Development of an early-stage multi-criteria decision support tool for indoor climate conditioning of archive buildings

EINDHOVEN UNIVERSITY OF TECHNOLOGY
Stan Ackermans Institute
SMART BUILDINGS & CITIES

Development of an early-stage multi-criteria decision support tool for indoor climate conditioning of archive buildings

By

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A thesis submitted in partial fulfillment of the requirements for the degree of
Engineering Doctorate

The design described in this thesis has been carried out in accordance with the
TU/e Code of Scientific Conduct

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It is getting lengthy and there are still so many unsaid things to express, so I would like to conclude with gratitude towards life, for whatever I have achieved and how I have managed to impart values in others' lives.

Public Summary

Archives act as a safekeeper of the cultural identity of any nation. The primary purpose of archives is to ensure the long-term preservation of its heritage collection, often leading to energy-intensive building operations.

Archive guidelines in the Netherlands prescribe a stringent indoor climate requirement as a favourable condition for the long-term preservation of hygroscopic collection objects. Pursuing such indoor climate targets requires year-round air-conditioning, resulting in high energy consumption. On the other hand, growing evidence suggests that most collections preserve well under a wider range of indoor conditions and prompt the preservation community to rethink the notion of "the more stable, the better". Due to a growing demand for physical archives that can preserve heritage collections and a lack of energy-efficient repositories, new archives will be constructed in the upcoming decade. The objective of designing a new generation of sustainable archives is to strike the right balance between long-term conservation and energy-efficient operation in coming years, in accordance with improved energy efficiency targets and changing climate. In this context, the term 'sustainability' refers to both the economical usage of energy and the durable preservation of cultural heritage.

To improve the design sustainability of archives, practitioners from different disciplines, such as conservators, architects, and building engineers, need to collaborate from the early design stage. Engaging such a wide spectrum of experts brings a plethora of insights to decision-making. On the other hand, it presents a new challenge due to a lack of commonality in knowledge between respective technical experts. The project envisions bridging the communication gap between stakeholders. Developing a user-friendly web-based tool which packages a state-of-the-art building simulation program has thus been objective of this project. Though the tool, stakeholders can evaluate the impact of different design options through different performance indicators like annual energy consumption, collection lifespan, and percentage share of renewable sources in end-use demand. The main feature of the tool is to enable early-phase design support which reduces designing effort and requirements of significant experience in building performance simulation for users.

The tool has been developed with continuous research on different design aspects of building energy simulation like reference weather information, building envelope properties, climate system and controls, discussion with relevant design experts and practitioners and feedback integration from such discussions. Additional focus has been put on assimilating all such insights and design decisions under an umbrella of a single user-friendly application.

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Acronyms

AHU	Air Handling Unit
AMY	Actual Meteorological Year
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BENG	Bijna Energie Neutraal Gebouwen
BPS	Building Performance Simulation
COP	Coefficient of Performance
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
DST	Decision Support Tool
DX	Direct Expansion
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
HAMT	Heat and Moisture Transfer Model
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
nZEB	nearly Zero Energy Buildings
OEF	On-site Energy Fraction
OEM	On-site Energy Matching
PaaS	Platform as a Service
RH	Relative Humidity
SRE	Special Report on Emissions
TMY	Typical Meteorological Year
TRY	Test Reference Year

Preface

This EngD report presents the outcomes of a collaborative project between the National Archives (NA) of the Netherlands and Eindhoven University of Technology (TU/e), which was financially supported by Metamorfoze Onderzoek under the name "Klimaatmodel Archieven Fase 2". The objective of this project was to develop a multi-criteria and user-friendly decision-support tool for the design of sustainable archive buildings. The project started in March 2021 and is completed in two years, by March 2023.

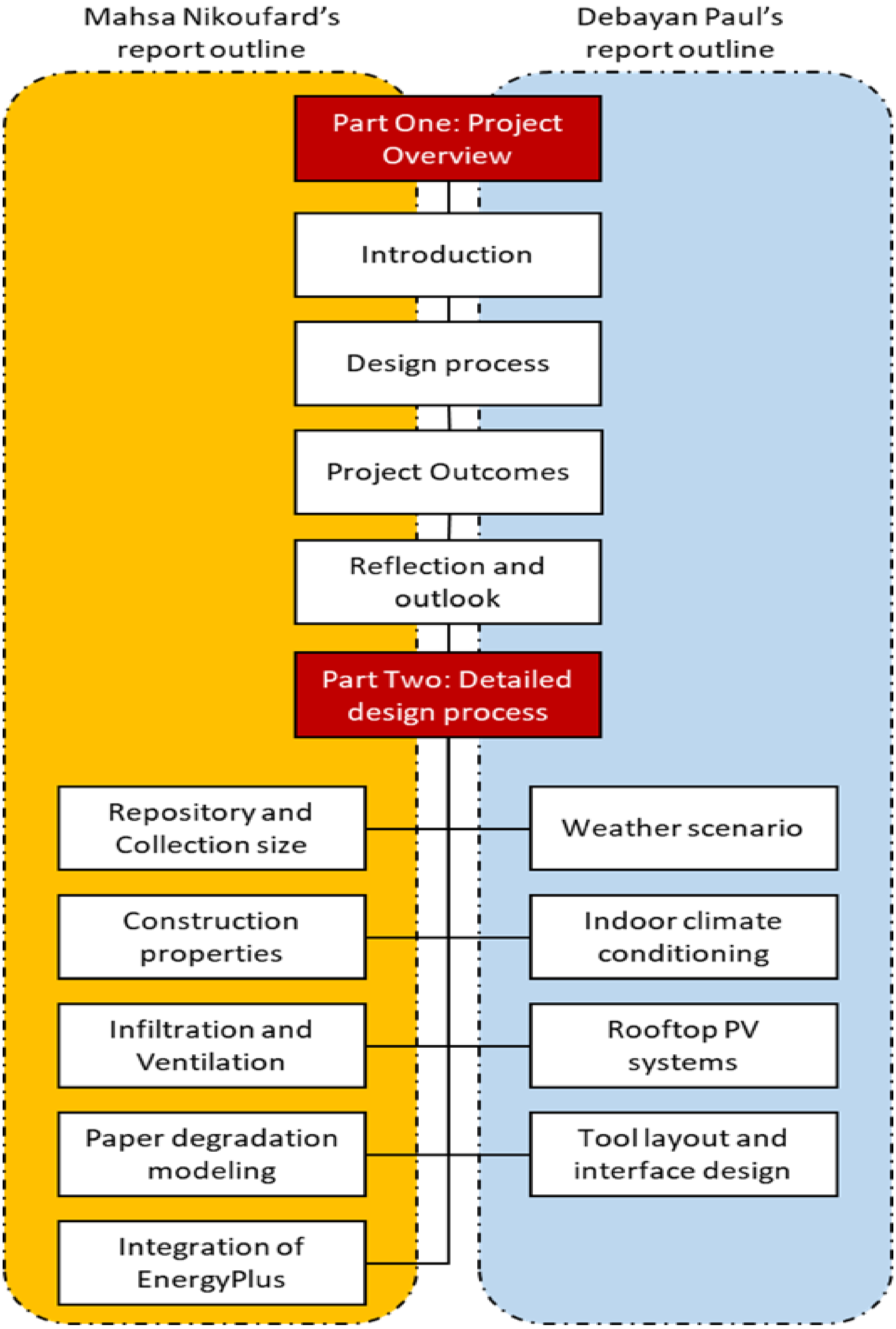
The developed tool is the outcome of close teamwork between two Engineering Doctorate trainees, Debayan Paul and Mahsa Nikoufard. In the design process of the tool, the two trainees jointly analyzed the project requirements and developed the outcomes. However, while working towards one common goal, many of the tasks were divided, and each trainee was individually responsible for specific parts of the final deliverable. Therefore, the EngD reports of both trainees are split into two parts: a commonly written part and an individually written part.

Part One of each of their Engineering Doctorate reports (Chapter 1 in this report) is the same and contains the project overview, providing an introduction on archive buildings and the problems associated with designing sustainable archives. Also, it introduces the users of this tool, the requirements defined for this project, the project timeline, and the outcomes of it.

Part Two of each report (Chapters 2 to 5 in this report) provides a detailed description of specific parts of the design and how it is developed to reach the project goals. The chapters under Part Two are mainly developed by its writer, though in some minor aspects, the other trainee has helped to increase the quality of the project by creating synergy.

The following figure shows the structure of the report of each EngD trainee. In the following chapters after Chapter 1, Debayan Paul, the author of this report, explains in his part the inputs related to weather scenarios, indoor climate conditioning (the HVAC system and thermal setpoints), and rooftop PV systems. Also, the trainee describes the development of the software architecture of the tool and the design of its interface in more detail.

Likewise, Mahsa Nikoufard explains the inputs related to repository and collection size, construction properties, infiltration and ventilation, and paper degradation modelling. The trainee also explains the creation of building energy simulation models in the software EnergyPlus, and how the tool runs EnergyPlus and extracts the outputs.



Structure of EngD report of individual trainees

Chapter 1

Design Project Overview

1.1 Introduction

In this section, a background on archive buildings and the challenges in designing sustainable archives is presented.

1.1.1 Background

Archives act as a repository for the cultural identity of each country. Their stored collection consists of a large bulk of hygroscopic material, such as paper, leather, photographs, and parchment [1]. One of archive buildings' principal functions is to provide suitable indoor climate conditions for protecting its storage [2]. While a poor climate causes oxidation and hydrolysis of paper collections and can promote biological, physical, and chemical damage, a proper indoor environment can prevent degradation risks [3]. Thus, conservators are always alert to the climate in their repositories.

There are many archival institutions in the Netherlands, all using dedicated repositories. The National Archives of the Netherlands is one of the largest, and is located in two buildings. The building in Den Haag has a capacity of 170 km of storage, and the building in Emmen another 95 km. Because of the still-growing amount of analog archives to be stored and/or because current repositories are too inefficient in energy use, there is still a need to construct new archives in the future, and this need will not cease in the foreseeable future. These new buildings need to be sustainable in terms of both durable cultural heritage preservation and responsible energy conservation.

1.1.2 Challenges in Designing Sustainable Archives

There are several challenges regarding the sustainable design of archive buildings. In this section, these obstacles, which are addressed in the current project, are presented.

New Energy Efficiency Requirements

The building stock and construction sector contribute towards almost 35% of total final end-use demand and 15% of direct CO_2 emissions worldwide, almost amounting to 3 Gton as of 2021, which further increases to approximately 30% including indirect emissions from utility use and heating demand in the buildings [4]. In order to align with global international conventions against climate change, various regulations for energy-efficient buildings have been drawn up in recent decades. In the Dutch situation, the new Bijna Energie Neutraal Gebouwen (BENG) regulation [5] from 2021 describes the minimum performance level of newly built buildings. This regulation consists of three requirements: BENG 1, 2, and 3 referring to increasing the quality of envelope, increasing the efficiency of systems, and integrating renewable, respectively [6]. Archive buildings are not an exception to this regulation, and to meet these changed performance standards, archives must be designed in radically different ways.

Dutch Archival Regulations

Archive guidelines in the Netherlands prescribe a strict indoor climate (annual average of 18 °C temperature and 50% relative humidity with a permissible fluctuation of ± 2 °C and ± 5%, respectively) as a favorable condition for the long-term preservation of hygroscopic collection objects [7]. The existing guidelines are mainly based on research and technical recommendations made by the conservation community in the 1970s [8]. Pursuing such indoor climate limits requires constantly operating Heating, Ventilation, and Air Conditioning (HVAC) systems [9], which leads to high energy consumption, frequent maintenance of the installations, and the risk of compromising the structural integrity of historic buildings [10]. On the other hand, there is growing evidence that most collections can be preserved well under a broader range of indoor conditions [11, 12] prompting the conservation community to reconsider the idea of “the more stable, the better” [8].

Consequently, new archival guidelines are under preparation, which have a wider range for temperature (13 to 22 °C) and relative humidity (35 to 60 %). Such wider range allows for higher fluctuations, which is unfavourable for the archival collection as it causes mechanical damage [13]. However, these fluctuations can be controlled with proper building design and system control. It is, therefore, necessary to communicate these new guidelines and their effect on the energy use and paper lifetime of the collection to relevant stakeholders in the design process of sustainable archives. This will facilitate the acceptance and broader use of recent improvements in archival regulations.

Multi-domain Stakeholders

Sustainability in archive buildings refers to the responsible use of energy and the durable preservation of the archival collection for future generations. To find a balance between these two aspects, professionals from different disciplines, such as conservators, architects, and building physicists/engineers, need to work together from the early design phase. In such knowledge groups, experts have the possibility to share their knowledge and experiences and explain to each other design challenges and the consequences of various design choices. Involving such a broad spectrum of experts leads to a multitude of insights into decision-making and enhances the quality of the design.

On the other hand, this interaction represents a new challenge due to a lack of shared background between the different experts and a lack of quantitative insights. In this situation, the mentioned disciplines do not speak the same professional language, and the explanation of regulations, quantities, and design challenges becomes difficult [14]. Therefore the need for a user-friendly platform to bridge the communication gap between these stakeholders by sharing information about the consequences of design changes across disciplines seems vital.

Unfitness of Current Tools for Early-stage Archive Design

When designing buildings, engineers often use Building Performance Simulation (BPS) tools to calculate energy consumption and heat transfer by creating computer models. BPS tools can be used to support informed decision-making in the design of sustainable archives. However, they are less suitable for the early design phases, as they require a great deal of technical expertise and a large amount of input data, making it time-consuming. Also, additional performance indicators, such as the risk of paper degradation in the case of archives, cannot be calculated with the commonly used BPS software.

On the other hand, several tools exist to assess the effect of indoor climate (Temperature and Relative Humidity) on the lifetime of archival collections. However, this set of tools cannot model the archive building and its energy systems. Their inputs (Temperature and Relative Humidity data) are provided from existing data sets and are not calculated based on a proposed design for the building. Therefore, such tools cannot show the effect and consequences of certain design choices.

1.1.3 Project Objectives

Considering the previously mentioned challenges in designing sustainable archive buildings, the ultimate purpose of this project is to create a user-friendly DST for:

- Designing the most suitable building concept for archive buildings in a specific climate;
- Selecting the most appropriate HVAC system for the designed concept;
- Understanding the effect of the chosen building design and HVAC system on paper degradation;
- Obtaining information on the impact of the building and its system on its indoor climate and energy use.

The project also aims to gain insight into the relationship between building characteristics, climate system installations, and heritage collection. For this, the developed tool supports input of different values for; weather, repository and collection size, building construction properties, climate control system and its' setpoints, collection chemical properties, and PV.

1.2 Design Process

This section introduces the users of the tool, and explains the requirements of the project based on the user profiles. It also elaborates on the evolution timeline of the design project and how the project is developed during two years.

1.2.1 User Profiles and User-based Requirements

The primary purpose of developing the DST is to enable participation of a broad category of archive design project stakeholders in the early decision making or concept design phase. Successful participation and seamless collaboration in such a phase can significantly improve the multidisciplinary design aspects and exchange of domain-specific knowledge, which in turn helps to deliver improved design decisions. However, as the envisioned tool will cater to multiple user disciplines, the design ideology has been focused on three pillars of user experiences, depicted in Fig. 1.1. The tool is primarily designed in purpose of improving communication about meaningful design decisions for sustainable archives in an easily accessible way. The main driver of developing the DST is providing user ease of use, and it should require specific technical expertise to use the tool, which requires a simplification of the entire complex design process. However, the tool needs to ensure that accounting for the simplicity should not come at the expense of scientific reliability.

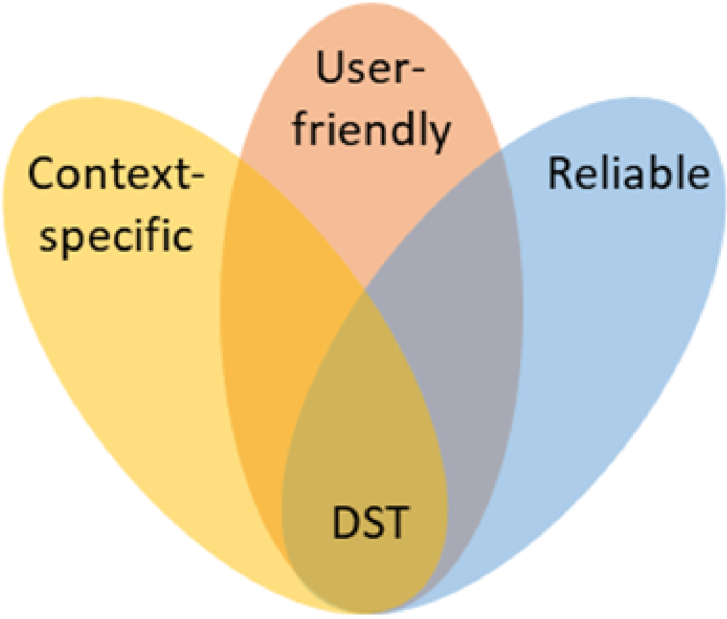


Figure 1.1. Three pillars of DST experience

Visual usage of fictional personifications of possible users of the tool can be a good stepping stone to analysing initial background, difficulty in participation in the design process and overall motivation. Such usage has been proved as a meaningful assessment framework for stakeholder communication improvement and human-technology interactions in multiple studies [15, 16, 17]. The DST aims to provide decision support capability for mainly three types of user profiles which are represented below.

Tim

Tim is an architect working for a design consulting firm based in Rotterdam. He has several years of experience in designing commercial buildings and familiarity with building performance analysis. Recently, he has been tasked with a design project from the National Archives in Den Haag for which he needs to deliver a final design layout for specialized design engineers for optimized calculations. However, Tim is unfamiliar with the impact of design parameters such as insulation level and building sizing compactness in archive buildings. Also, setting up a reliable model for doing such simulations will take much time, while this is just the initial phase of the project. He needs to have a solution to speed this process up. Another challenge for him is that he knows about paper degradation in archives but does not know how to calculate it based on his simulation results.

Anna

Anna is a collection preservation expert for the National Archives in Den Haag and the person in charge of the new archive repository design project to move provincial historical records to a newly designed archive facility located in Groningen within the next two years. She has to communicate the new archive's design and indoor climate conditioning requirements to building design professionals. However, Anna has little familiarity with the building codes, energy requirements, and climate conditioning system inputs, which influences the energy performance and sustainability performance of the collection. Therefore, properly selecting such inputs is pivotal to the success of the entire project. She needs to find a balanced trade-off between sustainable design, collection risk, and project budgeting.

Kevin

Kevin is a professional with expertise in sizing, installation, and monitoring of HVAC systems. He needs to prepare an early-stage load estimation of the required system to avoid potential oversizing of climate solution systems. However, he has very limited familiarity with climate conditioning requirements tailored to the archive repository, possible scope of modifications for energy-efficient behavior and assessing such decisions on collection preservation, and avoidance of HVAC operational risks.

Based on analysis on the three previously mentioned fictional profiles and discussions with practitioners and professionals in the field, the following requirements are defined for the project:

Context Specific:

- The tool should have inputs which cover newly built and historical buildings.
- The tool should cover various climate scenarios.
- The tool should have inputs specifically for archives and related to new and previous archival regulations.
- The tool should cover different configurations for HVAC sizing and the possibility of analyzing the consequences of undersizing the system.
- The tool should show results related to indoor climate, paper lifetime and energy-use.

User-friendly:

- The tool should include default options, helping the user to select some settings without having prior knowledge about them.
- The tool should be able to enter numeric and non-numeric values to cover multi-domain users' knowledge of each input.
- The tool should provide information and instructions to clarify inputs.
- The tool should have options for saving the user inputs for the comparison of different scenarios.
- The tool should be time-effective, and the simulation runtime should be short.
- The tool should not need any prior knowledge for using it, about programming languages and building performance simulations.
- The tool should have a user-friendly interface and have guides on how to use it.
- The tool should be maintenance-free (no updates needed).

Reliable:

- The tool should be built on top of reliable building performance simulation software.
- The tool should have modeling approaches based on informed assumptions, which are supported with extensive literature review, tests, and analysis.

1.2.2 Evolution Timeline of Design Project

The design project was initiated in March 2021 with an expected completion duration of 2 years. The first year of the design project mainly focused on reviewing contextual literature on archive design and modelling, gathering primary information on user requirements for the tool and exploring relevant modelling complexities for such designing. Examples of the complexity level analysis are: the level of detail of the HVAC system, the type of heat and moisture transfer algorithm for the building, and the automated modeling strategy of multi-level buildings. In this regard, several industrial practitioners, mainly from academia and the collection preservation domain, have been contacted to understand the current practice, possible scope of improvements and a brief useability and feature requirements for such tool.

The final half of the design project focused on cumulating collective design insights from collection preservation expert and developing the indoor climate models for archives with specific adjustments drawn from first year conclusion. However, the second year follows a more feedback-focused approach than the initial one, as this period involves more recursive designing steps (constructing a specific aspect of the model, collecting feedback from archival design specialists and collecting experts and adjusting the model).

Several dissemination activities (mockup tool development, article posting on collection community etc.) have been conducted to promote the outreach of the tool. Also several discussion has been conducted with experts regarding HVAC operations in context of archives during the first two quarters. The final two quarters followed a more agile software development approach, usually in a weekly and monthly time-boxed period, which involved designing the tool architecture, developing the actual DST, collecting feedback on its features and experience from users and integration of user comments to improve the design tool incrementally. The very end phase of the entire design project, focuses on final testing and deployment of the tool for future users. A brief timeline has been presented in Figure 1.2.

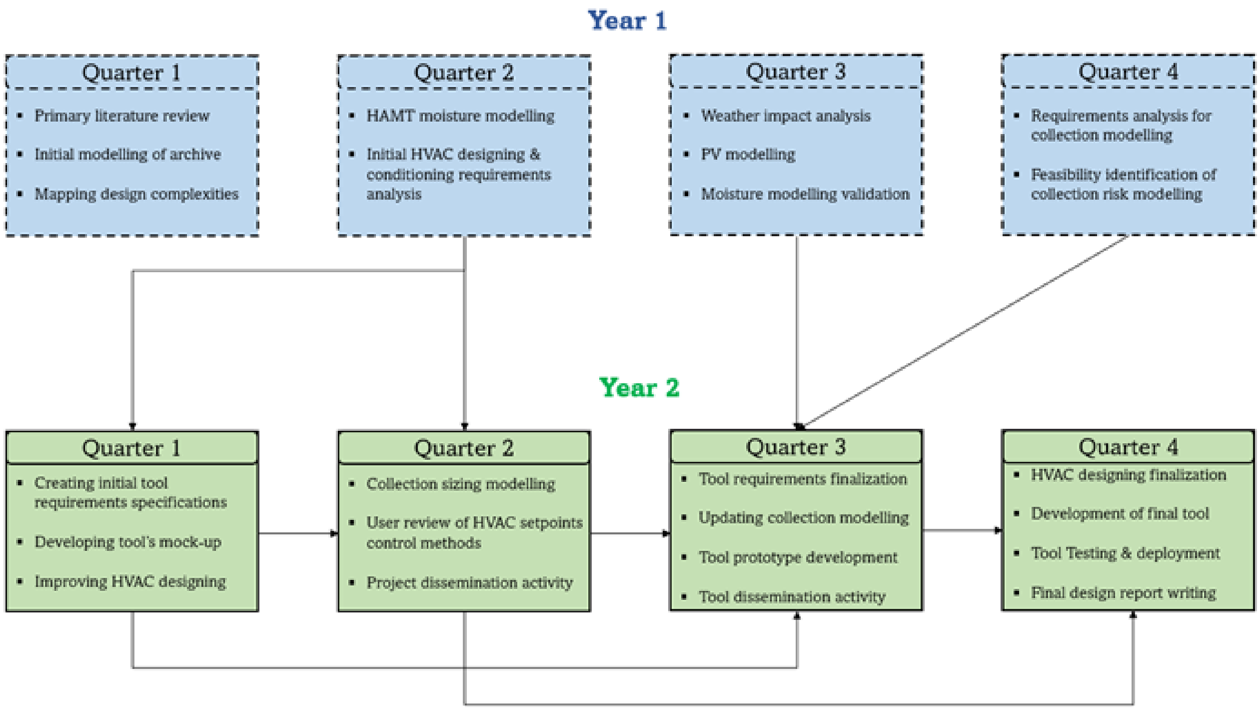


Figure 1.2. Design Project Timeline

1.3 Project Outcomes

In this section, the outcomes of the project are described. Afterward, an overview is provided of the design inputs of the tool, which are later explained in more detail in the individual parts. Next, the tool workflow is clarified for readers. Ultimately, efforts to create outreach on the project and sustainable archives are summarized.

