SIRCULAR

DELIVERABLE 1.3:

SIRCULAR tools methodology (T1.3)

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OVERVIEW	
Project Acronym	SIRCULAR
Project Title	Sustainable and Integrated people centRiC solUt ons for buiLding decArbonisat on and circularity
Project Coordinator	RINA-C
Project Durat on	42 months
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Deliverable Lead	CERTH
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Abbreviations and Acronyms

Acronym	Descript on
CERTH	Centre for Research and Technology, Hellas
CIAT	Circularity Index Assessment Tool
D	Deliverable
HPHI	Hellenic Passive House Inst tute
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
MRT	Mean Radiant Temperature
NTUA	Nat onal and Technical University of Athens
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissat sf ed
RR	Renovat on Repository
WP	Work Package

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Nomenclature

Lat n Symbols	Quant ty	Unit
clo	Clothing resistance value, 1 clo=0.155 Km^2/W	Km^2/W
Cp	Specific heat capacity	J/kgK
d	Material layer thickness	m
f_{cl}	Ratio of the clothed body	-
f_{eff}	Fraction of human surface effective for radiation	
f_{Rsi}	Temperature factor at the internal surface	-
$f_{Rsi,min}$	Design temperature factor at the internal surface	-
g	Density of water vapour f ow rate	$kg/(m^2 \cdot s)$
H	Internal heat production per occupant per unit area	W/m^2
h_{cond}	Conductive heat transfer coefficient	W/m^2K
h_{conv}	Convective heat transfer coefficient	W/m^2K
h_{evap}	Evaporative heat transfer coefficient	W/m^2kPa
h_{fg}	Enthalpy of vaporization	J/kgK
L	All modes of losses from the human body per unit area	W/m^2
n	Air change rate	h^{-1}
p	Water vapour pressure	Pa
P	Vapour pressure	kPa
Q	Load	W
q	Specif c load	W/m^2
R	Thermal resistance	$m^2 \cdot K/W$
R_v	Gas constant for water vapour = 462	$Pa \cdot m^3/(K \cdot kg)$
s_d	Water vapour dif usion-equivalent air layer thickness	m
T	Thermodynamic temperature	K
t	Time	s
T	Temperature	K
U-value	Thermal transmittance	$W/(m^2 \cdot K)$

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V	Respiratory ventilation rate	m^3/s
w	Moisture content mass by volume	kg/m^3
w_{skin}	Skin wettedness	-
Greek Symbols	**Quant ty**	**Unit**
γ	Humidity ratio	-
δ_0	Water vapour permeability of air with respect to part al vapour pressure	kg/(m·s·Pa)
Δp	Internal vapour pressure excess, $p_i - p_e$	Pa
Δv	Internal moisture excess, $v_i - v_e$	kg/m^3
ε	Emissivity of clothing and skin	-
θ	Temperature	°C
$\theta_{si,min}$	Minimum acceptable surface temperature	°C
λ	Thermal conductivity	W/(m·K)
M	Metabolic rate per unit area	W/m^2
μ	Water vapour resistance factor	-
v	Humidity of air by volume	kg/m^3
ρ	Density,	kg/m^3
σ	Stefan-Boltzmann constant	$5.67 \cdot 10^{-8}$ W/m^2K^4
ϕ	Relat ve humidity	-

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Subscripts and Superscripts

Subscript and Superscript	Descript on
air	Surrounding air
conv	Convection heat transfer
cond	Conductive heat transfer
e	Expired air
evap	Evaporation cooling through skin
i	Inspired air
outerbody	Human outer body surface including clothing and skin
rad	Radiative heat transfer
res	Heat transfer through respiration
saturated	Saturated air
skin	Human skin
surface	Contacting solid surface
v	Water vapor
an	annual
c	condensat on
cr	crit cal value
e	external air
ev	evaporat on
eq	equivalent (outside temperature)
i	internal air
min	minimum value
an	annual
c	condensat on
cr	crit cal value
e	external air
ev	evaporat on
m	mean
n	interface

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s	surface
sat	value at saturation
se	external surface
si	internal surface
T	total over the whole component or element

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Background: About the SIRCULAR project

SIRCULAR is coordinated by RINA-C and combines the expert se of 22 partners from six European countries, including universit es, SMEs, NGOs, and industries. During the next three-and-a-half-years, SIRCULAR will transform the building sector into a circular and sustainable industry, aligned with the Built4People partnership principles.

We will test and demonstrate innovat ve technologies and services across four regional clusters: init ally in Estonia and Spain, followed by Germany and Greece. These clusters will engage construct on companies, housing companies, universit es, and local administrat ve ent t es, focusing on buildings owned or occupied by vulnerable populat on groups, in line with the SIRCULAR just and af ordable transit on approach.

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1. Introduct on

The primary purpose of Deliverable D1.3 is to present a comprehensive report on the methodology used to develop the examined SIRCULAR tools. For the purpose of the SIRCULAR project, three innovat ve tools will be developed to promote sustainable and circular construct on pract ces throughout the building performance across two demonstrat on sites. Specif cally, the Nat onal and Technical University of Athens (NTUA) will develop a Comfort Evaluat on Tool, which will contribute to an accurate comfort evaluat on process that can ident fy and est mate a building's indoor condit ons. Respect vely, the Hellenic Passive House Inst tute (HPHI) designs a Hygrothermal Tool by assessing the hygrothermal performance of building components and elements based on the Internat onal Standard ISO 13788:2012. Finally, CERTH, in collaborat on with GENEGIS, will develop the Marketplace and Recycling Plant Mapping Tool, which will automate the generat on of databases for materials and building renovat on products, emphasizing sustainability through material circularity and mapping recycling plants based on geo-database integrat on.

The core of the SIRCULAR project lies in designing and developing the Circularity Index Assessment Tool (CIAT), which plays a pivotal role in evaluat ng the impact of circularity act ons implemented in the project. The above-ment oned developing tools will support CIAT, and they will be tested in the proposed Spanish and Estonian demos of the project.

The respect ve partners of each developing tool designed the methodology for their tools, and, through a later interdisciplinary approach, a common format followed for the SIRCULAR tools methodology is introduced in this Deliverable. Moreover, the VERIFY tool, developed by CERTH, const tutes the main part of the CIAT and is also shortly presented, since it of ers dynamic and detailed LCA/LCC analysis. Finally, it is considered appropriate to ment on the in-house CERTH's tool, INTEMA, which is the backbone of the whole process, facilitat ng the BIM to BEM approach and providing all the essent al building and construct on materials informat on to the VERIFY plat orm.

1.1 Object ves of the Deliverable

The primary object ve of Deliverable 1.3 is to establish a standardized methodology framework for the SIRCULAR digital tools, ensuring compat bility, interoperability, and ef ect veness. Specif cally, the deliverable aims to document the methodological approach used for each tool, detail the technical and funct onal specif cat ons, and outline how these tools contribute to the overarching goal of circularity and decarbonizat on within the building sector. The main is to address Task 1.3 by establishing a common methodology for SIRCULAR tools. The task involves coordinat on with all the partners who are developing the tools and ensures that they use a compat ble f le format.

Table 1. Task 1.3 – Ef ort analysis per associated partner.

Partner	Specif c Contribut on	PMs
CERTH	Task leader. Collect on and analysis of the developing tools under a common SIRCULAR tools methodology. Coordinate the partners involved in the compat bility of the input data.	3

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RINA-C	Support will be provided to the task leader regarding tracking of the recycling plants, giving input to the mapping tool.	5
GENEGIS	Support will be provided to the task leader regarding the def nit on of the methodology for deriving a geo-database from the BIM model and will gather informat on on the methodology by which the other tools will be developed (T2.1) and how they should communicate with the plat orm (T2.3)	4
IteC	Even if our plat orm won't be one of the Sircular tool, our contribut on will ensure compat bility with the standards in construct on sector as we work with standardized f les	0.5
HPHI	Def ne the methodology of the tool regarding hygrothermal behavior, conduct research regarding similar tools in the market.	1.5
NTUA	Create a new methodology following ASHRAE and ISO norms regarding thermal comfort. Research among dynamic simulat on sof ware and choice of the proper ones in order to conduct the baseline simulat on in order to program the new tool.	2.5
STRESS	Contribut ons related to the ident f cat on of exist ng structured databases (Italian) related to CDW collect on and recycling plants	2
ICLEI	Aligning the methodology for the marketplace with the needs of users	1
RIMOND	Support ng the task leader to def ne the comprehensive methodology given the need to integrate the de-risk tool with the SIRCULAR overall methodology	1

The present task is divided into the following subtasks:

- **T1.3.1 Marketplace and Recycling Plant mapping (CERTH):** In this subtask, CERTH will develop a methodology to automat cally create databases of building materials and building renovat on products from public sources that include environmental and circularity informat on. The repository will enable users to select the most suitable materials based on their environmental impact. Moreover, CERTH will provide a methodology for mapping recycling plants using a Geodatabase implementat on.
- **T1.3.2 Hygrothermal Simulat on Tool (HPHI):** This subtask aims to assess the issue of mold growth and condensat on in building structures through a simplif ed glazer method-based tool.
- **T1.3.3 Comfort Evaluat on Tool (NTUA):** This subtask will develop a tool that measures and improves the indoor thermal comfort of building occupants, while also considering energy

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ef ciency. The tool will use dynamic simulat ons to account for dif erent factors that af ect thermal comfort and through that a steady state assessment simulat on tool will be created.

1.2 Structure of the Document

The present report is structured to provide clarity and guidance for both the developed and developing SIRCULAR tools, beginning with an introduct on to the SIRCULAR project and its core object ves. Following this, a summary of the main developed tools, specif cally the VERIFY tool, the GENEGIS digital plat orm, and the CIAT tool is presented to enlighten the interoperability and funct onality of the f nal SIRCULAR plat orm. Then, detailed methodologies and specif cat ons for each of the three main developing tools are described: the Marketplace and Recycling Plant Mapping Tool, the Hygrothermal Simulat on Tool, and the Comfort Evaluat on Tool. Each tool's sect on contains clearly def ned input data specif cat ons, methodologies, expected outputs, verif cat on and validat on procedures, and innovat ve features that surpass the current state-of-the-art. The document concludes with a synthesis of f ndings and an overview of how these tools collect vely support the project's broader aims.

1.3 Relat on to Project Documents

The presented Deliverable 1.3 builds upon and complements earlier project outputs, notably the decarbonizat on and circularity framework analysis (Task 1.1) and the def ned SIRCULAR methodology for evaluat ng circularity and recyclability indices (Task 1.2). Furthermore, the deliverable const tutes the fundamental basis for the following project phases, part cularly those outlined in WP2, which involve the pract cal implementat on and integrat on of the tools within the SIRCULAR digital plat orm. This ensures cont nuity, consistency, and coherence across the various phases and outputs of the project.

1.4 Overall Approach

The overall approach outlined in this report emphasizes the integrat on of mult disciplinary methodologies within user-centric design principles. Emphasis is placed on developing pract cal, f exible, and interoperable tools that facilitate their broad adopt on by both technical and non-technical users. The approach priorit zes robust data management and advanced analyt cal capabilit es to provide real-t me insights and decision-making support. Cont nuous feedback and iterat ve enhancements are incorporated throughout the project lifecycle, ensuring the developed tools remain adaptable, relevant, and ef ect ve in promot ng circular and sustainable construct on pract ces.

The examined tools described in the present Deliverable 1.3 demonstrate signif cant progress beyond current industry standards by integrat ng advanced methodologies, dynamic life-cycle analysis capabilit es, and robust data interoperability. VERIFY provides dynamic environmental and economic life cycle assessments, which are crucial for informed decision-making in sustainable construct on

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pract ces. CIAT provides a comprehensive and systemat c approach to evaluat ng recyclability and circularity, thus ef ect vely support ng material sustainability and circular economic principles. The GENEGIS plat orm of ers a user-centric and technologically advanced solut on that streamlines data integrat on and enhances tool accessibility. Overall, these tools represent signif cant advancements toward the sustainable transformat on of the construct on industry, opt mizing both environmental and economic outcomes.

2. Introduct on to SIRCULAR Tools

2.1 Overview

The SIRCULAR project aims to create digital tools, technological solut ons, and non-technical services to support the decarbonisat on of the built environment. Its goal is to provide an ef cient methodology for assessing the circularity of buildings, supported by a set of evidence-based KPIs. These tools are designed to improve non-experts' access to decarbonisat on and sustainability informat on, while equipping construct on professionals with user-friendly resources to evaluate and enhance building circularity. The SIRCULAR framework takes a mult disciplinary approach, integrat ng technical, economic, and social perspect ves with a focus on social and policy innovat on. This ensures that policymakers receive clear and valuable insights for promot ng decarbonizat on strategies. The framework is built on a people-centric approach, priorit zing the needs, aspirat ons, and well-being of individuals and communit es, recognizing them as key contributors to the decarbonisat on of the construct on sector.

Specif cally, the project introduces an innovat ve digital plat orm designed to equip non-experts in the building sector with the necessary tools and resources to promote sustainable and circular construct on pract ces. The primary object ve is for users to incorporate circular principles into their projects, providing a range of advanced tools that simplify otherwise complex processes. Further details on these tools are provided in the following paragraphs. A detailed tool methodology has been applied, following cont nuous feedback from partners and end-users. The plat orm's tools, detailed in the subsequent sect ons, are designed for both technical users seeking to evaluate the circularity of a building and non-technical users interested in init al assessments, such as evaluat ng a building plan’s thermal comfort or hydrothermal performance.

The core of the SIRCULAR project lies in designing and developing the Circularity Index Assessment Tool (CIAT), which plays a pivotal role in evaluat ng the impact of circularity act ons implemented in the project. As outlined in Figure 1, the methodology is designed to assess and measure building recyclability and circularity using two dist nct algorithms developed by RINA-C. These algorithms will consider material recyclability and reuse, providing realist c and detailed decision support tools for both planning and operat onal phases.

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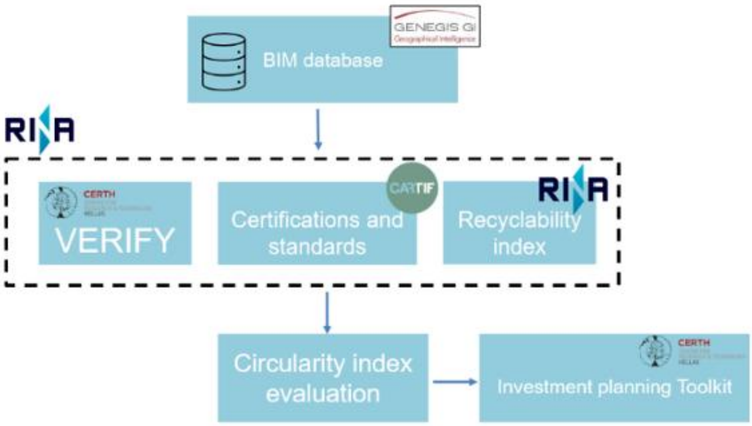

Figure 1. Circularity Index Assessment Tool (CIAT) methodology.

