical modification of polymer macromolecules based on PET or LDPE aim to confer improvements in their rheological or mechanical behavior. CIDAUT, who has extensive experience in this type of modifications (lab and industrial scale, as it provides services of material production in short series as an industrial service), will scale the production of the modified materials to reach the construction and validation of the prototype composites (TRL 7).

5.2 Smart Engineering Technologies and Materials applied to Pavements and Concrete Structures

5.2.1 Technology Description

Smart Engineering Technologies and materials applied to pavements and concrete structures include a wide range of innovations. In this project ACCIONA focuses on the development of innovative concrete and asphalt mixes with reduced environmental impact. In particular, ACCIONA will develop sustainable road pavement and low carbon concrete. These technologies will potentially be implemented in the neighbourhood concept of the Madrid LL.

i. Sustainable road pavement

Road construction is a sector where measures need to be taken to reduce the energy demand and environmental impact, and to reduce the use of raw materials cost-effectively. ACCIONA aims to support this by providing technologies that facilitate asphalt recycling and the use of recycled concrete aggregates. These will be integrated appropriately into an optimal design of asphalt pavements and thereby increase their commercial viability (Figure 24).

Thus, medium, and high rates of reclaimed asphalt (RA) will be incorporated for the preparation of new asphalt mixtures in the structural layers (surface, binder and base). Also, recycled aggregates from concrete waste will be used as secondary aggregates in replacement to natural graded aggregates for the subbase.

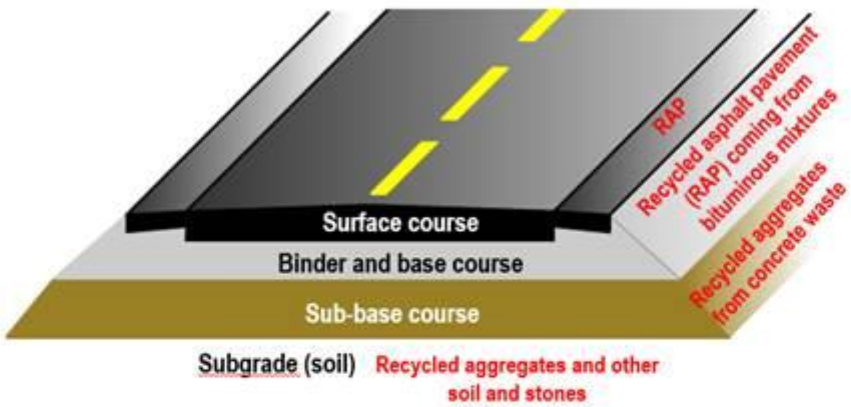

Figure 24: Recycled aggregates used in pavements (source: PROBONO GA)

Such a solution improves both sustainability and cost-efficiency of the asphalt pavement industry, reducing the CO_2 footprint of pavements, the environmental impact and associated costs related to the waste generation and disposal.

ii. Low carbon concrete

ACCIONA will develop innovative concrete mixes formulation with reduced CO_2 footprint using recycled aggregates to replace natural aggregates. Alternative supplementary cementitious materials (SCMs) like fly ash and slags may be also investigated to partially replace the Portland cement.

In addition, CELSA investigates the use of black and white slag generated during steel production as additive to cement, concrete and asphalt production, respectively.

Magnetic black slag impurities are removed by using a hard magnet decantation. Next, the material is submitted to a vibration process to grill it and finally separated by particle diameter as different particles sizes could have different applications. This new material, called steel slag aggregates are part of the mix of asphalt and concrete production.

On the other hand, white slag is submitted to a particle size separation and used as clinker replacement for cement production.

5.2.2 SOTA for Smart Engineering Technologies and Materials applied to Pavements and Concrete Structures

The sustainability of the construction industry is a priority in innovations made towards mitigating its notoriously high carbon emissions. Developments in low-carbon concrete and sustainable asphalt technologies are of peak interest today under the scrutiny of emerging policy pressures.

One of the main policies focused on the circular economy is the EU waste policy. A key principle of this policy is to move waste management up the 'waste hierarchy' and to follow the principles of a circular economy. In this context, the aim is to maintain resource value in the economic cycle, to prevent and reduce the negative effects of using primary resources on the environment and society. Recycling is one of the main ways to reduce the consumption of primary resources, by replacing them with secondary materials made from recycled waste (Agency, 2019).

The construction sector is responsible for over 35% of the EU's total waste generation (Eurostat, 2018). As a result, Construction and Demolition Waste (CDW) is one of the priority waste streams in the EU, with a mandatory target under the Waste Framework Directive (2008/98/EC) (EuropeanUnion, 2008), Article 11.2, of 70% recycling. CDW consists of the debris generated during the construction, renovation, and demolition of buildings, roads, bridges. There, a wide variety of materials are contained, such as concrete, bricks, wood, glass, metals and plastic, including hazardous materials like asbestos. The mineral fraction of CDW is the main one used in construction applications, like asphalt pavement and concrete elements, as recycled aggregates.

Besides the recycled CDW aggregates, there are several waste materials and industrial by-products, which are mostly landfilled, that can be used in concrete and asphalt to contribute to a circular economy in the construction industry.

Sustainable road pavement

The construction of a new road has a number of implications for the environment, consuming large amounts of materials and energy. Aggregates make up the largest share of the mass and volume in a pavement structure, whether used without a binding material (e.g., unbound sub base or base material), or as part of an asphalt bound layer. Specifically, aggregates undertake more than 90%wt of asphalt mixtures and 100% of unbound layers.