1.3.1 A Brief Overview of the DST and KPIs

The final outcome of the design project is a browser-based, user-friendly DST. The main feature of the tool is to enable early-phase design support which reduces designing effort and requirements of significant experience in building performance simulation for users. The tool leverages the whole-building energy simulation capabilities of EnergyPlus® with multiple functionalities (application development, data pre-processing, post-processing, and several additional custom functionalities) of the open-source programming language Python. The end product is available for users through a GitLab repository as an open-access project. The tool enables its user to provide relevant design decision inputs for energy and collection performance simulation of archive buildings. Figure 1.3 demonstrates one of the input pages and its various options. The DST also visualizes performance indicators in the tool interface as dashboards. Such performance summary can also be exported as a report for future use.

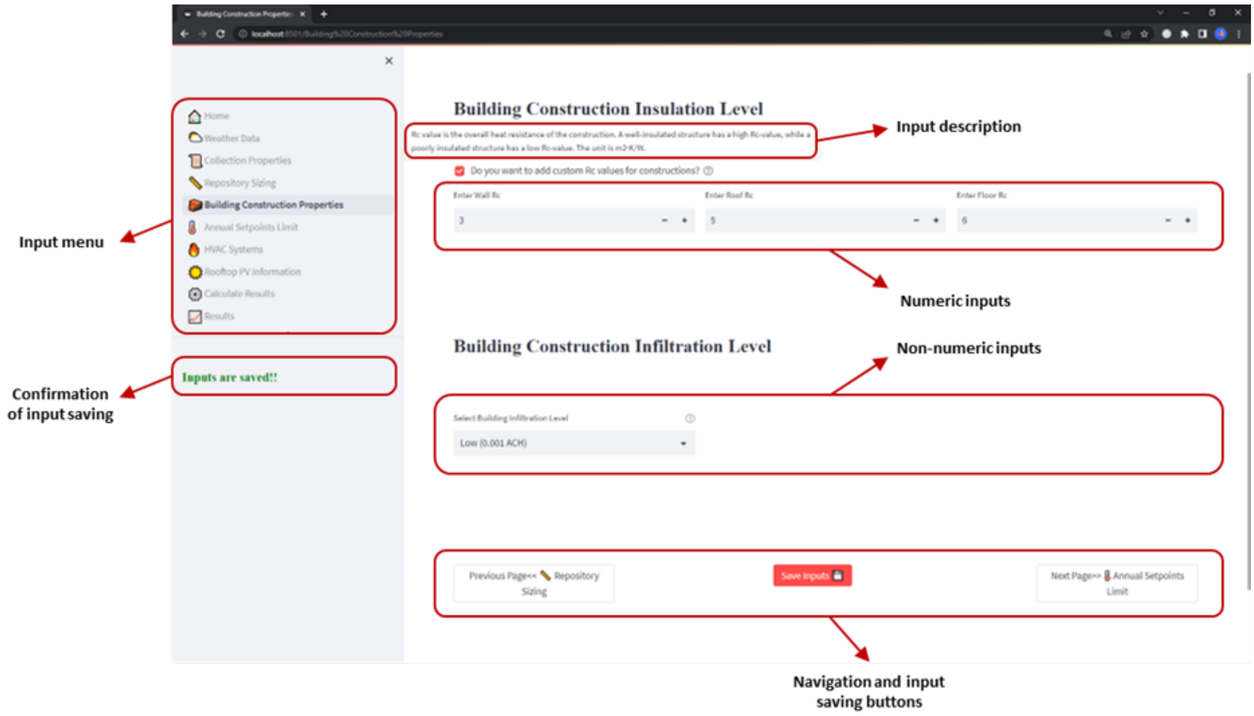


Figure 1.3. An Exemplary Input Page of DST

Figure 1.4 shows a screenshot of one of the output pages and its components.

Based on the design choices, the users of the DST can obtain the following performance indicators:

- Space Conditioning Performance (Actual annual average Temperature and Relative humidity, Unmet hours of setpoints)
- Energy Performance (End-use annual utility consumption per area, categorized, sizing of heating and cooling systems)
- PV performance (Annual PV Yield & On-site energy fraction and matching)
- Collection lifespan and relative lifetime

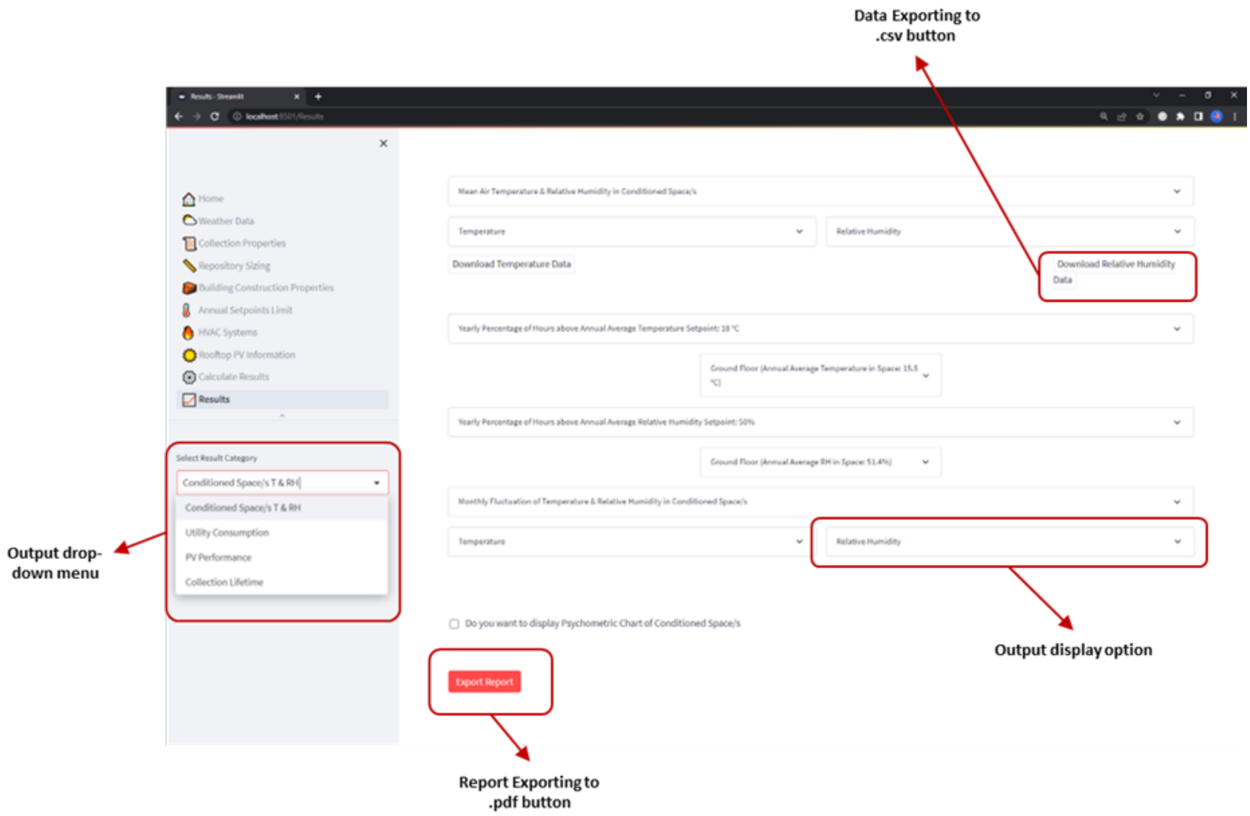


Figure 1.4. An Exemplary Result Page of DST

1.3.2 Brief Description of Final Design Inputs

This section describes different design parameters which individually and interactively influence the performance of the building and collection preservation. The following design input parameters are part of the final DST, based on the outcome of design-driven research activities during the time horizon of the entire design project. A graphical outline has been presented in Figure 1.5 for readers about the metadata of design inputs, which are categorized as the input pages of the DST in both trainees' reports. It indicates where more detailed information about the individual category of design inputs can be found.

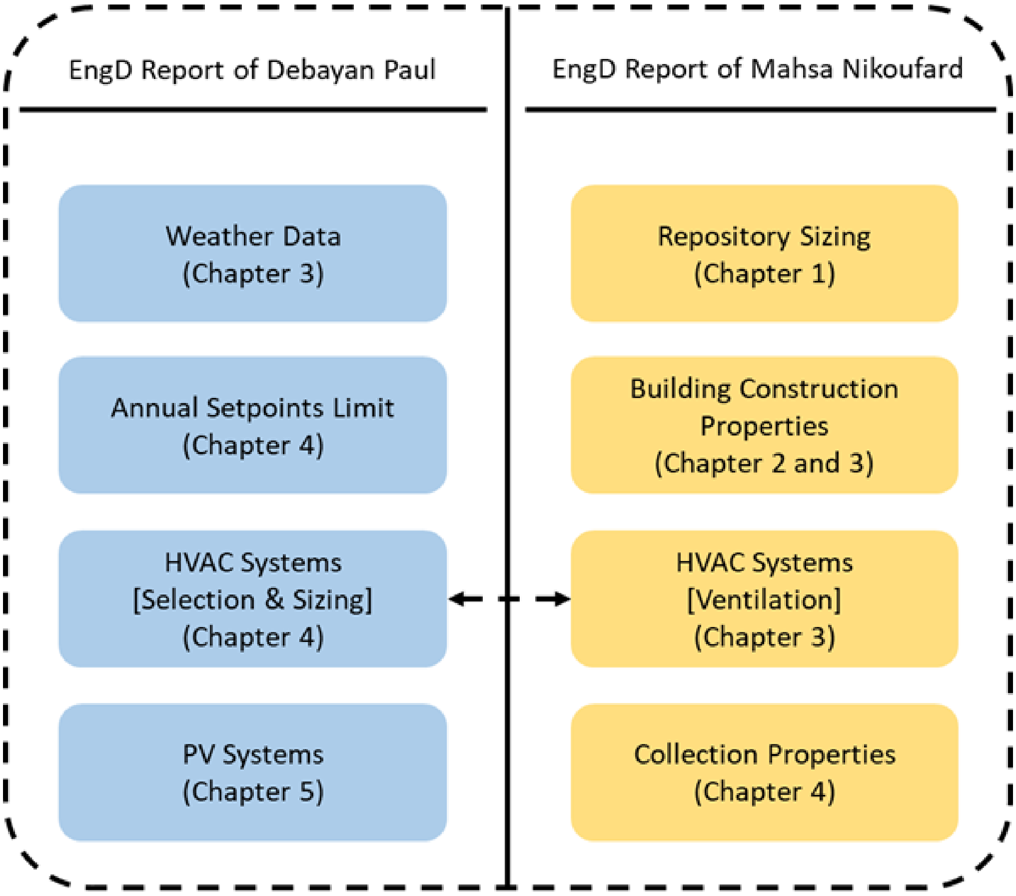


Figure 1.5. Metadata of Design Inputs in Both Trainees Reports

Weather Scenario:

The energy performance of an archive relies on the reference climatic data utilized for whole-building energy simulation. For determining the hygrothermal performance of buildings and sizing of heating, cooling, and air conditioning installations in the Netherlands, the NEN 5060:2018 standard [18] and two additional scenarios with an "exceedance probability" of 1% and 5%, respectively, have been selected as the primary weather data sources. Along with these, three different future-oriented Intergovernmental Panel on Climate Change (IPCC) climate scenarios have also been considered for the reference years 2050 and 2100.

Paper Type & Specifications:

The user initially selects whether the model will have single or multiple collection objects and provides their pH, initial DP, and critical DP for the collection. These inputs are necessary for the degradation risk assessment method that is chosen for the tool [19]. In this tool, only chemical degradation can be assessed. Due to discussions with relevant experts, other types of degradation, such as mechanical degradation, have not been implemented in this tool.

Storage & Repository Size:

In this tool, users can size the repositories based on the amount of archival collection (in km) and the filling percentage. The user can also determine each floor's length, width, and height, based on which the tool automatically calculates the number of floors of the building. As discussed with experts, considering different adjacencies for the archive rooms could have resulted in a complicated model, which is not necessary for this stage of design. Thus, it has not been a design option and has been discarded from the tool.

Insulation Level & Infiltration Rate:

The construction material and building engineering details of the archive building affect the indoor climate of the repositories and its energy consumption. However, many variations are possible for building elements and materials that are unsuitable for the design process's concept phase. A more straightforward approach is to provide the user with four insulation levels (No insulation and Minimum, Medium, and High insulation levels) for the walls, roof, and floor of the repository in the user interface or provide the user the flexibility of adjusting the thermal resistance of constructions individually. Both approaches can be achieved through changes in the insulation thickness based on user-provided input. The construction material has been modeled in EnergyPlus® [20] using the Heat and Moisture Transfer Model (HAMT) algorithm to ensure that the hygrothermal effect of the material is considered.

The infiltration rate of the building directly affects its indoor climate, especially when ventilation is turned off (which is allowed in the new regulations), and is therefore taken into account in the tool. The user can opt for default values of low (0.001 ach), medium (0.01 ach), and high (0.015 ach). The very low value of 0.001 happens when the doors are closed, and the construction is very airtight. The medium and high values of 0.01 and 0.015 are for cases when doors are opened and closed during the day. These values are generally very low compared to commercial and residential buildings (which use values around 0.5 or at least 0.2 in airtight cases). Also, older construction with many cracks and old window and door frames has higher infiltration values. Therefore, the user can also select a custom number up to 0.5 ach and explore the effect of different variations in this matter.

Setpoint control:

Currently, Dutch Archival Legislation defines the guidelines for the indoor environment of storage rooms, which requires a temperature of 18 ± 2 °C and relative humidity of 50 ± 5%. However, the newly proposed guidelines suggest a modification to these limits. It allows the air temperature near the collection from a minimum of 13 °C to a maximum of 22 °C while relative humidity ranges between 35-60%. The limit suggests an annual average of maximum 18 °C and 50% relative humidity, allowing a maximum of 5 °C/month and 5% RH/month change to meet annual averages. From the users' point of view, to achieve the annual average setpoint values and explore energy-saving potential, three different types of fluctuation level have been designed:

- The indoor condition is continuously maintained near the annual average setpoints of Temperature and Relative humidity. This type of HVAC operation in a narrow bandwidth thus cannot exploit to fluctuate the setpoints resulting in a possible energy-intensive solution in this scenario.
- The indoor condition can fluctuate Temperature and Relative humidity, per current archival regulation, which is also the default option for HVAC setpoint control.
- The indoor condition is allowed to fluctuate between the minimum and maximum possible limits of Temperature and Relative humidity, with a safety tolerance resulting in a temperature range between 14 to 21 °C and RH between 40 to 55%. However, this might enable a significant variation in RH between months, possibly violating monthly fluctuation limits. Thus a further option has been added to limit such fluctuation between months.

The tool also allows the user to set a custom combination of Temperature and Relative humidity rather than Dutch Archival averages, which can also be aggregated with the previous three fluctuation level types. However, a limitation in user-interface of the tool has been implemented for users to prevent accidental violation of operating the HVAC beyond archival setpoints thresholds.

Space Conditioning Systems Selection & Sizing:

Compared to residential/office buildings, the archive storage needs to maintain relative humidity within specific limits. A solution for both temperature and relative humidity control can be achieved using all-air systems, which introduces adequately conditioned air to the archive zone and can react quickly to temperature and humidity fluctuations.

For relative humidity control, it is assumed that the AHU has an integrated Direct Expansion (DX) coil for efficient dehumidification and a humidifier for humidification. A few different system configuration options have been provided to the user, including heating sourced from an electric resistance boiler, district heating, or ground-source heat pump. Proper sizing of air conditioning systems is required to meet the building energy demand. However, in practice, the systems are sized based on the average of sensible hourly loads experienced by the heating/cooling system on the worst climatic day (design day) of the reference climatic data with an additional design safety factor multiplied. This typically results in an oversized conditioning system as such climatic conditions occur very rarely, max 1-2% time of the entire year. In this tool, an option has been provided for the user to either automatically size the system capacities, resulting in a possible oversizing of systems, or intentionally under-sizing the system capacities based on the load-duration curve to explore energy-saving and possible risk for collection degradation.

The tool also has additional features for switching off the air conditioning during the night during defined off-work hours. It can also let the user define the additional rate of mechanical ventilation, which is not a requirement for archive conditioning.

PV System:

New energy efficiency requirements mandate increasing renewable energy resources to meet building energy demand and having a minimum percentage share of renewable energy, which can be met by different sources like the integration of PV panels in the roof or building facades. Only the scope of rooftop PV installation has been considered for this project. This part estimates a rough annual potential of PV yield based on user-defined roof dimensioning of the archive. The tool automatically optimizes the tilt angle and inter-row distance between modules to minimize mutual shadings for south-oriented panels. However, it also includes an additional option to place PV panels in an east-west arrangement, which is a growing choice among PV designers due to the higher coverage area in a flat roof.

1.3.3 Tool Workflow (How the Tool Works)

Development options of the DST were explored based on the functional and non-functional requirements mentioned in Section 1.2.1. Two possible solutions were initially identified. One involves developing a database of pre-simulated design concepts, where a design concept is a simulation output file generated based on a combination of user-provided design inputs.

However, such a database could only be developed at the expense of a significant reduction in the selection of pre-developed options, as it is not feasible to perform simulations of all possible design cases, limiting its broader scope of useability.

The second option provides more flexibility as it can modify the design concepts based on user inputs, i.e. performing a dynamic simulation of the design concept while using the tool. The process have been further explained in the EngD report of Mahsa Nikoufard [21]. For this implementation method, whole-building energy simulation software EnergyPlus® and several functionalities of Python scripting language (web-based interface development through Streamlit framework [22]; modification and simulation of EnergyPlus® simulation files through Eppy [23], and GeomEppy [24]; data pre-processing, post-processing, visualization, and automated PDF report creation) have been utilized. The interface (front-end) for collecting user design inputs and providing performance visualization is created through Streamlit, an open-source Python web development framework that integrates standard Python packages (Matplotlib) for creating visualizations. The input pre-processing and simulation module of the tool (combinedly can be termed as back-end) includes the capability to use Python scripting for pre-processing of inputs provided by the user in the interface (front-end), automatic selection of the most appropriate simulation file and running such file through Eppy (Python package for EnergyPlus® application), post-processing of simulation and performance dashboarding in the interface (front-end).

The integration of capabilities of both EnergyPlus® and Python and the detailed step of how further exploitation has been done to navigate, modify and simulate the design files programmatically are more explained in the EngD report of Mahsa Nikoufard [21]. Streamlit framework has been utilized to interlink both the 'front-end' and 'back-end' parts, where users can only visualize the 'front-end' part in their local systems. The 'back-end' part has been abstracted (black box for user) for users and is strongly recommended not to modify. The following figure shows a user view of the tool in a simplified manner.

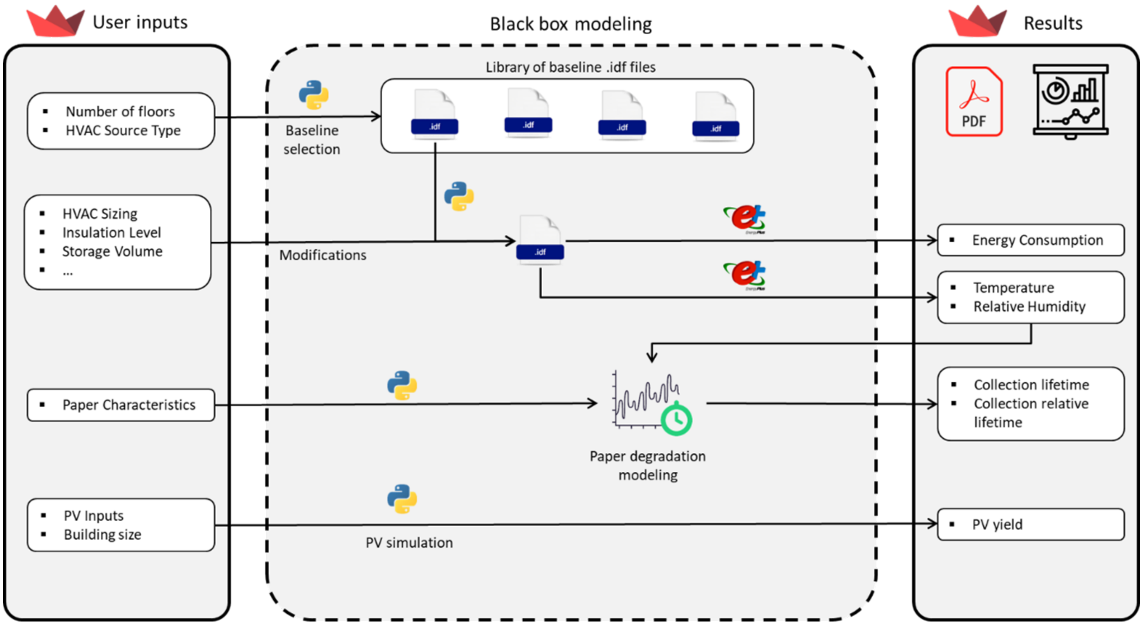


Figure 1.6. User-view of the DST

For developing the final tool based on the 2^{nd} option, initially three different software architectures were considered, which enables dynamic simulation of design concepts based on user inputs rather than utilization of a limit pre-simulated design concepts database, as shown in Figure 1.7. These options enable the design of the tool in three choices for user interfaces and deployment methods. Advantages and disadvantages from both the user and designer points of view, based on design complexity, user-friendliness, potential implementation and deployment risk, etc., have been further detailed in Chapter 2.