The first algorithm will analyze the building's composition, disassembly, material separation, and the recyclability of individual materials. The second algorithm will assess the building's circularity using the Material Circularity Indicator (MCI) tool, developed by The Ellen MacArthur Foundation and Granta Design. This circularity index algorithm will integrate the first one and adhere to widely recognized sustainability certifications and standards, including the EU Level(s) framework indicators.

Both algorithms will be integrated into the SIRCULAR platform through a digital module utilizing Application Programming Interfaces (APIs), enabling users to assess the building's sustainability and environmental impact throughout its entire life cycle. The input required for these evaluations will be a Building Information Modeling (BIM) file using the Industry Foundation Classes (IFC) data model. The IFC file will need to include material properties, material layer sets, thermal zones, and the relationships between building elements and spaces, ensuring a comprehensive evaluation for circularity assessment.

Moreover, the CIAT index utilizes the VERIFY tool, an online platform developed by CERTH. VERIFY performs dynamic environmental and economic life cycle assessments for individual buildings and portfolios, accounting for key passive and active energy systems. It includes an Investment Planning Toolkit that calculates financial metrics for energy upgrades, such as Net Present Value (NPV), Internal Rate of Return (IRR), Investment Payback Time (IPBT), and Levelized Cost of Energy (LCOE). VERIFY offers robust life cycle costing (LCC) functionality alongside life cycle assessment (LCA), providing valuable insights to decision-makers through an integrated web-based interface. VERIFY can utilize real-time data to offer tailored recommendations for energy, environmental, and financial sustainability by automating the dynamic LCA/LCC of energy systems and technologies. It includes an open-access/editable Life Cycle Inventory module, interoperable connections to IoT sensor networks, and open data exchange layers linked to large data repositories. The Investment Planning Toolkit will be expanded to support long-term energy financial planning, considering factors such as economic trends, loan conditions, and land acquisition costs. Key performance indicators (KPIs) from VERIFY will provide insights into the expected gains and losses throughout the building's life cycle. More information and details about the function of this tool will be provided in Section 3.1.

Finally, the SIRCULAR project will provide two versions of the CIAT toolkit: a comprehensive version that uses BIM files for monitoring and leverages VERIFY's capabilities, and a simpler version requiring only scalar values, designed for non-technical users conducting high-level feasibility assessments or

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for replicat on purposes. Throughout CIAT's design phase, the main developing tools that will comprise its technological core will be the Marketplace and Recycling Plant mapping tool, the Hygrothermal tool, and the Comfort evaluat on tool, as seen in Figure 2.

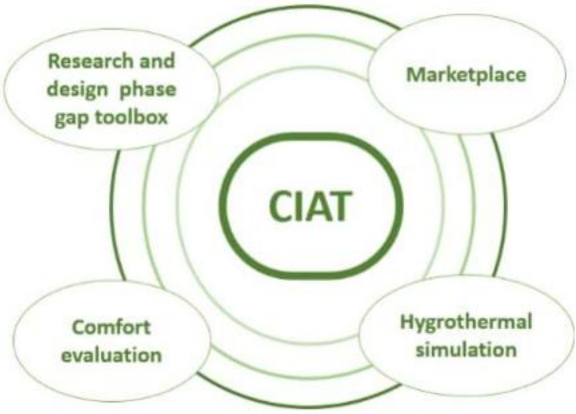

Figure 2. Schemat c illustrat on of SIRCULAR plat orm.

The Marketplace is designed to facilitate the exchange of used construct on materials and components, streamlining the ent re user journey from searching and comparing opt ons to implement ng decarbonisat on solut ons. Making the process more ef cient promotes new business opportunit es in the building sector. The Marketplace leverages the Renovat on Repository (RRR), which includes retrof t ng envelope solut ons, renewable energy systems, hybrid and storage technologies, process enhancement techniques, and business models. Third-party contribut ons populate the RRR, ensuring it features modern and tradit onal solut ons and remains up-to-date and relevant for various renovat on scenarios.

The Marketplace tool, known for its user-friendly interface, is currently implemented in the RINNO project. During SIRCULAR, the RRR's capabilit es will be expanded to automat cally generate databases of materials and renovat on products from publicly available sources, such as EPD and ELCD, helping users make eco-friendly decisions. The Marketplace will priorit ze materials based on their environmental impact and circularity, evaluat ng specif c categories to ensure sustainability. Addit onally, it will integrate emerging technologies, such as Building Informat on Modeling (BIM) and the Internet of Things (IoT), to further streamline the renovat on process and boost overall ef ciency.

The BIM methodology enables more accurate and detailed designs, ensuring sustainable solut ons are integrated during the early design phase. Within the project, a geodatabase derived from BIM models will be developed and made accessible to users, enabling industry professionals to locate reusable materials within their local region during the design phase. This will help reduce construct on costs and lower the carbon footprint associated with producing new materials. The Marketplace's interface will simplify the search, comparison, and implementat on of renovat on solut ons while also incorporat ng sustainability mapping to highlight recycling points. This will increase access to reusable construct on products, further promot ng circularity in the building sector.

Another crit cal SIRCULAR tool that will support the CIAT plat orm is the Hygrothermal tool, which aims to evaluate the building components using the Glaser method. The tool streamlines the complex process of hygrothermal performance analysis by of ering straight orward calculat ons based on the widely recognized Internat onal Standard ISO 13788:2012, making it accessible to a broad range of

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professionals. It enables users to calculate essent al parameters such as hygrothermal performance and internal surface temperature within building components, all of which are crit cal for prevent ng condensat on. Although the calculat ons are simplif ed, the tool remains aligned with ISO standards, ensuring consistency in assessments that will be validated against more advanced sof ware, such as WUFI. Moreover, it provides a user-friendly interface that encourages engagement and helps users extract key informat on, such as material moisture content, essent al for maintaining healthy indoor environments. Addit onally, the tool can integrate data from other building simulat on sof ware to assess building elements. It is designed as an assessment tool rather than a precise predict on model, of ering an easy yet reliable way to verify a complex aspect of building physics.

Finally, the Comfort Evaluat on tool uses dynamic simulat on sof ware capable of est mat ng indoor condit ons in exist ng buildings. This tool will provide valuable insights to help decision-makers priorit ze building renovat ons and compare dif erent building types while also of ering informat on on indoor air quality. Recognizing the importance of indoor comfort in building renovat ons, SIRCULAR bridges the gap between energy ef ciency and occupant well-being. Through dynamic simulat ons using tools such as TRNSYS and EnergyPlus, this innovat ve solut on quant f es indoor thermal condit ons, empowering stakeholders with pract cal insights for informed renovat on decisions. The tool will be compat ble with data from various building simulat on sof ware and will focus on assessing the building's thermal comfort.

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3. SIRCULAR Developed Tools Methodology

3.1 VERIFY - Virtual Plat orm on Life Cycle Analysis

3.1.1 Overview

The VERIFY plat orm, developed by CERTH (Centre for Research & Technology Hellas), is a powerful tool for conduct ng both environmental (LCA) and economic (LCC) life cycle assessments. It is designed to support decision-makers in evaluat ng buildings or districts by providing real-t me insights into the infrastructure's environmental and f nancial performance over its ent re life cycle. The plat orm enables users to connect with IoT devices, allowing for real-t me data collect on and ongoing analysis. This data is processed and presented through dynamic indicators and charts, helping users assess and opt mize projects based on sustainability and cost-ef ect veness.

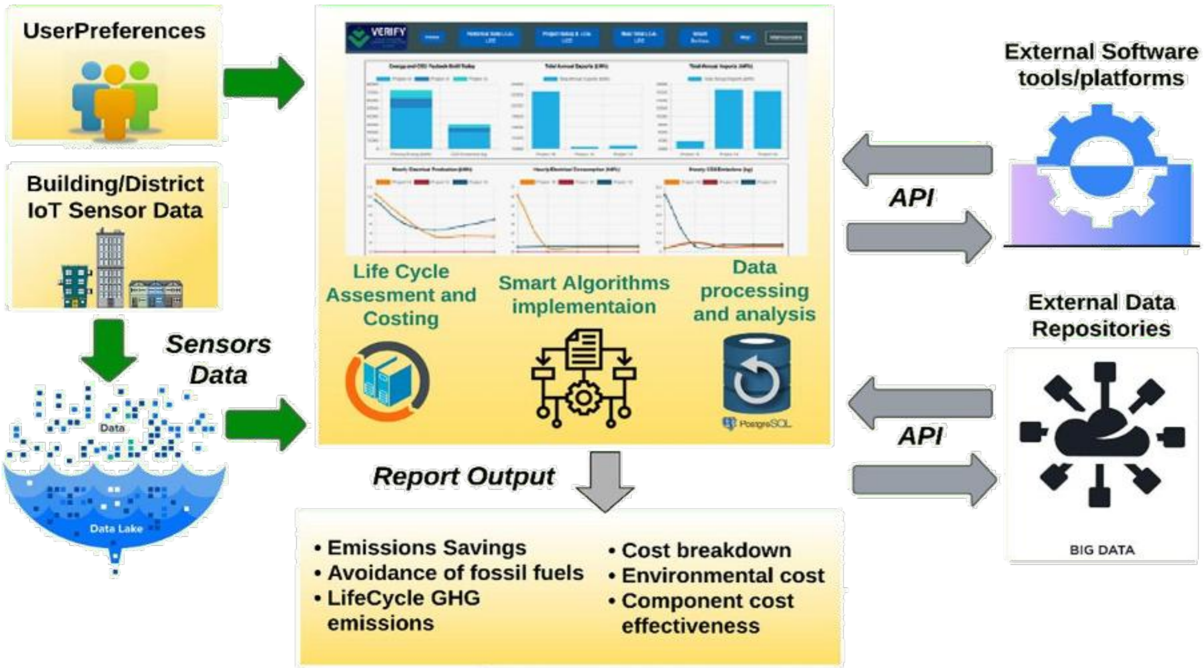

Figure 3. Presentat on of the VERIFY plat orm methodology

The VERIFY plat orm is designed to accommodate large-scale infrastructure projects and individual building evaluat ons, making it a highly versat le and user-friendly tool for various stakeholders in the construct on and renovat on sectors. It conducts environmental and cost analyses, focusing on energy systems across various networks, such as gas, electricity, heat ng, and cooling. These analyses can be performed using either synthet c data from third-party sources or real-t me data collected from IoT sensors. Key features include Life Cycle Assessment (LCA), Life Cycle Cost ng (LCC), and energy system investment planning, applicable from individual buildings to ent re districts and cit es. The plat orm is integrated with IoT sensor networks, enabling seamless data ingest on and exchange with large data repositories. Addit onally, VERIFY connects to Emissions Trading Systems (ETS) to retrieve real-t me CO_2 values, providing up-to-date environmental metrics.

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The intuit ve user interface provides a dashboard with visual and graphical analyt cs, as well as a hypothesis-test ng engine, enabling users to explore and benchmark alternat ve scenarios based on their custom parameters. This ensures ef ect ve analysis and decision-making for sustainable and cost-ef cient projects.

The VERIFY methodology (Figure 3) is based on the relevant internat onal circular economy standards (ISO 14040), modifying and extending them as needed to extract results based on near real-t me data from remote measurement systems using sensors. The dynamic, t me-based analysis enables decision-making both before and during the operat on of energy systems (such as a building and its heat ng/cooling systems). This is achieved by applying mult -criteria methods that assess energy, environmental, and techno-economic indicators. The object ve is to opt mize energy use, minimize both investment and operat ng costs, and reduce the environmental impact. Techno-economic evaluat ons are conducted through the applicat on of f nancing models that incorporate energy pricing and assessments of pollutant costs. VERIFY's applicat on range spans from individual building systems to grid-level complexes, covering mult ple energy networks with diverse act ve and passive energy systems and technologies. This broad scope enables comprehensive analysis and opt mizat on across a wide range of energy infrastructures. Below are summarized some of the crit cal advantages of the VERIFY plat orm, which will contribute to the CIAT tool and SIRCULAR project as a whole:

- Trustworthy and accurate LCC funct onality in addit on to LCA capability, which supports an investment planning tool for giving important informat on to decision makers and policymakers in a single online tool.
- Accountability for real-t me data and not only by est mat ons, of ering tailored suggest ons for energy, environmental, and f nancial sustainability by delivering automated dynamic life cycle and life cost ng analyses of energy systems.

For the SIRCULAR project, part cularly for building-level est mat ons, the automat on process relies on Building Informat on Modeling (BIM). In addit on to real-t me data ingest on from various act ve and passive energy systems across mult ple vectors, including Power-to-X integrated systems (e.g., a key aspect of Task T4.2), the system incorporates energy, environmental, and techno-economic data to support the mult -criteria evaluat on of scenarios for designing new or upgrading exist ng energy systems. An online data preparat on and storage engine addresses common issues such as missing data or corrupted databases. Furthermore, it is an open-source and interoperable sof ware, i.e., external APIs can be connected to the VERIFY plat orm to receive data automat cally in real-t me through communicat on channels (e.g., Act on Cable and MQTT protocol). The possibility of est mat ng environmental and economic Key Performance Indicators (KPIs) is provided over a period of up to 50 years, considering relevant forecasted data, using actual monitored data as a basis for the various assets.

So far, VERIFY has been implemented in several energy-related H2020 and HEU research projects. These various demonstrat ons are necessary to populate the life cycle database of VERIFY with highly innovat ve products and processes adapted for dif erent temporal and spat al scales. Focusing on the SIRCULAR project requirements, CERTH will ut lize and further advance its two in-house developed tools:

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1. **VERIFY**, an IoT plat orm capable of performing building LCA/LCC using real-t me use-stage data (following ISO 14044, ISO 15686-5, and Level(s)), as well as support ng data-driven renovat on investment planning and techno-economic analysis based on historical energy consumpt on.
2. **INTEMA**, a dynamic modelling and simulat on tool, is used to analyze the energy performance of buildings and mult -energy networks. INTEMA supplies accurate energy performance data to VERIFY through dynamic simulat ons, which VERIFY later ut lizes to perform detailed LCA and LCC analyses.

