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Smart buildings as Cyber-Physical Systems: Data-driven predictive control strategies for energy efficiency

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ABSTRACT

Due to its significant contribution to global energy usage and the associated greenhouse gas emissions, existing building stock's energy efficiency must improve. Predictive building control promises to contribute to that by increasing the efficiency of building operations. Predictive control complements other means to increase performance such as refurbishments as well as modernizations of systems. This survey reviews recent works and contextualizes these with the current state of the art of interrelated topics in data handling, building automation, distributed control, and semantics. The comprehensive overview leads to seven research questions guiding future research directions.

1. Introduction

1.1. Motivation

This survey focuses on the topic of energy efficiency in buildings by improving operations using information and communications technologies (ICT). That approach is complementary to building stock refurbishment and modernization. In 2010, buildings accounted for 41% of the primary energy use of the US with close to 75% of this consumption being served by fossil fuels [1]. In the EU-28, fossil fuels are also responsible for almost 75% of the total energy consumption [2]. Buildings used more than two-thirds of their energy consumed for space heating (37%), water heating (12%), space cooling (10%) and lighting (9%) purposes [1]. For the US, residential buildings used slightly more than half of the total building energy consumption [3]. Ref. [4] shows that in 2013, 60% of New York City's emissions stemmed from buildings in general – residential buildings as the largest source accounted for 37%. In Europe, the ODYSEE and MURE databases indicate that buildings accounted for 40% of the EU-28 final energy use in 2012, with residential buildings being responsible for two-thirds of the total building consumption [5]. Various building life-cycle analysis (LCA) case studies reveal that for typical buildings, irrespective of the type of construction, the building operational phase "dominates the life cycle energy use, life cycle CO2 emissions" [6]. For conventional buildings, the operational phase accounts for up to 90% of the life cycle energy consumption, for low energy buildings up to 50%. These figures confirm earlier findings in [7].

1.2. Political context and survey focus

Recognizing the contribution of human-made greenhouse gases (GHG) to climate change, the 2015 UN conference on climate change held in Paris, France, developed an unprecedented climate framework agreement that was signed by 180 countries. The UN agreement marks a significant step towards globally coordinated efforts to reduce humankind's contribution to climate change [8]. Even before that agreement, e.g. the EU issued its energy efficiency guideline 2012/27/EU [9] which requires 20% savings on primary energy usage by 2020 and 50% savings by 2050, compared to 2008. These targets translate into annual savings of 1.5% for all EU member states. In 2016 more than the required minimum of 55 individual nations that jointly account for at least 55% of GHG emissions formally ratified the agreement, including China and the US. Now being in effect, each country ratifying this agreement will develop individual action plans that detail how it intends to reduce its GHG emissions. The agreement formulates the aim to keep global warming below 2 K compared to pre-industrial temperature levels – ideally even keeping warming below 1.5 K. Regularly, each country will report its progress on these plans, and will also develop further plan amendments.

As buildings account for a major fraction of the total energy consumption politics aim to improve buildings' energy efficiency levels by issuing appropriate regulations. Typically, these rules target newly constructed buildings or modernization measures. Building labels and certifications such as EPBD (EU) and LEED (US) do value the presence of building automation systems positively. However, macroscopic

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works targeting building stock energy efficiency such as [3,10–14] do not explicitly discuss energy efficiency potential in light of the possibilities offered by predictive techniques as surveyed in Section 3. This survey specifically targets buildings equipped with some level of building instrumentation and with sensors installed at strategic points to improve the efficiency of building operation - the lion's share of lifetime building energy use. It reviews recent studies that apply computational methods to implement predictive control strategies integrated into the daily building operation. Efficiency gains by these predictive methods are complementary to possible modernization and refurbishment measures. The surveyed works lead to research questions to guide future advances in this field. Other approaches rooted in analyzing building data, e.g. along the lines of [15], which analyzes data offline in regular intervals to infer operational inefficiencies and enable building staff to adapt operation schemes manually, are not covered by this survey. Similarly, studies that purely focus on improving modeling accuracies such as [16–18] are beyond its scope - while they may become relevant as tools in predictive control work, there is no energetic impact by these studies per se.

1.3. Structure

This work is structured as follows: Section 2 provides background information to contextualize Section 3, which summarizes recent literature on data-driven predictive control applications for buildings. Section 4 formulates open questions guiding future research. Section 5 summarizes and concludes the survey.