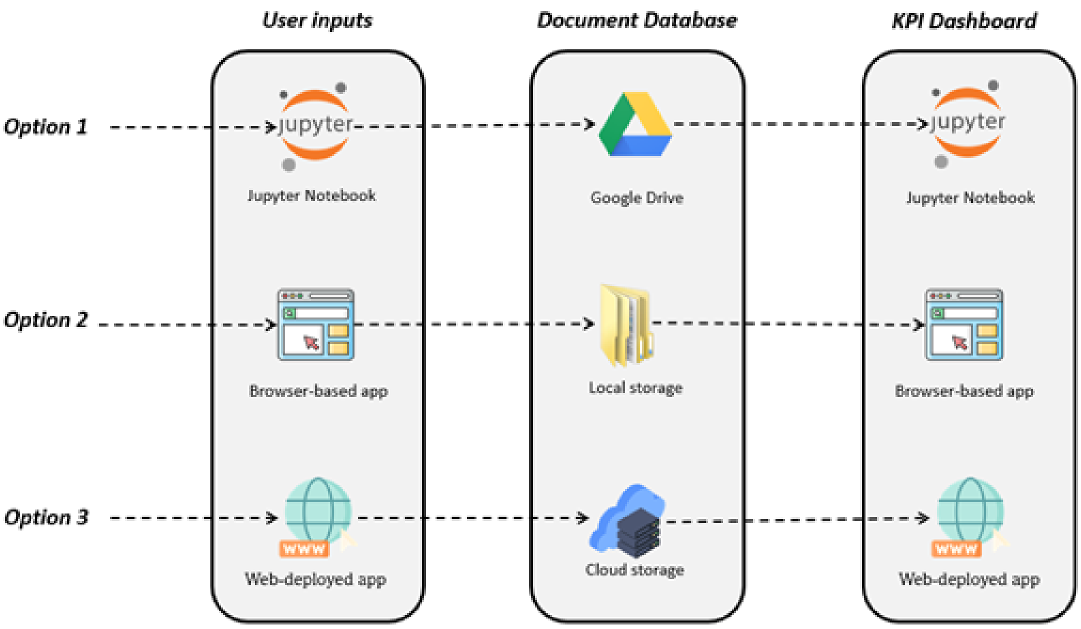


Figure 1.7. Three Options for DST's Software Architecture

1.3.4 Dissemination about Tool and Project

As many of the tool's users will be collection experts, and preservation specialists, impact of building design and operation on collection preservation is an important concern. In this context, the main objectives of the design project, which is developing familiarity of building design decision's impact on both collection performance and energy performance, was required to build over time. Thus, dissemination activities and outreach efforts toward the archive community have been integral to the design process. Highlights of the main activities or dissemination events have been presented below:

- Publication on KIA platform: KIA is a social collaboration platform for archive professionals to exchange knowledge, discuss ideas and contribute towards innovation in various directions. Individual users can join different open, specific research focus groups to bring their expertise. A blog post (originally in Dutch) was published briefly describing the project objectives and deliverables (tool) for gaining community awareness on the platform in June 2022.
- Further, an article titled "Samen bouwen aan een duurzaam archiefgebouw: Innovatieve ontwerptool verbetert afstemming" (originally in Dutch), on the projects objective, newer findings, interim outcomes and vision, had been published on Archievenblad, managed by KVAN (Koninklijke Vereniging van Archivarissen in Nederland) for their October 2022 issue. Archievenblad is a trade magazine for the archive community which is published on a bi-monthly basis and offers an attractive mix of current affairs and in-depth professional knowledge.

Figure 1.8. Article Published on DST in Archievenblad

- Later, on Nov. 24, 2022, at Metamorfoze's annual symposium (Kennisbijeenkomst onderzoek papierconservering), both researchers presented their latest findings for a broader scope of dissemination and face-to-face interaction with the collection community. Furthermore, during this event, the performance scope and usability of the tool were demonstrated with a closed test users group on a prototype version of the tool for feedback.
- As the final part of the outreach activities, the final developed tool has been shared with several professionals for their opinion on usability and scope of improvements. The final version of the tool has also been made openly accessible on an online repository, hosted in TU/e's Building Performance unit's Gitlab page, from where any user can access and download the tool for their individual uses.

1.4 Reflection and Outlook

The previous sections focused primarily on the design project and its challenges, as well as the requirements of the tool, which is a final outcome of this design project. Also, the developed tool, its features, and other project outcomes are explained. This section reflects on the design project journey and how pertinent it has become in achieving its objectives. In order to assess whether the project has achieved its goals in terms of being context-specific, user-friendly, and reliable, the tool features that respond to the previously defined requirements are presented in the following Table 1.1.

Through all sections, careful attention is given to making the tool fit for the early-stage design. Therefore, features related to, for example, construction material selection and detailed HVAC system type are eliminated. Also, climates related to other countries and regions are not incorporated since they would require other types of HVAC and construction design. However, this would be a possible strategy for the future development of the tool.

Furthermore, the test group participants in the Metamorfoze annual symposium, who were mainly conservators, showed interest in adding other types of collection (such as photographs) to the tool, which can also be a possible strategy for future developments. Also, another possible future development of the tool can be developing a completely cloud-based solution to improve user-friendliness and user outreach, possibly with additional functionalities and design concepts. Finally, future outreach is necessary to bring the tool to use in the design practice of sustainable archive buildings in the Netherlands.

Requirements category	Tool feature
Context-specific	The user has the flexibility to insert various levels of insulation and infiltration to cover both newly built and historical buildings.
	The user can select between multiple options for the Dutch climate, based on current and future climate scenarios.
	The tool does not have openings, occupancy rates, or lighting inputs. Very low infiltration levels (as low as 0.001 ach) are added. The tool has the feature to model current and new archival regulations for T & RH setpoints and ventilation. Paper degradation modeling is added to the tool based on client wishes.
	Different HVAC System sizing options (auto-sizing and manual sizing) are made possible with the tool. The user can also see load duration curves on the results page.
	The tool shows all the requested results (indoor climate, paper lifetime, and energy use) to the users. Also, these results can be separately saved as .csv and .pdf files.
User-friendly	The tool preloads default options regarding all design inputs. The default values/settings are mainly adopted from minimum regulation requirements or general practices.
	The user can specify non-numeric settings using drop-down menus and numeric settings by typing values.
	The tool has the option to provide information on several inputs by clicking on the question mark and has an extra link with instructions for the inputs of paper properties.
	The tool has the option to save inputs and results as .pdf files for future comparisons.
	The simulation runtime is about 5 mins for standard simulation and 10 mins for HVAC manual sizing simulation. The simulation time is lowered by using minimum timesteps and lowering the amount of EnergyPlus outputs.
	The user interacts with a user-friendly browser-based interface, and utilizing the tool does not require knowledge of Python and EnergyPlus.
	The tool has a user-friendly interface that guides the user through different pages and shows warnings or extra information on all pages. To assure user-friendliness, the tool is checked several times with practitioners. Also, the user is provided with manuals for installation.
	The tool uses stable versions of Python (version 3.9) and EnergyPlus (version 8.9).
Reliable	The tool is built on top of a reliable, well-known, and widely-used building performance simulation software, EnergyPlus.
	The used heat and moisture transfer algorithm (HAMT) is validated. The modeling approaches related to the HVAC design in DesignBuilder are tested for various design scenarios. Also, many other modeling approaches are selected carefully among several options to ensure the tool's reliability. Furthermore, demonstration cases are developed to test the tool.

Table 1.1. Tool Features Corresponding to the Defined Requirements of the Tool

Chapter 2

Development of Decision Support Tool

This chapter briefly outlines the design methodology for developing the DST, which is the final outcome of the design project.

2.1 Architecture of DST

2.1.1 Development Options of DST

Development options of DST were explored based on the functional and non-functional requirements mentioned in Sec 1.2.1 . Two possible solutions have been identified, which are listed below:

Option 1 - Database of prior simulated design concepts

The initial idea was to develop a database of simulated design concepts, where a design concept is basically a simulation output file generated based on a combination of user-provided design inputs. This would result in a significantly shorter wait time for user design concept evaluation and the possibility of performing a simulation of multiple design concepts in a shorter time frame. However, such a database could only be developed at the expense of a significant reduction in the selection of pre-developed options, as it is not feasible to perform simulations of all possible design cases due to time constraints and the risk of modelling errors. Such functional behaviour of the tool could limit its usability in future projects.

Option 2 - Dynamic simulation of the appropriate design concept from a database

The idea of performing modification of design concept files during simulation and corresponding building energy simulation is developed to mitigate the inflexibility issue of a static database-based approach. In this scenario, the user can provide a more customized range of design inputs. Based on a subset of user design inputs, an appropriate initial design concept file (termed as **Baseline** idf) is first selected from the design concepts database based on and further modified based on the rest design inputs as required, creating a modified design concept file (termed as **Modified** idf). The pre-processing and modification of the design concept are done with Python. Further, the Modified idf is used by EnergyPlus to perform simulation and post-processed in Python to present the performance visualization of the entire design concept.

This procedure and methodology are further detailed in the EngD thesis of Mahsa Nikoufard [21]. A schematic of the solution is shown in Fig. 2.1. Considering the robustness and flexibility requirement of the DST, solution 2 has been adopted, as it provides an opportunity to make amendments or improvements later.

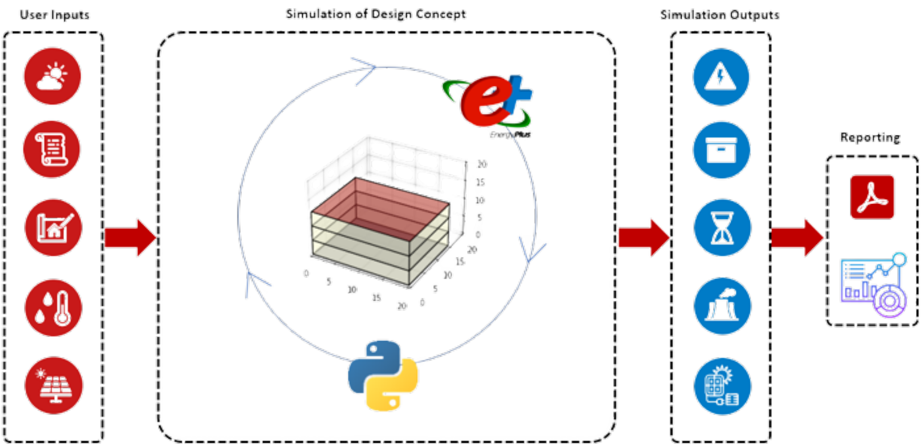


Figure 2.1. Schema of Option 2

2.1.2 System Architecture Options of DST

Option A

In Option A, the user can provide inputs and visualize performance summary in a Jupyter Notebook, a web-based interactive computing platform, which uses a Python script and idf files kept in the connected Google Drive. Users do not require to install or learn any additional software like Python or EnergyPlus.

Figure 2.2. Simplified program flow from user-perspective (Option A)

Option B

Option B requires the user to install Python and EnergyPlus and set up the tool environment following a one-time procedure, which is further supported with documentation. In this option, after setup, users can open the tool in a browser through "Command Prompt" afterwards.

Figure 2.3. Simplified program flow from user-perspective (Option B)

Option C

Option C is envisioned as a completely web-deployed application running on any commercial Platform as a Service (PaaS) solution. As the entire application is deployed on a cloud platform, users would not require to perform any installation activities.

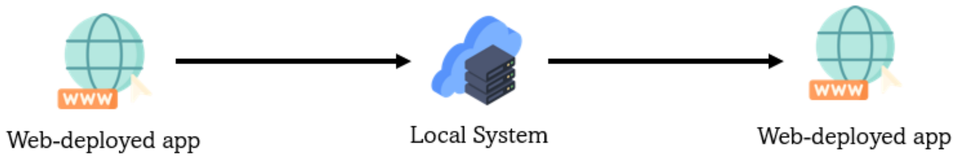


Figure 2.4. Simplified program flow from user-perspective (Option C)

In the following Table 2.1, benefits and drawbacks of individual options are mentioned.

System Architecture Options	Benefits	Drawbacks
Option A (Jupyter Notebook-based, web-based DST with cloud/local storage)	+ No user installations are required + Least challenging technical implementation	- Poor user experience, manual navigation through scripts are required - Accidental edits of scripts are possible
Option B (Browser-based, Downloadable DST with local storage)	+ Independent of cloud server capacity + More user-friendly interface	- User installations required for the first time
Option C (Completely web-based with cloud storage)	+ Most user-friendly interface + No user installations are required	- Susceptible to complex runtime error - Most challenging technical implementation

Table 2.1. Benefits & drawbacks for System Architecture options for DST

Option C presents the most user-friendly experience for all categories of project stakeholders; however, due to time constraints and significantly higher software implementation challenges, the tool deliverable strategy has been considered between only Option A & B. Though Option B requires a one-time installation and setup procedure to follow for users; it can present a more customized performance dash-boarding and slightly reduced processing time than Option A. Therefore, Option B has been selected as the software architecture option. A detailed software architecture of Option B has been presented in Fig. 2.5.

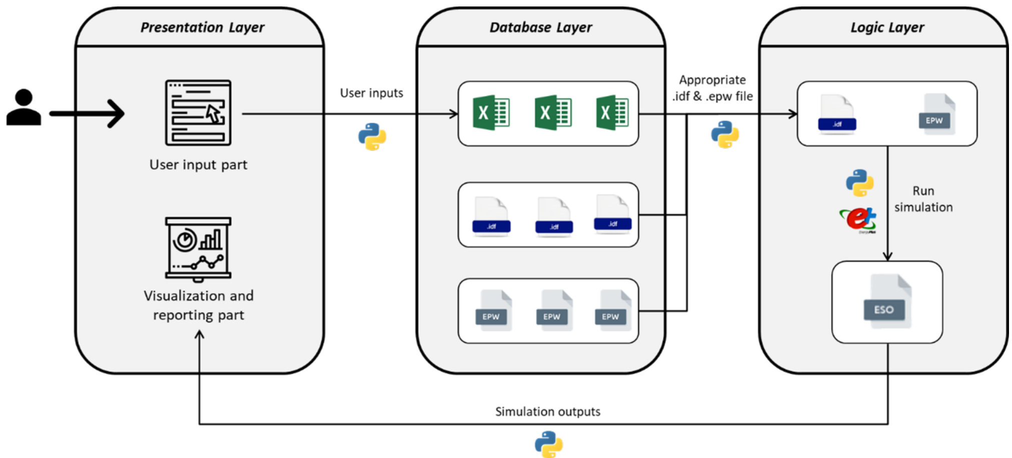


Figure 2.5. Software system architecture of DST (Option B)

2.2 Final Layout of User Interface

The final DST is built based on the program flow, as described in Fig. 2.3. It is a multi-page browser-based application that gives users options to provide design inputs. The design inputs are divided into several categories of inputs and further presented in separate pages of the applications, as shown in Fig. 2.6. Multiple pages also help users to segregate the cluster of inputs, and the application dynamically changes the view based on the category of inputs selected by the user. User views of the input pages of the application have been further added to the Appendix Section (User Views of Input Pages of DST).

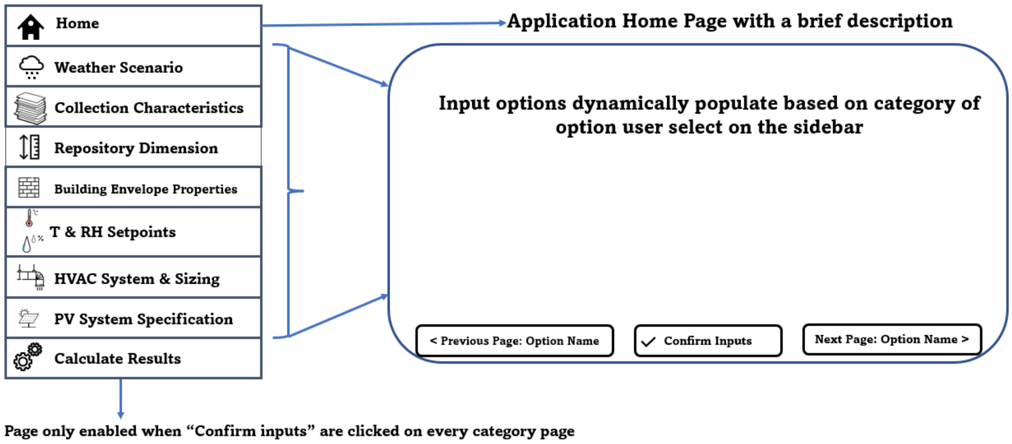


Figure 2.6. Layout of input pages

Similarly, several performance indicator summaries after performing the simulation can be visualized in the results pages of the application, separated into multiple pages. User views of the results pages of the application have been further added to the Appendix Section (User Views of Result Pages of DST).

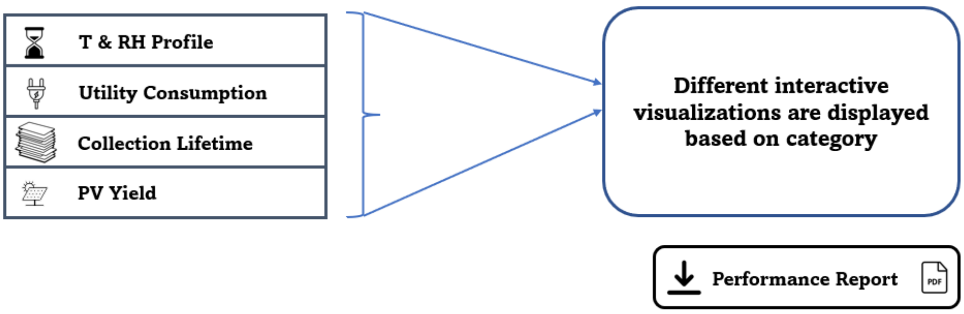


Figure 2.7. Layout of results pages

Chapter 3

Location & Weather

This chapter briefly discuss the impact of selecting reference climatic data for building energy performance and further describes how current and future climate scenarios can have impact of designing of archive buildings.

3.1 Reference Weather Effect on Building Energy Simulations

Weather data has an influential role in whole-building energy simulations as it contains information about numerous physical parameters like air temperature and humidity, solar radiation, wind velocity, snow and precipitation, which impact building's energy consumption. Buildings' sensible heating and cooling demand are primarily dominated by external temperature (dry bulb) and solar irradiance, while relative humidity and dew point temperature affect the building's latent load; based on both of these sizing of HVAC are performed. Comparison between two different weather datasets for energy performance evaluation should not be made with the comparison of a single weather parameter, as weather parameters are strongly correlated. With increasing temperature and solar radiation, relative humidity will be decreased, as suggested in study of Lisa Guan et al. [25].

Building energy simulation tools are usually employed to estimate the energy performance of the design, which takes into account the building's location and representative weather information; thus validity of such tool outcomes is highly dependent on the representativeness of the weather data. For properly analysing the changes in weather conditions at a certain location over the years, several methodologies have been defined in past decades to average weather information and create design reference weather data, mostly for a year. Test Reference Year (TRY), Typical Meteorological Year (TMY) are a few of those developed methods to consider the changing weather to improve the representativeness of the weather scenario. TRY approach is the current best practice for designing representative weather dataset for building energy simulation which is developed from historical 20-30 years of meteorological information by combining most typical months (not necessarily from a same year) and further statistically smoothed to form a composite and continuous one year of weather data, usually in hourly temporal frequency. Drury B Crawley [26] describes the suitability of TRY in their studies mentioning high representative accuracy in forming a characteristic year and reducing the impact of missing or improper weather information in Actual Meteorological Year (AMY) [27].

3.2 Current & Futuristic Dutch Weather Scenarios

3.2.1 NEN Weather Scenarios

For determining the hygrothermal performance of the buildings and sizing of the heating, cooling, and air conditioning installations in the Netherlands, NEN 5060:2018 standard [18], an adapted version of European standard EN-ISO 15927-4 [28], is being used currently, which has been slightly modified in 2021's version (time zone clarification and solar radiation calculation on inclined surfaces). This data consists of weather information like outdoor temperature, solar radiation, relative humidity, wind, precipitation etc., for a test reference year based on long-term weather data measured at De Bilt KNMI meteorological station near Utrecht from 1986 to 2018. De Bilt is selected as a representative location for the whole country primarily due to the availability of long-term, reliable weather measurements since 1901 and its position at the very central location of the country [29]. NEN 5060 also provides two additional scenarios with an "exceedance probability" of 1% and 5%, respectively, i.e., there is a 1% and 5% chance that at any time during the summer period (April-September), the actual temperature is higher than the temperature from the reference year which further leads to the construction of a climate reference year individually for each scenario, primarily for summer comfort and overheating risk assessment [30].

3.2.2 IPCC Weather Scenarios

With the advent of rising global warming and climate change, building design with a life expectancy of several decades, it is therefore not beneficial to consider the current weather situation as a design indicator. Various methods have been developed in the past two decades to create a futuristic reference weather year which includes dynamical down-scaling of a high-quality regional climate model, further developing software like WeatherShift, Meteonorm, and CCWorldWeatherGen to predict future building energy use [31]. Such predictions also take into account progressing level of Greenhouse Gas (GHG) emissions in the atmosphere. However, forecasting the long-term level of GHG emissions globally is a very complicated task due to combined effects and embedded uncertainties in technological progress rate, socio-economic development and evolution of legislative changes. Developed as part of the United Nations Environment Programme (UNEP) with the World Meteorological Organization (WMO), IPCC drafted a set of scenarios to better represent the emissions in light of future changes, SRE scenarios [32]. The emissions scenarios account for a wide range of demographic, societal, technological, and economic changes in the future landscape; however, they are open to subjective interpretations. SRE scenarios are distinctly differentiated under four storylines, where similar types of scenarios are part of the same "scenario family". A1 storyline represents an accelerated growth of the world economy and population till the 2050s, followed by a sharp decline. A2 storyline represents a more disproportionate growth in technological advancements and economy around the world, a more representative of a fragmented world and self-reliance. B1 storyline represents similarity in the population pattern like the A1 scenario family, however, it introduces a more accelerated change in economic structures and introduction of carbon-neutral technologies. Meanwhile, the B2 scenario family represents a middle-ground between all three other storylines with a difference in scale of change in the economy, technological advancements, demography etc. Based on these scenarios, quantitative estimates have been performed to indicate possible levels of global CO_2 emissions annually from 1990 to 2100, as shown in Fig. 3.1.

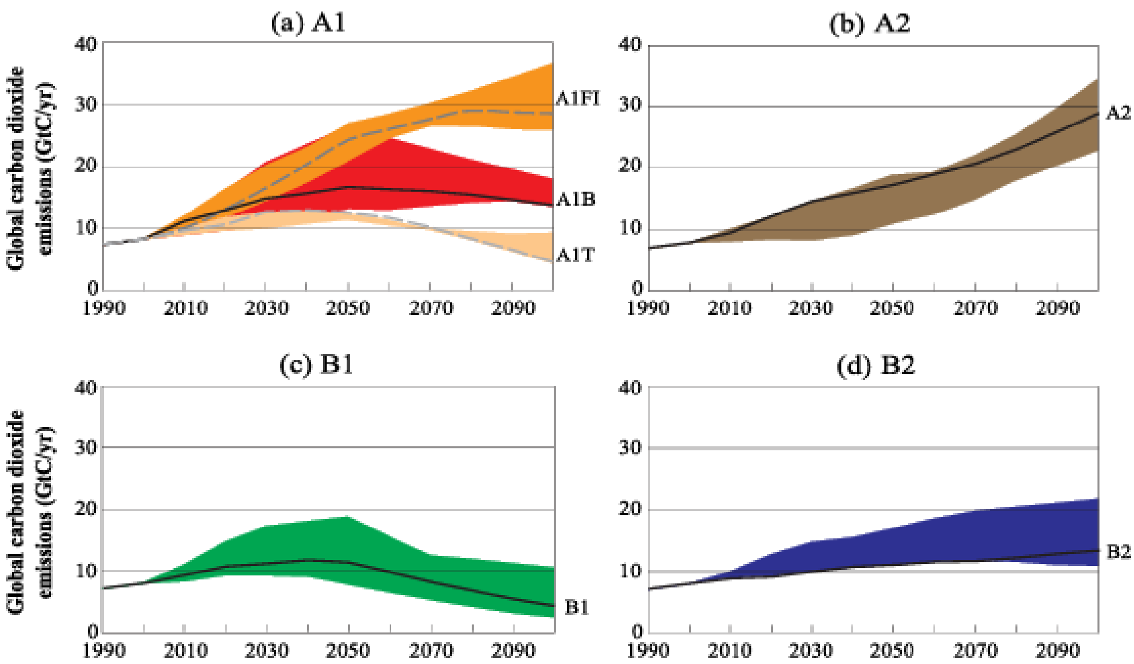


Figure 3.1. Annual global CO_2 emission from year 1990 to 2100 in SRE scenarios

In our DST, a user can assess building design for total 9 reference weather data or scenarios: - Dutch NEN 5060:2018 (current weather reference for the Netherlands), NEN 1% and 5% probable weather scenarios, as mentioned in Sec 3.2.1 and three commercially available IPCC SRE scenarios (A2, A1B, B1), as mentioned in Sec 3.2.2, for De Bilt location based on the year 2050 and 2100, retrieved from Meteonorm 7.1. A comparison between three different weather scenarios (NEN 5060, NEN 1% and IPCC A2-2100) can be seen in Figs. 3.2 and 3.3. IPCC A2 scenarios predict an overall warmer reference year for the whole year, while NEN 1% shows warmer summer periods and colder winter periods than the Dutch current climatic reference. However, significant deviations in relative humidity level can be seen between months due to intrinsic relations with other weather parameters like solar radiation amount, air temperature etc. Such differences will further result in a slightly different energy consumption for archives. The impact of changing future weather, especially temperature and considerably higher indoor relative humidity due to increasing precipitation, has damage potential for collection objects is such reflected in work of Zara Huijbregts et al. [33, 34].