Although aggregates are relatively low cost and have a low environmental impact per unit mass relative to other materials that are used in pavements, they can have a significant impact on pavement sustainability because they are consumed in such large quantities.

Aggregate used in unbound bases and sub bases may be derived from natural sources or may be manufactured or derived from recycled pavement materials or other suitable demolition materials, such as concrete from construction and demolition waste (CDW). For hot mix asphalt, aggregate may be used from natural sources, reclaimed asphalt (RA) or manufactured sources. From a sustainability perspective, it is convenient to combine manufactured aggregates with medium to high amounts of recycled materials, while achieving a level of long-term performance at least comparable to that of conventional pavement structures.

Reclaimed asphalt (RA) is most often produced when existing asphalt layers are cold milled from an existing asphalt pavement, as part of a rehabilitation or maintenance overlay, and the removed materials stockpiled for use in new asphalt mixtures. Being composed of two valuable non-renewable resources, i.e., aggregates and bituminous binder, its conscious use can ensure the sustainability of asphalt pavement construction. The inclusion of RA in new asphalt mixtures has traditionally been restricted to binder and base courses, as well as in the unbound layers, with limited use in surface courses. However, with increasing demand on limited resources of high-quality aggregate resources, there is a growing emphasis on increasing the percentage of RA in all pavement layers. Utilisation of RA as a component of asphalt mixtures depends primarily on the capabilities of typical mixing plants, but their use in the range of 15-20% is becoming a standard practice for the production of bituminous mixtures (Tarsi, Tataranni, & Sangiorgi, 2020).

Recycled aggregates coming from recycling and re-use of CDW have a high potential, as there is a re-use market for these aggregates in roads. Technology for the separation and recovery of construction and demolition waste is well established, readily accessible and in general inexpensive. However, the level of recycling and re-use of CDW waste varies greatly (between less than 10% and over 90%) across the Union. In some member states, this waste stream is to a large extent disposed of, using up valuable space in landfills. In addition, if not separated at source, it can contain small amounts of hazardous wastes, the mixture of which can pose particular risks to the environment and can hamper recycling.

Today, recycled aggregates are mainly used in the lower layers, such as subgrade, sub-base, and base. However, in rural roads they can be adopted also for bound layers, towards the surface of the structure and may be constituents of bound layers and of novel surfacing applications (Pourkhorshidi, Sangiorgi, Torreggiani, & Tassinari, 2020).

Other materials used in asphalt and in unbound base and sub bases include slags and foundry sand, depending on local availability.

Low carbon concrete

Concrete plays a major role in the construction industry, being the most widespread construction material worldwide used for buildings, infrastructural systems, geotechnical works, industrial plants, road pavements, etc. However, the concrete industry is a key player in the global emissions of carbon dioxide, which is acknowledged to contribute by a percentage of approximately 8%, whereby 90% of such emissions are related to cement fabrication (Andrew, 2019). Such a huge contribution of the construction industry to excessive releasing of greenhouse gases in the atmosphere is stimulating scientific researchers, as well as decision-makers, toward the development of innovative concrete with reduced environmental impact.

Current practices geared towards the use of supplementary cementitious materials (SCMs) and various admixtures as alternative to cement, as well as recycled CDW and steel slag as alternative to natural aggregates. These technological changes can be accelerated through regulation and legislation, but unfortunately the current directives in some countries are still obsolete.

The SCMs adopted are often industrial by-products or landfill waste such as ground granulated blast-furnace slag (GGBS), fly ash (FA) (Vanoutrive, 2022), coal bottom ash (CBA) (Sanjuán, 2017) (Baig & Varghese, 2019) (Mohammed, et al., 2021), recycled concrete powder (Medina, 2022), glass (Tamanna, Mohamed Sutan, Lee, & Yakub, 2013), ceramic waste powder (Mas, 2015) (Singh & Srivastava, 2018) (El-Dieb, Taha, & Abu-Eishah, 2018), wind turbines blades (Miceli, 2019), etc. These alternatives to cement are in the early stages of development and cement itself remains highly profitable for companies to change.

Regarding the recycled aggregates, there are numerous scientific works (McNeil & Kang, 2013) (Meddah, 2017) (Dharan & Chithra, 2017) (OBE, 2019) (Plaza, 2021) as well as European research projects (RE4 Project, n.d.) (VEEP Project, n.d.) that have demonstrated the viability of using recycled aggregates, mainly from concrete waste, for low carbon concrete. Recycled concrete aggregates (RCA) are produced in stationary recycling plants similar to those used for natural, crushed aggregate production. Processing usually includes two-stage crushing (primarily with jaw crushers and secondarily with impact crushers), removing the contaminants and screening. After primary crushing, the residual reinforcement is removed by large electro-magnets. All types of contaminants, such as dirt, plaster, gypsum and other building waste, must be carefully removed by water cleaning or air sifting. RCA can also be processed in mobile recycling plants. These are typically used for demolition sites with large amounts of homogenous waste which will be reused on site. The main obstacle to implementing RCA is the lower quality of recycled than natural aggregate and consequently of recycled than conventional concrete, especially with regards to durability. So, depending on the quality of the RCA, the replacement of natural aggregates with RCA can be total (100%) or partial (<100%), although most of the current national legislations does not allow or recommend such a high replacement ratio. However, the use of fine RCA below 2 mm is uncommon because of the high-water demand of fine material smaller than 150 µm, which lowers the strength and increases the concrete shrinkage significantly. This high-water absorption and high cohesion of fine RCA also makes the concrete quality control very difficult (Marinković & Carević, 2019). Therefore, some standards and specifications do not specifically mention or even forbid the use of fine RCA in concrete for structural use and limit the use of RCAs. In fact, in many European countries the use of 20% RCAs (just the coarse fraction) in structural concrete is standard practice (ACI, 2019) due to the very strict national regulations. Higher percentages of recycled aggregates require specific analysis, study and testing for each case.

