HVAC Control Methods - A review

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***Abstract*—Making buildings more energy efficient while keeping thermal comfort has been an important topic in last decades, including improving efficiency of Heating, Ventilation and Air Conditioning (HVAC) systems. One approach to this goal is to use better control methods. This paper presents a review of methods which have been researched in scientific papers in last couple of years. Most papers focus on one of the following trends: improving "classical" control methods; use of predictable control based on models; use of intelligent control methods.**

Keywords—HVAC systems, control, review, Classic Control, Predictive Control, Intelligent Control

I. INTRODUCTION

Energy efficiency is a popular topic in last decades, both in scientific and popular literature. Data [1], [2] shows that developed countries use up to 40% of energy on buildings, and that almost half of it is used for heating, ventilation and air conditioning (HVAC systems, henceforward). This means that up to 20% of energy in USA today is used for HVAC systems, shown in Table 1. And if we consider that total energy consumption is 28×10^{12} kWh (data for USA in 2010), this proves quite a large amount.

TABLE I. ENERGY USE IN USA, PER CONSUMERS OVER YEARS

	Energy used		
Consumer / Year	**2006**	**2008**	**2011**
Buildings (% of total)	39%	40%	41%
Residential (% of buildings)	54%	54%	54%
Commercial (% of buildings)	46%	46%	46%
Space heating (% of buildings)	20%	21%	37%
Lighting (% of buildings)	18%	13%	9%
Space cooling (% of buildings)	13%	13%	10%
Water heating (% of buildings)	10%	9%	12%
Other (% of buildings)	39%	44%	32%
HVAC (% of buildings)	33%	34%	47%
HVAC (% of total)	**13%**	**14%**	**19%**

There are several approaches to reducing this energy and making buildings more energy efficient: use of modern materials with better thermal characteristics; applying design methods that consider energy efficiency during design phase; replacing equipment with more efficient one; use of better control methods; etc. [3] Some of these methods can be applied only before and during construction; some of them are expensive to apply. Upgrading HVAC system to be more energy efficient by use of modern control techniques can be noninvasive and cheaper approach. At the same time, these control methods must provide existing or even upgraded feel of comport to occupants, which is a primary goal of HVAC system.

This article presents an overview of some recent researches that deal with improved control methods in HVAC systems. Second part of paper presents some general topics dealing with control strategies in HVAC systems. Reviewed papers are presented in this part, divided to groups by approach. Third part will try to find some common characteristics and trends in presented articles. Final part will give conclusion and propose possible further steps.

II. CONTROL STRATEGIES FOR HVAC SYSTEMS

As already mentioned, HVAC originates in Heating, Ventilation and Air Conditioning. Nowadays, HVAC system is considered a part of system called air-conditioning system, which takes care of the total control of temperature, moisture in the air (humidity), supply of outside air for ventilation, filtration of airborne particles, and air movement in the occupied space [4]. Nevertheless, HVAC is still used in most literature. HVAC comprises following processes:

- Heating – addition of thermal energy (heat) to air with purpose of maintaining zone's temperature
- Cooling - removal of thermal energy from air with purpose of maintaining zone's temperature
- Humidifying – addition of moisture to air with purpose of maintaining zone's humidity
- Dehumidifying – removal of moisture from air with purpose of maintaining zone's humidity
- Ventilating – replacing of interior air with fresh air from outside with purpose of maintaining zone's air quality
- Cleaning – removal of dust and other particles with purpose of maintaining zone's air quality
- Air movement – circulation and mixing of air with purpose of maintaining zone's temperature, humidity and air quality

This article focuses only on first four or five processes of HVAC systems (heating, cooling, humidifying, dehumidifying; sometimes ventilation).

A. Approaches to Control of HVAC Systems

For analysis of control methods for HVAC systems, it is first necessary to make a distinction by approaches.

In paper [5] author shows development of control methods in industry (not just in HVAC) through history. Control strategies are developed in four stages, which can be seen in Table II. First stage is labeled Conventional PID Control: second stage (Advanced Control I) is marked by different versions of Multiple Input Multiple Output Control; stage three (Advanced Control II) comprises different types of industrial implementations; fourth stage (Advanced Control III) is signed by different hybrid, expert and soft-computing techniques. Second part of article deals with trend of implementation of various ICT (Information and Communication Technology) techniques in process control.