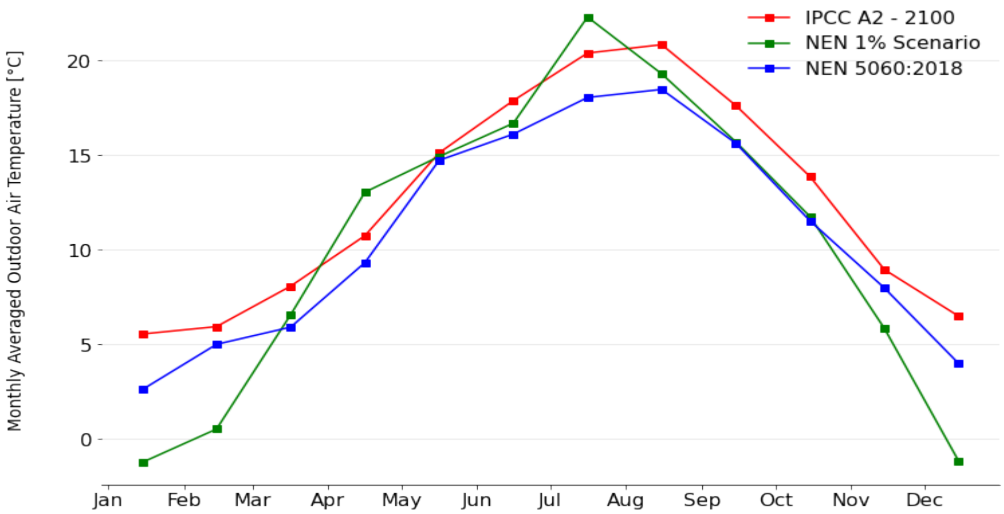


Figure 3.2. Comparison between monthly averaged air temperature for three different scenarios

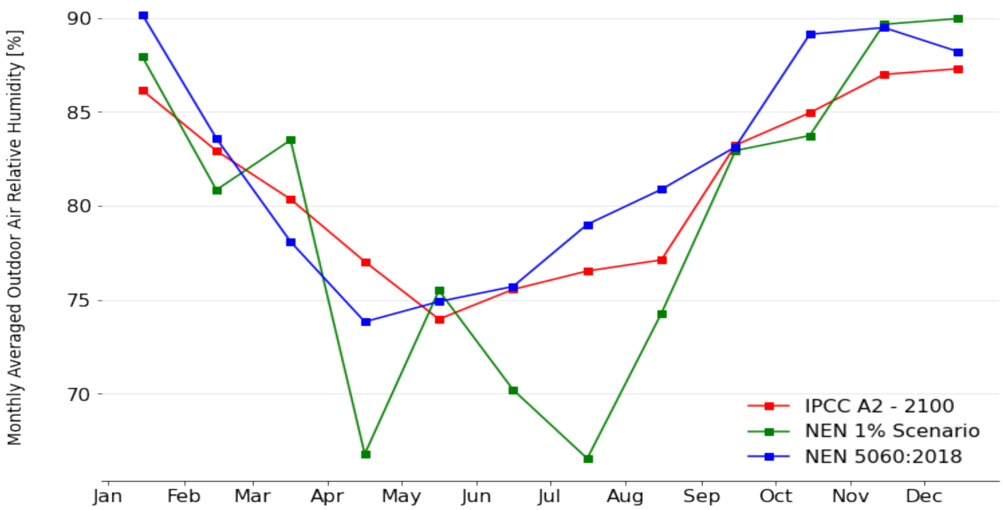


Figure 3.3. Comparison between monthly averaged relative humidity for three different scenarios

Chapter 4

Indoor Climate Conditioning

This chapter briefly introduces the challenges for indoor climate conditioning for archives and how controlling temperature and relative humidity impacts both energy performance and collection preservation performance. Different design options for such HVAC controls has been described with relevant implementation in the DST and performance indicators.

4.1 Climate Conditioning Challenges & Risks

The indoor climate of archives has a major impact on the preservation lifespan of cultural heritage, like hygroscopic paper collection. Different environmental factors, especially indoor air temperature and relative humidity in higher range, can accelerate deterioration of objects. There are mainly three types of degradation; biological, mechanical and chemical degradation. Biological degradation is mostly caused due to higher temperature and relative humidity level, which triggers fungal growth. Michalski [35] analysed how relative humidity higher than 70% impacts germination growth, which can occur in cold surfaces of rooms without proper air conditioning. Mechanical degradation is mostly caused due to dimensional variability because of slow changes or a rapid fluctuation in a short period in the Relative Humidity (RH) level. Short fluctuation causes disproportional changes to the object, especially near the surface portion. Fluctuation in humidity level can also impact hygroscopic materials as it absorbs or releases moisture [36]. Łukasz Brataz et al. [37] had estimated in their research about risk of permanent curling of parchments under increased amplitudes of RH changes. For most objects, research community and practitioners usually agree on a maximum allowable limit of rate of change on different time scales. Chemical degradation is a primary concern for the preservation of hygroscopic materials. However, chemical degradation rates are very slow in nature and respond very variedly between different kinds of collection materials, so it is often hard to estimate realistically. In practice, low temperatures are usually maintained for long-term storage facility [38]. The expected lifespan of paper collection can be almost two times of the typical conservation environment (20 °C and 50% RH) in the case of reducing storage temperature by 5 °C [39]. However, controlling temperature and relative humidity in a lowered range might conflict with operative limits for mechanical degradation prevention, especially if a rapid fluctuation occurs. based on discussion with experts, chemical degradation risk assessment has only been considered for the scope of the tool in this work.

4.2 Indoor Climate Control Guidelines for Dutch Archives

Preventive conservation of collection objects is mostly achieved by employing dedicated air conditioning systems nowadays, like Air Handling Unit (AHU), which supplies conditioned air to the storage area. The air conditioning includes adequate temperature and relative humidity control, along with mechanical ventilation and re-circulation of air. The energy and operational performance mostly depends on the design typology of the archive, construction materials, retrofitting measures and installed climate systems. Based on works of Michalski, Erhardt, and Mecklenburg [40, 41, 42], an additional chapter was added to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook [13] about climate systems guidelines for archives, which has been revised over the years. This acts as a design guideline for operational limit of HVAC systems in museums, libraries and archives around the globe. It provides different classes of climate control, from class AA to D, with annual average of thermal setpoints and allowable fluctuations. Class AA is the most stringent climate class advising an annual average temperature between 15-25 °C and RH of 50% with maximum fluctuation of ± 2K and ± 5% RH to limit mechanical damage for most chemically stable materials. In the Dutch context, a similar adaption of ASHRAE climate AA has been the standard indoor climate requirements guideline [7, 43] for archives, resulting in energy-intensive solution as shown in a similar energy impact case study for four museums in Amsterdam [44]. The current Dutch archival guidelines [7] requires an annual average temperature and relative humidity of 18 °C and 50% RH, respectively, with an air exchange rate of 1.5 ach (10% ventilation and 90% re-circulation) and additional air contaminants filtration requirements. The temperature and relative humidity are only allowed to fluctuate ± 2 °C and 5% respectively during the year, which makes it challenging for climate conditioning systems to be energy-efficient and effective in that short range of operation. However, sustainability became a growing concern as pursuing such strict climate control resulted in higher energy consumption, which is often further exacerbated by extreme weather conditions. The pursuit for energy efficiency improvement was hindered by collection institution's pre-occupied notion of 'stability over efficiency' for preventive preservation [45]. One of the key reasons for such mindset was mostly due to pre-agreed loan agreements to transfer collection between collection institution [46]. With respect to museums, conditioning of libraries and archives are viable to lower range in temperature due to limited presence of visitors and human thermal comfort requirements, leading to energy-saving opportunities. Recent waves of energy performance requirements for the building sector inspired archive community to rethink about existing design practice and climate control strategies for archives.

Recently, the Dutch archival guidelines has been updated and due to be published in a legally binding manner by the end of 2023. The new regulation provides a relaxation for indoor temperature and relative humidity control, which allows the temperature to fluctuate between 13 to 22 °C and relative humidity between 35 to 60% near the collection. However it still targets to attain similar annual averages of temperature and relative humidity (18 °C and 50%). It also limits a very rapid fluctuation in temperature and relative humidity values between months and days (monthly fluctuation limit is 5 units, and daily fluctuation limit is 3 units). Also requirements for mechanical ventilation (i.e., addition of external fresh air to replace internal air) has been removed for energy-efficiency improvements, since the occupants enter the repositories for a very low number of times and short periods. The new guidelines also suggest investigating impact of switching climate control devices (fans in AHU) during the night on energy-saving potential.

4.3 Impact of Different HVAC Setpoints Strategies

4.3.1 Types of Setpoints Strategies

As explained in Sec 4.2, Archival regulation [7] recommends attaining an annual average temperature and relative humidity of (18 °C and 50%, respectively, to minimise collection risk. The DST facilitates selecting user the temperature and relative humidity setpoints to assess the energy and collection preservation performance. However, achieving the indoor climate requirements can be performed in multiple combinations of these two design parameters. For determining the possible limits of fluctuation of temperature and relative humidity, following four setpoints might be required to set in the HVAC system for appropriate space conditioning:

- Heating Setpoint: The temperature below which if air temperature falls, heating system will be activated.
- Cooling Setpoint: The temperature above which if air temperature goes, cooling system will be activated.
- Humidification Setpoint: The relative humidity, below which if air relative humidity falls, a humidification system is used.
- Dehumidification Setpoint: The relative humidity, above which if air relative humidity goes, dehumidification process is utilized, which involves first sensibly cooling air till Dew-point temperature and then reheating the air to adequately till Heating Setpoint.

These setpoints activate and control the systems accordingly, based on indoor condition requirements, the amount of heating, cooling and humidity controls required. HVAC setpoints are one of the most influential decision parameters that dictate the energy consumption level of archive buildings. However, setpoints are needed to be defined for all four of the process, i.e, threshold values for activating heating, cooling, humidification and dehumidification processes. From perspective of the user, they are accustomed to two individual input parameters (T and RH setpoints), while in reality, there are four input parameters for HVAC systems (Heating & Cooling setpoints; Humidification & Dehumidification setpoints) required to operate the system. The following two options has been evaluated to determine the format of providing the input:

Option 1: User-provided T & RH limits

In this method, the user determines four setpoints, which has the highest flexibility in defining bandwidths of system operation and also easiest to implement. However, this approach can lead to user-defined error, which might cause due to improper selection of range.

Option 2: User-provided annual T & RH averages

In this method, the user is required to provide only the intended annual averages, which is easier to provide and has familiarity. However, it requires the tool to adjust the bandwidth automatically, which is more complex to automate in the climate models. It reduces the flexibility for users to determine the level of fluctuation in setpoints. Considering both options' advantages and disadvantages, Option 2 has been selected as the preferred method for user input format. To overcome the limitation of user flexibility in determining the possible level of fluctuations in temperature and relative humidity, three different types of fluctuation level has been added in the tool as user option, as listed below:

- 'Very Small' option indicates the temperature and relative humidty are allowed to fluctuate in a very narrow bandwidth (± 0.5 °C and ± 1% respectively).
- 'Current Archival Limit' option indicates the temperature and relative humidty are allowed to fluctuate as per existing archival guidelines allowable bandwidth (± 2 °C and ± 5% respectively).
- 'New Archival Limit with Safety Tolerance' options indicate the temperature and relative humidity can fluctuate closer to newer archival regulation thresholds. The limitation has been set with a safety tolerance for operational purpose from proposed thresholds, which are 14 to 21 °C and 40 to 55%.

The user can define the expected annual averages and type of fluctuation level in the tool as shown in Fig. 4.1, which in combination determines the permissible bandwidth for HVAC operation.

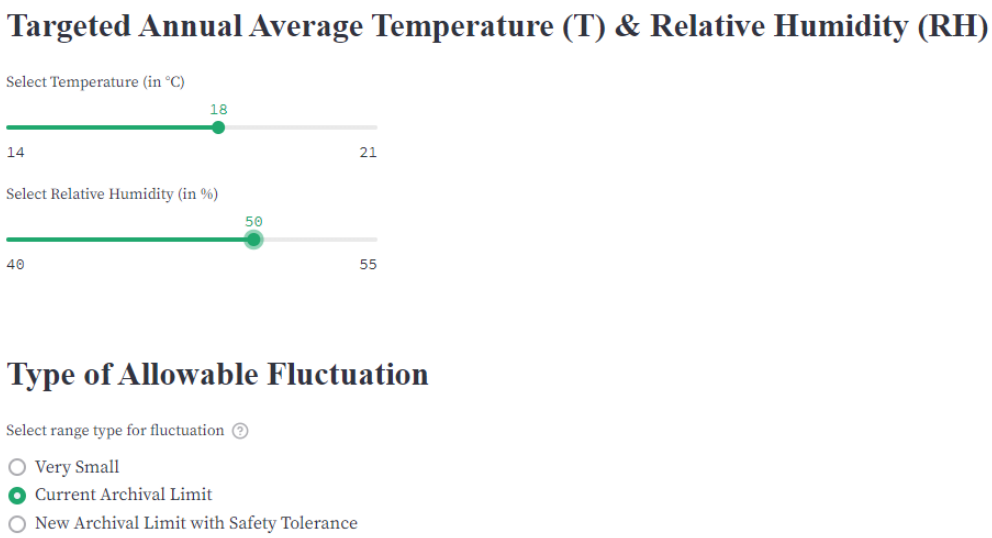


Figure 4.1. An example of user input format of HVAC setpoints

The tool also displays an error accordingly if the user selection of the combination of annual averages and type of fluctuation violates the archival setpoints thresholds. As an example in Fig. 4.2, it can be seen that when user defines an annual average of 15 °C and 'Current Archival Limit' option as type of fluctuation level, it leads to an error in the user interface. The error appears as the selected combination results the heating setpoint to be 13 °C (15 °C - 2 °C), which is lower than 14 °C threshold for operational limits.

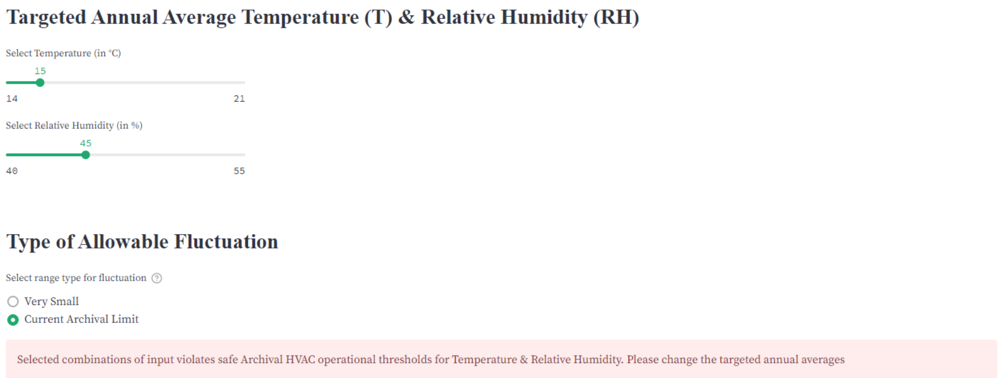


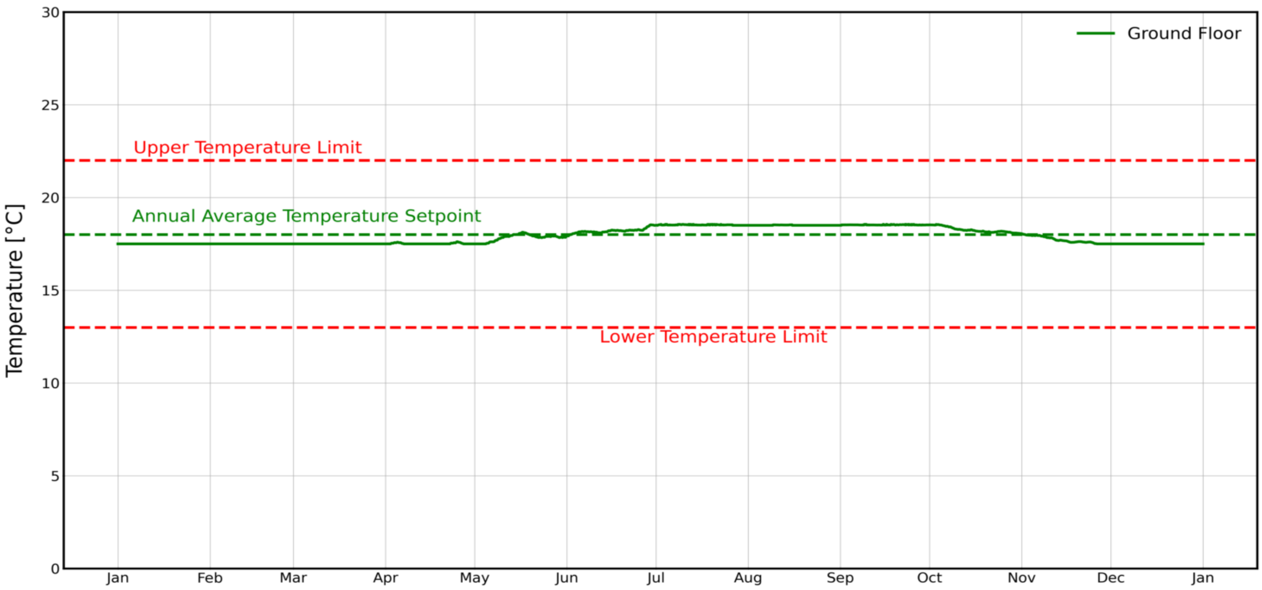
Figure 4.2. An example of user-defined error in HVAC setpoints

However, it is noteworthy to mention that the actual temperature and relative humidity inside the archive depends on other design factors like building compactness, envelope properties, infiltration rate and mechanical ventilation apart from setpoint values only. Also the hygroscopic nature of the collection might play a much greater buffering role for stabilizing indoor climate. Impact of such design factors on indoor temperature and relative humidity is further detailed in the EngD report of Mahsa Nikoufard [21].

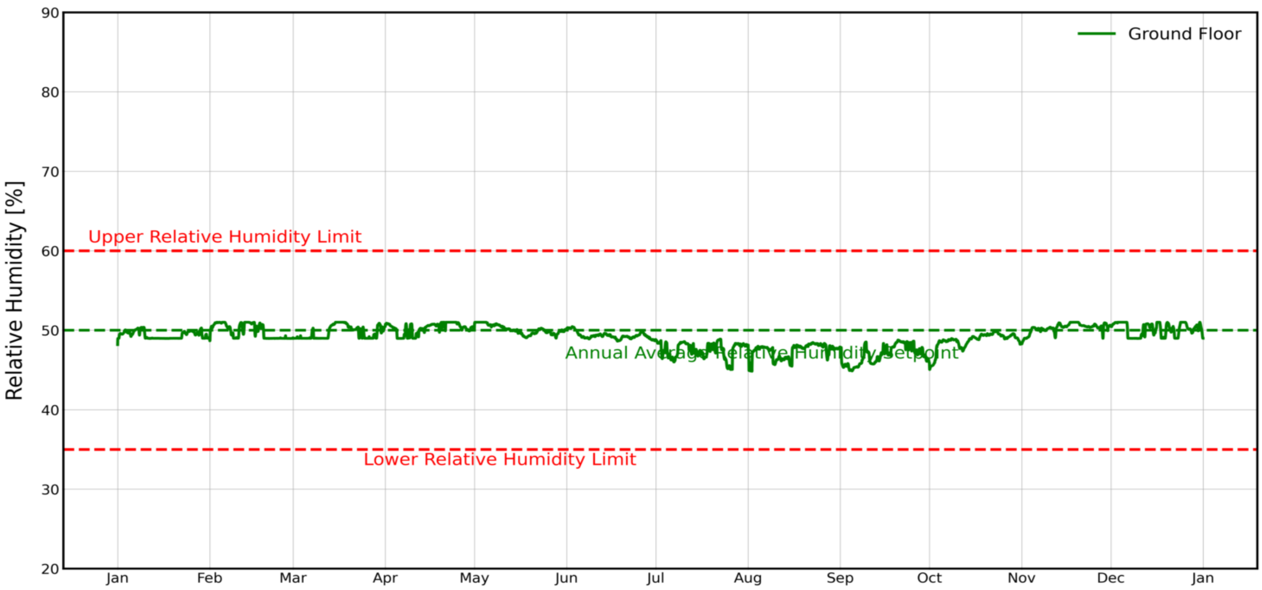
4.3.2 *Performance Comparison of Different Strategies*

For evaluating the impact of different strategies on energy consumption and collection preservation performance, annual average temperature and relative humidity of 18 °C and 50% has been targeted. For this comparison, all other design factors like collection, repository sizing, and building envelope characteristics have been kept the same. Figs. 4.3 to 4.5 depict the temperature and relative humidity profile of these strategies:

Fluctuation Level Type: 'Very Small'