More recent studies have reported the use of mixed recycled aggregates (MRA) for concrete. MRA is a kind of recycled aggregate containing discarded bricks and other impurities that is inferior to ordinary recycled concrete aggregate. MRA account for a substantial fraction of the total CDW The main hurdle to MRA valorisation is its non-uniformity and certain intrinsic properties (i.e high water absorption) that have a direct effect on the performance of recycled concrete. Some research articles reported a decrease of the compressive strength of mixed recycled aggregate concrete by more than 50% compared with ordinary concrete (Meng, et al., 2021). In light of those drawbacks, some studies assessed a surface treatment consisting in soaking these mixed materials in polymers to improve their physical and mechanical properties (Velardo, Properties of concretes bearing mixed recycled aggregates with polymer-modified surfaces, 2021) (Velardo, Durability of concrete bearing polymer-treated mixed with recycled aggregates, 2022).

Several investigations in the literature deal with use of steel slag as aggregate in concrete, as the steel slag presents good morphological and mechanical properties. Steel slags are by-products generated in high volumes in the steel manufacturing industry. Their main constituents are calcium, silicon, ferric, aluminium, and magnesium oxides. Larnite, alite, brownmillerite, and ferrite are also found. Promising mechanical and durability performances in cement-based composites encourage further research to promote the use of steel slag (Pereira Martins, 2021).

Another strategy that is gaining attention in the last 15 years is the development of geopolymer concrete. This technology is out of the scope of this project, but the authors of this deliverable wanted to mention it to have a complete view of the low carbon concrete technologies. Geopolymer concrete replaces cement with industrial waste materials i.e., utilizes fly ash and slag for its mixture along with the addition of a small quantity of alkali activator required for the geopolymerization process (Wasim, 2021).

5.2.3 DT Models of Innovation for Smart Engineering Technologies and Materials applied to Pavements and Concrete Structures

DT model vision and scope

To support and extend the use of demolition materials in the eco-structures, an innovative DT concept is associated with tracking, monitoring and assessment of the material use, and embodied emissions of the whole construction process, including the deconstruction phase of the existing buildings in Madrid Nuevo Norte (urban development in which Madrid LL is located).

The main idea is to close the cycle in Madrid LL by treating and processing the material from demolition and reuse it in new materials for the new area to be built, e.g., sustainable concrete and pavements.

Basic functionality / high level services and needs to be covered

- Track material workflow from demolition, treatment, and reuse.
- Track environmental impacts related to the material upcycling.
- Database for utilization of secondary raw materials coming from demolition.
- Monitor environmental impacts of demolition activities.

Phase of building / GBN life cycle the DT services are aimed for

Demolition, construction, recycling, design.

Targeted Stakeholders / Users

Distrito Castellana Norte (DCN).

Construction/de-construction companies.

Physical twin

In this case, the physical twin could be both the buildings in the area that will be demolished and/or the future buildings and infrastructure that will be built in the future.

User interface requirements

Visual for the entire area of MNN with indication of buildings to be demolished and their inventory information, visual graphs for air pollution measurements. In part this will rely on information provided by a GIS based tool owned by DCN.

6. SOTA and DT Models of Innovations for Social Distancing Considering Epidemiology Risks

This chapter explores three concepts of DT models associated with the blueprints detailed in T3.5. These cover both behavioural and technical mitigation means, and hereafter the focus is on three of the key aspects of pandemics resilience:

- Air quality management and integration in a feedback loop to optimize air quality and minimize airborne contamination.

- Managing users flows to minimize human cross contamination.
- Managing information so to provide the best information to a LL/GBN and minimize the spread of mis/disinformation.

6.1 Mitigating Infection Risks by controlling air quality

6.1.1 Technology Description

Vision

To protect against the mortality associated with indoor air pollution, while reducing the carbon footprint attached to the provision of comfortable indoor environments.

Scope

To automatically interpret indoor environmental quality with a view to preventing the spread of viruses and reducing the energy consumption.
There is no single approach to a single technology, it is rather a consolidation of different technologies used to control the quality of the air, and as needed, to support the destruction of pathogen agents through a feedback loop. This is one of the most common approaches to decreasing the contamination levels in closed spaces, where many people live, spend time and work. Without even utilizing digital twin solutions, most countries have adopted indoor environment measures to control spread of COVID-19.

6.1.2 SOTA for controlling air quality

Indoor air quality (IAQ) has always been a topic of choice for improving users' wellbeing and has been extensively reviewed (Saini, Dutta, & Marques, 2020). Such reviews take advantage of the development of wireless technologies to feed in a cyber-physical systems representation for monitoring and action. This has even led to reviewing building designs for post-pandemic considerations (Megahed & Ghoneim, Antivirus-built environment: Lessons learned from Covid-19 pandemic, 2020).

Many of the actions to be taken from the data fed back from IEQ systems can be linked between the digital and the physical world, so to enable mitigation measures e.g. controlling HVAC, disinfection devices, filtering, etc. (Elsaid, Mohamed, Abdelaziz, & Ahmed, 2021).

Complete IEQ-monitoring solutions have been reviewed in the literature (*Figure* ***25***) (Calvo, et al., 2022; Parkinson, Parkinson, & de Dear, 2019; Geng, et al., 2021).

