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Modeling uncertainty in positive energy districts through a non-probabilistic approach

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Abstract. Positive Energy Districts (PEDs) transcribe an emerging energy transition paradigm for rapid upscaling of building energy efficiency programs to match the urgency of climate mitigation and adaptation. PEDs facilitate pro-active sharing of information and experiences, responsive learning and dissemination, and cooperation across sectors and disciplines. The rapid evolution of technologies for energy efficiency and integration of renewable energy in buildings requires a research-to-design approach. Therefore, it is imperative that a designer makes informed decisions at an early stage of design from an energy-efficiency perspective. However, since PED design involves a significant number of stakeholders, the design parameters could be highly uncertain, which eventually affect the quality of the design solution space. This study uses a bilateral process workflow to quantify risks using a nonprobabilistic technique and a PED roadmap structure. The workflow evaluates different PED scenarios and quantifies the PED potential for the city of Sint-Niklaas in Belgium. The results indicate that risk quantification significantly improves PED decision-making when evaluating collective solutions (district heating) for a district.

1. Introduction

Urban buildings in Europe account for a significant portion of energy consumption and emissions. To reduce their environmental impact, it is important to understand the energy performance of these buildings. Because cities are the major greenhouse gas producing centers, they use 65-70% of global energy and produce 70-75% of global emissions, European cities are encouraged to control and reduce emissions from their buildings and districts. Therefore, the European Union has introduced Positive Energy Districts (PEDs) to initiate and support 100 positive energy neighborhood planning, implementation, and replication by 2025 [1]. These districts are essential to create a comprehensive approach to sustainable urbanization and to take into account technological, spatial, regulatory, financial, legal, social, and economic considerations [2].

Implementing PED requires a deeper understanding and consideration of local contexts, policies, priorities, strategies, resources, and city solutions [4]. Although many European cities are accelerating the transition to low-carbon energy, the actual feasibility of PED design is not adequately defined, a roadmap and guidelines are not provided, mainly because the cities are in the planning or early phase of implementation [3]. In this regard, it is still necessary to establish the main requirements for PED implementation and understand the connections and synergies between these requirements.

Sibilla et al. developed and tested a multi-criteria decision making optimization framework to drive the transformation of a group of existing buildings in a Positive Energy Block [3]. The study establishes practical strategies for energy transition within a specific urban context. Castillo-Calzadilla et al. devised PathPED that evaluates the transition of buildings as high performance agents to provide a quantitative assessment of future urban scenarios [4]. Such assessments support urban planners, investors, and governments in the decision-making process. Another study by Lindholm et al. informs the public, decision makers and fellow researchers about the aspects that should be taken into account when planning and implementing different types of PED in different regions of the European Union [5].

Fatima et al. studied the city operations and current citizen participation methods to understand how efforts could be combined and improved [6]. The analysis indicated that the city of Espoo already has a well-established system that continuously promotes citizen engagement at various levels, and combining the available infrastructure with company experts on citizen participation will allow Espoo to seamlessly transition toward PEDs in the near future.

Although these studies provide valuable information on the design and implementation of PEDs, the studies do not take into account the risks/uncertainties existing in the current modeling framework. Furthermore, a structured way to evaluate PED roadmaps is often missing in these studies. This study presents a two-fold workflow to quantify risks in PED decision making and lays out the framework to define PED roadmaps. This study implements the Dempster-Shafer theory of evidence, which is regarded an effective data integration model and provides a mathematical framework for the representation and combination of information. With this theory, a belief interval is used, along with mass functions, for information representation. The Dempster rule of combination provides a tool to combine multiple data layers. Unlike traditional probabilities, the interval between belief and plausibility presents the uncertainty of knowledge about the target proposition.

The paper is outlined as follows: Section 2 discusses DST theory and describes the workflow of the process. Section 3 demonstrates the workflow for the city of Sint-Niklaas in Belgium and describes the results. Section 4 lists the conclusions from this study.

2. Methodology: Uncertainty-based PED Design

Uncertainty inevitably arises in practical engineering problems due to constraints such as cognitive levels, measurement technologies, and design costs, which has a significant impact on the prediction and assessment of system responses. Building energy models employ numerous parameters, the details of which are often not available to modelers. These uncertainties are seldom quantified when designing PEDs, creating a false sense of validity and engineering rigor. The methodology devised in this study provides a two-fold process workflow (Figure 1). The first workflow provides a framework to quantify epistemic uncertainties (arising from lack of knowledge) and evaluate associated risks, and the second workflow introduces a PED roadmap structure to analyze and evaluate strategies for PED.