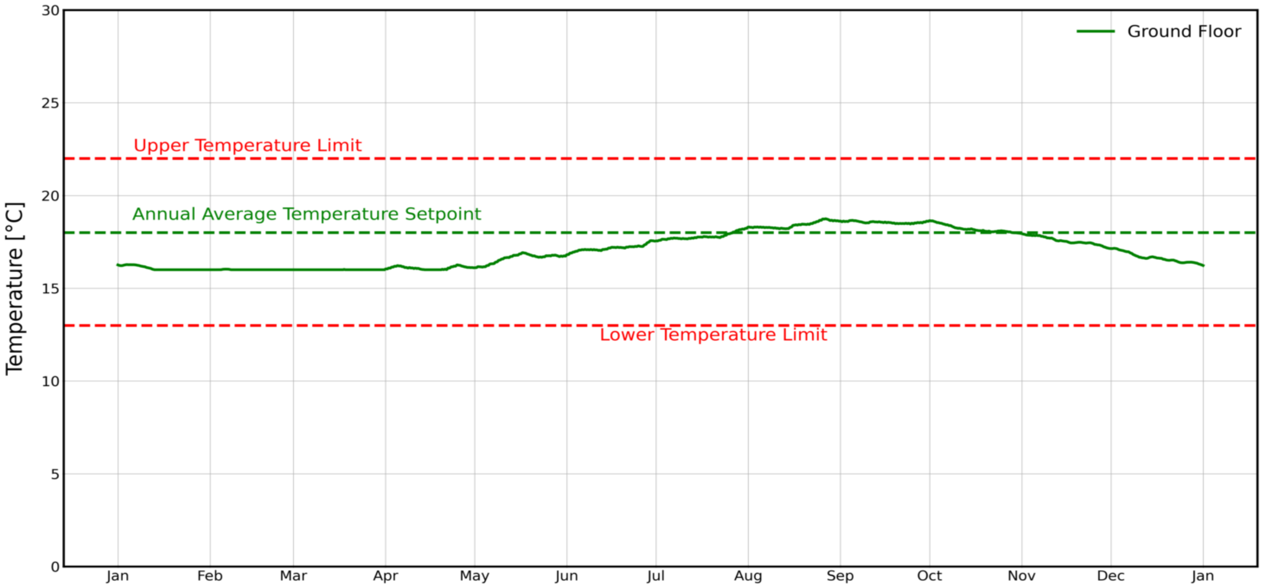
(a) Temperature



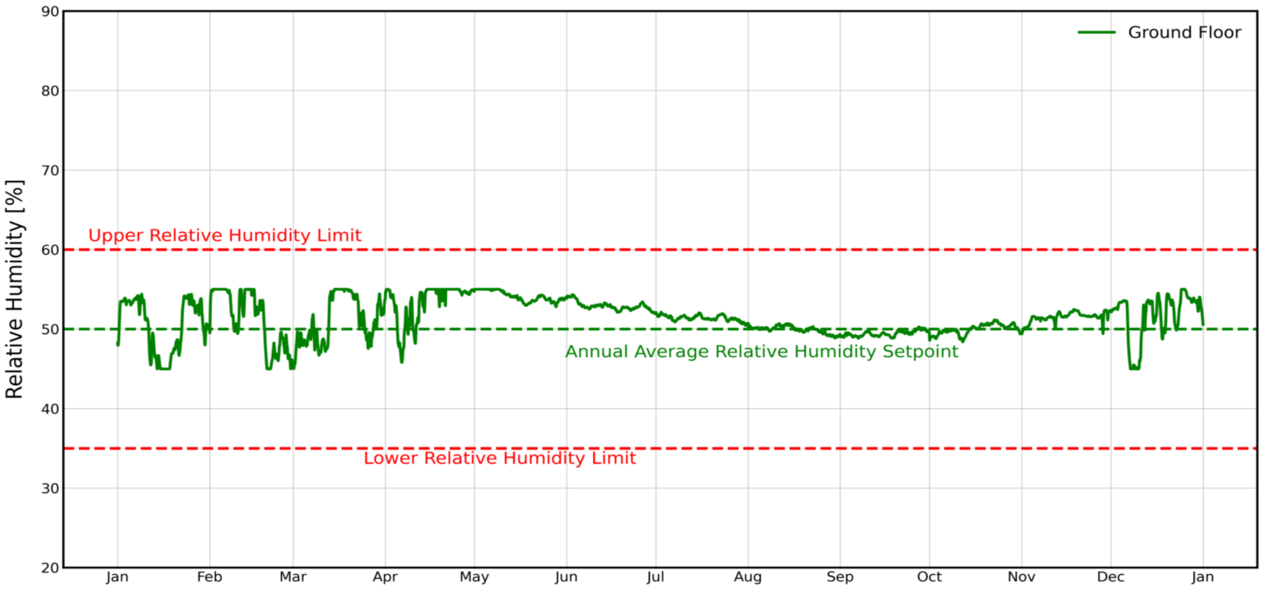
(b) Relative Humidity

Figure 4.3. Variation in T & RH in 'Very Small' option

Fluctuation Level Type: 'Current Archival Limit'



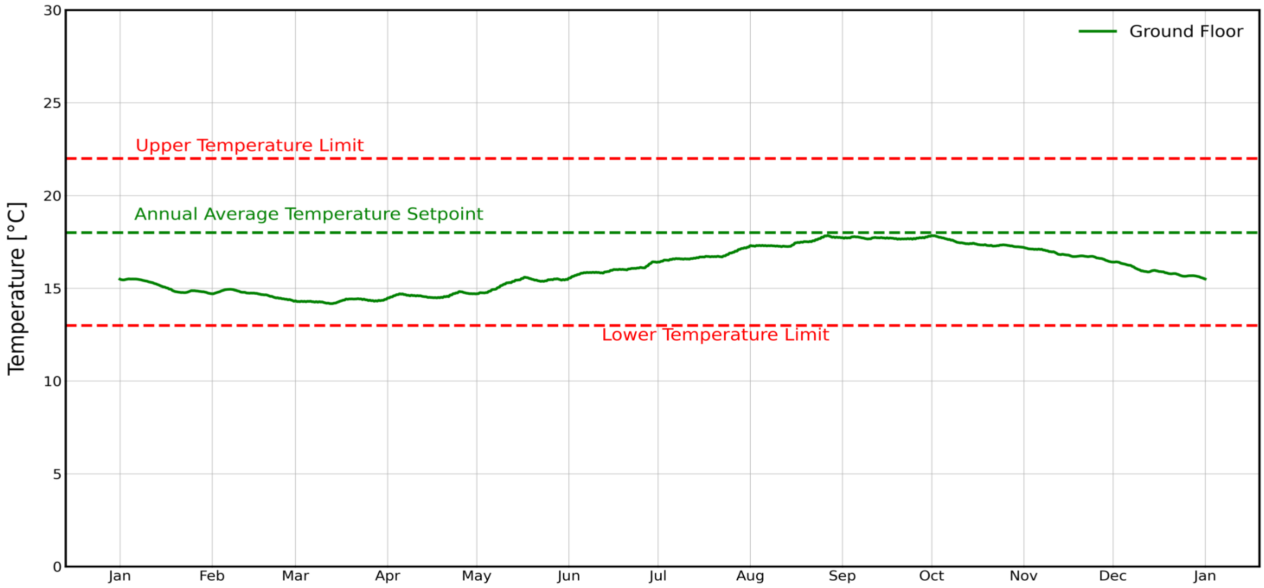
(a) Temperature



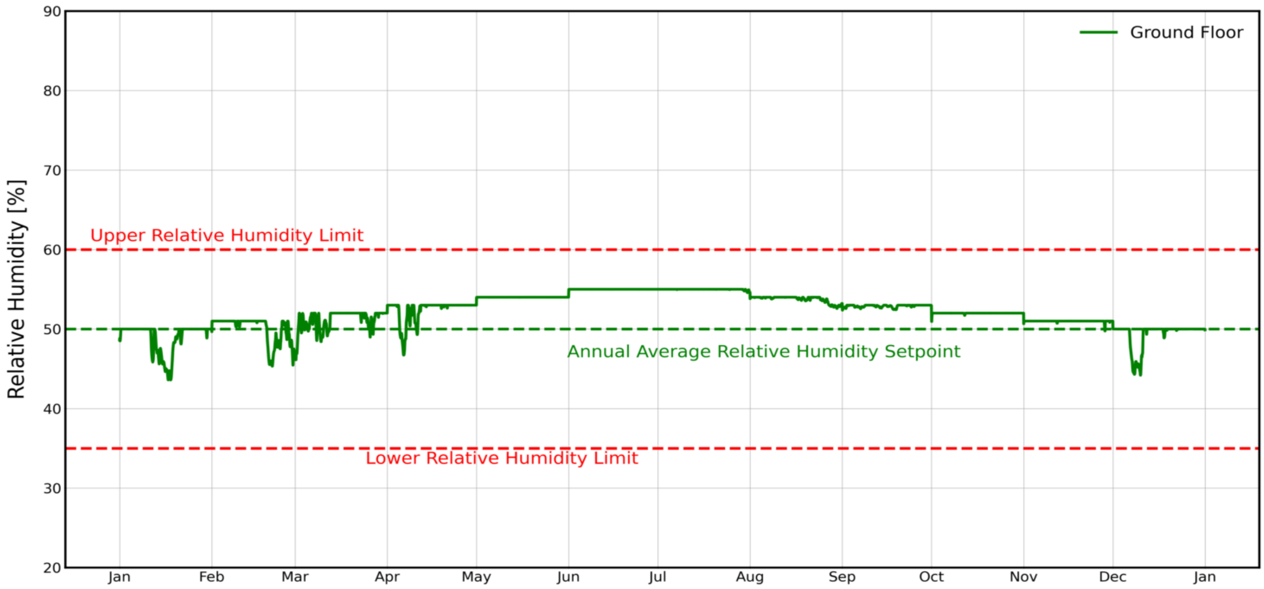
(b) Relative Humidity

Figure 4.4. Variation in T & RH in 'Current Archival Limit' option

Fluctuation Level Type: 'Current Archival Limit'



(a) Temperature



(b) Relative Humidity

Figure 4.5. Variation in T & RH in 'New Archival Limit with Safety Tolerance' option

As the 3rd option enables to fluctuate the temperature and relative humidity in a wider range, such operation can become susceptible to rapid fluctuations between months. Therefore, a seasonal control on relative humidity has been implemented to avoid rapid fluctuation between months and calculated if the fluctuation between months are within acceptable range (Archival guidelines suggests maximum 5% change between months), as shown in Fig. 4.6.

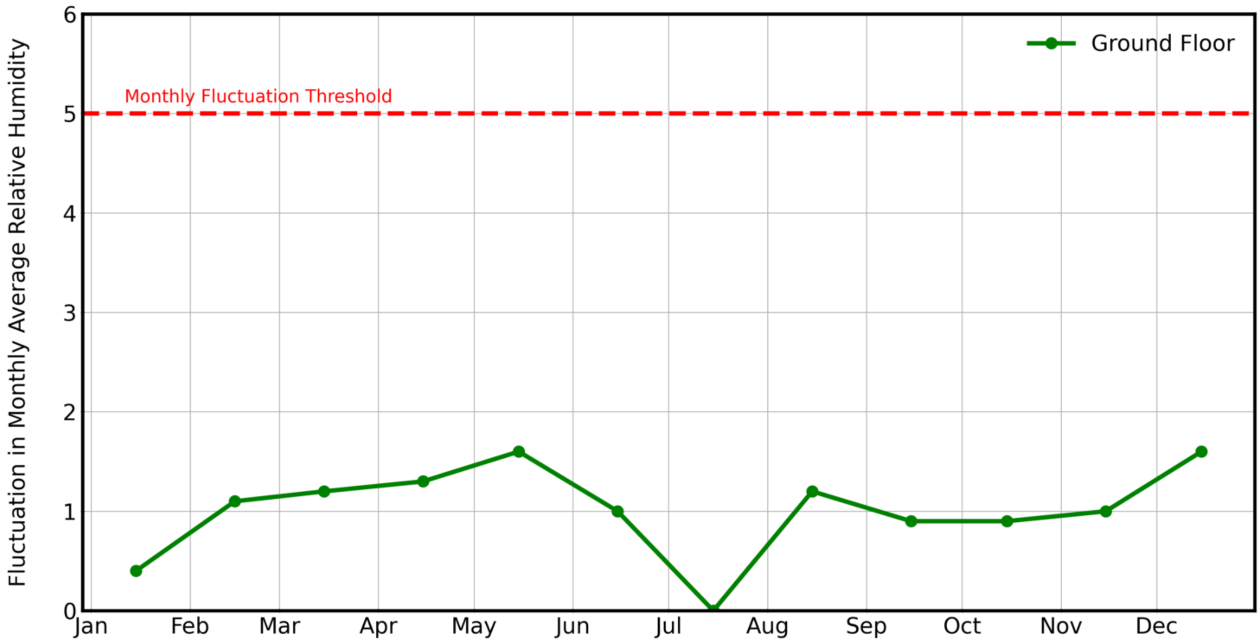


Figure 4.6. Fluctuations in monthly averaged relative humidity during the entire year

Tables 4.1 and 4.2 compare the energy and collection performance of the three above-mentioned setpoint strategies.

Setpoint Strategy	Heating Consumption (kWh/m^2)	Cooling Consumption (kWh/m^2)	Humidifier Consumption (kWh/m^2)	Fans & Pumps Consumption (kWh/m^2)
Very Small	22.48	10.73	0.15	2.01
Current Archival Limit	17.97	9.03	0.01	1.43
New Archival Limit with Safety Tolerance	14.19	8.46	0.00	0.95

Table 4.1. Energy Consumption comparison in different setpoint strategies

Setpoint Strategy	Annual Average Temperature (C)	Annual Average RH (%)	Collection Lifespan (Years)
Very Small	17.9	49.1	2791
Current Archival Limit	17.1	51.4	2914
New Archival Limit with Safety Tolerance	16.0	52.1	3354

Table 4.2. Collection Performance comparison in different setpoint strategies

The results show how the energy performance improves while using a more relaxed bandwidth due to less sensible heating and dehumidification requirements. Although in such scenario, the annual average results in a slightly higher than the user-defined average relative humidity, such impact on collection lifespan is offset by achieving a lower temperature in archive. Aiming for both low temperature and relative humidity is particularly difficult to achieve, as lowering relative humidity requires reheating cold air after dehumidification. HVAC designers have to further make an optimized trade-off between lowering both temperature and relative humidity level based on discussion with collection experts.

4.4 Suitable HVAC Systems for Archives

4.4.1 Selection & User-representation of Systems

Selecting a suitable HVAC system for archive requires consideration on multiple design factors like location of building, properties of building envelope. F. Verberne et al. [47] assessed feasibility of implementing low temperature heating solution like floor heating, which can uniformly distribute heating across the space in an exhibition space of Stedelijk Museum. The work highlights potential concerns like thermal gradient between floor and display case, dust deposition due to increased air exchange rate. One primary requirement for selecting a suitable HVAC is effective control over relative humidity over the year, which requires a dedicated dehumidification and/or humidification unit. A solution for both temperature and relative humidity control can be achieved using all-air systems with dedicated air handling units, commonly known as AHUs. It introduces adequately conditioned air to the archive zone through diffusers from a central plant via ductworks and can react quickly to temperature and humidity fluctuations. It usually embeds electric/water heating and cooling coils with humidifiers and appropriate controlling logic within the dedicated air handling box. The water coils can be powered via different heating systems like boilers, heat pumps, and cooling systems like water/air-cooled chiller units or direct expansion coils. Only variation of AHUs integrated with DX coils has been selected for this work. There a few reasons for selecting DX coil over water coil-based systems as follows:

- DX coil are more effective in dehumdification of air as they can cool the air below sub-zero temperature [48], while water-based systems can use a cooling temperature until 6 °C to avoid operational risk of freezing. As explained about different combinations of temperature and relative humidity in the Section 4.3, the dew point of air might be lower than 6 °C (temperature $\leq$16 °C and relative humidity $\leq$45% has dew point temperature $\leq$4 °C) which limits the capability of removing moisture from the air for water-based systems. Meanwhile, DX coil can utilize refrigerant to cool the air temperature way below 0 °C.
- DX coil systems also have a greater efficiency than water-based coil as it operates at a reduced air speed which allows a higher time for contact between the air and refrigerant to remove moisture [48].

Thus, in scope of this work, only alteration has been provided in the source of heating for the heating coil in AHU. Three different sources for heating has been selected, reference diagram of the HVAC systems are added in Appendix Sec A.5. The systems has been designed in DesignBuilder® [49] initially, which is later converted to EnergyPlus® [20] simulation files. The process is further explained in the EngD report of Mahsa Nikoufard [21]. The selected heating sources in scope of this project are following:

- Electric boiler uses electrical resistance coil to heat water for heating purposes. Electric boilers are generally smaller in size than traditional boilers, and they do not require a separate fuel storage tank, chimney, or flue.
- Ground heat exchanger based heat pump uses the earth's thermal energy or stable ground temperature as a heat source. It consists of a number of vertically buried pipes (boreholes) that are filled with a heat transferring fluid. In the winter, these pipes serve as a heat exchanger, drawing heat from the earth. Using a heat pump, the heat transfer fluid is moved between the ground source exchanger and conditioning system (AHU). Also, in contrast to an electric boiler, which has a Coefficient of Performance (COP) of 1 usually, COP of a water heat pump can be significantly higher, ranging from 3 to 5, depending on the specific system and operating conditions. However, its appropriateness depends on the local geology and soil conditions, and their installation costs might be greater than those of conventional heating systems.
- A centralized heating system that distributes heat across a defined geographic region is known as a district heating system. In a district heating system, heat is produced centrally at a facility like a power plant or a heating plant and transferred to nearby buildings via a series of insulated pipes. A source of heating to the supply side of a heat pump's hot water loop has been characterized as a hypothetical centralized heating object for the purposes of this study in order to increase efficiency. The district heating system's operational temperature is set at operating temperature of a 4^{th} generation district heating 55 °C [50].

The option to select HVAC has been fairly simplified in the tool, which does not require design/construct the system in entirety from scratch or component-wise. Users can select the preferred system from a drop-drown menu options list in the user-interface of the tool, as shown in Figure 4.7.

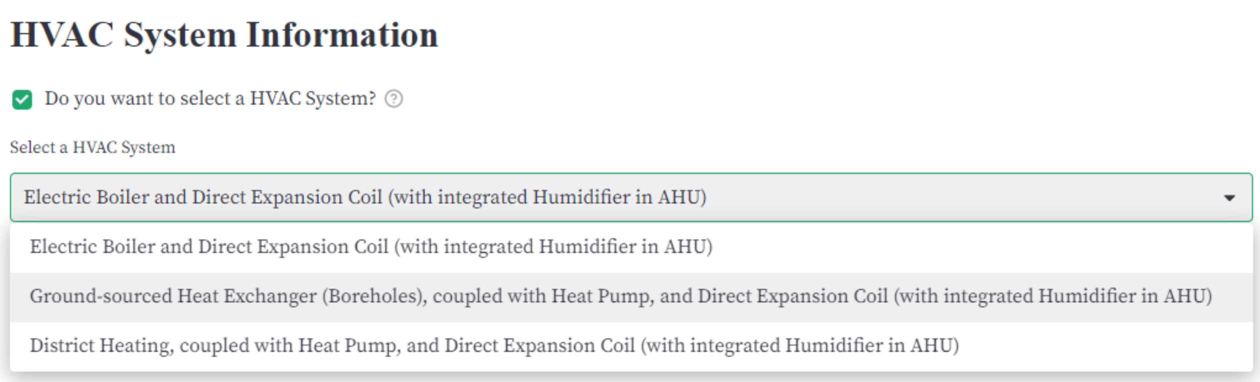


Figure 4.7. User-view for HVAC system selection in DST interface

However, it is also possible for user to not select any system, as shown in Fig. 4.8, which then automatically select the electric boiler based system.

Figure 4.8. User-view for HVAC system page (in case of no selection with help tooltip)

4.4.2 *Energy Performance Comparison of Selected HVAC Systems*

For the energy-efficiency comparison between HVAC systems, other design factors (size of repository, construction properties, annual T & RH setpoints, mechanical ventilation rate) has been kept constant. From the Fig. 4.9, it can be seen that utility consumption for an electric boiler is considerably higher than other two systems. Boiler has a nominal thermal efficiency close to 1 while both other systems are coupled with a water-source heat pump with seasonally varying COP between 4 to 5, resulting in lower end-use utility consumption. However, pump consumption slightly increases due to additional number of pumps in the entire systems.

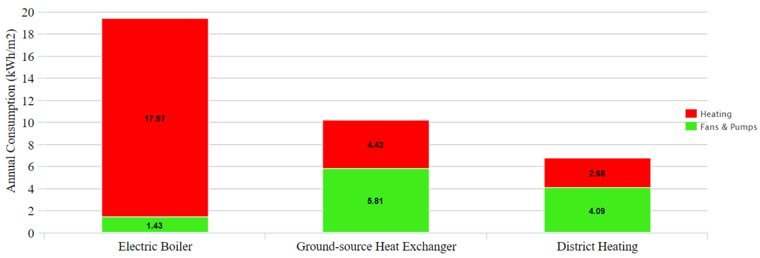


Figure 4.9. Energy consumption comparison between selected HVAC Systems

4.5 Evaluation of Different System Sizing Options Performance

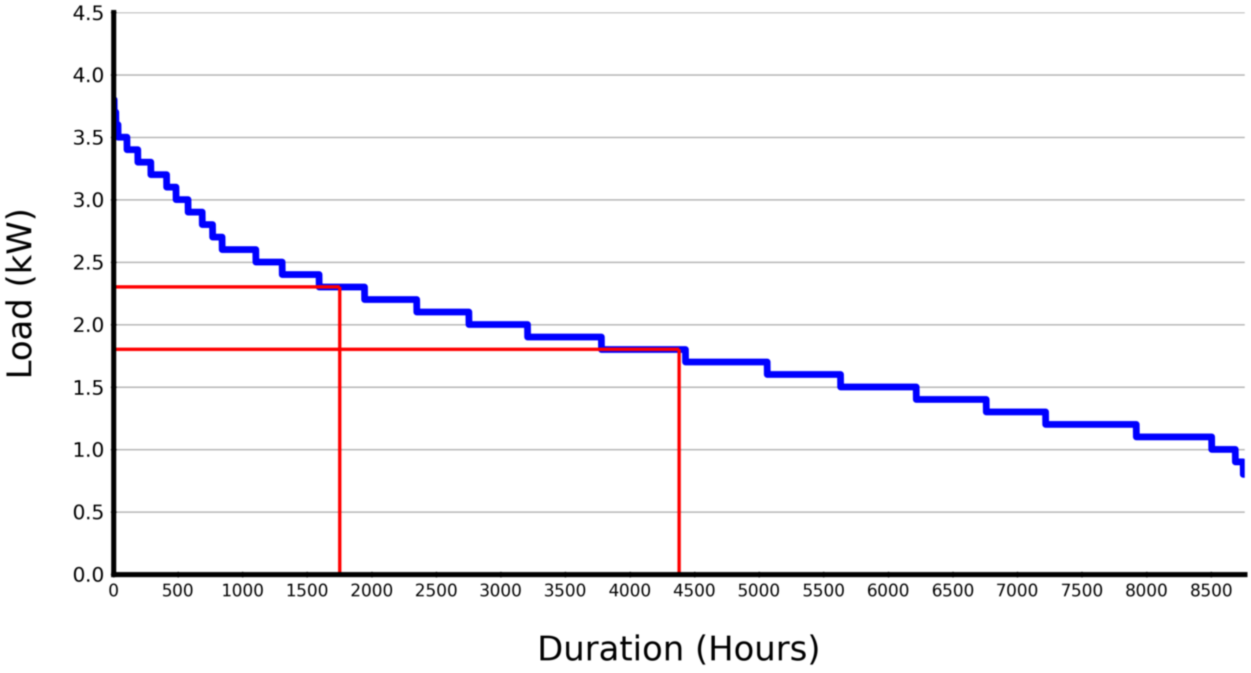
4.5.1 HVAC Sizing Options

When archive spaces are conditioned with actual HVAC systems, their system limitations and sizing play a critical role. It also involves continuous instrumentation controls and maintenance through engineers. However, replicating an exact real-life HVAC system in a simulation model, requires a significant number of design inputs collection. Due to increased complexity, such requirements make it infeasible to design a system for concept phase. Our tool aims to provide system installers with the basic design specifications (sizing and type) required so they can modify specifications based on practical space constraints, cost of HVAC system. In this work, the focus has been only on selecting a few suitable HVAC systems, discussed in Sec 4.4 and exploring their impact of sizing (heating and cooling system only). For sizing of HVAC systems "Autosize" feature of EnergyPlus® [20] has been used, which can automatically size the HVAC components depending on the building's design and other user-defined inputs (sizing routine, setpoints, plug-load etc.). EnergyPlus® uses some standardized design supply air conditions, reference weather information and a set of algorithms to determine the optimized size of individual HVAC components and airflow/waterflow rates to individual components to meet required building heating and cooling load. However, it also provides flexibility to modify design inputs for specialized users to meet specific performance requirements. Although the "Autosize" feature can facilitate designers in early stages to quickly estimate system sizing requirements, auto-sizing can lead towards potential oversizing of systems as the feature uses a extreme design day weather condition to define the limit of the system requirements [20]. Such weather conditions can occur very few times during the entire simulation (typically a reference year), so defining system sizing at a reduced capacity might be beneficial, leading to energy-saving and cost reduction. The tool provides users with different design options varying from building envelope, setpoints, etc., but the resulting building loads are also case-specific. As the "Autosize" feature calculates the automatically sized capacities after simulation of a design concept, thus it would not be possible to know the possible ranges of systems capacities a priori to simulation. For this reason, user would be unable to provide a custom capacity for sizing. In this work, the manual sizing (intentional undersizing) works in the following way:

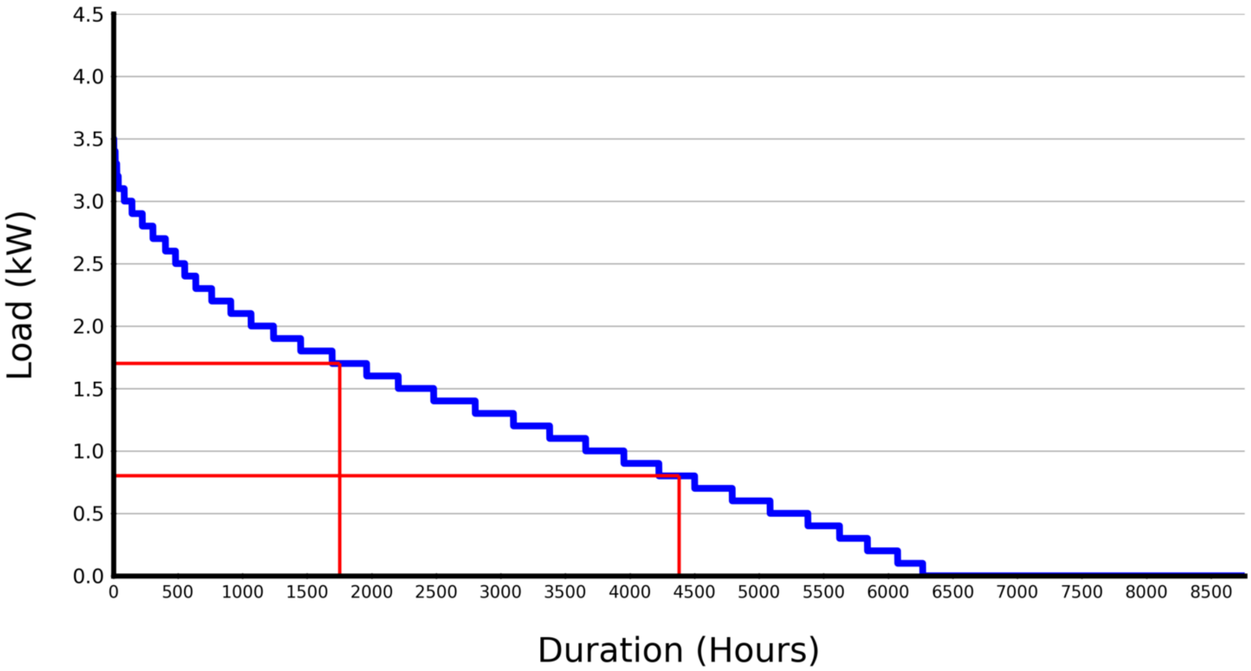
- User runs a simulation of the design concept through the tool, which runs in EnergyPlus® with "Autosize" feature.
- After the simulation completion, load duration curves are generated for heating and cooling systems. Load duration graphs describe how long a specific load of the system persists over time. It also indicates the peak load and percentile distribution of loads during the entire duration.
- User can provide an option to manually size the system by providing a specific percentile amount of the system capacity, which can be set to the max capacity for that system. From the load-duration curve, this value is further calculated and further replaced by the "Autosize" feature in EnergyPlus®. The design concept is simulated again with the newer reduced system capacities.