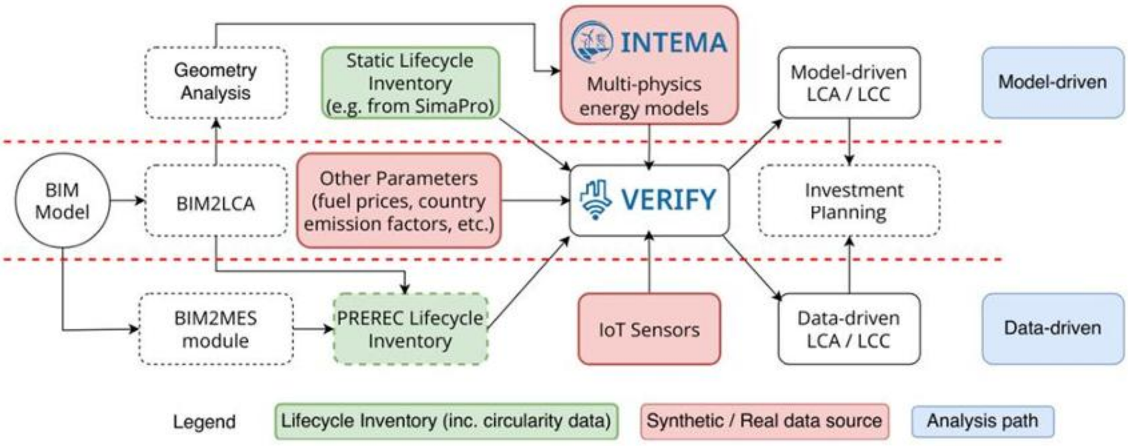

Figure 4. VERIFY holist c approach for the BIM2LCC2LCA process.

These two tools were developed as part of CERTH's part cipat on in several past and ongoing H2020 and HEU projects (incl. RINNO [1] and POCITYF [2]). VERIFY ut lizes INTEMA's thermal and electrical consumpt on/storage/modelling capabilit es to perform LCA / LCC analyses, which can be fully model-driven (i.e., white-box approach if real-t me data are not available), ent rely data-driven (i.e., black-box approach, where energy consumpt on data available through IoT-deployed energy consumpt on and environmental sensors are ut lized), or hybrid (i.e., grey-box approach, combining real-t me data and parametrically-adapted models for future consumpt on est mat ons). For developing a BIM2LCA2LCC module, the following advances will be made on the two tools, as illustrated in Figure 4. Specif cally, a BIM2LCA advancement will be integrated with both INTEMA so that BIM geometry in-format on is ut lized directly for modelling, a BIM2LCA advancement will be integrated with VERIFY so that the lifecycle inventory of the renovat on materials is directly taken into account during the LCA/LCC processes, with the same benef ts as in the case of INTEMA, and an energy consumpt on data from the BIM2MES module will be ut lized to increase the accuracy of the LCA / LCC.

At this point, it is important to introduce INTEMA's dynamic modelling and simulat on tool. This tool is the core of the VERIFY plat orm and provides the main database of the building's energy behaviour and sustainability.

3.1.2 Introduct on to INTEMA Tool

INTEMA is a comprehensive suite of sof ware tools designed for accurate simulat ons of mult -domain energy systems, encompassing energy product on, storage, and consumpt on across various scales. It supports applicat ons ranging from individual thermal zones to ent re districts, neighbourhoods, and

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even islands. INTEMA's primary goal is to enhance the synergy between dif erent sectors, maximize the integrat on of renewable energy, improve energy ef ciency, and achieve signif cant energy savings.

Among its key features, the INTEMA tool can dynamically simulate interact ons among mult -vector energy systems, such as electrical grids, heat ng and cooling networks, and storage systems. This funct onality gives INTEMA an edge over many commercially available alternat ves. INTEMA ut lizes open-source Modelica libraries, providing users with a customizable and adaptable experience within a user-friendly web plat orm. The plat orm is designed to be accessible even to non-experts in the energy sector, with an intuit ve graphical interface.

Moreover, INTEMA leverages white-box models (based on physical principles) and black-box models (enhanced by machine learning algorithms), result ng in powerful grey-box models when historical or real-t me data is available. This feature enables the development of digital twins to be integrated into real-t me control systems, further opt mising system performance through predict ve algorithms and mathemat cal programming models. As part of the plat orm's development and interoperability, possibilit es are of ered to connect the tools through developed Applicat on Programming Interfaces (APIs), allowing for the automat c integrat on of the tools with other applicat ons to post-process results. Through this architecture (Figure 5), INTEMA provides operat ng data for the systems under considerat on, which serve as the basis for calculat ng the emissions of greenhouse gases and other air pollutants throughout their life cycle. Finally, by using an adjustable and variable t me step, INTEMA can perform opt mizat on studies that consider transient phenomena and control system decisions.

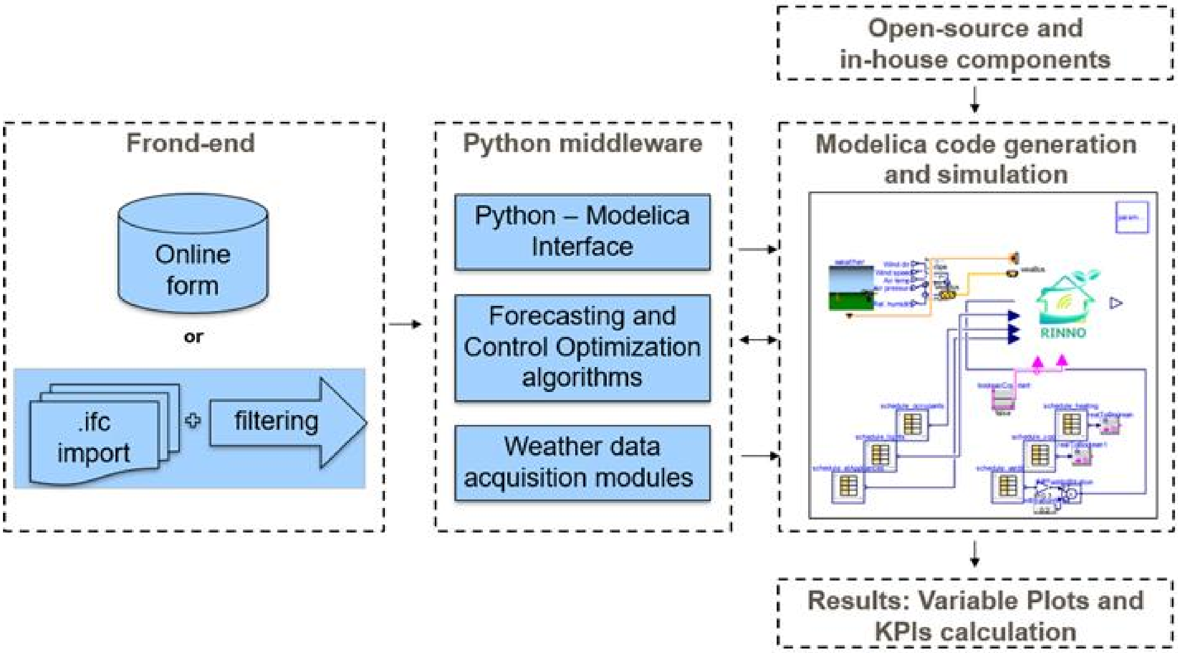

Figure 5. Illustrat on of the INTEMA sof ware architecture.

Overall, as a sof ware tool, INTEMA is designed to be a reliable solut on for the dynamic simulat on of energy systems, part cularly in a t me when the challenges of the energy transit on are cont nually increasing and the engineering and research community is seeking ef ect ve solut ons. INTEMA focuses on (i) buildings and (ii) mult -energy network analyses, enabling engineers to model the synergy of

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systems. Concerning buildings, the sof ware submodule INTEMA.building can accurately est mate the electrical and thermal loads of buildings, as well as the contribut on of the available generat on and storage assets. It supports the def nit on of mult ple thermal zones and considers the dynamic interact on between them, as well as with the environment. The variables considered to est mate the heat load include, among others: i) solar radiat on, ii) the presence of occupants, their act vity and the type of use of the premises iii) psychrometric charts and the operat on of the cooling, heat ng and vent lat on systems (HVAC), and iv) the power generat on of electrical systems, if any.

Unt l now, INTEMA has been implemented in various H2020 research projects (i.e., RINNO, SMILE, and InteGRIDy), addressing dif erent needs regarding the systems to be modeled and the funct onalit es to be demonstrated. Although the core sof ware, addit onal modules, and Graphical User Interface (GUI) have been completed, they are cont nually being expanded with new possibilit es and cert f ed results based on specif c ISO standards, thereby enhancing the user experience. Moreover, INTEMA is currently involved in HEU's ongoing projects, including REHOUSE, IANOS, POCITYF, and RENplusHOMES, which simulate the behavior of dif erent energy systems in buildings to est mate their performance before and af er renovat on.

The exist ng models and components of the INTEMA tool will be properly adjusted to meet the needs of the proposed SIRCULAR technologies and will be extended to enhance their accuracy. Emphasis will be placed on the suitable incorporat on of novel renovat on packages in the INTEMA libraries for the purposes of the proposed demo building renovat on (e.g., prefabricated insulat on panels, BIPVs, etc.).

3.2 SIRCULAR Digital Plat orm (GENEGIS)

3.2.1 Overview

The SIRCULAR project will introduce an advanced digital plat orm designed to equip non-experts in the construct on sector with the necessary tools and resources to promote sustainable and circular building pract ces. Funct oning as a centralized hub, SIRCULAR provides a structured environment tailored for users aiming to integrate circular principles into their projects. The plat orm hosts a suite of state-of-the-art tools that streamline complex processes, as detailed in the following sect ons. By of ering an intuit ve and structured interface, SIRCULAR facilitates navigat on through the complexit es of sustainable construct on, making circularity a tangible and achievable goal.

The plat orm architecture will ensure seamless accessibility to all integrated tools, enabling ef cient data exchange and interoperability. An agile development methodology will be employed to incorporate cont nuous feedback from project partners and end-users, ensuring rapid issue resolut on and iterat ve improvements.

The tools available within the plat orm, further elaborated in the other sect ons, cater to both technical and non-technical users. Technical users will be able to assess the circularity of buildings—whether exist ng or in the design phase—while non-technical users can perform preliminary evaluat ons, such as assessing a building plan's thermal comfort or hygrothermal performance.

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3.2.2 General infrastructure and communicat on

The SIRCULAR plat orm will leverage Azure as its cloud provider, ensuring a robust and scalable infrastructure. A Single Sign-On (SSO) solut on will be implemented, allowing users to log in once and seamlessly access all integrated tools without requiring mult ple authent cat ons.

To support scalability and modularity, the plat orm will adopt a container-based development approach, with Kubernetes managing container orchestrat on and deployment (AKS - AZURE KUBERNETES SERVICE). This approach will facilitate ef cient resource ut lizat on and streamline the integrat on of various tools. In fact, communicat on between the plat orm and both internal and external tools will be facilitated via APIs, ensuring seamless data exchange and interoperability. The API standards will be def ned within Task T2.3, set ng a structured framework for integrat on.

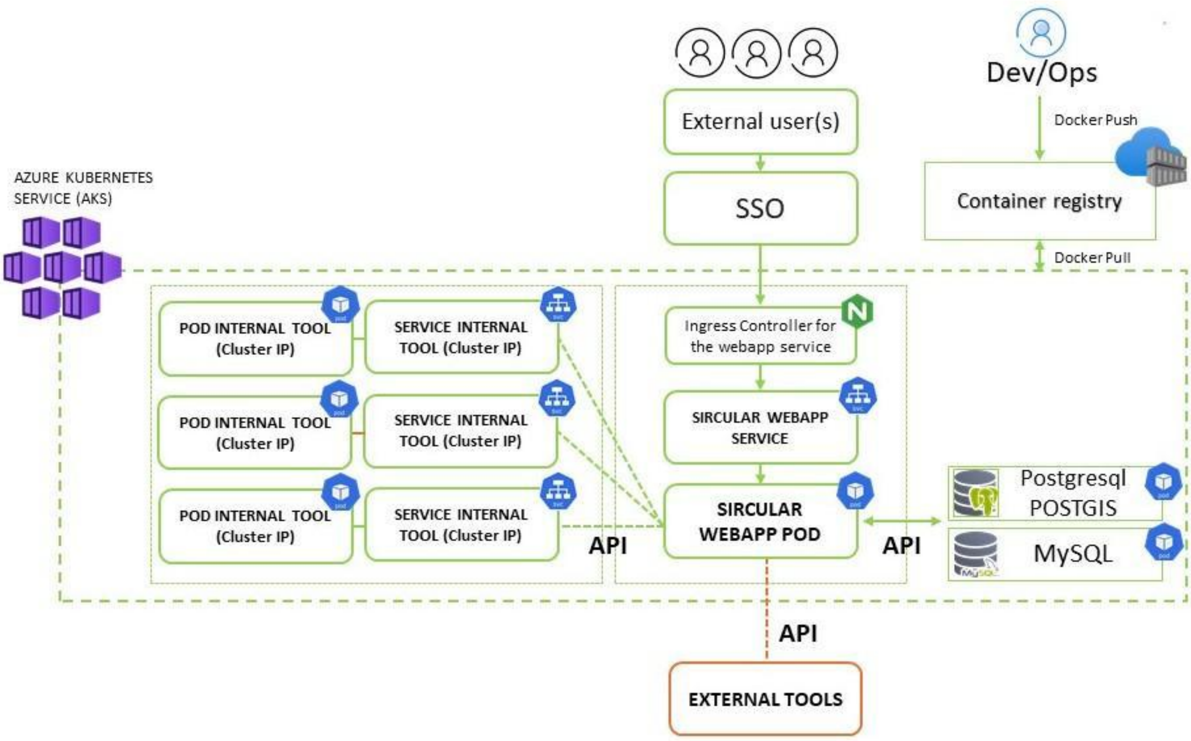

Figure 6. Infrastructure diagram

A dedicated development and test ng environment will be established to support the iterat ve enhancement of the plat orm and its associated tools. Once the plat orm reaches a beta-ready stage, this environment will be duplicated to create a product on environment. The init al development environment will remain operat onal, allowing for cont nuous test ng and further ref nement.

To manage data ef ciently, the plat orm is proposed to incorporate two PostgreSQL-based databases: one designated for geospat al data storage and the other for tool-generated data. This structured data management approach will enhance performance, scalability, and accessibility across the plat orm's ecosystem.

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In the SIRCULAR plat orm, the integrat on of a unif ed Front-End is essent al to ensure a seamless and ef cient user experience. By providing a single, cohesive interface, users can access and ut lize mult ple tools without the need to switch between dif erent environments or interfaces. This approach enhances usability, accessibility, and consistency across all tools, allowing both technical and non-technical users to navigate the plat orm intuit vely. Moreover, a unif ed Front-End facilitates bet er interoperability between the plat orm and the various tools by ensuring a standardized design and interact on framework. This consistency not only improves the overall user experience but also simplif es tool integrat on, maintenance, and scalability.