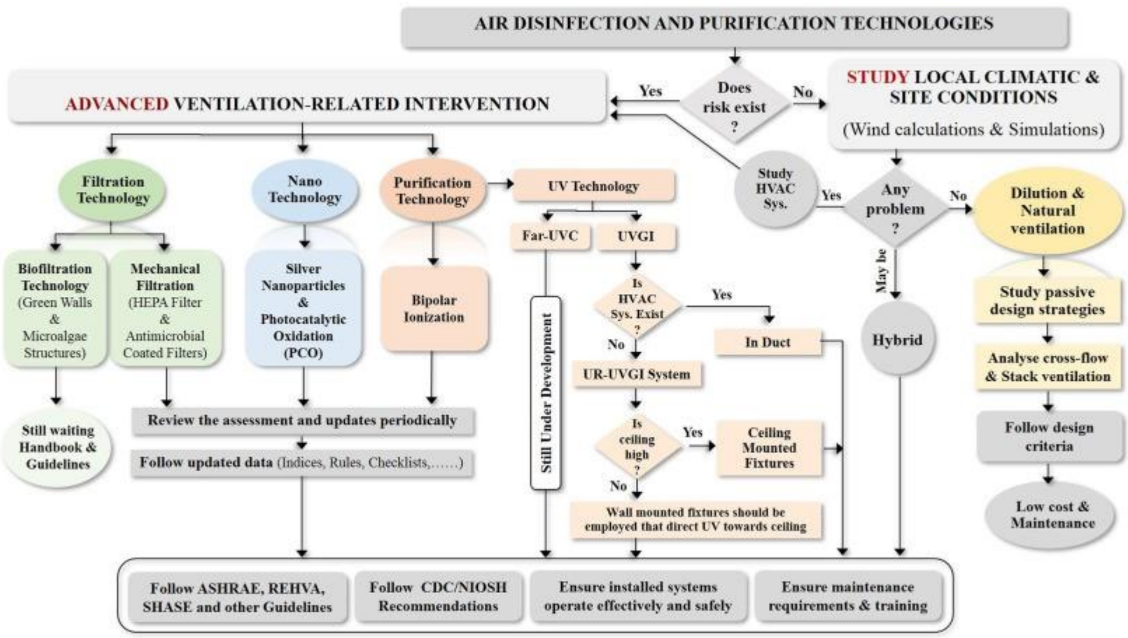

Figure 25: IEQ-monitoring solutions (Megahed & Ghoneim, Indoor Air Quality: Rethinking rules of building design strategies in post-pandemic architecture, 2021)

6.1.3 Digital Twin for indoor environmental quality monitoring

6.1.3.1 Narrative

The DT objective is to monitor IEQ (indoor environmental quality) so as to be able to provide the best environmental conditions to the LL/GBN users. It relies on multiple data sources such as sensors continuously measuring air temperature, relative humidity, CO_2 concentration and illumination. The measured data are transmitted wirelessly to the cloud and analysed. Finally, depending on the result of the analysis, guidelines are issued to achieve the defined levels of comfort and user safety. This can be operationalized and automated e.g. using control systems of the HVAC systems.

6.1.3.2 Blueprint

Basic functionality / high level services and needs to be covered

See section 6.1.3.1 above.

Phase of building / GBN life cycle the DT services are aimed for

Operational

Targeted Stakeholders / Users

- Building operator

- Sustainability managers
- HVAC system maintenance personal

Physical twin

As an example of the physical twin, a school building may be considered. The focus would mainly be on rooms occupied by people, such as classrooms but also include technical facilities, so to make sure in general that the provided and circulated air is appropriate for the intended usage and within norms. The twin would then be represented by the physical rooms, as well as HVAC networks.

DT model associated KPIs

To ensure continuous and real-time operation of the system, the data transmission latency of sensors is a parameter that needs to be evaluated. Apart from it, accuracy and range of sensors must be taken into account with a view to guaranteeing the accuracy of monitored parameters.

DT model associated tools

Two are required: one for data transfer and storage (cloud server and database) and one for data presentation (web platform). For data transmission and storage, an architecture based on the software-as-a-service concept is proposed. For the databases, a master-slave backup mode would be applied to ensure that all data is synchronised over the intranet.

On the other hand, the web platform would provide the information bridge between the indoor environment and the necessary operational policies. The web platform would be open to professionals for visualisation and download of data.

Required Measurements

According to several studies, there is a significant correlation between air quality and the spread of COVID -19 indoors. Measurements would focus on:

- Particulate matter: Dust and other fine particles can accumulate in office environments, especially in areas with poor ventilation or frequent foot traffic.
- Volatile organic compounds (VOCs): Office buildings often contain a variety of products and materials that can release volatile organic compounds (VOCs), such as furniture, office supplies and cleaning products.

- Carbon dioxide: Occupants of office buildings can produce carbon dioxide through their breathing and other activities, and high levels of this gas can indicate poor ventilation or a high occupancy rate.
- Temperature: Maintaining a comfortable temperature is important for the comfort and productivity of office workers.
- Humidity: High humidity can lead to mould growth and other indoor air quality problems, while low humidity can cause dryness and discomfort.
- Ventilation rates: Adequate ventilation is important for diluting and removing pollutants in indoor air.