2.1. Dempster-Shafer Theory Process Workflow

This section describes the process workflow towards implementation of the DST method to enrich building stock energy simulations when limited information is available for the building stock. The DST provides a mathematical framework for the quantification of incomplete knowledge. This theory provides a mathematical basis for presenting and combining information. In this theory, a belief interval is used alongside mass functions to represent information and to represent it in terms of belief intervals. Unlike conventional probabilities, the interval between belief and

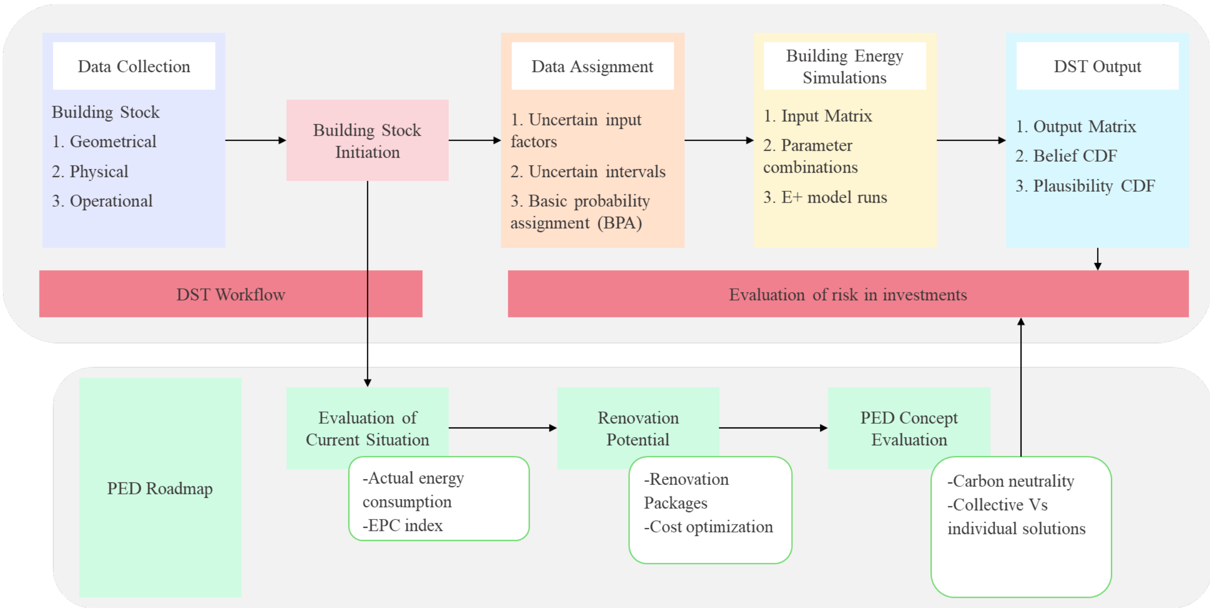

Figure 1. The devised workflow to implement DST theory and provide PED roadmaps for districts.

plausibility represents the uncertainty of knowledge about the target proposition compared to the distance between belief and plausibility [8].

The DST technique for urban building energy models uses a standard modeling procedure, which involves data collection, the initiation of building stock, and the production of preliminary renovation advisories using a static calculation engine. This workflow extends to the implementation of DST for the considered stock that includes data assignment, urban building energy modeling, and the formulation of cumulative DST distribution functions (belief and plausibility). The DST output refines the preliminary PED solutions and identifies risks that facilitate informed investments for PEDs. This workflow is further explained in detail in Section 2.2.

2.2. PED Roadmap Workflow

This workflow devises and evaluates various trajectories to achieve a PED. The process evaluates the current situation of a district to identify the actual consumption and energy performance of the existing building stock. Taking into account a future timeline for the progress of PED in a district, the workflow evaluates the potential for renovation of the district based on cost optimization routines, namely total cost of ownership. System cost perspective in early stage allows to identify if techno-economic potential exists. The PED concept evaluation step mainly identifies the suitability of individual vs. collective renovations. These outputs are then integrated with the output from the DST implementation.

3. PED Decisions: Quantifying risks and potential

This study demonstrates the implementation of DST for the city of Sint-Niklaas, located in the Flemish province of East Flanders in Belgium. The modeled buildings include the residential building stock of three regions of Sint-Niklaas, which amounts to 1455 residential establishments. The average current EPC index of the modeled buildings is approximately 437kWh/m2year.