3.3 CIAT - Circularity Index Assessment Tool

3.3.1 Overview

The Circularity Index Assessment Tool (CIAT) is a pivotal component of the SIRCULAR project, designed to evaluate the recyclability and circularity of the materials and products developed within the project. The methodologies developed in Task 1.2 by RINA-C (and described in Deliverable D1.2, Recyclability and Circularity Index) provide a foundat on for the development of the CIAT tool. However, as the project progresses and based on feedback from partners, certain aspects of the methodology may be further adapted and modif ed. The CIAT tool sof ware will be created in task T2.3.4.

Inputs for the recyclability and circularity methodologies include material types, origin, and quant t es used in the building or product, as well as material end-of-life. These data will have to be inserted into the CIAT tool by the users in order to calculate the desired outputs.

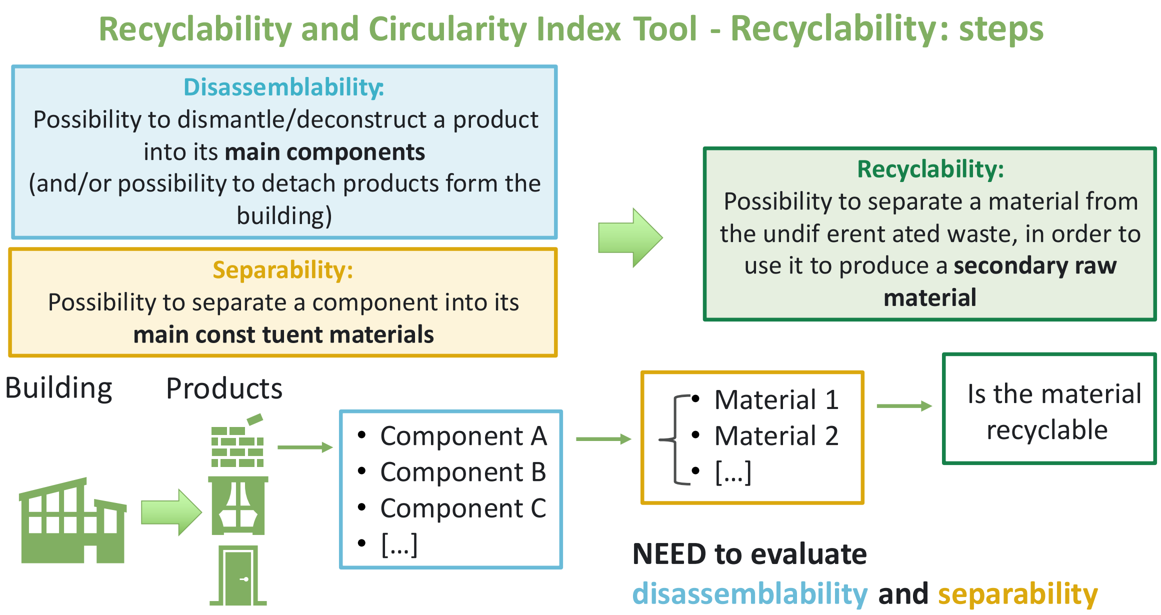

Figure 7. Logical steps to evaluate a building's disassemblability, separability, and the recyclability of const tuent materials. Taken from D1.2.

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The outputs of the recyclability assessment are the potential recyclability rate of each material and the actual end-of-life recycling rate of the material. The circularity assessment provides circularity indexes at the level of single materials, of construction products, and a comprehensive evaluation of whole systems.

Some of the input data for the CIAT tool are in common with what is required in the VERIFY tool, so the two tools can possibly run the respective assessments “in parallel”, starting from data that is manually entered by users into both tools, and automatically extracted from BIM files created in the SIRCULAR project, using software developed by CERTH. Further details on the tool’s functioning and relationships will be better outlined in future project tasks.

Going into more detail on the two methodologies that underpin the CIAT tool, both the recyclability and circularity methodologies start from the subdivision of the buildings into subsystems, each composed of construction products, which in turn can be seen as a combination of materials.

Recyclability is evaluated at the level of materials, considering two indices. The first is the potential recyclability rate represents the percentage of a material that can be potentially recycled at the end of its lifecycle, considering the amount of material that can be collected for recycling, but without accounting for the efficiency of the recycling process. The second index is the actual end-of-life recycling rate, which considers the overall losses in the recovery process by including the recycling process efficiency.

Circularity assessment is primarily based on the comprehensive approach of the Ellen McArthur Foundation and the Granta Design Material Circularity Indicator (MCI) methodology. To adapt it to building components, the approach by layers is applied, and the circularity assessment is organized into steps of increasing complexity and dimensions. Circularity is assessed first at the material level with an MCI for each material (MCI_m). Then, a product-level circularity (MCI_p) is calculated via a mass-weighted average of the MCI of the materials that constitute the product. If information on product disassemblability is available, another product circularity index can be calculated (PCI) by reweighing the MCI_p via disassemblability factors, allowing for a more realistic evaluation of the product circularity. Whenever relevant, a system-level analysis (SCI) can also be added by mass-weighting the PCI (or MCI_p) of the products included in the system. The system could be defined in a custom way, depending on the user’s needs.

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4. SIRCULAR Developing Tools Methodology

4.1 Marketplace and Recycling Plant Mapping (T1.3.1)

4.1.1 Overview

This methodology outlines the implementation process for the marketplace and recycling plant mapping components as part of the SIRCULAR platform. The primary focus is to automate the generation of databases for materials and building renovation products, emphasise sustainability through material circularity, and map recycling plants based on geo-database integration. This methodology will guide the development of a marketplace that integrates emerging technologies such as BIM and IoT while supporting eco-conscious construction practices. Moreover, this methodology outlines the creation of an advanced, user-centric marketplace that automates the collection and evaluation of materials from public databases, integrates geo-database technology for recycling plant mapping, and emphasises sustainability. The SIRCULAR marketplace will promote green transition practices, support SMEs, and contribute to a more sustainable construction sector by utilising emerging technologies such as BIM, IoT, and RESTful APIs.

4.1.2 Input Data Specif cat ons

The marketplace component will automatically generate databases of materials and building renovation products from publicly available sources. This will include:

- **Data Sources**: The Environmental Product Declarations (EPD), the European Reference Life Cycle Database (ELCD), and other publicly available repositories that offer structured and standardised data on construction materials.
- **Data Collection**: A system for gathering and parsing relevant data from these sources will be implemented, enabling the creation of a regularly updated database that reflects new products and materials. The use of web scraping techniques will be examined to be applied where possible, allowing for the automatic collection of information on products from open sources. Moreover, possibly available open HTTP RESTful APIs will be utilised to retrieve data from existing product repositories and keep the information up-to-date.
- **Database Structure**: The repository will prioritize the environmental impact and circularity of materials. Key impact categories such as global warming potential (GWP), water use, energy use, and resource depletion will be selected for evaluating materials based on sustainability criteria. Special efforts will be made to include a variety of product properties in the database to support lifecycle assessments. Apart from the storage of basic information about the products' characteristics, the plan is to store and utilise also (a) information on the quantified performance of the products that will serve as a reference for the LCA, and (b) the quantitative data on environmental impact (use of resources, emissions, waste generation, etc.) associated with different stages of the products' life cycle (e.g., manufacturing, use, end-of-life, etc.).

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- **Automated Population**: Algorithms will be designed to automate the process of populating the repository, which will classify materials based on their sustainability attributes, including recyclability, energy efficiency, and lifecycle performance (after M12).

For recycling plants mapping, input data collect on will be performed following two dif erent methodologies:

- **Collect ng available data from recycling plants websites:** General informat on, such as the facility name, telephone/E-mail/Website, address, coordinates (i.e., Lat tude and Longitude) and operat on hours (e.g., Day of week, start hour-End-hour) will be collected by the SIRCULAR partners during the init al stages of recycling plants mapping act vity. The distance between the demonstrator buildings and the nearby recycling plants will be considered as one of the most relevant parameters to be considered in the ident f cat on of the recycling plant to be mapped.
- **Sending a survey:** A survey will be sent to the individualized recycling plants to collect informat on related to the materials and processes implemented in the plant, as well as behaviors related to good pract ces for environmental and sustainability aspects. A PDF module (See Appendix B) will be sent to the recycling plants by email. The survey, which realizes that the recyclers' ef ort in compiling it will be as lit le as possible, will focus mainly on the materials that recycling plants receive and in which quant t es, on the recycling process used, and on the costs related to waste materials.

Both methodologies will be used for each selected recycling plant because each of them provides dif erent informat on. A copy of the PDF module to be sent to the recycling plants is reported in the Annexes.

4.1.3 Materials and Method

A geo-database will be developed from BIM (Building Information Modeling) models, facilitating integration between spatial data and material attributes. GENEGIS must assist with this approach. This includes:

- **BIM Data Extraction**: Structured data will be extracted from BIM models, categorizing components such as doors, windows, beams, and other infrastructure elements by their geometry and material properties.

- **Geo-Database Structure**: The extracted data will be integrated into a geo-database, where each component is associated with a specific geographical location and categorized for easy search and retrieval.

- **Mapping Recycling Plants**: The geo-database will include a map highlighting the locations of recycling plants. Recycling facilities will be classified based on their processing capabilities (e.g., metal, glass, concrete), proximity to construction sites, and their environmental certifications or sustainability ratings.

Then, a seamless link will be established between the marketplace and the geo-database through a RESTful API. The core functionalities include:

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- **RESTful API**: This API will facilitate communication between the geo-database (containing categorized materials and recycling plant locations) and the marketplace, ensuring a smooth flow of information.
- **Map-Based User Access**: A **Google-style interactive map** will allow users to visualize recycling points and available materials, simplifying the decision-making process in renovation projects. The map will serve as an entry point to the marketplace.
- **Single Sign-On (SSO)**: Users will gain access to both the geo-database and the marketplace through a unified authentication system (SSO), streamlining the experience across both components.

4.1.4 Outputs to the End-User

The SIRCULAR Marketplace will provide end-users with various informat on about the products in its database, including images, technical characterist cs, environmental informat on and impacts, pricing, origin, vendor details, known selling points, and other relevant details. The goal is to enable easy searching of products that interest end-users through f ltering.

Furthermore, through the use of the interact ve map, users of the Marketplace will be able not only to view the locat ons and details of recycling plants closest to their building or facility, but also to ident fy the most suitable plants based on the types of materials processed, preferences, and other characterist cs (through mapping). Therefore, the Marketplace will recommend the best-suited recycling plants to each end-user in a dynamic way. Personalized recommendat ons also include the presentat on of products and materials lists that best suit a user's renovat on project in terms of environmental impact, cost-ef ect veness, and overall performance. To this end, the applicat on of an AI-based method for generat ng recommendat ons (e.g., LLMs) will be explored.

4.1.5 Verif cat on and Validat on

Specif c verif cat on and validat on processes are planned for the development and operat on of the SIRCULAR Marketplace. In part cular, regarding the automated collect on of products' propert es and their insert on into the database, verif cat on will be performed to ensure that the collected informat on is accurate. This will be achieved through specialized scripts developed to ident fy missing and erroneous values. A quality score will be calculated for each data entry, and if it falls below a selected threshold, the corresponding data entry will be discarded. Regarding the recommendat ons produced for both the most suitable recycling plants and the most suitable materials and products, tests will be performed to verify the recommended outputs by experts (selected consort um members) prior to the release of the SIRCULAR Marketplace plat orm. Lastly, validat on will be achieved through feedback from end-users, who will be asked to complete a short quest onnaire to log and evaluate their user experience. This process will also allow collect ng suggest ons for further improving the Marketplace plat orm.

4.1.6 Features and Progress Beyond State-of-the-Art

The SIRCULAR Marketplace will offer a user-centric interface with the following key functionalities:

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- **User-Friendly Design**: The marketplace will feature an intuitive interface, enabling users to easily search, compare, and select materials and renovation products based on technical performance and sustainability criteria.
- **Sustainability Mapping**: The marketplace will integrate with the geo-database, enabling users to access information about local recycling points and materials. This will promote the reuse of construction products, reducing environmental impacts.
- **Personalized Recommendations**: Data from the CIAT tool (which performs Life Cycle Analysis) will be analysed to offer personalized recommendations. These recommendations will suggest the most suitable materials for each user's renovation project, balancing cost-effectiveness**,** environmental impact**,** and overall performance (after M12)**.**

The marketplace is centred on sustainability by giving priority to products that promote circular economy principles, such as materials that are recyclable or have a reduced carbon footprint. Each product's environmental impact will be evaluated against specific criteria, including CO2 emissions, energy consumption, and material longevity, with a particular focus on products that help achieve net-zero objectives.

By incorporating BIM and IoT, the marketplace will provide more accurate and real-time data about materials and products, further promoting sustainability during the design and construction phases.

Current marketplace challenges include insufficient environmental information, pricing inconsistencies, and limited support for small and medium enterprises (SMEs). This methodology aims to address these gaps by:

- **Green Solutions Section**: The marketplace will include a dedicated section for environmentally friendly solutions, offering transparent environmental data and third-party certifications to ensure accountability.
- **Intelligent Search Capabilities**: Advanced search algorithms will facilitate easy access to eco-conscious products, promoting a smooth user experience.
- **SME Engagement**: By simplifying the supply chain and increasing outreach, the marketplace will provide innovative solutions for SMEs, fostering business opportunities in the building renovation sector.

4.2 Hygrothermal Simulat on Tool (T1.3.2)

4.2.1 Overview

The development of a Hygrothermal Simulat on Tool is essent al for accurately assessing the hygrothermal performance of building components and elements. This tool is primarily based on the Internat onal Standard ISO 13788:2012 [3], which provides guidelines for calculat ng internal surface temperatures to avoid crit cal humidity and interst t al condensat on. The complexity of moisture

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transfer necessitates a structured approach to data collect on, modelling, and calculat on, which this methodology outlines in detail.

The foundat on of the Hygrothermal Simulat on Tool is rooted in various ISO standards that guide the calculat ons and methodologies employed:

- **ISO 13788:2012** [3]: This standard addresses the hygrothermal performance of building components, focusing on internal surface temperatures and condensat on risks. It provides a framework for monthly calculat ons, which serve as the basis for assessing moisture-related risks in building designs.
- **ISO 6946:2007** [4]: This standard deals with thermal resistance and transmit ance of building elements. It of ers vital calculat on methods that inform the thermal propert es of materials, which are essent al for understanding heat transport in conjunct on with moisture dynamics.
- **ISO 9346:2007** [5] : This standard provides a vocabulary for physical quant t es related to mass transfer, aiding in the clear def nit on of terms and metrics used in the tool's calculat ons.
- **ISO 15927-1** [6]: This standard of ers guidelines for the calculat on and presentat on of climat c data, focusing on monthly averages of meteorological elements that impact hygrothermal performance.