2. State of the art in buildings as green Cyber-Physical Systems

2.1. Building energy application key performance indicators

For any building energy application to act sensibly, appropriate key performance indicator (KPI) definitions are required. In an attempt to allow benchmarking of Energy Service Company (ESCo) efficiency measures and service contracting, [19] defined several KPIs of relevance, among which:

- *CO_2 emissions.* Reducing these emissions is an intuitive target for buildings, considering the discussions surrounding GHG emissions. However, in the building domain, CO_2 is only measured for monitoring Indoor Air Quality (IAQ, see below), not in the context of the energy supply. Therefore, this KPI is usually derived from the energy consumption by a conversion factor related to the energy source as e.g. provided in [20].
- *Comfort*: This term expresses how well a control application can create conditions in which human occupants feel comfortable. As this concept is very generic, the literature covers several different aspects:
  For *thermal* comfort, the current practice typically treats maintaining indoor air temperature or operative temperature ranges [21,22] as a proxy to meeting comfort targets. However, these parameters do not reflect the actual thermal sensation of an individual due to a set of other factors, such as solar radiation or humidity [23]. For example, the solar radiation effect on comfort has been studied in [24] and the references within. Industry and research communities express the need for appropriate thermal comfort definitions for the purpose of building control [25–27]. To date, the most common thermal comfort index adopted by international standards is Fanger's *Predictive Mean Vote* (PMV) model [28]: ISO 7730 [23], and the adaptive standards EN 15,251 [29] and ASHRAE 55 [30] rely on it. Derived from PMV, the *Predicted Percentage Dissatisfied* (PPD) expresses dissatisfaction of occupants due to poor thermal comfort. The suitability of these comfort indexes and standards is subject to debate: studying classroom thermal environments [31] concludes that these indexes are "mainly found to be inappropriate for the assessment". To overcome questionnaire-based methods traditionally used to assess thermal discomfort, [32] investigates an alternative form of data collection in addition to temperature sensors: by observing occupants' activities (e.g. activating heating, pouring a hot drink, changing clothing level).
  Despite thermal sensation also *Indoor Air Quality* (IAQ) can be a source of (dis-)comfort. CO_2 and humidity levels, as well as the concentration of different pollutants, are the main parameters of concern. For example, [33] models the impact of air conditioning in an office room in Panama City from measured temperature, humidity, and CO_2 levels. [34] provides a more extensive discussion of air quality and thermal comfort.
  Discomfort has a substantial socio-economic impact: based on the data of 3766 pupils taught in more than 150 different classrooms of 27 schools, [35] identified a significant impact of the environmental factors light, sound levels, IAQ, and temperature on the academic progress. [36] used online surveys to analyze the self-reported work performance of 114 office workers over a period of 8 months about perceived thermal comfort, lighting comfort and noise of their offices. Discomfort in one or more of these factors acts as stress that reduces work performance by 2.4–14.8%. For a more comprehensive overview, we refer to [37], a recent survey on how building occupants' discomfort affects productivity.
- *Energy.* Measured during a period of concern, typically in kilowatt-hours [kW h], kilojoules [kJ] or tonnes of oil equivalent [Toe]. Depending on the context of comparison and benchmarking, often the energy consumption of a period (e.g. one year) is normalized per visitor (e.g. public buildings), employee (e.g. office buildings), or floor area. When considering heating and cooling systems, weather normalization by Heating/Cooling Degree Days [38] is appropriate. That allows comparing consumption across climatic zones and years. As indicated in [13], there is a crucial difference of perspective between assessing energy efficiency from a *primary* energy (i.e. the total energy of the natural resource used) or a *final* energy viewpoint (i.e. the final use form, e.g. used for electricity or space heating). Studies and surveys targeting political frameworks and policies usually reason about the primary energy effects whereas studies on building equipment or operation strategies typically take the final energy perspective. So-called primary energy factors (PEFs) establish a connection between both energy notions. However, there are variations in the definition and calculation of PEFs that can have significant consequences e.g. when comparing different heating systems regarding primary energy use [13].
- *Exergy* measures the maximum available energy for doing work. A thermodynamic system's exergy depends on the distance to the system's equilibrium. Unlike energy, exergy is not conserved. According to the Second Law of Thermodynamics, exergy is related to the quality and quantity of energy. Thus, a control scheme around exergy must address energy quality in addition to quantity [39]. In theory, using boilers as the heat source in buildings creates a mismatch between exergy supply and demand, which should be avoided. For example, low-temperature floor heating outperforms other (high-temperature) space heating systems regarding exergy [40].
- *Green factor.* The fraction of the energy used from renewable energy sources divided by the total energy consumption.
- *Light* levels, measured in lux, are relevant for applications of smart blinds and lighting control, often as part of a comfort KPI assessment.
- *Temperature*, measured in the controlled zone or system, can be used as an absolute reading or put in relation to an application specific target temperature. Often, temperature is part of comfort KPI assessment.
- *Underperformance Time (UPT).* Building systems have a defined range of indoor conditions related parameters, e.g. temperature, CO_2 levels, relative humidity or lux levels. Often, this range may