The data collection process uses urban building stock datasets that include 3D GRB data, energy consumption data, kadaster data, census data, and VKBO data. These data are openly sourced datasets and hence are publicly available. This process also uses renovation financial cost

Table 1. PED scenarios for the city of Sint-Niklaas

Scenario	Current situation	Current Renovation Rate (1%)	CO2-neutral min TCO per building	CO2-neutral min TCO per neighborhood (renovation)	CO2-neutral on neighborhood with district heating
Description	No investments in energy-efficiency measures or renewables	Buildings are renovated (to A-label min TCO) at a 1% annual rate (assuming random sampling for building selection)	All buildings are renovated so that each building achieves CO2 neutrality with a packages that has the lowest TCO for that building	Buildings in the neighborhood are renovated so that the neighborhood achieves CO2 neutral level whilst minimizing its combined TCO	District heating + complementary investments are made so that the neighborhood reaches CO2 neutral whilst minimizing its combined TCO
		Current practice and policy		Positive energy district approach	

data and EPC sampling data, which are not publicly available. The geometrical characteristics are extracted from the 3D-GRB database. The construction year is extracted from the Kadaster database. The aggregated electricity and gas demands are extracted from the open data from Fluvius, which is a distribution system operator in the Flanders region.

These datasets are used to initiate the building stock models of Sint-Niklaas. We use a static energy calculation engine to create a baseline of the current situation and identify gas and electricity consumption costs. The static calculation engine uses bottom-up energy models and uses probabilistic distribution functions (PDFs) to assign characteristic building values, namely U values (roof, wall, and windows) to individual buildings using random sampling. The PDFs are constructed using open EPC data where possible. Therefore, this process associates features with individual Sint-Niklaas buildings that are used to provide renovation advisories (fabric renovations, ventilation systems upgrades, rooftop PV or collective heat solutions). The static energy calculation engine provides renovation advisories through cost optimization routines that use the total cost of ownership as the objective function. In this study, we investigate collective and individual renovation solutions for the Sint-Niklaas building stock. The investigation of collective solutions for the district is quite crucial when designing PEDs. The scenarios evaluated are listed in Table 1.

Individual renovations include rooftop photovoltaic solar installations, boiler upgrades, external wall insulation upgrades, roof upgrades, cavity insulation upgrades, ventilation upgrades, and heat pump installations. The collective solution includes the installation of a district heating network. The preliminary results of this analysis indicate that collective solutions are more promising than upgrading individual buildings (Figure 2). For instance, achieving CO2 neutrality per building through renovations costs more than achieving CO2 neutrality per neighborhood that falls within the basic definition of a PED (Figure 2). Some assumptions for these calculations consider renovations until 2050, a discount rate of 3% and CO2 neutrality as 60% reductions compared to expected emissions.

The baseline scenario produces deterministic investment costs. However, these costs are calculated using uncertain parameters; the nature of these parameters is often epistemic in nature. The uncertainties in these calculations could be reduced with additional data collection. For example, A-label renovation scenarios have the least uncertainties in the total cost of ownership, as renovation advisories are estimated at the individual building level. At the collective neighborhood level, the uncertainties associated with this cost increase with additional considerations required to implement collective solutions. For example, when installing a district heating network, the willingness of a home owner to connect to the network introduces additional uncertainty in the PED decision-making process in addition to existing uncertainties in technical installations.

To facilitate informed PED decision making, DST is introduced in this instance in the

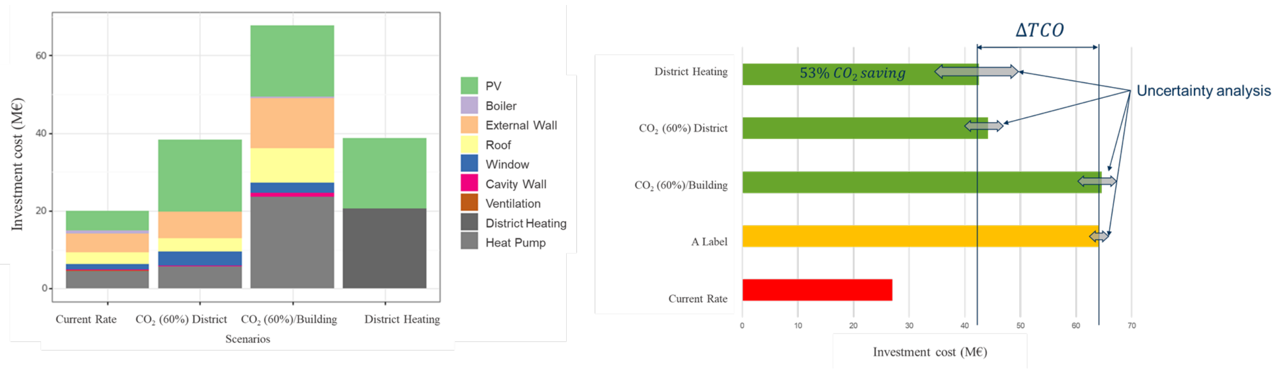

Figure 2. Investment costs for the different scenarios listed in Table 1 considering different optimization routines.