The development of the Hygrothermal Simulat on Tool is a crucial step in advancing the assessment of building materials and components in terms of their moisture performance. The tool models moisture transport in one-dimensional (1-D) steady-state condit ons, assuming that moisture transfer occurs through pure water vapor dif usion. By adhering to ISO standards and employing a structured methodology, the tool aims to deliver pract cal insights while recognizing the complexit es inherent in hygrothermal behaviour. Ult mately, this tool will serve as a vital resource for designers and engineers, enabling them to make bet er-informed decisions in building design and construct on.

4.2.2 Input Data Specif cat ons

The standard EN ISO 13788:2012 acknowledges the complexity of moisture transfer and the necessity of various parameters for accurate building simulat ons. To develop an accurate simulat on tool, a variety of data is needed, including but not limited to:

1. **Material and Product Propert es**:
   a. Design values for thermal conduct vity (λ) and thermal resistance (R) must be obtained or determined in accordance with ISO 10456 [7].
   b. Water vapour resistance factor (μ) and water vapour dif usion-equivalent air layer thickness (sd) should be obtained from ISO 10456 or determined in accordance with ISO 12572 [8].
2. **External Boundary Condit ons**:
   a. The external condit ons used must be representat ve of the building's locat on, taking alt tude into account where applicable.
   b. Monthly mean values for climat c data should be derived using methods described in ISO 15927-1 or nat onal standards.
3. **Internal Boundary Condit ons**:
   a. Internal air temperature values should be based on the building's expected use.

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   b. Internal humidity can be derived from the internal moisture excess or given as a monthly mean value when known.
4. **Surface Resistances**:
   a. The value of surface thermal resistance (Rsi) should be obtained from specif ed tables for assessing interst t al condensat on or surface condensat on on windows and doors.

4.2.3 Materials and Methods

The standard EN ISO 13788:2012 acknowledges the complexity of moisture transfer and the necessity of various parameters for accurate building simulat ons. It specif es that the internal air temperature and humidity condit ons should be derived from the expected use of the building, taking into account dif erent occupancy levels and act vit es that generate latent loads.

For the calculat ons, the internal humidity can be obtained from the internal moisture excess or given as a monthly mean value when the internal relat ve humidity is known. The standard emphasizes that accurate assessments of moisture condit ons require detailed input data, including material propert es, external boundary condit ons, and internal boundary condit ons, to ef ect vely evaluate the hygrothermal performance of building components. The mathemat cal background relies on simplif ed approaches while recognizing the limitat ons of such methods.

The limitat ons of the simplif ed approaches ment oned in the standard EN ISO 13788:2012 include:

1. The variat on of material propert es with moisture content is not considered.
2. Capillary suct on and liquid moisture transfer within materials are not considered.
3. Air movement from within the building into the component through gaps or within air spaces is neglected.
4. The hygroscopic moisture capacity of materials is not addressed.

These limitat ons mean that the method is applicable only where the ef ects of these phenomena can be considered negligible.

Regarding the def nit on of hygrothermal performance, the most common values available for building materials are insuf cient for accurately describing the moisture transfer process. The moisture transfer theory is complex and requires informat on that is typically hard to gather; the theory requires highly specif c knowledge of hygrothermal calculat on. The designer needs more data e.g. moisture and capillarity funct on, moisture content of the material, inclinat on of the component, short and long-wave radiat on, hourly climate data etc., to obtain more precise and complete results. The Glaser Method, which simplif es the calculat on process, serves as the basis for the tool to overcome the stated limitat ons. The steps involved include:

1. Def ning the external temperature in accordance with the specif ed climat c data.
2. Def ning the external humidity condit ons using vapour pressure calculat ons.
3. Determining the internal air temperature based on the building's expected use.
4. Calculat ng the internal relat ve humidity using the internal moisture excess or given monthly mean values.
5. Calculat ng the minimum acceptable surface temperature to avoid crit cal surface humidity and interst t al condensat on.
6. Assessing the thermal quality of each building envelope element, represented by thermal resistance and internal surface resistance.

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7. Calculat ng the temperature factor at the internal surface to ensure it exceeds the minimum acceptable value throughout the year.
8. Surface Temperature Est mat on: The tool will calculate internal surface temperatures of the system to determine the risk of condensat on in the connect on of the elements. This involves evaluat ng the thermal transmit ance of building elements and using climate data to assess potent al surface humidity.

The evaluat on of water and humidity movement through structural elements using mean monthly values assumes that moisture transport is primarily by vapour dif usion, which simplif es the complex nature of moisture transfer. The standard acknowledges that while this method does not account for all physical phenomena, it provides a robust analysis for certain structures, part cularly lightweight and airt ght construct ons that do not store large amounts of water.

The use of mean monthly values enables a generalized assessment of moisture condit ons over t me, which can lead to designs that are typically on the conservat ve side. This approach is part cularly useful in climates where temperature and humidity variat ons can be averaged out over the month, thereby providing a conservat ve est mate of worst-case scenarios for moisture accumulat on and condensat on risks.

However, the standard also recognizes that if a construct on fails to meet specif ed design criteria based on these simplif ed calculat ons, more advanced methods can be employed to provide a more accurate assessment of moisture condit ons, part cularly during extreme weather events or specif c hours of the day. Therefore, while mean monthly values may not capture the nuances of daily f uctuat ons, they serve as a pract cal start ng point for evaluat ng moisture performance in building components.

- **Limitat ons and Assumpt ons**: The methodology will clearly state the limitat ons of the tool, including its inability to account for dynamic factors such as f uctuat ng thermal propert es, three-dimensional moisture transport, and detailed environmental inf uences. It will be emphasized that the tool is designed to provide numerical outputs for assessing building components and elements.

The mathemat cal background that is expected to be used in the present tool follows the methodology of EN ISO 13788. The main goal of the tool is to determine the condensat on risk. The formulas that def ne relat ve humidity and the temperature factor at the internal surface are indispensable units for this risk assessment. The equat on (1) helps quant fy the moisture content in the air relat ve to the maximum point that can be held at a given temperature. Equat ons (2) and (3) measure the risk of mould growth and the risk of condensat on by evaluat ng surface temperatures and ident fying crit cal points within the envelope.

$$\varphi = \frac{p}{p_{sat}} \tag{1}$$

$$f_{R_{si}} = \frac{\theta_{si}-\theta_e}{\theta_i-\theta_e} \tag{2}$$

$$f_{R_{si,min}} = \frac{\theta_{si,min}-\theta_e}{\theta_i-\theta_e} \tag{3}$$

Where:

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φ = Relat ve humidity [-]
p = Water vapour pressure [Pa]
p_{sat} = Saturated water vapour pressure [Pa]
$f_{R_{si}}$ = Temperature factor at the internal surface [-]
$f_{R_{si}}$ = Design temperature factor at the internal surface [-]
θ_{si} = Temperature at the internal surface [°C]
θ_e = External temperature [°C]
θ_i = Internal temperature [°C]
$\theta_{si,i}$ = Minimum acceptable surface temperature [°C]

Below are the formulas to be used, in the order that they will be performed as calculat ons. Firstly, the def nit on of the boundary condit ons of the external condit ons is necessary. The average temperature of the climate for each month and the external air humidity condit ons are going to be calculated with equat ons (3) and (4), respect vely. Both values inf uence condensat on risk.

$$\theta_e = \frac{\theta_{an} + \theta_m}{2} \quad (4)$$

$$p_e = \varphi_e \cdot p_{sat}(\theta_e) \quad (5)$$

Where:

θ_{an} = Annual mean temperature [°C]
θ_{an} = Monthly mean temperature [°C]
p_e = Water vapour pressure [Pa]

φ_e = External relat ve humidity [-]

Secondly, the def nit on of the boundary condit ons of the internal condit ons is necessary. It will be useful to calculate internal vapour pressure by adding the dif erence to the external vapour pressure to ref ect the addit onal moisture generated by occupants, act vit es, and indoor condit ons.

$$p_i = p_e + \Delta p \quad (6)$$

$$\Delta p = \Delta v \cdot R_v \cdot T_i = \frac{G}{n \cdot V} \cdot R_v \cdot T_i \quad (7)$$

Where:

p_i = Internal pressure [Pa]
p_i = External pressure [Pa]
Δp = Internal vapour pressure excess
Δv = Internal moisture excess $[\frac{kg}{m^3}]$
R_v = Gas constant for water vapour $\left[Pa \cdot \frac{m^3}{(K \cdot kg)}\right]$
T_i = Internal temperature [K]
G = Internal moisture product on rate $\left[\frac{kg}{h}\right]$
n = Air change rate $[h^{-1}]$
V = Internal volume of the building $[m^3]$

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The def nit on of internal surface thermal resistance R_{si} [(m^{2}K)/W] and the external surface thermal resistance R_{se} [(m^{2}K)/W] will be necessary to quant fy the resistance to heat f ow on internal and external surfaces. Surface resistances are crit cal for calculat ng temperature distribut on and heat transfer across building components. These values feed into calculat ons of surface temperatures and help determine whether they exceed dew point condit ons. The thermal resistance depends on the direct on of the heat f ow, and specif c values will be def ned accordingly with the ISO13788:2012.

To assess indoor condit ons against crit cal mould thresholds, crit cal humidity can be calculated with the equat on (8). To ensure that the accumulat on of moisture within the materials will not degrade insulat on and cause structural issues that can lead to mould, the density of water vapour f ow rate will also be calculated (9). The value of g will be used to evaluate condensat on within the building envelope layers.

$$\varphi_{si,cr,monthly\ mean} = 0{,}8 \cdot \varphi \tag{8}$$

$$g = \frac{\delta_0}{\mu} \cdot \frac{\Delta p}{d} = \delta_0 \cdot \frac{\Delta p}{s_d} \tag{9}$$

$\varphi_{si,cr,monthly\ mean}$ = Crit cal monthly mean internal surface relat ve humidity [-]
φ = Relat ve humidity [-]
p_i = Internal pressure [Pa]
δ_0 = Water vapour permeability of air with respect to part al vapour pressure $[\frac{kg}{(m^2 \cdot s \cdot Pa)}]$
μ = Water vapour resistance factor [-]
d = Material layer thickness [m]
s_d = Water vapour dif usion - equivalent air layer thickness [m]

Af er the boundary condit ons of the external and internal surfaces of the material assembly are def ned, a select on of other variable units will be def ned based on the material propert es. The total thermal resistance, the total water vapor dif usion-equivalent air layer thickness are among them. To evaluate the dif erent assemblies, the distribut on of temperatures and saturated vapor will be calculated along with the thickness of the assembly, as well as the condensat on and evaporat on rate with equat ons (10) and (11).

$$\theta'_n = \theta_e + \frac{R'_n}{R'_T}(\theta_i - \theta_e) \tag{10}$$

$$g = \delta_0 \cdot \left(\frac{p_i - p_e}{s'_{d,T}}\right) \tag{11}$$

θ'_n = Density of water vapour f ow rate $[\frac{kg}{m^2 \cdot s}]$
θ_e = External Celsius temperature [°C]
R'_n = Accumulated thermal resistance $[\frac{kg}{(m^2 \cdot s \cdot Pa)}]$
R'_T = Total thermal resistance [m]
θ_i = External Celsius temperature [°C]
p_i = Internal pressure [Pa]
p_e = External air pressure [Pa]
$s'_{d,T}$ = Total water vapor dif usion-equivalent air layer thickness [m]

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To calculate the density of water vapor f ow rate, it is necessary to use the following equat ons (11) - (13) to def ne the accumulated thermal resistance, the total thermal resistance, and the total water vapour dif usion equivalent air layer thickness.

$$R'_n = R_{se} + \sum_{j=1}^{n} R_j \tag{12}$$

$$R'_T = R_{si} + \sum_{j=1}^{n} R_j + R_{se} \tag{13}$$

$$s'_{d,T} = \sum_{j=1}^{N} s_{d,j} \tag{14}$$

Where:

R'_n = Accumulated thermal resistance $[\frac{m^2 \cdot K}{W}]$

R_{se} = External surface thermal resistance $[\frac{m^2 \cdot K}{W}]$

n = Interface [-]

R'_T = Total thermal resistance $\left[\frac{m^2 \cdot K}{W}\right]$

R_{si} = Internal surface thermal resistance $[\frac{m^2 \cdot K}{W}]$

$s'_{d,T}$ = Total water vapour dif usion-equivalent air layer thickness [m]

The condensat on and evaporat on rates (14) and (15) will enable us to see how the building envelope can manage its moisture load.

$$g_c = \delta_0 \cdot \left(\frac{p_i - p_c}{s'_{d,T} - s'_{d,c}} - \frac{p_i - p_c}{s'_{d,c}}\right) \tag{15}$$

$$g_{ev} = \delta_0 \cdot \left(\frac{p_i - p_c}{s'_{d,T} - s'_{d,c}} - \frac{p_i - p_c}{s'_{d,c}}\right) \tag{16}$$

Where:

g = Density of water vapour f ow rate $[\frac{kg}{m^2 \cdot s}]$

p_i = Internal pressure [Pa]

p_c = Condensat on pressure [Pa]

δ_0 = Water vapour permeability of air with respect to part al vapour pressure $[\frac{kg}{(m^2 \cdot s \cdot Pa)}]$

s_d = Water vapour dif usion-equivalent air layer thickness [m]

$s'_{d,T}$ = Total water vapor dif usion-equivalent air layer thickness [m]

$s'_{d,c}$ = Water vapor dif usion-equivalent air layer thickness for condensat on [m]

Since the tool has not been developed yet, the calculat on process is not fully def ned and thus a full f owchart that would describe it cannot be provided in this report.

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4.2.4 Outputs to the End-User

The end-user will receive several key outputs from the Hygrothermal Simulat on Tool:

1. **Detailed Reports**: Comprehensive reports summarizing the hygrothermal performance of building components, including internal surface temperatures and condensat on risk assessments.
2. **User-Friendly Interface**: An intuit ve interface that simplif es data input and result interpretat on, making it accessible even for users without specialized expert se.
3. **Calculat on Outputs (Monthly)**: Clear outputs displaying calculated values for moisture levels, temperatures, and vapour pressures within building elements.
4. **Guidance on Material Select on**: Recommendat ons on materials based on their moisture performance, helping users make informed choices.
5. **Visualizat ons**: Graphical representat ons of data, such as temperature prof les and moisture distribut on, to aid in understanding complex interact ons.
6. **Reference Materials**: Access to relevant ISO standards and references used in the calculat ons, promot ng transparency and further learning.
7. **Customizable Parameters**: The ability to input specif c design scenarios, allowing for tailored assessments based on individual project needs.