DT model desired features

Data analytics and corrective decision making

Data requirements

- Sensors data
- HVAC system data
- HVAC system maintenance data

Such data could mainly come from four types of sensors:

- air temperature,
- relative humidity,
- CO_2 concentration and
- illumination

They all would have in common their low cost, high accuracy and remote transmission. In addition, the hardware also would include other functional modules as data transmission modules, data storage modules and power modules.

User interface requirements

UI would focus rather on visualization of data, which could cover for example:

- IEQ measurements visualisation
- Building performance metrics visualisation

- Historical measurements visualisation
- HVAC system maintenance logs
- IEQ diagnosis

Link with LLs

During the seventh wave of COVID-19, health public authorities recommend public buildings to take actions to prevent exposure and contagion by the virus. In this regard, the proposed IEQ monitoring system offers them an effective method to detect uncomfortable situations and prevent the spread of the SARS-CoV-2 virus by means of different environmental magnitudes monitoring.

Considering that all LLs are public places, the proposed DT model may potentially be linked to all of them, providing an effective way to detect indoor environmental risks in advance.

SOTA / Best practice example

SOTA is mainly associated with real-time monitoring of IAQ parameters and generation of alerts to the building occupants to avoid hazardous conditions.

Using an IoT series of tool has great potential for lesser power consumption, small lags, and has a better ability to interact with the physical world. Sensors have demonstrated their capabilities in monitoring both IAQ and IEQ, mostly enabled by low-cost computing, microcontrollers and boards (Calvo, et al., 2022; Geng, et al., 2021; Saini, Dutta, & Marques, 2020; Parkinson, Parkinson, & de Dear, 2019) .

6.2 Controlling disease progression by controlling people flow

6.2.1 Technology Description

The main vision is to minimise disease transmission due to person-to-person contact with the minimum impact on the mobility of users, while optimizing the number of needed resources to guarantee a good service. The scope is to organize the flow of the people in public places, promoting social distancing and avoiding overcrowding.

6.2.2 SOTA for controlling people flow

It has been widely recognized that social distancing was one of the key solutions to control the spread of epidemics.

Moreover, controlling users flows in the buildings and infrastructures help minimize cross-contamination due to human interactions (Rezaei & Azarmi, 2020). Agent-based modelling has been essential for example in modelling human-to-human interactions, and identify cross-contamination based on different transmission modes (Lee, et al., 2021) during the operation phase, but also to help identify and select optimal design of physical spaces (Ugail, et al., 2021). OccSim for instance, has been developed as "*a system that automatically generates occupancy behaviours in a 3D model of a building and helps users analyze the potential effect of virus transmission from a large-scale and longitudinal perspective*".

Together with a control of access and planning of space use, this would lead to a lower risk of contamination in infrastructure (Figure 26 & *Figure* ***27***).

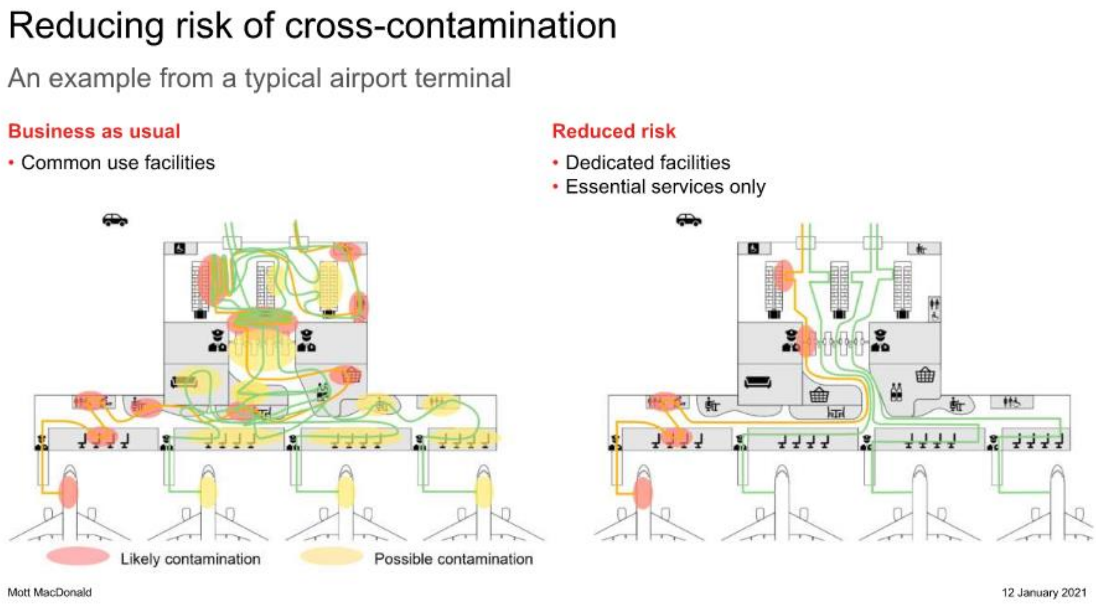

Figure 26: Study for the reduction of cross-contamination risks (Source: Mott MacDonald)