TABLE II. DEVELOPMENT OF CONTROL STRATEGIES OVER TIME

A Conventional PID Control	B Advanced Control I	C Advanced Control II	D Advanced Control III
Manual Control	Gain Scheduling Method	Robust Control Methods	Hybrid Predictive Control
Feedback Control	Adapting and Self-tuning Control	Optimal Control Methods	Fuzzy Control
Cascade Control	Multivariable Control Methods (State Space and Transfer Function Models)	Model Predictive Control	Neural Network Control
Feedforward Control	Multivariable Control Methods (Decoupling and Decentralized Control)	Decentralized Control	Discrete Events Control
Ratio Control	Pole Placement Methods	Algebraic Control	Nonlinear Hybrid Soft Computing Control
Combined Control Structures	Nonlinear Control	Robust QFT Control Methods	Expert Control Methods

To take a similar approach, this paper will divide reviewed articles into four categories: classic approach (Feedforward and Feedback Control, On-Off, PID, etc.); predictive control methods (in most cases, Model Predictive Control); intelligent control techniques (fuzzy logic in various combinations); and other approaches and general topics.

B. Classic Approach

Also called conventional control strategies, this approach is marked with use of methods with many decades of practical implementation, especially feedback control and PID (Proportional-Integral-Derivative) controllers.

Paper [6] is dealing with design of control systems. Even though authors admit that MIMO (Multiple Input Multiple Output) system provide better theoretical results, in practice it can be more convenient to have several SISO (Single Input Single Output) systems, especially when tuning is considered. They explain how to use decoupled approach to realize decentralized control system. A feedforward controller in combination with PID controller is selected as showcase, demonstrated on refrigeration system. Results show improvement of RMS (Root Mean Square) error of control system and more stable operation of components.

In paper [7] authors propose and discuss an improvement of existing optimal control of heat-exchangers in HVAC systems. Authors shortly discuss model of two heat-exchangers (air-to-air and water-to-air) and give a detailed control strategy: disturbance rejections; maximum exploitation of air-to-air heat-exchanger; keeping difference between supply water flow and tertiary water flow of water-to-air heat-exchanger on minimum. They discuss classical and optimal approach based on two independent controllers for heat-exchangers, conditions and constraints for control. Next they propose a simplified optimal control scheme, which solves problem of bypass flow, resulting in 82% reduction of energy consumption of tertiary pump.

Simple application of PID control is given in paper [8], where authors explain design of handheld instrument for automatic tuning of PID controllers that can be used in HVAC. They give theoretical background for tuning PID controllers and explain how it can be done based on process data. Paper [9] explain use of PID controllers for control of HVAC system of large commercial building. PID control is combined with expert knowledge to provide better results: simulating human divisional control (by providing different control scenarios); on-line tuning of PID parameters (depending on accumulative error); feed-forward control (depending on outside conditions); and lag compensation of particular HVAC sub-systems.

Paper [10] present a detailed explanation of classical control strategy based on PID controllers. Authors first describe building and HVAC system and use first-principles approach to build a thermal model which comprises all relevant thermal processes. They use Laplace transformations to get transfer functions. These equations are used to model PID controllers for humidifier and heating coil for heating mode, and for dehumidifier and cooling coil for cooling mode. PID controllers are tuned with Ziegler-Nichols method.

C. Predictive Control

Predictive control techniques rely on predicting the dynamic behavior of system in future and adjusting response of controller accordingly. Usually this means some variation of Model Predictive Control (MPC), where prediction is performed based on explicit model of building. These kinds of methods can achieve very good results, but often have problems with complex implementation. Fig. 1. shows relation between important values of MPC: setpoints, predictions and inputs that are adjusted based on these predictions.

Book [11] gives very extensive overview of Model Predictive Control, with focus on industry. MPC is reviewed as general control strategy, with several implementations: Model Algorithmic Control (MAC), Dynamics Matrix Control (DMC) and Generalized Prediction Control (GPC). Other associated topics are also reviewed: synthesis approach, optimization, robustness, etc. A survey of MPC applications in industry can be seen in [12].

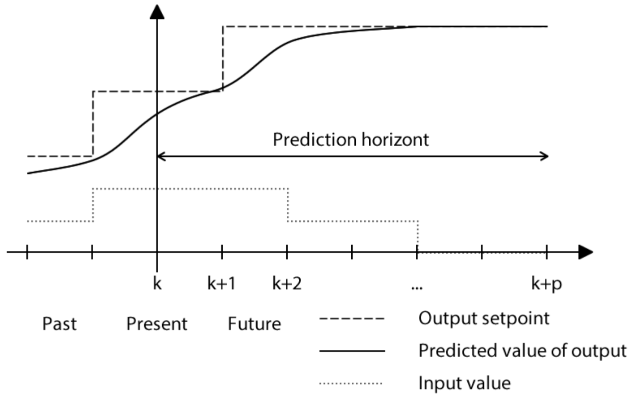

Fig. 1. Model Predictive Control – use of model of system to predict future behavior and optimally adjust inputs

A review of modern papers on Model Predictive Control for HVAC systems is given in paper [13]. Authors make a short introduction of HVAC systems and their modeling (which is integral part of MPC). Then they discuss MPC and its particulars (prediction horizon; inputs/outputs; constraints; cost function; etc.). Finally, they give a review of 10 current researches, comparing them on according to type (of model and controller), type of cost function, solution method, optimality, stage (computer simulation, experiment, actual building, prototype) and special features.