By providing these deliverables, the tool will empower users to ef ect vely assess and improve the hygrothermal performance of their building designs.

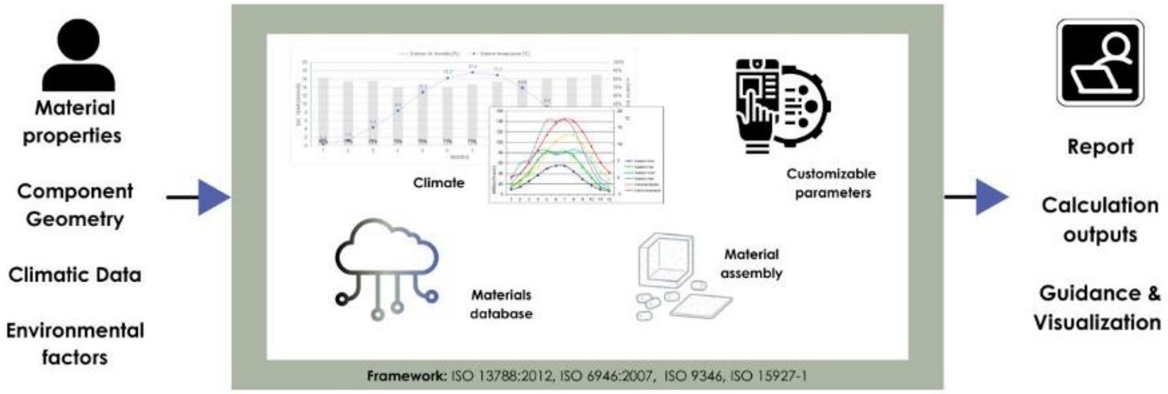

Figure 8. Depict on of the methodology behind the hygrothermal tool. On the lef is the input from the user, and on the right is the output of ered to the end-user.

4.2.5 Verif cat on and Validat on

While the Hygrothermal Simulat on Tool is based on simplif ed calculat ons, it acknowledges that verif cat on through more complex methodologies may be necessary for detailed studies. For example, results from the tool can be cross-referenced with dynamic simulat ons, such as WUFI sof ware, as

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outlined in EN 15026. WUFI® [9] is based on the latest knowledge in vapor dif usion and liquid transport in building materials. This approach will help validate the accuracy of the simplif ed results and provide insights into areas for further ref nement.

4.2.6 Features and Progress Beyond State-of-the-Art

The Hygrothermal Simulat on Tool will address several key needs in the assessment of building components and materials:

1. **Moisture Performance Assessment**: Evaluate the hygrothermal performance of building elements to prevent issues such as mold growth, rot, and material degradat on.
2. **Internal Surface Temperature Calculat ons**: Provide accurate calculat ons of internal surface temperatures to avoid crit cal surface humidity, which can lead to condensat on problems.
3. **Interst t al Condensat on Est mat on**: Est mate temperature and vapour pressure within building components to assess the risk of interst t al condensat on, a major concern in wall assemblies.
4. **Simplif ed Calculat on Methods**: Of er simplif ed methods based on ISO standards that allow designers and engineers to perform essent al assessments without needing extensive expert se in hygrothermal theory.
5. **Data-Driven Insights**: Ut lize comprehensive data on material propert es, climate condit ons, and component geometry to deliver more accurate and relevant results.
6. **Monthly Performance Evaluat on**: Implement monthly calculat on methods that align with industry standards, providing a pract cal approach to evaluat ng moisture behavior over t me.
7. **User-Friendly Interface**: Facilitate ease of use for pract t oners who may not be specialists in hygrothermal analysis, making the tool accessible for a broader audience.
8. **Guidance on Limitat ons**: Clearly communicate the limitat ons of simplif ed methods, ensuring users understand when more detailed analysis may be necessary.
9. **Support for Decision-Making**: Aid architects and engineers in making informed design choices that enhance building durability and indoor air quality.
10. **Integrat on with Other Standards**: Align with addit onal relevant standards (e.g., thermal resistance calculat ons) to provide a comprehensive tool that covers mult ple aspects of building performance.

By addressing these needs, the Hygrothermal Simulat on Tool will signif cantly contribute to enhancing building design and performance in terms of moisture management.

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4.3 Comfort Evaluat on Tool (T1.3.3)

4.3.1 Overview

The task aims to design and develop a simplif ed and accurate comfort evaluat on tool that can ident fy and est mate a building's indoor condit ons. The convent onal building simulat on approach is only associated with energy calculat ons based on the zone mean air temperature, and it does not consider thermal comfort calculat ons. The comfort evaluat on tool is a new, under-development simplif ed tool that will provide accurate est mat ons of indoor air condit ons based on data retrieved from suitable dynamic simulat on sof ware.

The main idea of this tool is to develop a simple regression model, based on a large dataset of indoor thermal comfort outputs, derived from analyt cal building energy models. For this simplif ed comfort evaluat on tool, single-story resident al buildings will be invest gated. Specif cally, appropriate and analyt cal building models will be developed using the DesignBuilder sof ware [10], a user-friendly interface that allows smooth and ef ect ve geometrical descript on of the examined buildings. Specif cally, DesignBuilder will be used for the creat on of appropriate input data f les that will be properly connected to the Python programming language. A Python-writ en code will be used to call the EnergyPlus [11] simulat on program and automat cally run mult ple simulat on cases with minimum execut on t me. The results will be further processed, and the f nal assessment indices will be calculated. Figure 9 illustrates the development process of the comfort evaluat on tool.

The present tool's primary object ve is to leverage accurate dynamic simulat on results to derive universal and accurate conclusions regarding energy savings and thermal comfort indices within the building envelope. This informat on will empower and support decision-makers in the building industry to correctly select building construct on methods and renovat on pract ces by priorit zing thermal comfort in combinat on with building energy performance and energy savings. Specif cally, through dynamic simulat ons conducted in Design Builder, SIRCULAR's innovat ve solut on aims to quant fy indoor thermal condit ons (temperature, humidity, PMV, PPD), bridging the divide between energy ef ciency and inhabitant comfort. The comfort evaluat on tool is a pract cal, user-friendly tool developed in an Excel Spreadsheet f le that will aid in recognizing the pivotal role of indoor thermal comfort and air quality in newly constructed or deeply renovated buildings, addressing a crucial gap in the building market.

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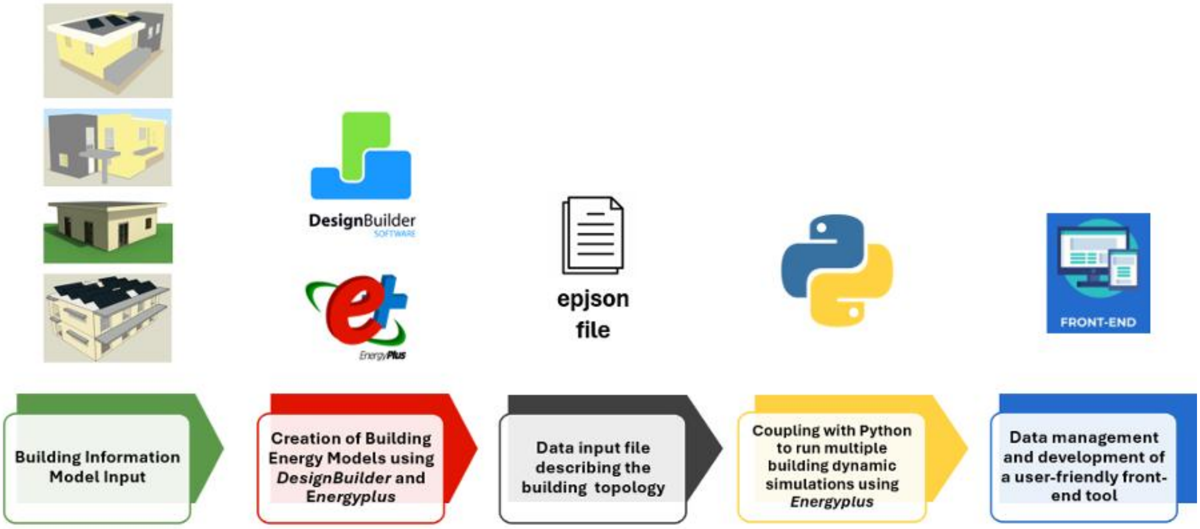

Figure 9. Schemat c process of dataset collect on and development of the Comfort Evaluat on tool.

Overall, the present task aims to develop a simple, user-friendly comfort evaluat on tool that is suitable for the evaluat on of thermal comfort and indoor air quality in buildings. Through a mult -parameter, systemat c building simulat on process, a detailed dataset will be created, which will be used for the development of regression models. According to the parameters inserted by the user, the developed polynomial regression models will provide a set of variables that will be automat cally used to describe indoor thermal comfort and air quality condit ons with the indexes PMV and PPD. The comfort evaluat on tool developed for the SIRCULAR project aims to give a clear image of the renovat on act ons in terms of energy savings and thermal comfort enhancement in the renovated buildings. This goal plays a signif cant role in the construct on industry and aids in the transformat on of the energy-consuming building sector into an energy-ef cient and sustainable sector.

4.3.2 Input Data Specif cat ons

The formulat on of the dataset will be based on the simulat on data retrieved from a series of dynamic energy analyses of suitable parameterized building models for dif erent locat ons. The building models will be developed using DesignBuilder sof ware, which combines a user-friendly interface and the dynamic simulat on calculat on of EnergyPlus. The simulated building models will concern typical one-story apartment topologies. To collect the necessary simulat on dataset, the respect ve building model will be parameterized by def ning several main parameters. The def nit on of the parameters will allow the simulat on of mult ple scenarios that will consider a wide variety of building designs and boundary condit ons.

The inputs in the dynamic simulat ons are the following:

- Building geometry and materials (f oor area, insulat on existence, type of glazing, shading devices, inf ltrat on/vent lat on rates, appliances-light ng-occupancy prof les, etc.)
- Hourly weather data (ambient temperature, direct & dif use solar irradiat on, humidity)

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During the invest gat on, dif erent types of buildings will be examined by using the following criteria. All the possible combinat ons of these parameters lead to dif erent building topologies (e.g. 32 building cases).

- Small/big room
- Room shape (Square and rectangle)
- Uninsulated/low-insulated building envelope
- Single/double glazing
- With/without shading element

For every building type, dif erent renovat on act ons will be studied separately and in combinat on. Specif cally:

- Addit on of external thermal insulat on layer (e.g., 5 cm)
- Replacement of the windows with energy-ef cient triple-glazed, novel gas-f lled windows
- Installat on of a mechanical vent lat on/cooling system with opt mal control in the summer
- Addit on of proper external shading elements

The aforement oned renovat on act ons lead to a total of 15 dif erent renovat on scenarios that will be examined for every building case. The f nal dataset of all simulat ons will be created by examining the dif erent renovat on scenarios and the baseline scenarios for the dif erent building topologies. Also, in the case that extra parameters are found to be important, they will be included in this work. Moreover, possibly, the extension of the data for dif erent cases (e.g., greater f oor areas) will be studied using regression polynomials.

4.3.3 Materials and Methods

For the development of the comfort evaluat on tool, informat on and guidelines were retrieved from various standards. Specif cally, the used standards include: i) the ASHRAE 55-2017 [12], which is a standard from the American Society of Heat ng, Refrigerat ng and Air-Condit oning Engineers that outlines criteria for thermal comfort in indoor spaces, ii) the ISO 7730:2005 [13], which is an internat onal standard that provides guidelines for evaluat ng thermal comfort in indoor environments, and iii) EN 16798-1:2019 [14], which is a European standard that specif es the indoor climate requirements for energy performance in buildings and outlines criteria for thermal comfort, indoor air quality, and vent lat on. The evaluat on of thermal comfort and air-quality indoor condit ons requires the considerat on of various factors, namely air temperature, humidity, and radiant temperature, promot ng occupant health and well-being while opt mizing energy ef ciency and emphasizing the role of personal factors such as clothing and act vity level.

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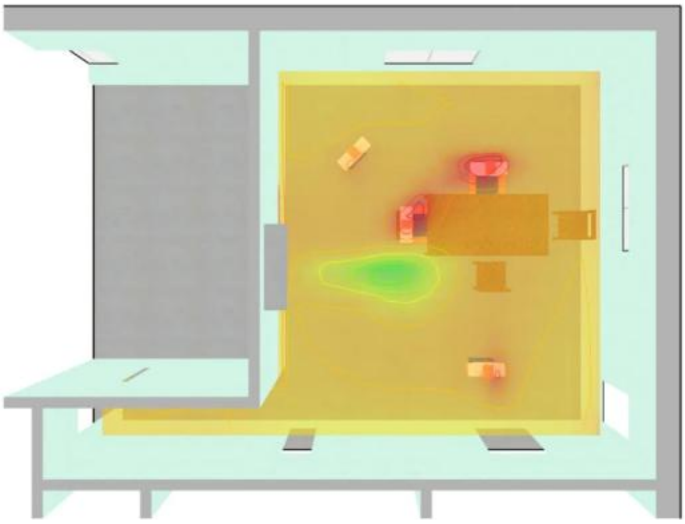

Figure 10. Spat al air temperature distribut on in a typical single zone.

The comfort evaluat on tool will be developed using dynamic simulat on in the Design-Builder tool using the Python programming language. The f nal tool will have a proper frontend, which will probably be based on the Excel spreadsheet sof ware. The tool will be simple and very user-friendly, and the user will be requested to insert various parameters that concern the climat c boundary condit ons, the building geometry, and thermal propert es. The comfort evaluat on tool aims to provide a useful assessment of indoor thermal comfort condit ons. Useful informat on regarding the thermal comfort condit ons inside the renovated buildings, as well as the expected energy savings, will be given as output. The results will provide useful insights and aid in the decision-making process of building renovat on projects.