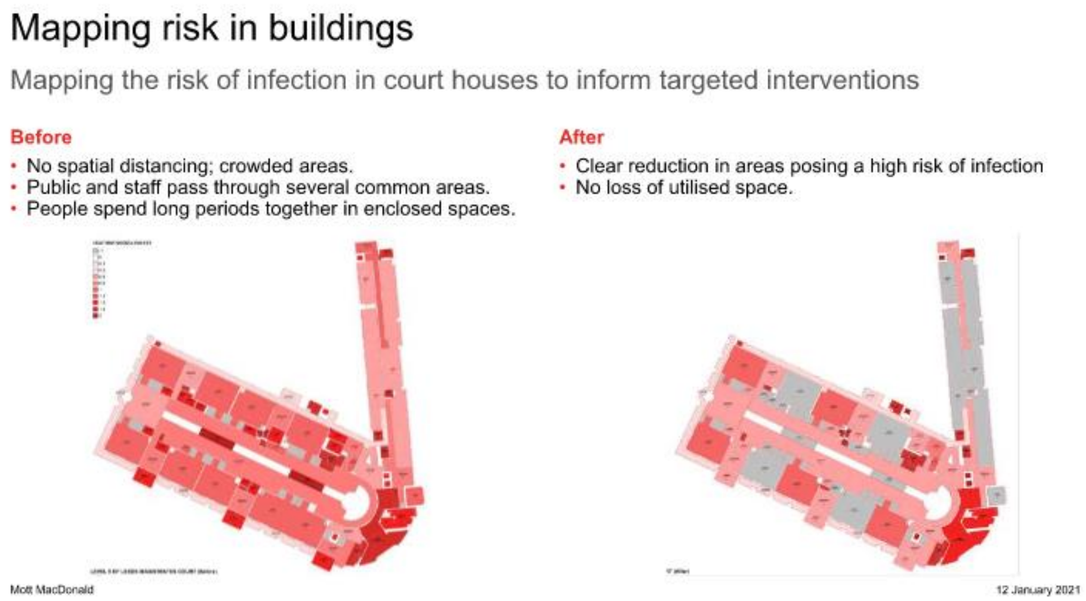

Figure 27: Mapping risk of infection to inform targeted intervention (Source: Mott MacDonald)

6.2.3 Digital Twin for mobility flows

6.2.3.1 Narrative

First, a virtual system which replicates the physical building is developed, based on real information such as time-related measures and/or stochastic models. Once developed, several scenarios are tested on the simulation model to find the best solution.

After the definition of the best configuration, the model is expanded with several sensors with a view to digitalizing the configuration and changing it dynamically. Specifically, with a number of cameras and beam sensors to automatically measure people flow.

Finally, and with this information, the system collects real-time measurements from the physical system, analyses them to find the drawbacks, runs the virtual model and transfers the improvements found to the end user.

6.2.3.2 Blueprint

Basic functionality / high level services and needs to be covered

Section 6.2.3.1

Phase of building / GBN life cycle the DT services are aimed for

Design & operational

Targeted Stakeholders / Users

- Building operator

Physical twin

As an example of the physical twin, a school building may be considered. The focus would be on human-centred circulations and rooms, including classrooms but also corridors and technical facilities, so to make sure in general that human circulations and flows are properly managed.

The twin would then be represented by the network linking the different physical spaces.

DT model associated KPIs

In particular, the most relevant KPI relates to the number of people who pass through a defined point every hour, because it gives a measure of the system efficiency.

DT model associated tools

Briefly, the two parts that constitute the proposed digital twin are: the simulation model and the digital technology for data collection. In relation to the simulation model, there are some agent-oriented simulation software tools, such as AnyLogic, that have the capability to simulate complicated people behaviours within buildings. However, it is common for researchers to develop their own models.

On the other hand, the needed digital technology for this DT would be composed of a hardware architecture and a web platform. Concerning the platform, it would be designed to be the link between the measurements of the sensors and the virtual model.

Required Measurements / frequency

- Number of people who pass through a defined point and their direction in order to have a measure of the people flow and building occupancy.
- Time measures with the aim of obtaining information about the situation in terms of queues and resource utilization.

Both measurements would be monitored on a continuous basis.

DT model desired features

Data analytics, people flow simulation and assisted decision making

Data requirements

For this case, the hardware part is represented by several cameras and beam sensors, located at the entry points. In addition, and as in the following system, other functional modules as data transmission modules, data storage modules and power modules are included in this part.

User interface requirements

- Number of people entering the building and percentage of people having their entry rejected
- Number of people attended per day
- Number of people attended / resource x hour
- Average waiting time

Link with LLs

Real-time people flow estimation is critical for both emergency events and normal building operations. Minimizing the waiting time and maximizing the throughput are the main objectives of service buildings. Moreover, in relation to the current pandemic situation, maintaining an orderly flow of people has become a key issue in any public building.

Considering that all LLs are public places, the proposed DT model may be linked to all of them, providing them with an effective way to organize people flow in view of controlling Covid spread.

SOTA / Best practice example

Social distancing and controlling the flow of people in buildings and infrastructure are effective measures for reducing the spread of epidemics. Agent-based modelling, which involves also simulating human-to-human interactions, has been used to identify and prevent cross-contamination in real-time and to optimize the design of physical spaces. Tools like OccSim can be used to analyze the potential for virus transmission in a building by generating occupancy behaviors in a 3D model of the building (Pilati, Tronconi, Nollo, Heragu, & Zerzer, 2021; Li, et al., 2016).

6.3 Mitigating Infection Risks by information management and sharing

6.3.1 Technology Description

Having a robust, reliable data-driven and interconnected system for transmission of relevant information to the users of buildings / GBNs will ensure a much greater visibility, easier, engaging and inclusive communication and immediacy of H&S analytics and news, obligations and recommendations. This will entail a clear definition of relevant criteria and communication processes which will in turn ameliorate the ability to prevent reaching critical thresholds before reactive stages.

This blueprint is mostly information driven and focuses on influencing and driving recommended behaviours. As such, the proposed DT model would closely adapt to WP2 considerations.