4.5.2 Performance Comparison

Three different sizing scenarios have been compared to assess the impact of such undersizing of components. Undersizing of components will lead to thermal setpoints beyond archives operational thresholds and reduction of collection lifespan. Fig. 4.11 shows the impact of such sizing in a H-X Diagram, and Fig. 4.12 depicts the effect on collection's relative lifetime. The damage function for evaluating collection relative lifetime and absolute lifetime depednds on chemical properties of the collection (pH, Degree of Polymerization) and indoor temperature and relative humidity based on Strilc's model [51], which is further explained in EngD report of Mahsa Nikoufard [21]. First the autosized scenario has been performed, based on which load-duration curves for heating and cooling systems has been calculated 4.10. In other two scenarios 80^{th} and 50^{th} percentile loads of both components are calculated individually, denoted with red lines in the figure.



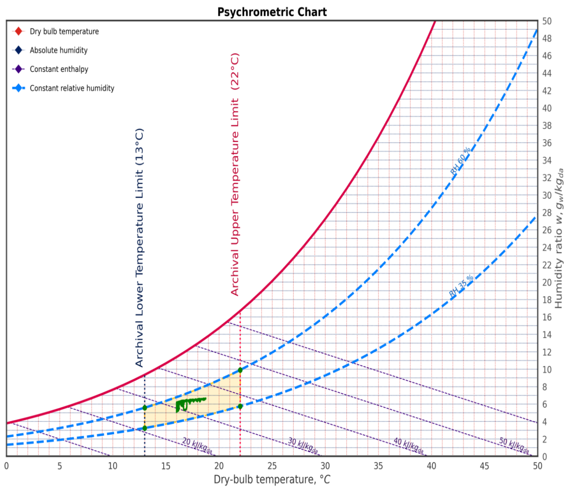
(a) Electric Boiler



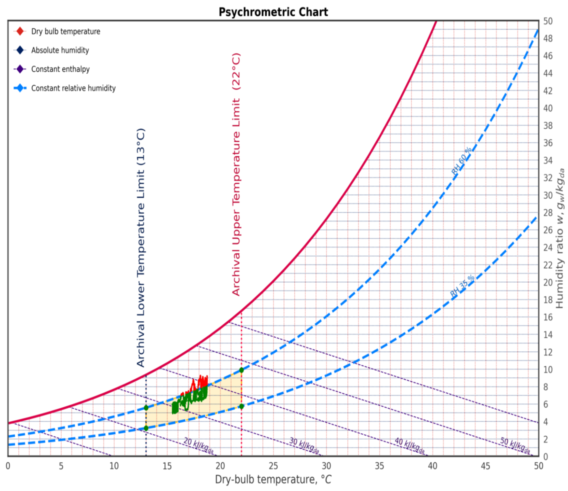
(b) Direct Expansion (DX) Coil

Figure 4.10. Load-duration curves of heating & cooling systems

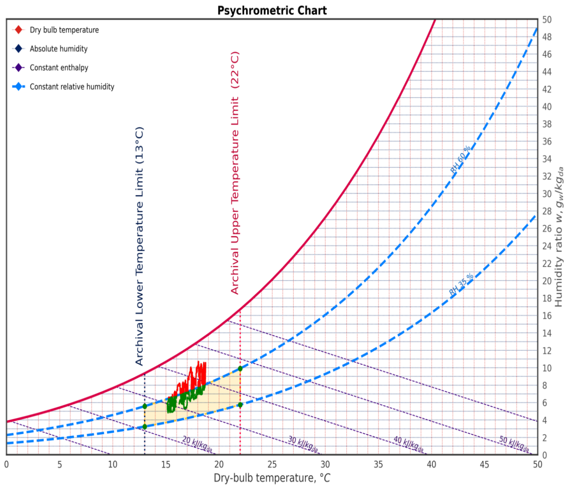
From the results in Figs. 4.11 and 4.12, it can be seen that collection preservation performance deteriorates in both the undersized scenarios. However, a calculation has been performed to estimate expected lifetime of collection in absolute years in these three scenarios, which are 2900 years, 2700 years and 2500 years. Though undersizing leads to a slightly reduced to collection lifespan, further collection experts and system designers should perform a trade-off between energy-saving potential, reduced cost and increased risk of collection.



(a) ‘Autosized’ capacity



(b) System capacity 80%ile of load-duration curve



(c) System capacity 50%ile of load-duration curve

Figure 4.11. Mollier (H-X) diagrams of archives operational period in three different system sizing

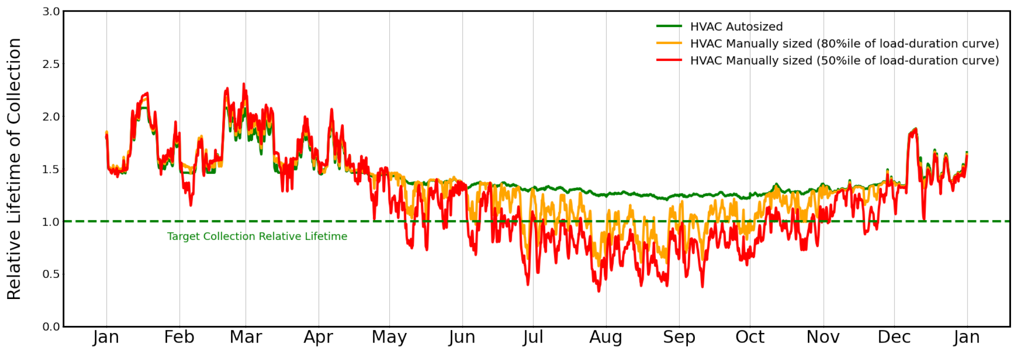


Figure 4.12. Relative lifetime of collection in archive in three different system sizing

An example of these three scenarios’ energy performance is presented in Table 4.3. The undersized scenarios show an energy-saving performance of approximately 10% and 25%, compared to the ‘Autosized’ scenario.

Sizing Method	Heating Consumption (kWh/m^2)	Cooling Consumption (kWh/m^2)	Humidification Consumption (kWh/m^2)	Fans & Pumps Consumption (kWh/m^2)	Total Consumption (kWh/m^2)
Autosized	17.97	9.03	0.01	1.43	28.43
80^{th} percentile capacity	16.08	8.34	0.0	1.28	25.70
50^{th} percentile capacity	13.86	6.86	0.0	1.09	21.81

Table 4.3. Energy Performance comparison in different sizing scenarios

4.6 Additional HVAC Operational Modifications

4.6.1 Night Shut-Off of Air Handling Units (AHUs)

The idea of switching off AHUs outside off the office hours was to assess potential of energy saving and risk of violating archival setpoints thresholds, leading to a reduced collection lifetime. In the tool, users can set the working hours of the AHU as shown in Fig. 4.13

Figure 4.13. User inputs for AHU working hours definition

In this following use-case, as shown in Fig. 4.13, the energy performance of the system improves approximately 25% (initial end-use consumption: 28.44 kWh/m^2 and end-use consumption while AHU switch off: 21.12 kWh/m^2). However, it leads to unstable control of relative humidity and thus reducing collection lifespan (a value below 1 indicates collection preservation risk), as shown in Figs. 4.14 and 4.15. There is also a reduction in actual lifespan of the collection (initial expected lifetime: 2915 years and expected lifetime while AHU switch off: 2537 years) which also depends on collection's chemical properties (pH, initial DP). Though, there is a great potential of energy saving in such operating conditions, it could lead towards increased collection damaging risk. Switching off the system during night can also lead towards higher load to ramp up the system in the morning while turning on, putting an additional strain on the system. Nonetheless, there could be other effective control like setting adjustable fan speeds or schedule setback setpoints range which requires further investigation from HVAC designers or systems installers in the detailed design phase.

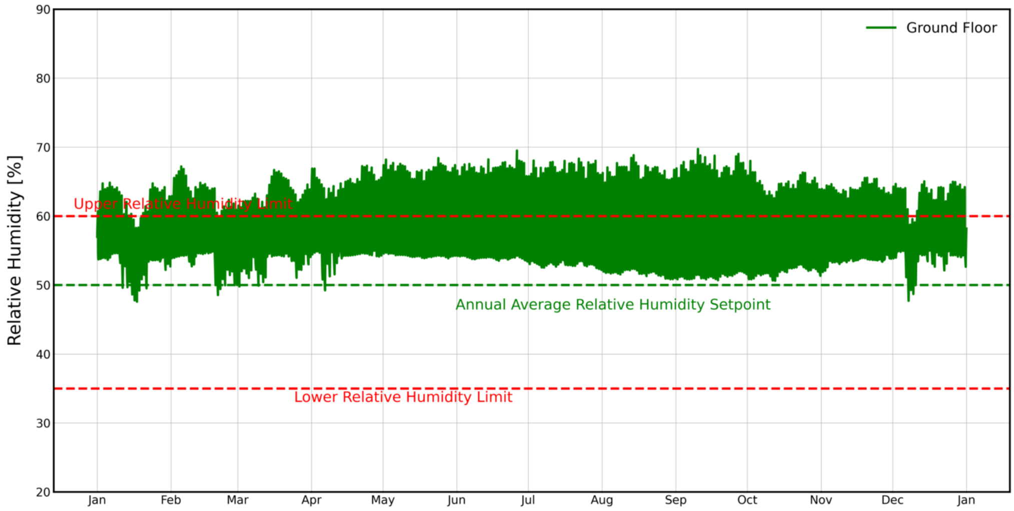


Figure 4.14. Relative Humidity (%), in case of AHU night shut down (from 18:00 to 08:00)

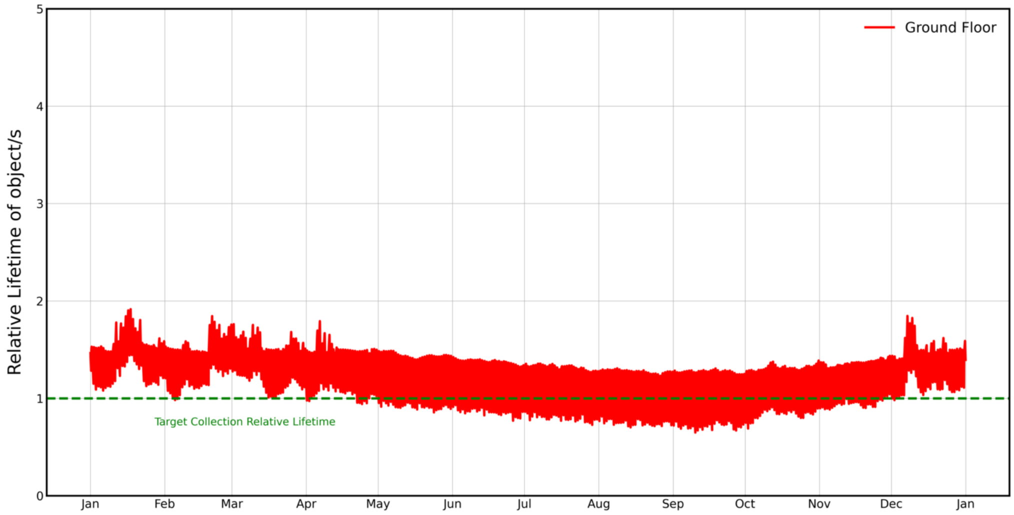


Figure 4.15. Relative lifetime of collection, in case of AHU night shut down (from 18:00 to 08:00)

4.6.2 Increased Fan Power Consumption Calculation

AHUs usually contain bag filters for dust filtration. Gaseous contaminant filters are utilised to eliminate or minimize dangerous gaseous pollutants and volatile organic compounds (VOCs) from the air. It functions by chemically reacting or adsorbing with the gaseous pollutants. The type of pollutant and the particular filter material employed determine how well the filter works. One of the most popular forms and a regular fixture in commercial and industrial environments are activated carbon filters [52]. However, additional filters installation in AHU increases pressure drop, requiring additional fan power to deliver air. Fan Specific Power (FSP) is a function of efficiency of fan, power and Total Static Pressure drop (ΔTSP). Total Static Pressure drop can be defined as

$$\Delta TSP = \Delta ESP + \Delta ISP$$

where ΔESP and ΔISP are External and Internal Static Pressure drop, respectively. ΔESP usually depends on Volume control dampers, fire dampers, air outlets, duct length pressure drop (i.e., friction losses), duct fittings (i.e., dynamic/velocity losses) while ΔISP depends on filters, cooling coils, heating cools, and heat exchangers. Based on standard AHU design values, for a good design, the amount of total pressure drop can be approximated around 700 Pa [53], which has common EU9 bag filters for dust removal. Additional filters for gaseous contaminant can contribute up to extra pressure drop of 300-400 Pa [54], leading to a higher specific fan power. A comparison has been performed between two situations when such filters are installed and when they are not, as shown in following Table 4.4.

Case	Heating Consumption (kWh/m^2)	Fan Power Consumption (kWh/m^2)
Without Additional Filter	17.1	1.4
With Filter	16.5	2.5

Table 4.4. Energy Consumption comparison due to additional gaseous filter in AHU

It can be seen that although fan power consumption increases due to additional pressure drop, it leads to slightly reduced heating consumption as increased fan usage leads to higher temperature of incoming air, thus reducing the heating requirement favorably.

Chapter 5

Rooftop Photovoltaic Systems

This chapter briefly describes a simplified procedure to estimate PV power generation potential from rooftop of the archive in the early design stage, leading to a reduced utility demand for space conditioning demand.

5.1 PV Integration in the Built Environment

From 1st January 2021 onwards, all newly designed constructions should comply with the latest BENG 3 [5] requirements which requires minimum share of renewable energy percentage to serve end-use utility demand between 30% and 50%. Integrating solar energy solutions in archival buildings, possible on rooftop, might be able to partially offset the need of energy requirements, as such buildings are energy-intensive in nature. One such example of implementation is the storage facility in Ribe, Denmark utilizes solar heating and hygrothermal strategy, known as the 'Danish Concept', as shown in Fig. 5.1, in conservation community for passive air-conditioning [55].

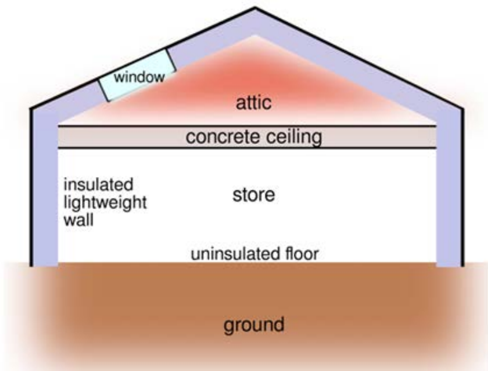


Figure 5.1. Ribe museum with uninsulated floor, airtight construction and PV

Though, rooftop PV panels can serve a portion of energy requirements for archive buildings, estimation of such potential must be done at the early phase of designing. Therefore, such estimation is required to calculate possible PV power generation from available rooftop area without requiring numerous design inputs for PV performance modelling, which are often unavailable at such stage. The tool features an integrated modelling solution for such estimation where most design input requirements are not needed from the user. The solution also enables user to select the most differentiating decisions like orientation of panel available area for installation. Further, it automatically calculates the total power generation potential from rooftop for any given area.

5.2 PV Performance Modelling

A model to estimate PV performance is usually a model-chain, where the output of one sub-model is fed to the next one downstream [56]. Such model has mainly two parts: solar irradiance modelling and electrical output generation. The main challenge is estimating solar irradiance, while electrical generation modelling is standardized. Solar irradiance modelling is comprised of estimation of three primary components: Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI), which are dependent on sun position, weather conditions, site location and ground reflectance properties nearby the location. The solar irradiance on a tilted surface comprises the beam, sky diffuse, and ground reflected components. The direct component is computed utilizing the sun position and the tilt angle. Ground reflectance is dependant on the ground albedo value. However, the real complexity lies in how different models like Klucher [57], Perez et al. [58] calculate the calculation of the sky diffuse components. A simplified model chain for PV performance estimation is depicted below in Fig. 5.2.

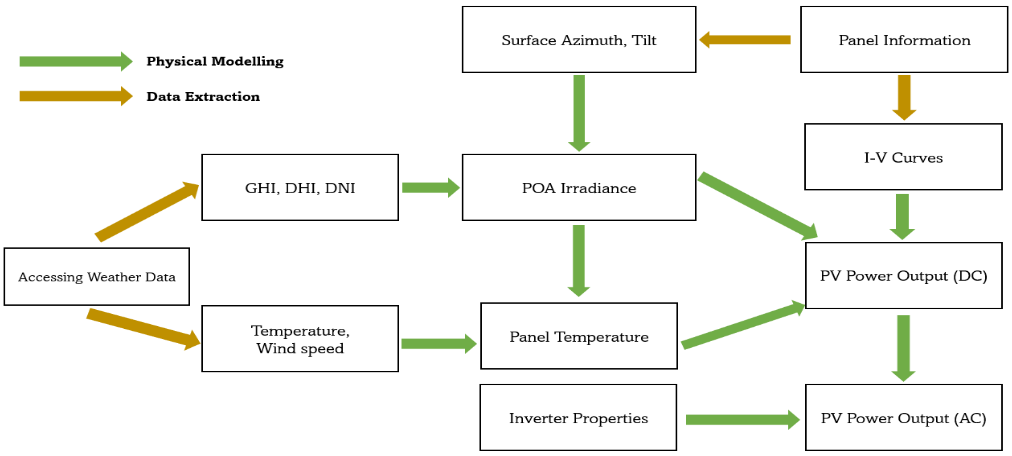


Figure 5.2. Simplified PV modelling chain

The PV power output calculation methodology follows mainly five steps listed below:

1. Extract weather information (solar irradiance, temperature, wind speed) from the weather scenario described in Chap. 3, selected by user.
2. Calculate Plane-of-array irradiance based on surface azimuth and tilt, as described in Sec. 5.2.1 using PVLIB [59].
3. Calculate the total number of panels on the available rooftop area based on the dimension of the roof and each panel, as described in Sec. 5.2.2.
4. Estimate effective PV generation (in DC) accounting temperature effect and losses.
5. Retrieve total PV generation from the entire PV array (in AC) based on the number of modules and inverter size using functionality of NREL's PVWatts module [60].

5.2.1 *Comparison between South & East-West PV Orientations*

Surface azimuth and tilt are the two most important parameters influencing the PV power output as it determines the plane-of-array irradiance for the panel. In the northern hemisphere, the general rule for solar panel placement is solar panels should face the true geographical south. Usually, this is the best direction because solar panels will receive direct irradiance throughout the day. However, for such orientations, shadow casting from the previous module to the next module can occur due to a lack of inter-row spacing when modules are placed close to each other, resulting in power production loss. In case of a very high spacing between modules, the resulting power yield from a given roof area could be significantly lower. Fig. 5.3 depicts that it is important to provide optimised spacing between modules in rows to minimize partial shading issues [61].

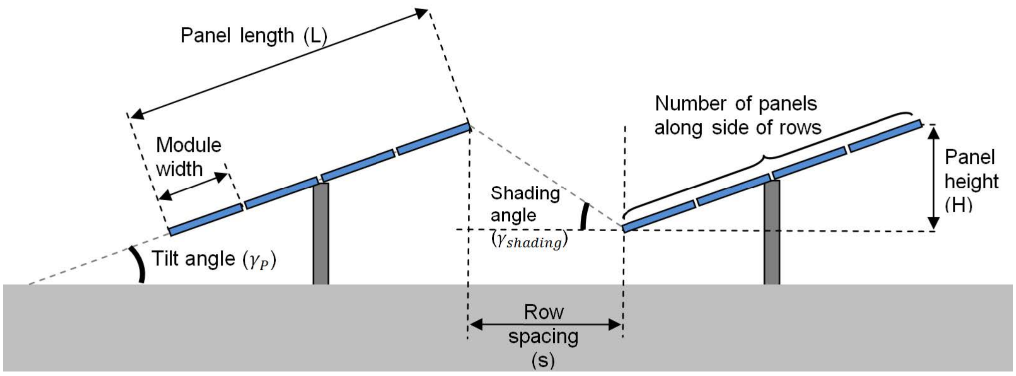


Figure 5.3. Module row inter-spacing

For this reason, orienting PV arrays in an east-west direction is gaining popularity as it has the following advantages:

(i) Due to back-to-back placing, it eliminates the need for inter-row spacing, thus can squeeze in more number of modules in a limited roof area than south-oriented ones.

(ii) Less wind loading in the panel.

(a) South-facing panels

(b) East-West PV structures

Figure 5.4. South & East-West oriented PV panels

Due to dust deposition and self-cleaning, the PV panels should be tilted more than 10°. The surface tilt of PV panels decides the amount of solar irradiance received on the plane, which requires to be optimized based on site location and type of panel orientation. Such data is often not available or roughly approximated as default the latitude of the location for south-facing panels. However, for higher latitudes in the northern hemisphere (ex: the Netherlands), such a generic assumption does not fit well due to the higher amount of cloud cover, which reduces the direct component of solar radiation, and the diffuse component becomes major resulting in lower optimum tilt angle (the Netherlands with 52° latitude has optimum tilt angle 34° for south-oriented PV panels) [62]. The tool enables user to either manually select a tilt angle for the south-facing panel or select the optimized value automatically for the Netherlands. For east-west structures, usually, 12°-15° are optimal to maximize solar generation.