Model Predictive Control and thermal modeling is used and explained in paper [14], but it is not main a topic. Instead, authors focus on establishing how perturbations of parameters affect results and energy efficiency of HVAC system. They build a thermal model of test building by Lumped Capacitance Method (wall example shown in Fig. 2.; this is a very common method for building thermal models for use in MPC) and build parameter estimation errors into this model. They develop Model Predictive Control system where they examine influence of each perturbed parameter. This controller was simulated over 2000 timesn performing Monte-Carlo simulations to get result. Two parameters, thermal resistances of floor and ceiling, are revealed to have majority of impact on system results.

Model Predictive Control is extensively described in paper [15]. Authors describe real-life application of MPC strategy for control of HVAC system on University of California at Merced, USA. They explain various topics, from modeling of HVAC system, its elements and building, to control on several levels of complexity. Many practical and expert details are revealed, with overview of current research, which makes this a very good starting point for researching Model Predictive Control. Authors start with introduction to principles of MPC and modeling of thermal processes in buildings. Control is developed hierarchically, on two levels: high level, where they model and control HVAC system, production of heating and cooling water, distribution, etc.; and lower level which deals with internal dynamic inside building and local elements of HVAC system. Earlier version of this paper and research can be found in [16].

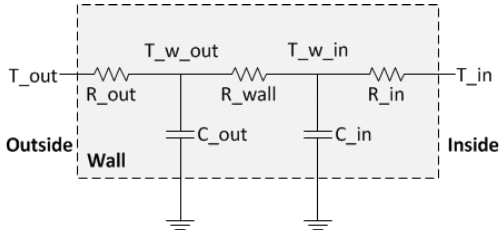

Fig. 2. Lumped Capacitance Method – 3R2C substitute for wall

There are many papers dealing with Model Predictive Control. Paper [17] describes a typical MPC problem and explains various problems and challenges when developing a control solution for HVAC system based on MPC. This implementation uses Sequential Quadratic Programming (SQP) to solve the optimization problem. Controller is based on detailed and simplified thermal model of building. Authors report that this solution is applicable in real-time control of HVAC system. Paper [18] follows a typical structure of MPC article, where in first part authors describe thermal model of building (HVAC system, AHU – Air Handing Units and VAV – Variable Air Volume units, room model based on variation of Lumped Capacitance Method, etc.) and in second part they deal with implementation of MPC (constraints, SQP method for solving, etc.). Paper explains how Decentralized MPC (DMPC) can be used for better results and how dual decomposition method can be used to decentralize the system. Authors of paper [19] follow a similar pattern but focus on Stochastic MPC, where uncertainties of weather predictions are built into model. Four control strategies are compared: Rule Based Control (If-Then rules for control); Certainty Equivalence MPC (uncertainty is neglected); Stochastic MPC (where uncertainties follow Gaussian distribution); and Performance Bound (optimal control with perfect knowledge of future weather and long prediction horizon). Paper [20] gives very detailed description of creating a Model Predictive Controller for test plant, where MPC is combined with feedback linearization (for linearization of input-output behavior of cooling coil). Implementation of MPC for family house is presented in [21]. Authors explain how to build a zone model with Lumped Capacitance Method and then use it for MPC. In paper [22] by same authors, focus is on indoor air quality by ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) standards. In [23] and [24] authors use subspace identification algorithm to find thermal model of building from data. They test both their identification strategy and control strategy on real building, Czech Technical University. Authors stress impact of quality of thermal model on prediction-based control strategies and address question of feasibility of MPC in particular cases.

Paper [25] also deals with feasibility of Model Predictive Control strategy. Authors question when is feasible to invest in Model Predictive Controller for HVAC system on existing building. To answer this, they compare energy balance of building calculated by three methods: by use of some of standard methods for static modeling (energy audit; energy label or certificate); actual energy balance (energy loses; data from Building Management System); and theoretical results achieved by Model Predictive Control. There are two steps for decision: first, if actual energy consumption is larger than standard consumption (static model); second, if theoretical MPC-based consumption is less than actual. Authors explain a simplified modeling method that can be used in MPC strategy.