Based on PwC's US Remote Work Survey from January 2021, 48% of surveyed employees stated that they had to expose themselves to health and safety (H&S) risks when they were obliged to return to their workplaces while 87% of them felt that this return is crucial for collaboration and networking. It is therefore quintessential for employers to not only be able to respond to critical periods or occurrences in a timely and efficient manner but also to reassure that safety of their employees is one of the priorities.

6.3.2 SOTA for sharing information

It has been demonstrated that a key step in absorbing the shock of a pandemic (Sakellarides, 2020), is to facilitate transparent communication and prevent the spread of the wrong information (Sharifi, Khavarian-Garmsir, & Kummitha, 2021)(Figure 28).

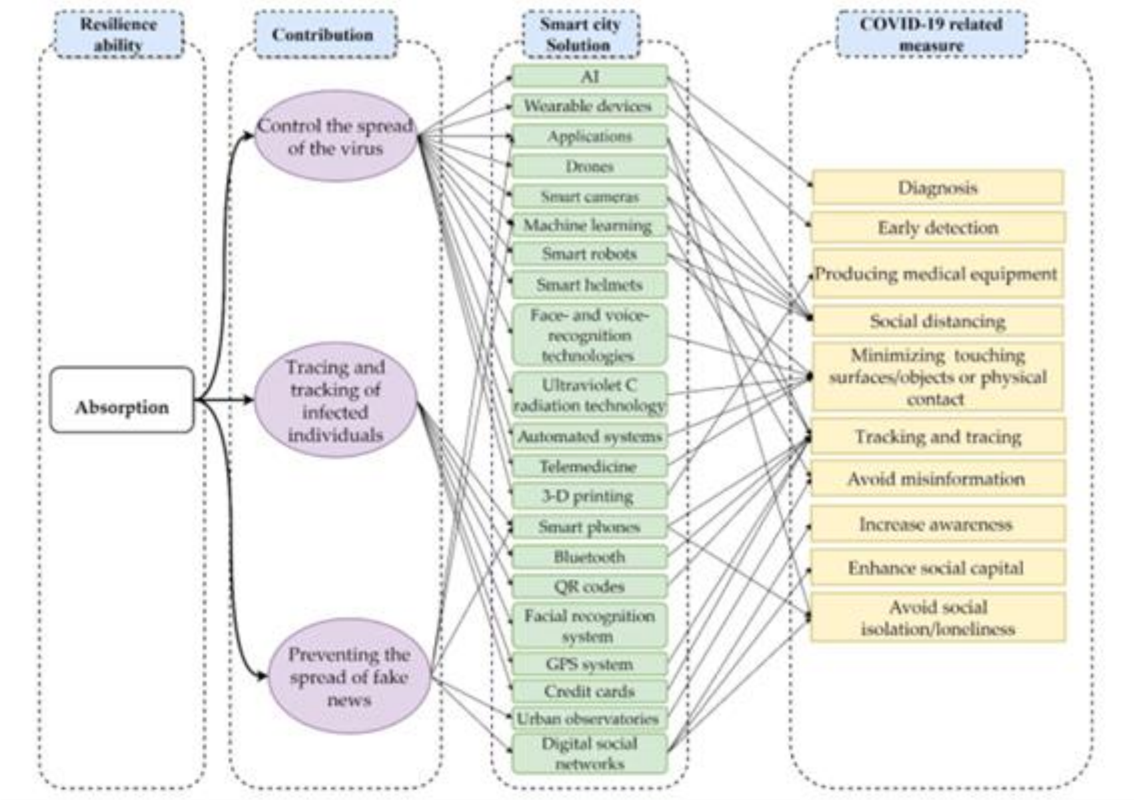

Figure 28: Absorption of shock in pandemic (Sharifi, Khavarian-Garmsir, & Kummitha, 2021)

As such, a DT, based on the right and timely management of information from different sources, could

- Facilitate transparent communication
- Contribute to controlling the diffusion of wrong information
- Raise awareness and facilitate social interactions

Failing to control the information reaching the public and misinformation can have effects that amplify the impacts of a crisis both at government and individual levels (Laatoa, 2020). Furthermore, the use of social networks has led to an increase of "cyberchondria". Clear examples of the impact of misinformation were attacks of 5G towers, because they were claimed to accelerate COVID19 spread. This led to a "media fatigue", leading to more unsafe behaviours, in particular due to the fact that social networks algorithms tend to create repetition chambers for individuals. This resulted in the fact that "The abundance of unclear, ambiguous and inaccurate information during COVID-19 led to information overload and accelerated health anxiety (cyberchondria) as well as misinformation sharing".

Other points of interest to further explore interactions between social networks and information-based human behaviours were for example in Location Based Games (Laato, 2020).

6.3.3 Digital Twin for information communication points

6.3.3.1 Narrative

The objective of this DT is to provide the LL/GBN ecosystems with an information management service that can expose and provide information to the wider users in public spaces.

The data can come from different sources, from government to facility managers and users themselves. It can be linked also to the DT for occupancy and models of the LL, so that users know what to do, how to move around, in short how to use the building.

It can provide a single source of trusted information to users, displayed for example at information points in the LL, or delivered through a mobile app to the building/GBN users and stakeholders.