5.2.2 Automated Calculation of Number of PV Modules

For calculating the total PV power output from the entire rooftop, it is required to calculate the total number of modules which are possible to fit in the available rooftop area. First, the available area for PV installation is determined from the dimensions of the roof (length, width), unavailable area percentage for installation and clearance spacing from roof edges (0.3 m), as shown in Fig. 5.5.

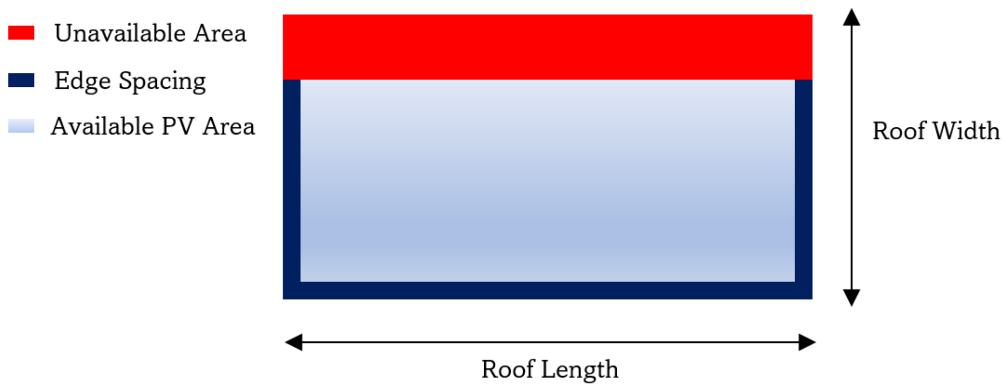


Figure 5.5. PV array distribution area in rooftop

Based on the available rooftop area for PV installation, two different approaches are followed based on the surface orientation:

(i) For south-oriented PV modules, firstly, inter-row spacing between PV arrays has been estimated, which is dependent on sun position, length of PV panel and surface tilt. To minimize shading losses between arrays, usually inter-row spacing on winter solstice day (21st December) is taken into account in practice for PV parks [63]. However, it results in a significantly higher spacing between arrays which would not be feasible to accommodate for a rooftop-based system. Thus, only days with a significant amount of irradiance (above 75 percentile of maximum) have been selected initially, along with discarding time periods of low solar elevation. Finally, an averaged value of the spacing of filtered periods has been selected. Based on inter-row spacing, available PV area and dimension of PV panel, a geometrical calculation has been done to determine the total number of PV panels possible to fit on the rooftop.

(ii) For East-west PV structures, providing a spacing between PV arrays is not required. However, a clearance distance has been taken into consideration between arrays for maintenance purposes. Based on clearance distance, available PV area and dimension of PV panel, the total number of PV panels has been geometrically calculated.

5.2.3 Calculation of OEF & OEM

Increased use of on-site renewable energy resources to meet building energy load can lead to a potential mismatch between renewable production and utility demand profile. For nearly Zero Energy Buildings (nZEB) or improved renewable share in the energy mix requires significantly higher number of on-site renewable generation units (ex: PV panels) to reduce grid imported electricity. Though such a higher yield covers a part of energy demand in winter months and reduces grid dependency, it could lead to potential congestion due to the export of electricity in summer months, as such time periods are less electricity-demanding periods as compared to PV generation. For quantitative assessment of such mismatch issue, usually, two parameters are used [64], known as On-site Energy Fraction (OEF) and On-site Energy Matching (OEM), as presented in Eqs. 5.1, 5.2, respectively:

$$\mathrm{OEF} = \frac{\int_{t_1}^{t_2} \mathrm{Min}[G(t); L(t)]\mathrm{d}t}{\int_{t_1}^{t_2} L(t)\mathrm{d}t}; 0 \leq \mathrm{OEF} \leq 1 \tag{5.1}$$

$$\mathrm{OEM} = \frac{\int_{t_1}^{t_2} \mathrm{Min}[G(t); L(t)]\mathrm{d}t}{\int_{t_1}^{t_2} G(t)dt}; 0 \leq \mathrm{OEM} \leq 1 \tag{5.2}$$

OEF calculates the ratio of renewable energy generation to the total building demand while OEM is utilized to indicate the nature of load balancing (import from grid or export to grid) between on-site generation and load profile. A higher number in both indices is naturally targeted; however usually, an optimized trade-off between these two is inevitable. In Eqs. 5.1, 5.2, G(t) and L(t) are the time-dependent profile of on-site generated power and building load, respectively and ‘dt’, ‘t_1’, ‘t_2’ are time frequency of estimation and starting and ending period of estimation. In our work, G(t) and L(t) have been measured in hourly frequency, but the final estimation of OEF and OEM has been scaled to daily frequency.

5.3 Case Study of South & East-West PV Performance Modelling

An exemplary case study has been done on both South, and East-west oriented PV performance modelling to illustrate the outcome from the tool. The study describes how the performance will vary between two different orientations to make relevant conclusions for users. The following information has been kept constant:

- Dimension of Roof (Length 24 m, Width 15 m)
- 10% area of the total roof is unavailable for PV installation
- Building Load (Total annual demand $\sim$ 41150 kWh)

For the south-oriented panels, the tilt angle has been considered automatically optimized one (34° for the Netherlands), while for the east-west structure, the surface tilt is 12°. The characteristics of the selected panel for both cases have been added to Appendix Sec A.6. A comparison of their performance summary is described in Table 5.1.

PV Orientation	Total Number of Panels	Total Annual PV Output Yield (kWh)	Yield/Panel (kWh)	Annual Average OEM (%)	Annual Average OEF (%)
South	60	27180	453	49.1	32.4
East-West	100	27900	279	52.4	35.4

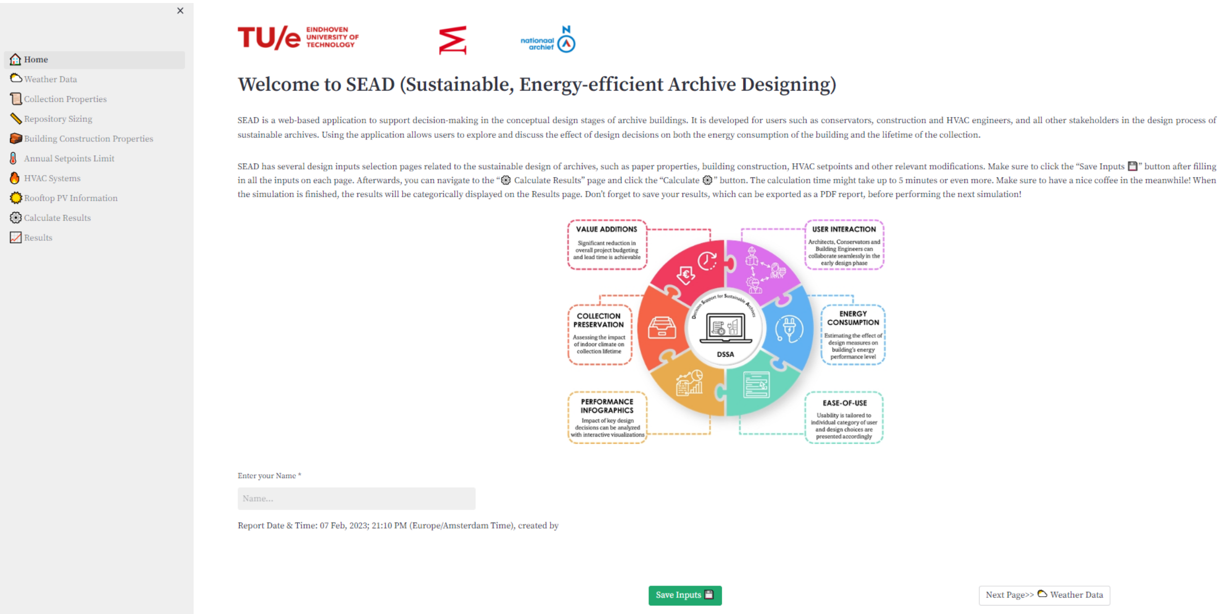
Table 5.1. Performance Summary comparison between South & East-west PV

From the performance summary, it can be deduced that though yield per panel is less for East-west as compared to south-oriented PV, such distributions can significantly increase the total number of available panels on the same available rooftop area. With an increased number of panels, the east-west structure can generate more amount of total PV power output from the same rooftop area than its' south-oriented counterparts. A slight improvement in OEF and OEM can also be noticed. However, users in the later stage of design, might require to make a trade-off between generation amount and possible cost and/or payback time for selecting the optimal direction. To improve OEF and OEM, it would be beneficial to test the increased rooftop area (i.e., dimension of the repository) in combination with adjustment in collection sizing and collection filling percentage.

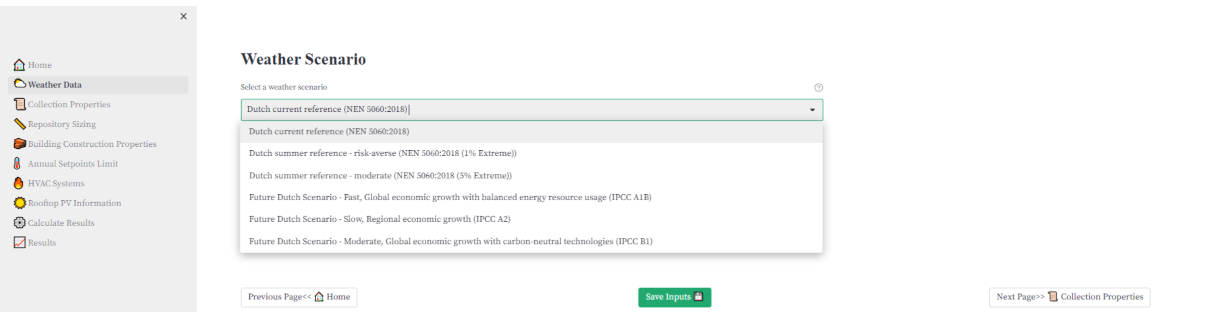
Appendices

A.4 User Views of Input Pages of DST

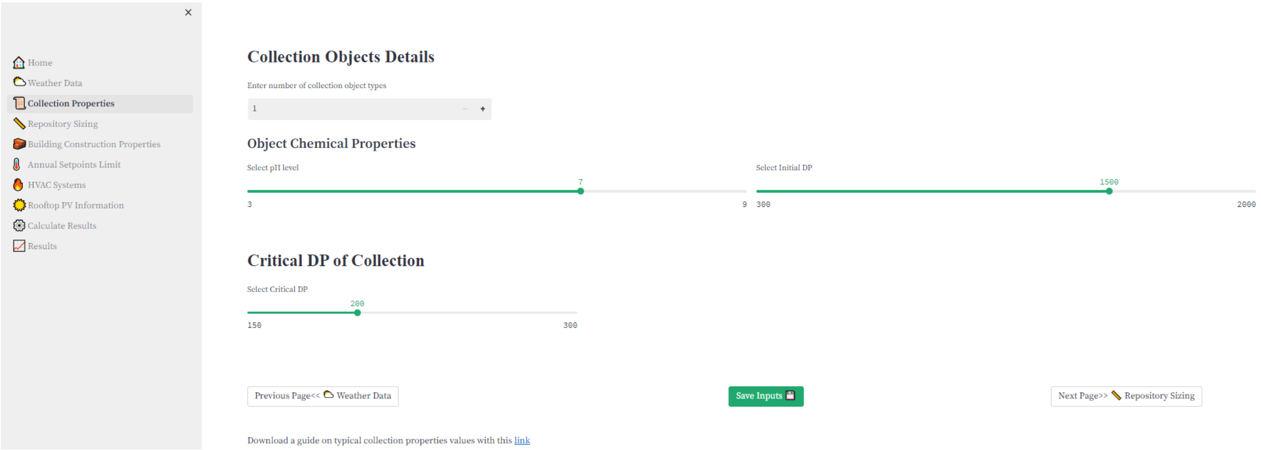
Following Figures, show the user views of the input pages of DST



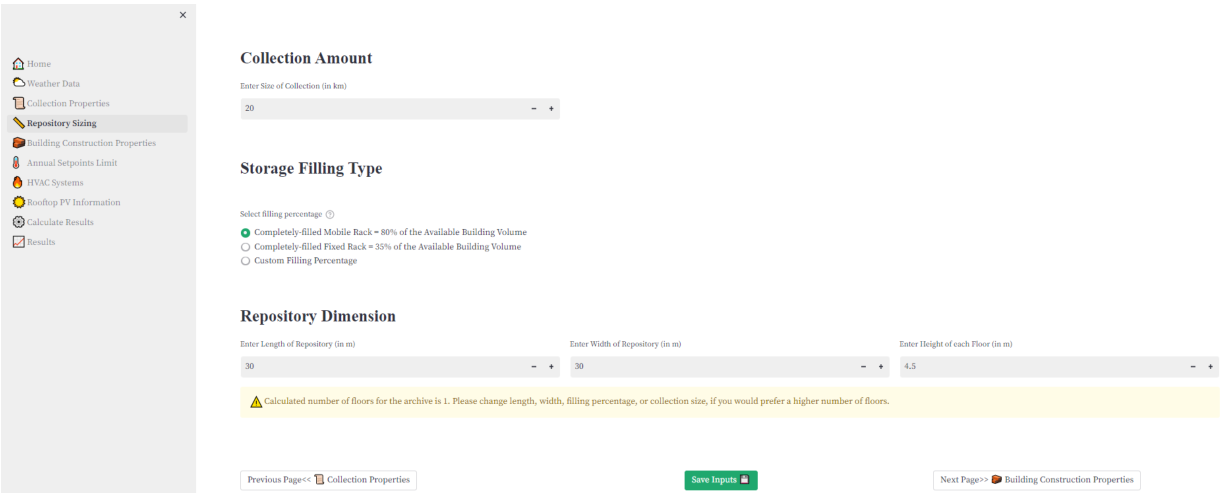
Home Page of DST



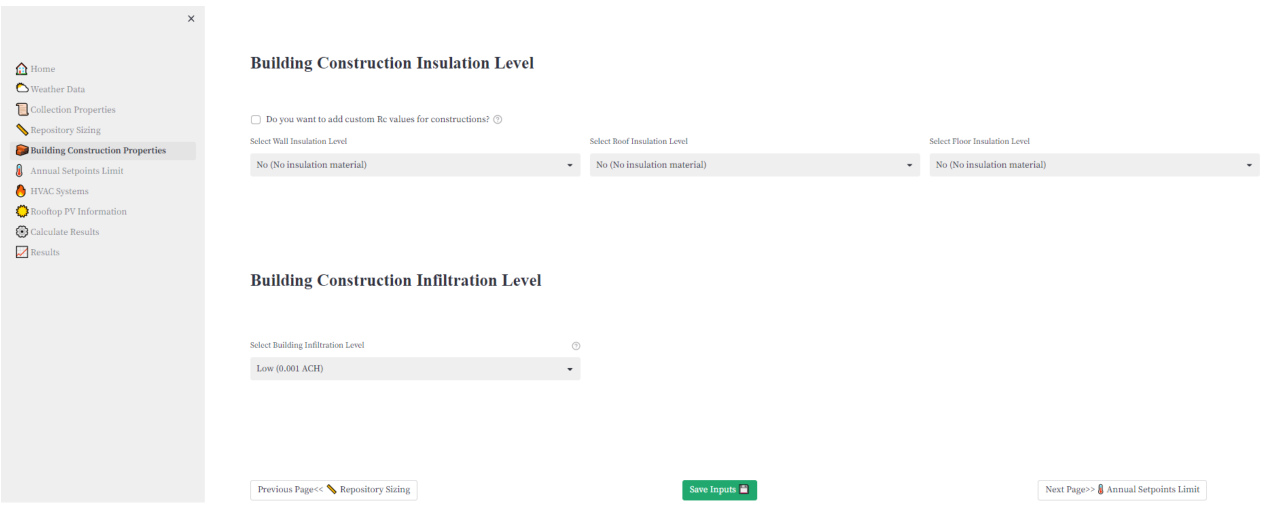
Weather Data Page of DST



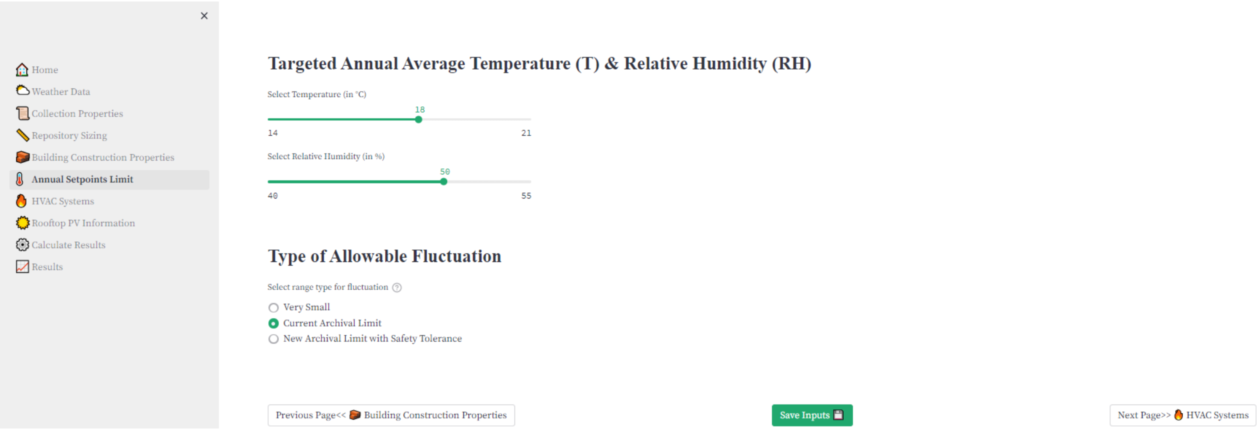
Collection Properties Page of DST



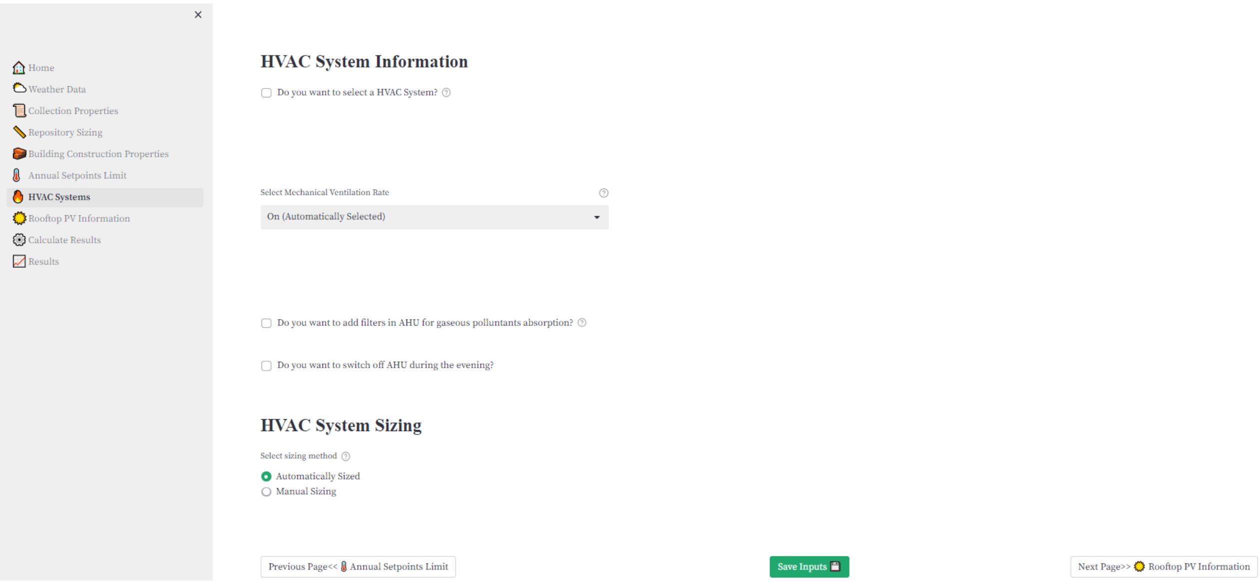
Repository Sizing Page of DST



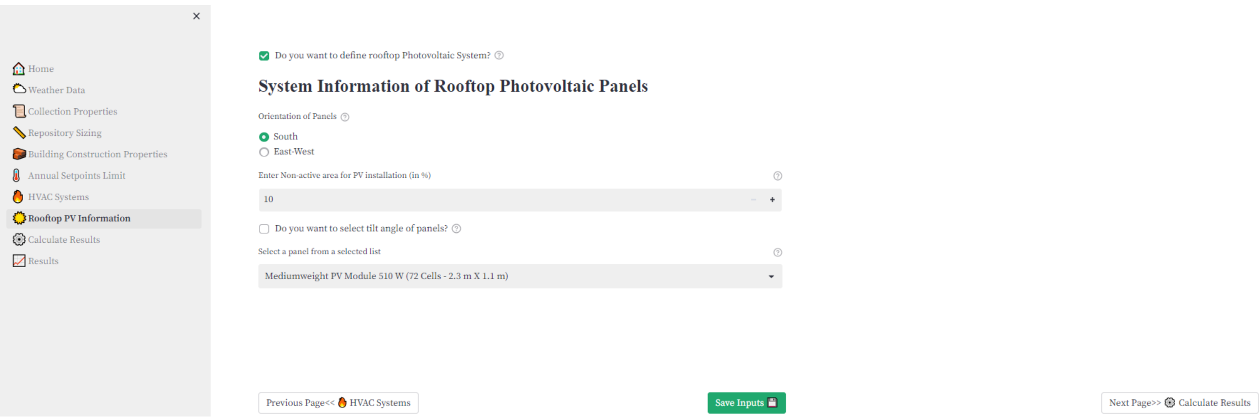
Building Construction Properties Page of DST