This section discusses the mathematical background of thermal comfort calculations. A person's specific internal heat production rate is denoted with H in [W/m^2] and corresponds to the difference between a person's rate of metabolism and work heat loss rate, denoted with M and W, respectively, both in [W/m^2].

$$H = M - W \tag{17}$$

Fanger's thermal comfort model [15] defines that a person is at a thermally steady state within the indoor environment of a building. Therefore, a person's specific metabolic rate M [W/m^2] equals the specific rate of thermal losses through respiration, clothes, and skin, L [W/m^2].

$$M = L \tag{18}$$

A person's skin and clothing level are referred to as the outer body surface. The heat exchange at the outer body surface is realized through heat conduction, convection, radiation, and evaporation at the skin surface. Heat conduction is realized primarily at the interfaces of a person's outer body surface and a solid surface. Convection regards the heat exchange from the skin surface to fluid or gaseous surroundings. The specific heat conduction rate q_{cond} [W/m^2] is given as:

$$q_{cond} = h_{cond} \cdot (T_{outerbody} - T_{surfcace}) \tag{19}$$

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Where $T_{outerbody}$ [K] and $T_{surface}$ [K] represent the outer body surface temperature and solid surface temperature, respectively, while h_{cond} [W/m²K] is the conductive heat transfer coefficient between the skin and the solid surface in contact. The overall heat transfer from the body via conduction is usually neglected because the conductivity of bedding and seating materials tends to be small.

The specific convective heat rate q_{conv} [W/m²] from the outer body surface is set as a difference between the body's outer surface average temperature, denoted with $T_{surface}$ [K], and the air dry-bulb temperature, denoted with T_{air} [K].

$$q_{conv} = h_{conv} \cdot f_{cl} \cdot (T_{surfcace} - T_{air}) \tag{20}$$

Where h_{conv} is the convective heat transfer coefficient expressed in [W/m²K]. The ratio of the body covered with clothes is given as f_{cl} [15].

The specific radiation heat emitted from the outer body surface of a person q_{rad} is calculated as:

$$q_{rad} = \sigma \cdot \varepsilon \cdot f_{eff} \cdot ({T_{outerbody}}^4 - {T_{MRT}}^4) \tag{21}$$

Where σ is the Stefan-Boltzmann constant, equal to $5.67 \cdot 10^{-8}$ [W/m²K⁴], ε is the clothing and skin emittance, f_{eff} is the fraction of surface effective for radiation, which is considered equal to 0.70 [15] while T_{MRT} represents the mean radiant temperature of the surrounding surfaces.

The specific heat transfer via evaporative cooling q_{evap} in [W/m²] is calculated using an evaporative heat exchange coefficient h_{evap}, given in [W/m²kPa], and the water vapor pressure difference between the skin and the surrounding air, according to the following equation [16]:

$$q_{evap} = h_{evap} \cdot w_{skin} \cdot \left(P_{skin,saturated} - P_{air}\right) \tag{22}$$

The skin wettedness is denoted with w (dimensionless), $P_{skin,saturated}$ in [kPa] is the water vapor pressure at the skin surface, assumed to be the pressure of saturated air at the skin temperature, and P_{air} in [kPa], is the water vapor pressure of the ambient air. The evaporative heat transfer coefficient for the outer air layer of a nude person can be estimated from the convective heat transfer coefficient using the Lewis ratio, which defines the relationship between convective heat transfer and mass transfer coefficients at a surface:

$$\text{Lewis ratio} = \frac{h_{evap}}{h_{conv}} \tag{23}$$

The Lewis ratio is equal to 16.5 K/kPa for typical indoor conditions [16] and as a result,

$$h_{evap} = 2.2 \cdot h_{conv} \tag{24}$$

The specific skin evaporative heat loss, expressed as q_{evap} [W/m²], is set as a function of the specific internal heat production rate, accordingly:

$$q_{evap} = \begin{cases} 0.00305 \cdot (5733 - 6.99 \cdot H - P_{air}), H > 58.2 \\ 0.00305 \cdot (5733 - 6.99 \cdot H - P_{air}) + 0.42 \cdot (H - 58.2),\ H \leq 58.2 \end{cases} \tag{25}$$

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An average person's area equals to 1.8 m^2 [17]. The rate of metabolism is usually given in mets, where 1 met = 58.2 W/m^2 [18].

Respiration heat transfer, Q_{res} [W], is the sum of latent and sensible respiratory heat transfer and is calculated according to the following equation:

$$Q_{res} = \rho_{air} \cdot \dot{V} \cdot Cp_{air} \cdot (T_e - T_{air}) + \rho_{air} \cdot \dot{V} \cdot (\gamma_e - \gamma_i) \cdot h_{fg} + \rho_{air} \cdot \dot{V} \cdot \gamma_i \cdot Cp_v \cdot (T_e - T_{air}) \quad (26)$$

Where ρ_{air} stands for the density of air [kg/m^3], $\dot{V}$ is the respiratory ventilation rate in [m^3/s], Cp_{air} is the air's specific heat capacity [J/kg K], T_e is the expired air temperature in [K], T_{air} is the air temperature [K], γ_ε and γ_i are the expired and inspired air humidity ratios, h_{fg} is the specific enthalpy of vaporization [J/kg K], and Cp_v is the water vapor specific heat capacity [J/kg K].

According to the EnergyPlus documentation [15] and Fanger's thermal comfort equations, the specific respiratory heat transfer q_{res} [W/m^2] is calculated as a function of metabolic rate M [W/m^2] according to the following equation:

$$q_{res} = 17 \cdot 10^{-6} \cdot M(5867 - P_{air}) + 0.0014 \cdot M \cdot (34 - T_{air}) \quad (27)$$

The total energy losses from a person's body are calculated as:

$$L = q_{cond} + q_{conv} + q_{rad} + q_{evap} + q_{res} \quad (28)$$

If the conductive heat transfer q_{cond} is neglected, then:

$$L = q_{conv} + q_{rad} + q_{evap} + q_{res} \quad (29)$$

The predicted mean vote (PMV) thermal sensation index is a psycho-physical scale that quantifies the deviation of the total specific energy loss (L) from the specific metabolic rate (M) and is given as [15]:

$$PMV = (0.303e^{-0.036 \cdot M} + 0.028) \cdot (M - L) \quad (30)$$

This thermal comfort equat on derives from regression analyses of the measured data obtained from steady-state experiments [19]. Fanger's model evaluates thermal sensat on based on the level of sat sfact on of the opt mal thermal comfort condit ons.

The predicted percentage of dissatisfied (PPD) is given as a function of the PMV index:

$$PPD = 100 - 95 \cdot e^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)} \quad (31)$$

4.3.4 Outputs to the End-Users

The comfort evaluat on tool will assess thermal comfort and energy performance to evaluate the ef ect veness of a renovat on strategy on mult ple levels. First, the user will input various parameters to describe the building of interest, forming the baseline scenario. Next, informat on about the planned renovat on act ons will be entered, def ning the renovat on scenario. The tool will then compare the two scenarios, providing thermal comfort and energy performance indexes. Specif cally, the outputs will indicate the percentage improvement between the renovat on and baseline scenarios. For thermal comfort, this may include the percentage dif erence in the mean annual PPD

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index or the mean absolute PMV index. For building thermal loads, the tool will calculate changes in yearly heat ng and cooling energy demands. In addit on to yearly average indexes, hourly output can also be provided. This may include indoor air temperature, mean radiant temperature, indoor air relat ve humidity, thermal loads, and PPD and PMV indexes for selected days of the year. These selected days could correspond to the coldest and warmest days when maximum thermal loads occur.

4.3.5 Verif cat on and Validat on

The verif cat on of the present model will be conducted by comparing the results of some cases with the IDA-ICE tool. The PMV, PPD, and other parameters linked to the building's thermal performance will be compared for some crit cal cases, aiming to determine the accuracy of the calculat ons. It is important to state that the presented methodology has been recently applied in a recently published scient f c work conducted by the present research team of NTUA [20]. Finally, the results derived from the development of this innovat ve tool will be published in accredited scient f c journals and presented at scient f c conferences.

4.3.6 Features and Progress Beyond State-of-the-Art

The comfort evaluat on tool will integrate the evaluat on of thermal comfort and energy performance into a compact tool, aiming to est mate the improvement achieved through the implementat on of various renovat on act ons. This is a novel idea that tries to take into considerat on the value of the indoor air condit ons by evaluat ng the enhancement of the living quality of the residents. The exist ng tools do not simultaneously address energy ef ciency and thermal comfort, and this gap will be f lled by the present tool.

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5. Conclusions

The SIRCULAR project presents an integrated approach to promote circularity and sustainability within the building sector by developing and ut lizing innovat ve digital tools and methodologies. The present Deliverable provides an analyt cal summary of the methodologies for the developed and developing tools that will be ut lized throughout the project. The so-called developed tools concern the VERIFY tool by CERTH, the SIRCULAR digital plat orm by GENEGIS, and the CIAT tool by RINA. Respect vely, the developing tools within the SIRCULAR project include the Marketplace and Recycling Plant Mapping Tool by CERTH, the Hygrothermal Simulat on Tool by HPHI, and the Comfort Evaluat on Tool by NTUA. Moreover, this report of ers the theoret cal backbone for all the technical processes that are involved in the f nal outcome of the SIRCULAR project, of ering a fundamental guide for all the associated partners. The examined tools will interact within the f nal SIRCULAR plat orm by exchanging data and results, aiming at enhancing the environmental, economic, and social performance of buildings throughout their lifecycle.

The developed tools (i.e., VERIFY, CIAT, and the GENEGIS plat orm) signif cantly contribute to the SIRCULAR project by integrat ng advanced methodologies, dynamic life-cycle analysis, and robust data interoperability. Specif cally, VERIFY provides dynamic environmental and economic life cycle assessments, which are crucial for informed decision-making in sustainable construct on pract ces. CIAT of ers a systemat c approach to evaluat ng recyclability and circularity, thereby support ng material sustainability and principles of the circular economy. Addit onally, the GENEGIS plat orm of ers a user-centric and technologically advanced solut on that streamlines data integrat on and enhances the accessibility of tools. Overall, these tools represent signif cant advancements toward the sustainable transformat on of the construct on industry, opt mizing both environmental and economic outcomes.

Respect vely, the developing tools (i.e., Marketplace and Recycling Plant Mapping Tool, Hygrothermal tool, and Comfort Evaluat on tool) embody SIRCULAR's commitment to provide pract cal, sustainable, and user-oriented solut ons towards a decarbonized building sector. The Marketplace and Recycling Plant Mapping Tool allows the generat on of a database for sustainable materials and building renovat on products. Ut lizing features, such as BIM and IoT, simplif es the select on of eco-friendly materials and opt mizes the ident f cat on of recycling plants. This plat orm represents a signif cant advancement over convent onal marketplace solut ons by integrat ng real-t me data, sophist cated mapping capabilit es, and personalized user recommendat ons. Moreover, the Hygrothermal Simulat on tool addresses crit cal issues related to moisture and thermal management within building components. Based on ISO standards and simplif ed calculat on methods, it mot vates users to ef ciently assess and mit gate risks associated with condensat on and mold growth. Its user-friendly interface promotes occupant health through informed design decisions. Finally, the Comfort Evaluat on tool signif cantly contributes to bridging the gap between energy ef ciency and occupant comfort. Using dynamic simulat ons, it delivers precise and act onable insights into indoor thermal condit ons. By facilitat ng accurate assessments of thermal comfort indicators, such as PMV and PPD, this tool aids stakeholders in making informed decisions regarding building renovat ons and new construct ons. Its simplif ed yet powerful approach ensures applicability across diverse building typologies and climates.

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The holist c integrat on and cont nuous validat on of these methodologies throughout the project underscore their potent al for signif cant long-term impacts, driving the European construct on sector towards a sustainable, resilient, and circular future.

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7. Appendix A

In the present Appendix, you can f nd at ached the VERIFY quest onnaire that is provided to the demo site partners to inform the VERIFY tool about the techno-economic specif cat ons of the examined building and the respect ve integrated energy systems. The reference cost for the associated f elds is in

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SIRCULAR

CPERI Chemical Process and Energy Resources Institute

General Informat on	
GENERAL INSTRUCTIONS, APPLICABLE TO ALL SHEETS	Cells with an "(i)' indicator have explanatory comments. Please read the comments before f lling them out.
	In cases where an "Other (Specify) value is available through a drop-down list, please add clarif cat on comments in the available f elds
	Please include any addit onal informat on you believe is relevant in the comment f elds available.

All information requested in this sheet is mandatory!

No.	Field	Value	Comments
	Identification		
1	Building Name (i)		
2	Country		
3	Address		
4	Latitude (i)		
5	Longitude (i)		
6	Altitude		
	Geometry		
7	Area covered by building surface (m²)		
8	Floor Height (m) (i)		
9	Total External wall surface (m²)		
10	Number of floors		
11	Common area surface / floor		
12	Total number of external windows		
	Usage		
13	Building Type		
14	Desired summer temperature (°C)		
15	Desired winter temperature (°C)		
16	Usage hours		
17	Average occupancy during usage hours (persons)		
18	Average occupancy during idle hours (persons		
	Analysis parameters		
19	Project Lifespan (i)		
20	Initial Year of Analysis (i)		
21	Number of floors retrofitted		

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HEATING AND COOLING

Please f ll out the following table (on the lef side) with informat on on the current HVAC infrastructures. Once the process for the exist ng infrastructure has been completed, please read and follow the instruct ons for the planned infrastructure (if applicable) on how to complete the right side of the table.

	Current Heating Infrastructure (i)										
No.	**Heating Component**	**Thermal rating (kWth) (i)**	**COP / Efficiency**	**Usage (%) (i)**	**Coverage (i)**	**No. of Users (i)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**Purchase Cost (i)**	**Maintenance Cost (i)**	**Comments**
1											
2											
3											

	Current Cooling Infrastructure										
No.	**Cooling Component**	**Thermal rating (kWth) (i)**	**COP / Efficiency**	**Coverage (i)**	**No. of Users (i)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**Purchase Cost (i)**	**Maintenance Cost**	**Comments**	**Upgrade Plan / EoL**
1											**Retained**
2											**Retained**

	Current Ventilation Infrastructure (i)										
No.	**Ventilation Type**	**Avg. air change per hour (ach)**	**Power rating (kWe)**	**Avg. Heat exchange efficiency (%)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**Purchase Cost (i)**	**Maintenance Cost (i)**	**Comments**	**Upgrade Plan**	**Ventilation Type**
1										**Retained**	

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HEATING AND COOLING
Please f ll out the following table (lef side) with informat on on the current exist ng HVAC infrastructures. Once the process has been completed for the exist ng infrastructure, please read and follow the instruct ons for the planned infrastructure (if applicable) on how to complete the right side of the table.