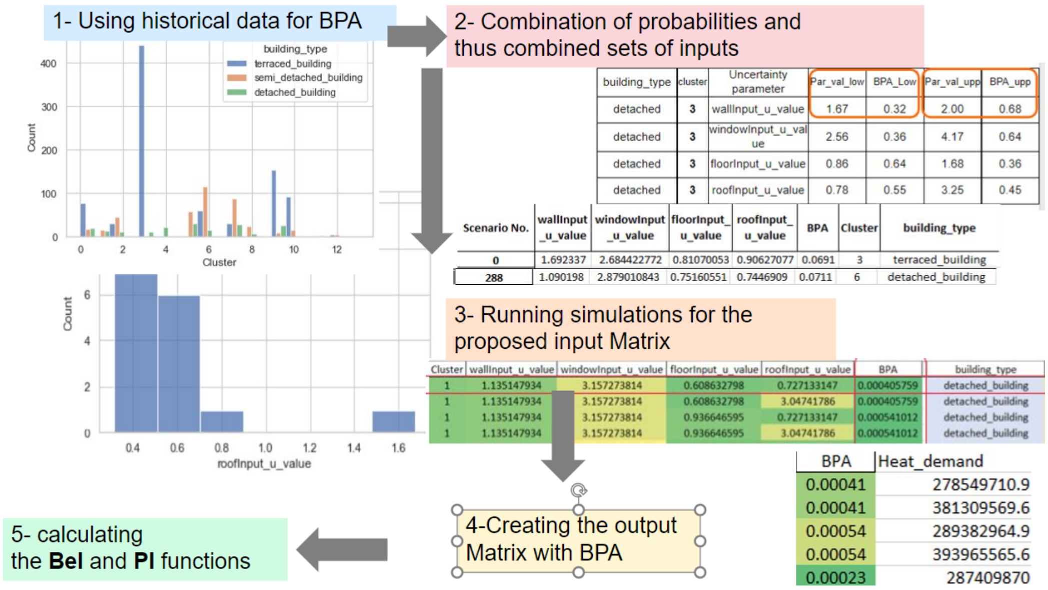

Figure 3. DST implementation workflow for the Sint-Niklaas district to associate uncertain intervals with the annual heat demand calculations.

designed workflow. This study uses data-driven clusters derived from the Sint-Niklaas building stock to reduce the computational burden of DST calculations (Figure 3). This study focuses primarily on uncertainties in the values of the building fabric (wall, window, roof, and floor U values) that are represented as $\theta = (U_{wall}, U_{roof}, U_{window}, U_{floor})$. We use historical data to assign basic probabilities to these uncertain inputs. The different combinations of the maximum and minimum of these inputs are then used as input matrices to run simulations using EnergyPlus. The simulations are then used to formulate the belief and plausibility functions.

The area between the belief and plausibility functions represents the uncertainty associated with the U values of windows, wall, roof, and floor. The cumulative distribution function illustrates the uncertainties in head demand calculations for a detached house located in Sint-Niklaas. The curve between 0.0 kWh and 8.0 kWh corresponds to low-frequency instances of heat demand (Figure 4). The curve above 8.0 kWh has a steep change in the cumulative probability value, and therefore represents the actual uncertainty in the output. This uncertainty is further reflected in the TCO calculations when evaluating the renovation packages for the detached house.

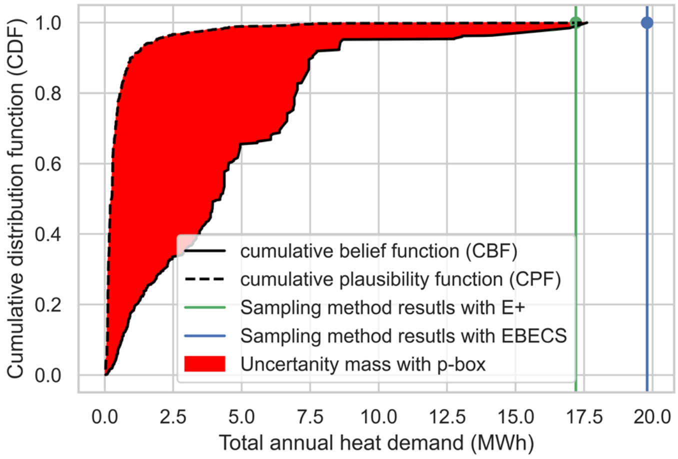

Figure 4. Belief and plausibility functions associated with the annual heat demand.

4. Conclusion

As new design ideas push the envelope of PED, performance evaluation must be justified by building energy performance simulation. Predictions from the deterministic model only provide limited confidence in the energy performance of any building. This study demonstrates a process workflow to facilitate informed PED decision making for districts considering uncertain input. It is crucial to identify risks and quantify them in a structured manner so as to efficiently implement collective PED solutions. Furthermore, considering the carbon neutrality goals, collective solutions offer a bigger market for PEDs compared to individual ones.

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