6.3.3.2 Blueprint

Basic functionality / high level services and needs to be covered

The main benefit of this single data-integrating platform (that can be in form of a mobile app or web platform accessible through a browser) will be the ability to provide the buildings' / GBNs users with:

- Real-time emergency information and alerts
- Potential explanation of reasons for higher rate of disease spread in a specific area of the building / GBN
- Evidence of H&S-related legislative and guidelines
- Visual and interactive recommendations for the improvement of personal hygiene and sanitary habits
- Other H&S information such as nearest hospital or localisation of first aid kits
- Information of specific spaces in relation to on-going, completed or planned sanitary procedures (i.e. deep cleaning within spaces with recorded disease cases).
- Sensor-monitored occupancy levels (both for hot-desk reservation system & space usage information) and wayfinding signage to disperse the users into less occupied spaces
- Contact tracing

Phase of building / GBN life cycle the DT services are aimed for

Operational

Targeted Stakeholders / Users

Building designers / owners / facility managers / technical departments / building users / local solutions and technology providers / data providers

Physical twin

A school building may be considered as a physical twin. The focus would be to make sure that transparent, accurate and information is dynamically and effectively managed and exchanged. The twin would then be represented by the possibly occupied spaces while linked with external information sources.

DT model associated KPIs

A plethora of indicative KPIs may be considered, including the following:

- number of information points (screens, end-users reached via computers or portable devices)
- number of information/alerts disseminated compared to the ratio of views
- updating of information
- number of connected IoT devices
- number of accesses to databases
- number of posts in discussion forums
- number of downloads and ratings of the accompanying application in the app stores

As well as KPIs demonstrating the effectiveness of the system (i.e. before and after its implementation) such as:

- rates of disease transmission
- use of the table reservation system
- occupancy rate

DT model associated tools

A companion application that allows:

- facility managers and other decision makers to have control over what information is shared with end users depending on the criticality of the situation. In addition, the information may vary depending on the user profile - i.e. a mobile worker, such as a caretaker, needs different information than an employee with a desk job)

- end-users have access to more detailed analysis and can communicate with other end-users or decision-makers, facility managers and other service providers

Required Measurements / frequency

In terms of KPIs, there is a wide range of parameters that can be monitored with varying frequency, depending on the capabilities and availability of the relevant IoT devices and technical systems already installed in the buildings or among the employees. However, monitoring through RT allows for the best possible solutions in the event of a crisis. This may include:

- number of confirmed cases of illness
- measurement of users' body temperature
- social distancing data
- information updates of relevant websites and databases (number of cases of illness, regulations, warnings, etc.)
- occupancy of individual departments and length of stay
- cleanliness of individual rooms
- data on bathrooms in terms of traffic and average hand-washing times,
  room temperatures, CO_2 and humidity levels, etc.

DT model desired features

Data analytics (real-time predictive) & assisted decision making

Data requirements

Accurate and up-to-date data is critical to the ability to respond effectively in times of crisis. Both quantitative and qualitative data from an operational and historical perspective can be analysed and used by the system to compare the effectiveness of the Digital Twin over time. If historical data is not available for the building / GBN, a comparative analysis can be performed based on data available citywide or nationwide.

This is to be enabled by a platform that will integrate aggregated data from various sources (sensors, databases, websites) and generate summarized information that will be then passed on to the end-users through screens, computers and portable devices.

User interface requirements

A (potentially 3D) model that visualizes the transmission of information to end users based on its number and reach. This visualization can reflect the real-time situation by default, but can also explore in time and predict future scenarios based on the choice of the above parameters.

Link with LLs

Porto LL: The Sonae campus' response to the pandemics by implementing risk-reducing measures (especially communication and signage of safety measures in common areas) may potentially be used as a test case for this DT concept.

Brussels LL: Digital signage can be used to increase awareness among the users of the school, as students are the part of the population with the most social contacts and therefore with the greatest potential for disease transmission.

SOTA / Best practice example

The simple use of digital signage for the purposes of COVID-19 information update and education concerning personal hygiene has been observed in public spaces including hospitals, commercial centers and airports. A rather limited number of relevant scientific articles have been produced in recent time (Huy-Tran, Park, & Chung, 2022; McNeish, 2020).

7. Conclusions

This report gathers innovative technologies in WP3 and provides a description, the state-of the-art and related initial DT models concepts that are so far identified.

The first section of technologies discussed in this report are GB Insulation and Green and Cool Roof-Centric Innovations i.e., high evaporative green roofs (HEGR), integrated thermal and acoustic insulation, cool roof combined with bi-facial PV and wood fiber insulation. The models of DT described in this section focus on the monitoring and optimisation functions in HEGR and cool roof combined with bi-facial PVs respectively.

Next, a section of GBN related Construction and lifecycle Blueprints, Processes and Controls Including Robots, includes modular construction techniques and applications of robots in construction. DT model concepts in this section include an LCA-based optimisation for GBN environmental performance focusing on prefabricated elements and the 3D mapping of building construction data. Furthermore, the next section focuses on building materials and upcycling, namely recycled plastics as raw materials and smart engineering technologies and materials applied to pavements and concrete structures. The DT model concepts presented in this section refer to the tracking of material workflows from demolition to treatment and reuse.

The last section focuses on technologies and methodologies for social distancing considering epidemiology risks and includes mitigating infection risks by controlling air quality, controlling disease progression by managing people flow and mitigating infection risks by sharing information at the right place, to the right person, at the right time. DT model concepts discussed in this section concern i) monitoring of IEQ based on various data sources and provision of best environmental conditions via data analytics and controls, ii) mobility flows replicated in a virtual representation to run simulation scenarios based on real information and iii) information communication points to manage information and share it with users in public spaces.

The next steps foreseen, concern specific actions for maturing the DT model concepts identified so far in collaboration with the development activities in LLs (WP7) and alignment with the digitalization platform high-level services and needs (WP5).

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