	Planned Heating Infrastructure (i)									
Upgrade Plan / EoL	**Heating Component**	**Thermal rating (kWth) (i)**	**Usage (%) (i)**	**Coverage (i)**	**No. of Users (i)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**EoL Cost (i)**	**Maintenance Cost (i)**	**Comments**
Retained										
Retained										
Retained										

Planned Cooling Infrastructure (i)									
Cooling Component	**Thermal rating (kWth) (i)**	**COP / Efficiency**	**Coverage (i)**	**No. of Users (i)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**Purchase Cost (i)**	**Maintenance Cost**	**Comments**

Planned Ventilation Infrastructure (i)							
Avg. air change per hour (ach)	**Power rating (kWe)**	**Avg. heat exchange efficiency (%)**	**Year of Installation (i)**	**Nominal Lifetime (i)**	**Purchase Cost (i)**	**Maintenance Cost (i)**	**Comments**

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INSULATION

Please fill out the following table (left side) with information on the current insulation infrastructure, as per the instructions in the comments. Please include the external wall material as well. Once the process has been completed for the existing infrastructure, please read and follow the instructions for the planned infrastructure (if applicable) on how to complete the right side of the table.

External wall material (i)		Wall thickness (mm)		Th. Transmittance / U-Value (W/m²K)	

	Current Insulation Infrastructure (i)										
No.	**Insulation Material**	**Surface (m²)**	**Thickness (mm)**	**Th. Conductivity (W/mK)**	**Th. Transmittance / U-Value (W/m²K)**	**Application**	**Year of Installation (i)**	**Nominal Lifetime**	**Maintenance Cost**	**Comments**	**Upgrade Plan**
1											**Retained**
2											**Retained**
3											**Retained**

	Current Window Infrastructure (i)										
No.	**Glass Type (i)**	**Frame Material**	**Orientation**	**Opening Surface (i) (m²)**	**No. of panes (layers)**	**Pane (Layer) Thickness (mm)**	**Frame Coverage (%) (i)**	**Glass Thermal Conductivity (W/mK)**	**Glass Thermal Transmittance / U-Value (W/m²K)**	**Year of Installation (i)**	**Nominal Lifetime**
1											
2											
3											
4											
5											

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INSULATION

Please fill out the following table (left side) with information on the current insulation infrastructure, as per the instructions in the comments. Please include the external wall material as well. Once the process has been completed for the existing infrastructure, please read and follow the instructions for the planned infrastructure (if applicable) on how to complete the right side of the table.

Planned Insulation Infrastructure (i)									
Insulation Material	Surface (m^2)	Thickness (mm)	Th. Conductivity (W/mK)	Th. Transmittance / U-Value (W/m^2K)	Application	Year of Installation (i)	Nominal Lifetime	Maintenance Cost	Comments

			Planned Window Infrastructure (i)							
Maintenance Cost	Comments	Upgrade Plan	Glass Type (i)	Frame Material	Orientation	Opening Surface (i) (m^2)	No. of panes (layers)	Pane (Layer) Thickness (mm)	Frame Coverage (%) (i)	Glass Th. Conductivity (W/mK)
		Retained								
		Retained								
		Retained								
		Retained								
		Retained								

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<u>INSULATION</u>

Please fill out the following table (left side) with information on the current insulation infrastructure, as per the instructions in the comments. Please include the external wall material as well. Once the process has been completed for the existing infrastructure, please read and follow the instructions for the <u>planned</u> infrastructure (if applicable) on how to complete the right side of the table.

Planned Window Infrastructure (i)													
Glass Th. Transmittance / U-Value (W/m^{2}K)	Year of Installation (i)	Nominal Lifetime	Maintenance Cost	Comments									

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HOT WATER

Please f ll out the following table (on the lef) with informat on on the current hot water infrastructure, per the instruct ons. Once the process for the exist ng infrastructure has been completed, please read and follow the instruct ons for the planned infrastructure (if applicable) on how to complete the right side of the table.

	Current Hot Water Infrastructure (i)											
No.	Tank Material (i)	Tank Capacity (litres)	Tank Insulation material	Tank insulation thickness (mm)	Energy source (i)	Thermal Rating (kWth) (i)	Distribution thermal losses (%)	Set Temperature	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost (i)
1												
2												
3												
4												
5												

	Current Solar Thermal Infrastucture (i)											
No.	Collector type	Collector surface (m^2)	Tilt Angle (°)	Azimuth (°)	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost	Comments	Upgrade Plan	Collector type	Collector surface (m^2)
1										Retained		
2										Retained		
3										Retained		
4										Retained		
5										Retained		

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HOT WATER

Please f ll out the following table (lef side) with informat on on the current exist ng hot water infrastructure, as per the instruct ons. Once the process for the exist ng infrastructure has been completed, please read and follow the instruct ons for the planned infrastructure (if applicable) on how to complete the right side of the table.

		Planned Hot Water Infrastructure (i)												
Comments	Upgrade Plan	Tank Material (i)	Tank Capacity (litres)	Tank Insulation material	Tank insulation thickness (mm)	Energy source (i)	Thermal Rating (kWth) (i)	Distribution thermal losses (%)	Set Temperature	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost (i)	Comments
	Retained													
	Retained													
	Retained													
	Retained													
	Retained													

Planned Solar Thermal Infrastructure (i)										
Tilt Angle (°)	Azimuth (°)	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost	Comments	Nominal Lifetime (i)	EoL Cost (i)	Maintenance Cost (i)	Comments

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Renewable Energy Sources

Please fill out the following table (left side) with information on the renewable enenrgy sources (RES) supplying the Building. Once the process has been completed for the existing infrastructure, please read and follow the instructions for the planned infrastructure (if applicable) on how to complete the right side of the table. If no RES installation exists but one planned, please fill in the right side of the table.

	Current PV Infrastucture (i)												
No.	Material	No. of Panels	Mounting (i)	Nominal Efficiency (%) (i)	Nominal Panel Power (KWp) (i)	Tracking	Tilt Angle (°)	Azimuth (°)	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost	Comments
1													
2													
3													
4													
5													

	Current WG infrastructure (i)												
No.	Power (kWp)	Ground Roughness	Hub Height (m)	Base Altitude (m)	Rotor Diameter (m)	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost	Comments	Upgrade Plan	Power (kWp)	Ground Roughness
1											Retained		
2											Retained		
3											Retained		
4											Retained		
5											Retained		

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Renewable Energy Sources

Please fill out the following table (left side) with information on the renewable enenrgy sources (RES) supplying the Building. Once the process has been completed for the existing infrastructure, please read and follow the instructions for the planned infrastructure (if applicable) on how to complete the right side of the table. If no RES installation exists but one planned, please fill in the right side of the table.

	Planned PV Infrastructure (i)												
Upgrade Plan	Material	No. of Panels	Mounting (i)	Nominal Efficiency (%) (i)	Nominal Power (KWp) (i)	Tilt Angle	Tilt Angle	Azimuth	Year of Installation (i)	Nominal Lifetime (i)	EoL Cost (i)	Maintenance Cost (i)	Comments
Retained													
Retained													
Retained													
Retained													
Retained													

Planned WG Infrastructure (i)							
Hub Height (m)	Base Altitude (m)	Rotor Diameter (m)	Year of Installation (i)	Nominal Lifetime (i)	EoL Cost (i)	Maintenance Cost (i)	Comments

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Electrical plan				
Please fill in the requested informaton on your current electrical plan. If you plan to conduct upgrades, please fill in the correspoding information on for				
Electricity Consumption (i)				
Consumption report scope (i)				
Annual Consumption (kWh) (i)				
Monthly Consumption (kWh) (i)	January			
	February			
	March			
	April			
	May			
	June			
	July			
	August			
	September			
	October			
	November			
	December			

Current Owner Profile & Pricing Policy (i)					
Current RES availability (i)					
RES Comments					
Profile (i)					
Autonomous (i)	Generator Fuel Type (i)		Price		
	Power Rating (kW)				
	Annual Fuel Consumption		Fuel measurement unit (i)		
	Comments				
Consumer	kWh Price (€) (i)				
	Access charge (€) (i)		Application basis (i)		
	Fixed charge (€) (i)		Charging period		
	Comments				
Prosumer	Scheme applied (i)				
	Import price (€/kWh)				
	Access charge (€/kWh)				
	Export price (€/kWh)				
	Fixed charge (€) (i)		Charging period		
	Comments				
Battery Storage (i)					
Type					
Nominal Capacity (kWh)					
Replace State of Health (%)					
Depth of Discharge (%)					
End-of-Life fate					
Financial Information	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost (i)	
Commments					

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	Planned Owner Profile & Pricing Policy				
	Current RES availability (i)				
	RES Comments				
	Profile (i)				
	Autonomous (i)	Generator Fuel Type (i)		Price	
		Power Rating (kW)			
		Annual Fuel Consumption		Fuel measurement unit (i)	
		Comments			
	Consumer	kWh Price (€) (i)			
		Access charge (€) (i)		Application basis (i)	
		Fixed charge (€) (i)		Charging period	
		Comments			
	Prosumer	Scheme applied (i)			
		Import price (€/kWh)			
		Access charge (€/kWh)			
		Export price (€/kWh)			
		Fixed charge (€) (i)		Charging period	
		Comments			
Upgrade Plan	Battery Storage (i)				
Retained	Type				
	Nominal Capacity (kWh)				
	Replace State of Health (%)				
	Depth of Discharge (%)				
	End-of-Life fate				
	Financial Information	Year of Installation (i)	Nominal Lifetime (i)	Purchase Cost (i)	Maintenance Cost (i)
	Commments				

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Investment Plan		
Please f ll out the following table with informat on on the planned infrastructure upgrade's investment plan.		
Economic Parameters		
VAT (%) (i)		
WACC (%) (i)		
Inf at on (%)		
Corporate Tax Rate (%) (i)		
Inf at on of electricity cost (%)		
Electricity tax rate (%) (i)		
Comments		
Loans (leave blank if no loan will be used)		
Loan principal amount		
Down payment (%)		
Interest (%)		
Durat on (years)		
Amort zat on method (i)		
Comments		
Engineering Works Costs		
Engineer Fees (€) (i)		
Permit Costs (€) (i)		
Equipment Costs (€) (i)		
Comments		
Land Acquisit on		
Land ownership (i)		
Land Rental (€/month)		
Land Purchase cost (i)		
Comments		

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8. Appendix B

In the present Appendix, you can f nd the recycling plant mapping survey. This survey will be sent to the associated recycling plants to collect informat on related to the building materials and capture behaviors related to good pract ces for environmental and sustainability aspects.

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SURVEY

SIRCULAR

European Union's Horizon Europe research and innovation programme under grant agreement No 101147412

Recycling Plant Information

NAME: **LOCATION**

INSTRUCTIONS

SIRCULAR project introduces an innovative digital platform designed to equip non-experts in the building sector with the necessary tools and resources to promote sustainable and circular construction practices. The main objective is for the users to incorporate circular principles into their projects, offering a range of advanced tools that simplify otherwise complex processes.

Please fill the questions below to be part of the project!

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QUESTIONS ON MATERIALS/PROCESSES					
Collected material	Max Quantities per single disposal (tons)	Typology of process			Cost/Compensation (€/ton)
☐ Plastics ☐ Metals ☐ Wood ☐ Glass ☐ Inert ☐ Batteries ☐ Special wastes ☐ Others	☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______	☐ Mechanical ☐ Mechanical ☐ Mechanical ☐ Mechanical ☐ Mechanical ☐ Mechanical ☐ Mechanical ☐ Mechanical	☐ Chemical ☐ Chemical ☐ Chemical ☐ Chemical ☐ Chemical ☐ Chemical ☐ Chemical ☐ Chemical	☐ Others ☐ Others ☐ Others ☐ Others ☐ Others ☐ Others ☐ Others ☐ Others	☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______ ☐ ______
If **"Special waste" or "Others"** was selected please specify which: • ______ • ______ • ______	In case of **Special waste" or "Others"** added materials specify quantities • ______ • ______ • ______	If **"Others"** was selected, please specify the process: Material ______ Process ______ ______ ______ ______ ______			Please insert a positive value if you are paid for accepting waste materials and a negative value if you pay the waste materials

Certification	☐ EU Construction & Demolition Waste Management Protocol ☐ RCI Certification of C&D recycling facilities ☐ CDW recycling plant certification ☐ RecyClass ☐ QA-CER ☐ APR-PCR ☐ Others
	If **"Others"** was selected, please specify :
Sustainability	☐ Use of RES (e.g. PVs) ☐ Waste minimization approaches ☐ Use of recycling water ☐ Low emissions (tech. to minimize air pollution/greenhouse gas) ☐ Others
	If **"Others"** was selected, please specify :
Other services	☐ Recycling Consulting ☐ Material pickup service ☐ Others
	If **"Others"** was selected, please specify :

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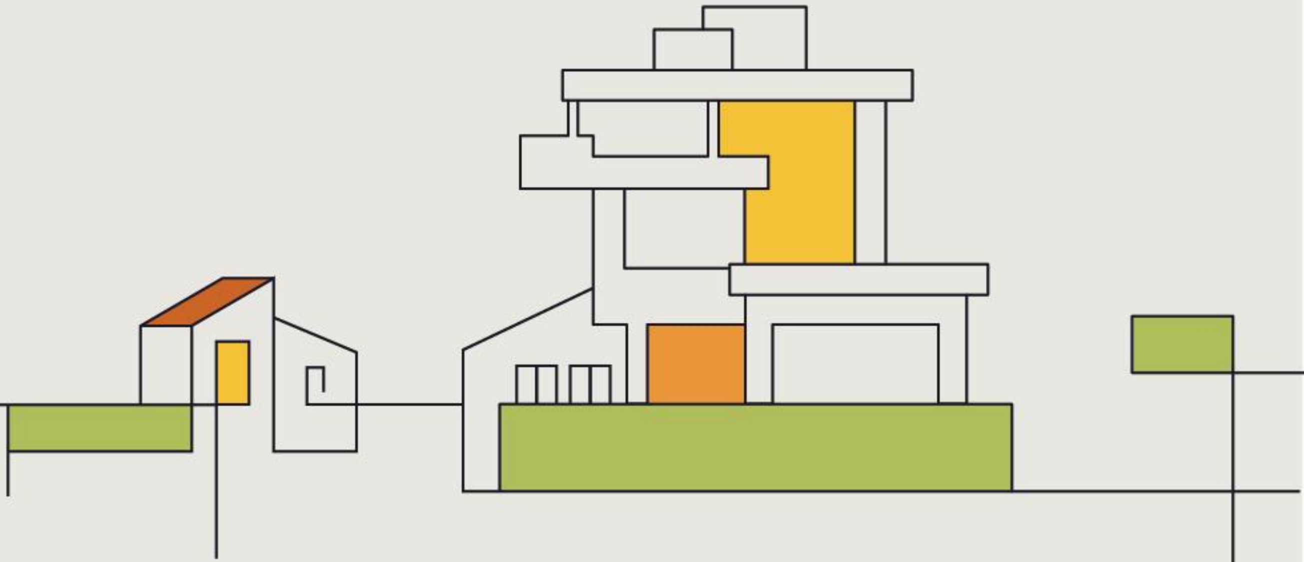

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