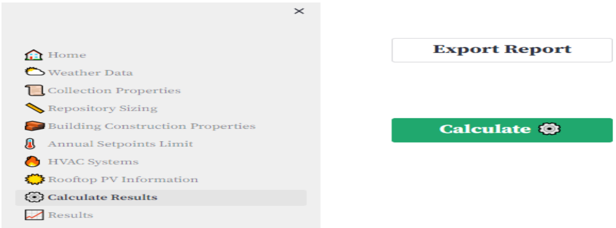
Annual Setpoints Limits Page of DST



HVAC Systems Page of DST



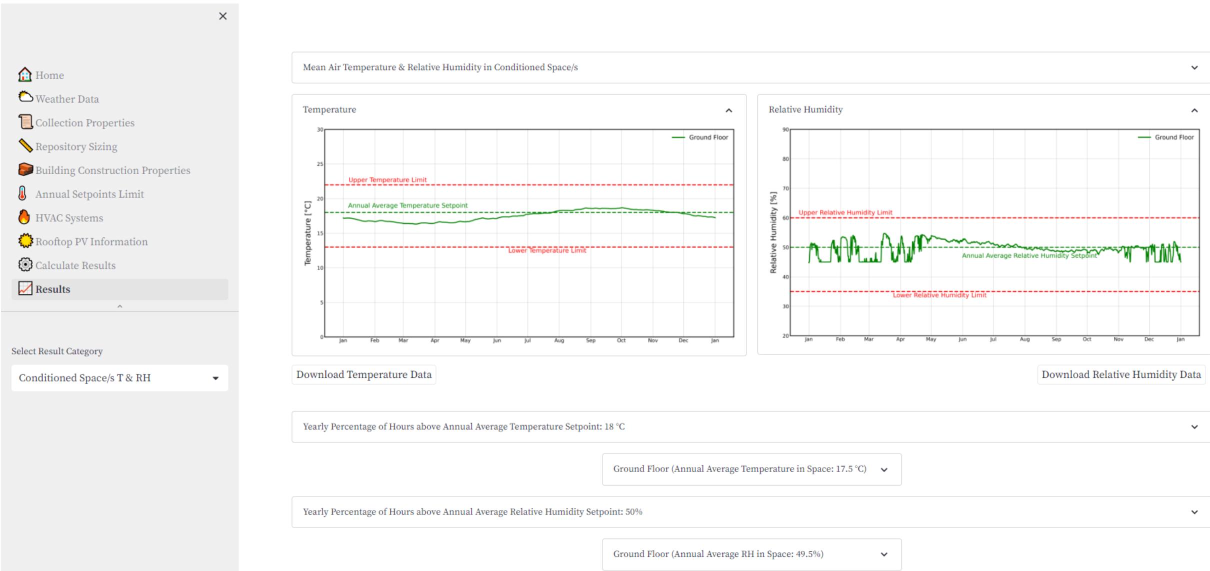
Rooftop PV Information Page of DST



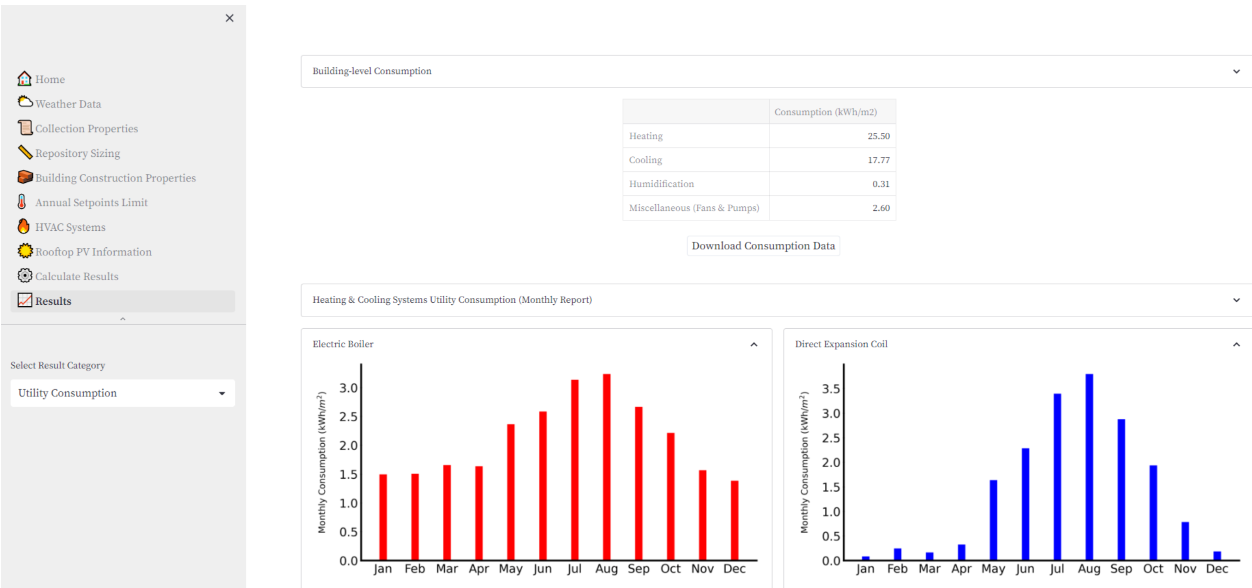
Calculate Results Page of DST

User Views of Result Pages of DST

Following Figures, show the user views of the results pages of DST

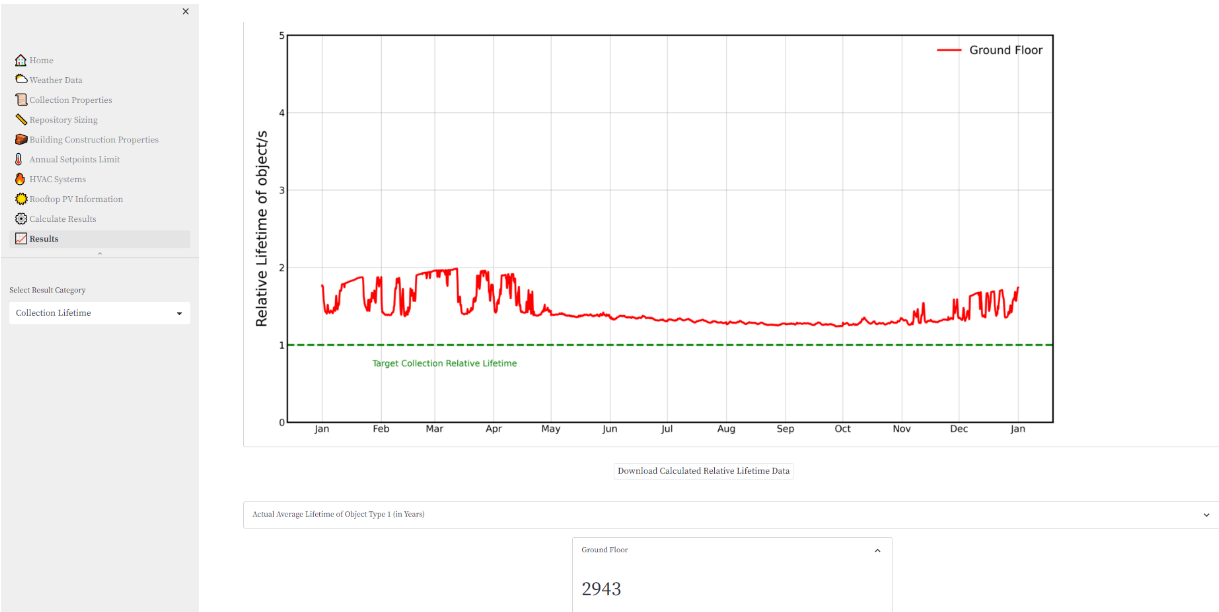


Conditioned Space/s T & RH Results Page of DST



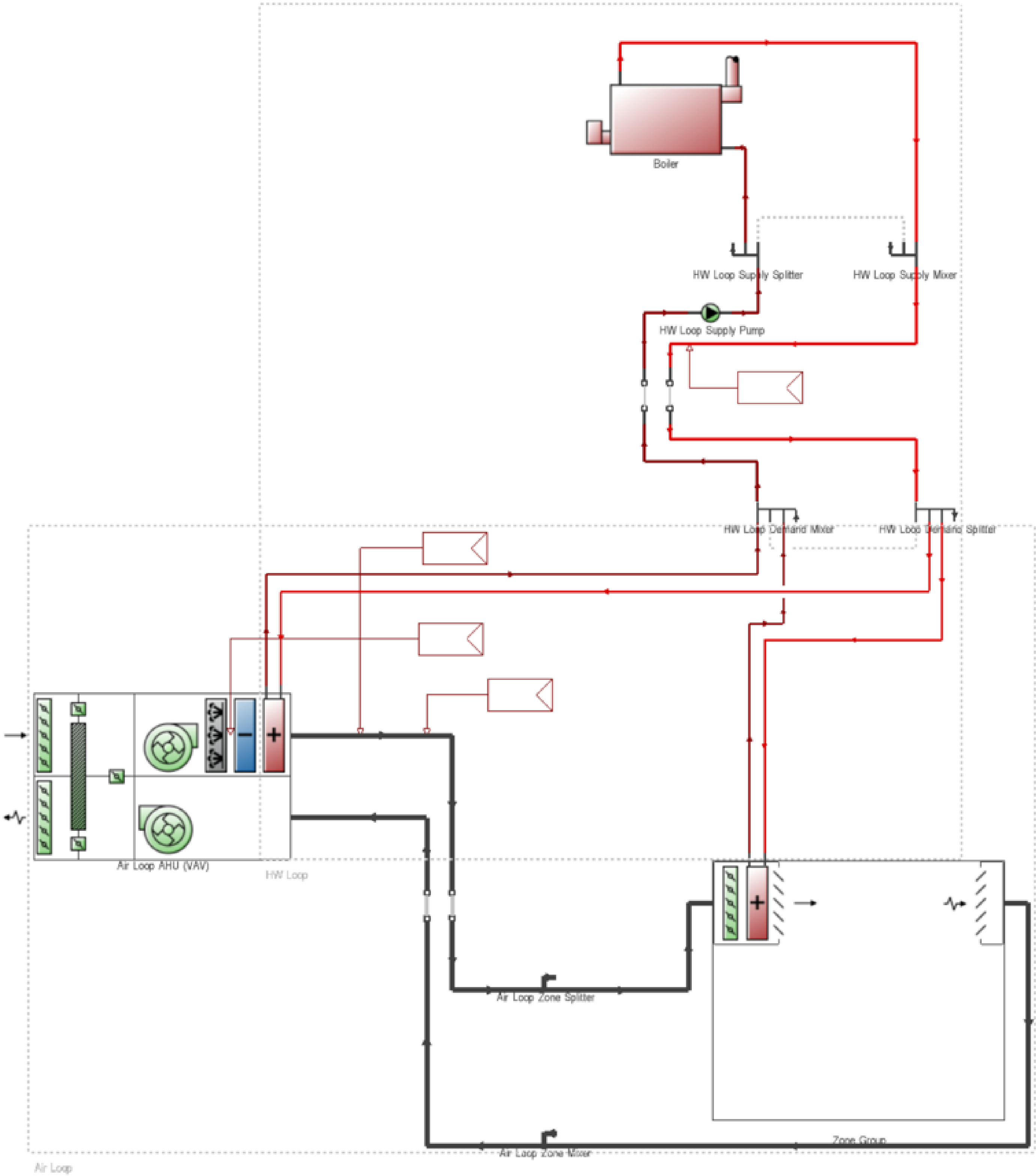
Utility Consumption Results Page of DST

PV Performance Results Page of DST

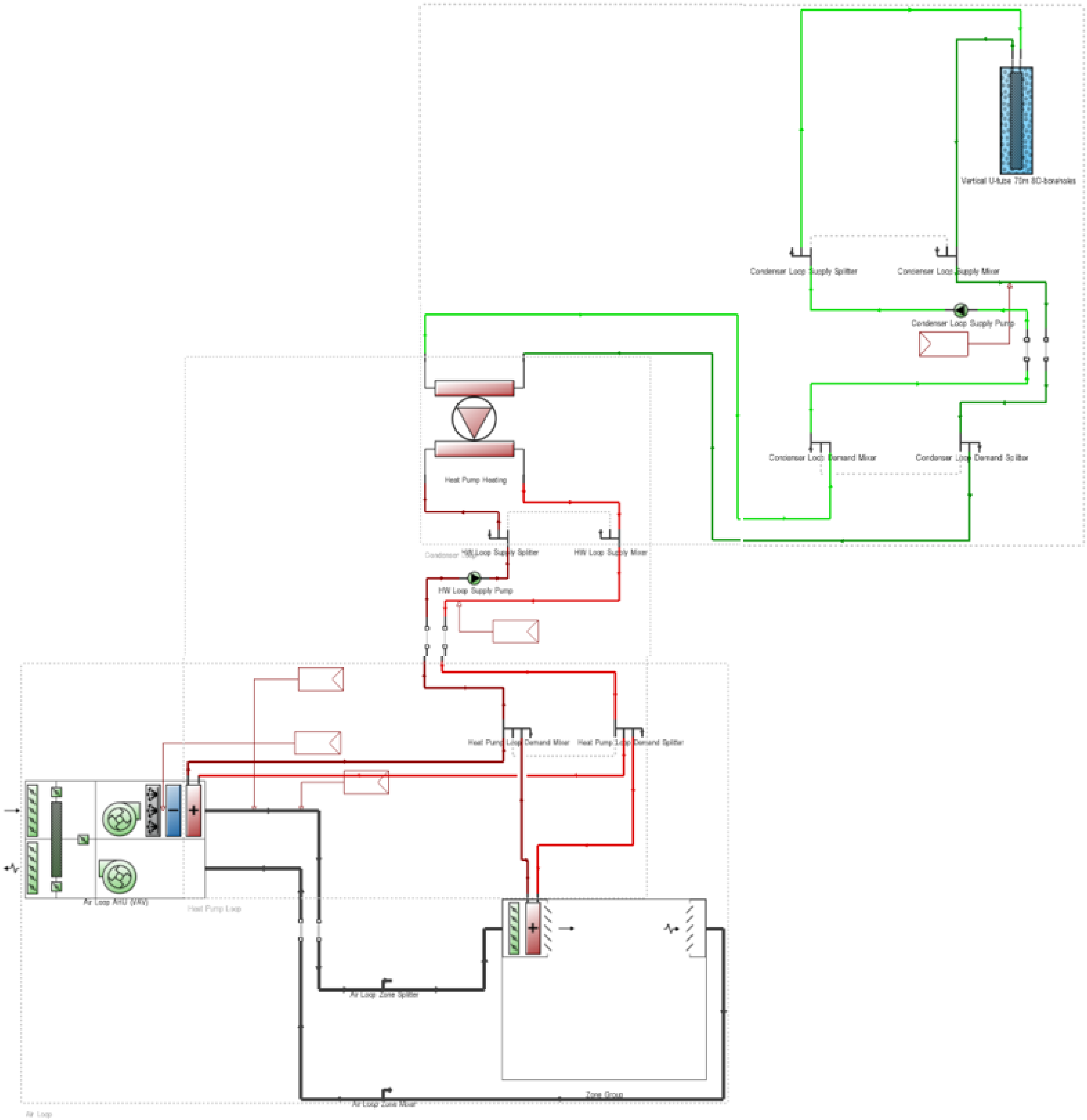


Collection Lifetime Results Page of DST

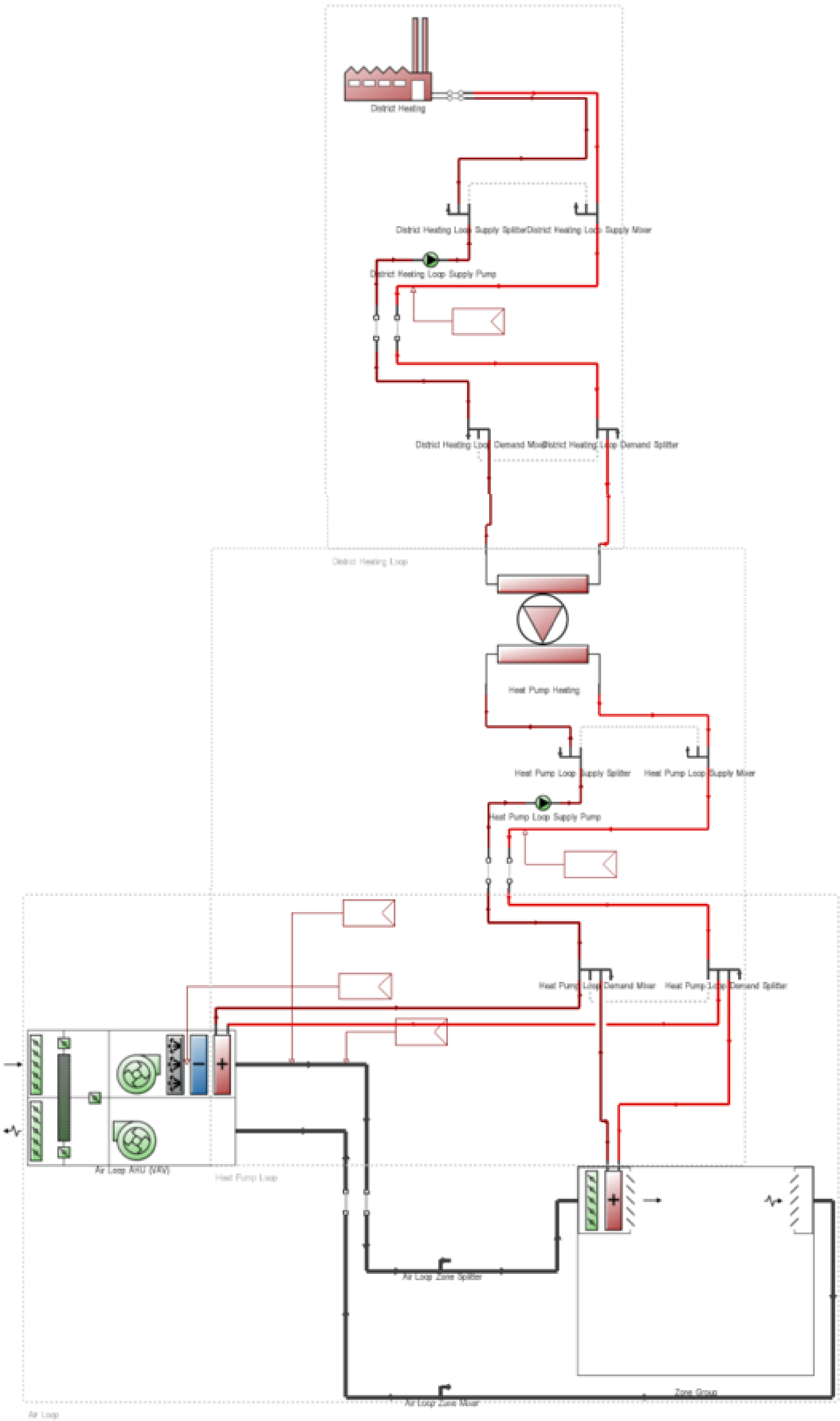
A.5 List of HVAC Diagrams



Electric Boiler and Direct Expansion Coil (with integrated Humidifier in AHU)



Ground-sourced Heat Exchanger (Boreholes), coupled with Heat Pump, and Direct Expansion Coil (with integrated Humidifier in AHU)

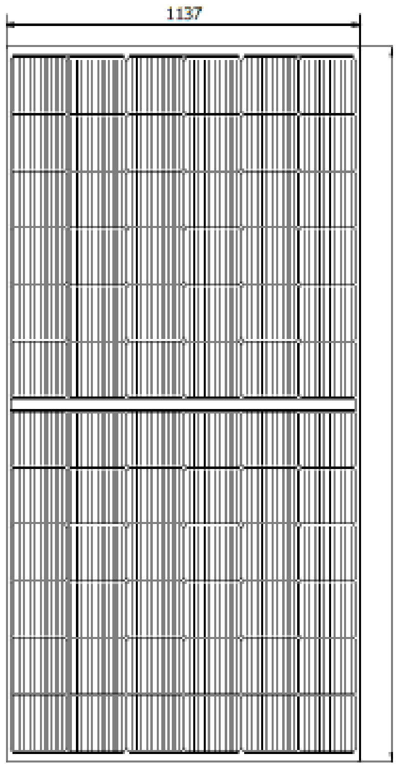


District Heating, coupled with Heat Pump, and Direct Expansion Coil (with integrated Humidifier in AHU)

A.6 Information Manual of PV Panels Used in Case Study

South-oriented PV

solarge

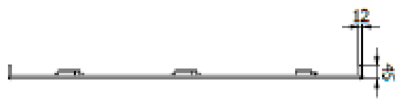


Specifications

Cell type:	M10 MONO PERC c-Si
Amount of cells	72
Weight	14,5 kg = 5,5 kg/m²
Dimensions (length x width x thickness)	2303 x 1137 x 14 mm
Cable length & cross section	2 pcs 1200 mm x 4 mm²
Connector type	MC4
By-pass devices	6 pcs in junction box
Configurations:	Model reference:
Natural	SA.500.MNN.001
Black	SA.500.MBN.001
CO_2 footprint	220 kg/m² - 1130 kg/kWp
Shadowcost (MPG)	23 €/m²/25yr
Country of Manufacturing	The Netherlands

Electrical parameters at STC

Nominal Max. Power (PMax) [W]	510 (tolerance + 2%)
Open Circuit Voltage (Voc) [V]	49
Short Circuit Current (Isc) [A]	12,4
Maximum Power Voltage [V]	42,6
Maximum Power Current [A]	11,8
Overcurrent protection [A]	15
Fill Factor (FF) [-]	0,78
Temperature Coefficient (Isc) [%/K]	+0,06
Temperature Coefficient (IVoc) [%/K]	-0,3
Temperature Coefficient (Pmax) [%/K]	-0,39



Operating conditions

Maximum System Voltage	1000 V DC
Operating temperature	-40°C / +85°C

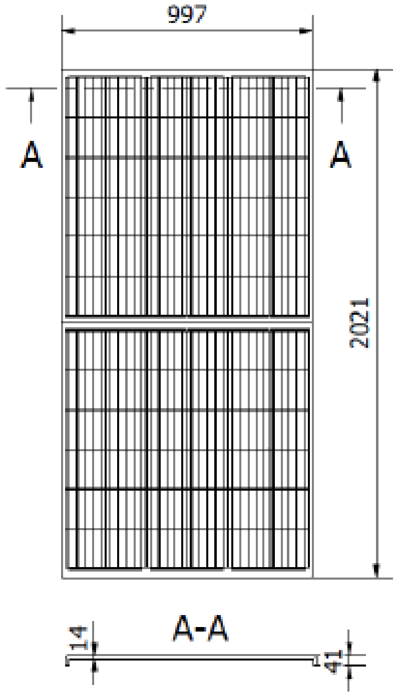
IEC CE

East-west PV Structure

solarge

Specifications

Cell type	5 BB PERC MONO c-Si
Amount of cells	72 (2 x 36)
Weight	11 kg (5,5 kg/m²)
Dimensions (length x width x thickness)	2021 x 997 x 14 mm
Cable length & cross section	4 pcs 1000 mm x 4 mm²
Connector type	MC4
By-pass devices	6 pcs in junction box
Model reference:	DA.365.MNN.001
Country of Manufacturing	The Netherlands



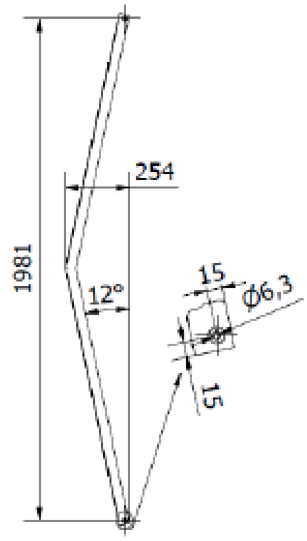
Electrical parameters at STC*

Nominal Max. Power (PMax) [W]	365 (tolerance + 2%)
Open Circuit Voltage (Voc) [V]	25 + 25
Short Circuit Current (Isc) [A]	9,6
Maximum Power Voltage (Vmpp) [V]	20 + 20
Maximum Power Current (Impp) [A]	9,2
Overcurrent protection [A]	15
Fill Factor (FF) [-]	0,78
Temperature Coefficient (Isc) [%/K]	+0,07
Temperature Coefficient (IVoc) [%/K]	-0,38
Temperature Coefficient (Pmax) [%/K]	-0,37

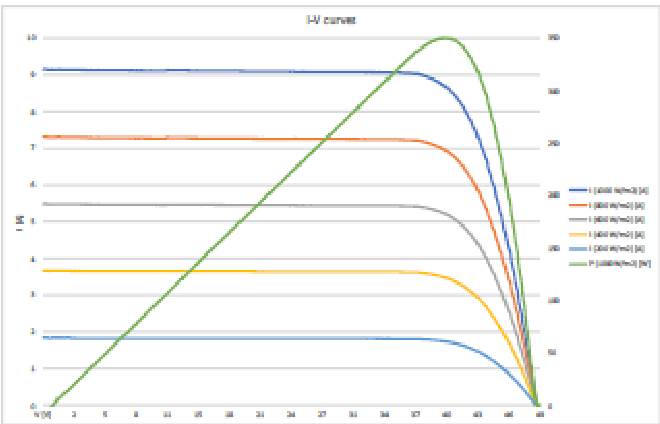
* Note: electrical performance measured with perpendicular irradiation on full surface

Operating conditions

Maximum System Voltage	1000 V DC
Operating temperature	-40°C / +85°C



Characteristics



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