Another paper dealing with distributed MPC is [26]. Authors first give an explanation of Model Predictive Control and develop a controller for a single room (or zone). They focus much on possibility that MPC takes occupancy of zones into consideration. Classic controllers (PID) usually use a lower set-point for unoccupied periods (e.g. night-setup) which saves energy; but MPC (especially if occupancy is known in advance by schedule) can give much better results by ignoring periods of inoccupation and preparing for future periods of occupancy. In second part, authors develop their dMPC (distributed MPC) that combines properties of centralized control strategy (optimal results, because model of whole building is taken into consideration) and decentralized control strategy (lower computation costs and better robustness) by making each of distributed controllers share data with its neighbors. Paper [27] gives a review of distributed approach to MPC. Authors have reviewed 35 approaches to dMPC (not only in HVAC) and marked distinctive features, which enabled them to speculate on future roadmap of dMPC research.

Usually MPC is used for control of HVAC system on high level. In paper [28] MPC, in form of Inferential Model-based Predictive Control Scheme (IMPCS), is used for control of a single boiler, although again on high level, for defining set-points, while PID control is used for direct control of actuators. Detailed model of system is again needed, but in this case it is much simpler model than in case of whole building. Model is provided from hybrid method where structure of model (including boiler and room) is based on first-principles approach, while parameters are estimated by data-driven approach. MPC is compared to classical ON/OFF control and optimal control (Average Room Temperature-Based Control – ARTBC), where results are very favorable to IMPCS. Authors admit high costs of tuning this controller for each application.

A framework that couples building topology, estimation and control routines is presented in paper [29]. Authors extend their hybrid (gray-box) method for identification of thermal model of building, which they developed in paper [30] (based on Unscented Kalman Filter), and combine it with Energy Management/Building Automation System. This enables online identification through self-excitation that doesn't disrupt normal routines of occupants (meaning that historical results of control system are used to improve thermal model of building). Finally, this online model is combined with Model Predictive Control strategy. This would eventually lead to developing a universal and automatic algorithm for identification and control.

Paper [31] deals with variation of MPC called Economic MPC (EMPC). In this case, the primary goal of control is not to follow set-point exactly, but to use minimal amount of resources. Here, price of electricity (or other energy sources) is embedded directly into cost function. Drawback of EMPC are high computation cost, which can be solved by reducing the prediction horizon, which again results in poor results; and occurrences of spikes (rapid changes of input signal), which can be solved by imposing constraints on input, again affecting cost of performance. To solve this drawback, authors developed their method called Infinite-Horizon EMPC, which they explain.

Authors of paper [32] deal with Generalized Prediction Control (GPC), which is a variant of prediction control developed during 80s. They propose three different model types for thermal processes in building (LTV – Linear Time Varying; BTV – Bilinear Time Varying; BTI – Bilinear Time Invariant), all of which are inherently nonlinear. Two new forms of GPC are presented: Modified incremental GPC (MGPC) and Modified Non-Incremental GPC (MNIGPC); in contrast to original (incremental) GPC and Non-Incremental GPC (NIGPC). Also, it is possible to additionally adapt (formulate) GPC to type of model: Linear Self Tuning Control (LSTC) for LTV; Bilinear Self Tuning Control (BSTC); and Fixed Bilinear Control (FBC). Detailed modeling of building elements (room, wall, radiator, valve and boiler) is given and results in bilinear product term that describes the whole system, for which authors perform parameter estimation. Finally, authors conduct simulations for each control algorithm (GPC, NIGPC, MGPC, MNIGPC) and for each system representation (LTV, BTV, BTI). Results favor incremental forms of GPC and nonlinear forms of system.

Paper [33] describes a simple form of predictive control of cooling in building, based on load-shifting. Three control strategies will be compared: Night-Setup (NS), where cooling is turned on only during period of occupancy; Load-Shifting (LS), where building is pre-cooled during night (when energy is cheaper) and cooled during day when interior temperature rises above limit; and novel strategy called Demand-Limiting (DL) that is proposed by authors. DL strategy also uses pre-cooling during night, but instead of cooling during day, it uses pre-cooling during day so that temperature never leaves limited range. Goal of this method is to reduce peak loads, instead of usual goal of lowering energy consumption. DL strategy is based on model of building, which is explained in the paper.

In paper [34] three different control strategies are explained and compared, applying on experimental HVAC system and building. First, basic, strategy is classical On-Off control with hysteresis (Bang-Bang), where controller just turns heater and humidifier on and off when they leave defined ranges. Second, advanced, strategy is based on On-Off controller, but considers inertia of system, particularly temperature. Third, optimal strategy is based on Model Predictive Control and achieves best results, but expects large effort in modelling thermal processes.

D. Fuzzy Control

Methods based on Fuzzy Logic Control are used quite often in HVAC control, one of reasons being very simple implementation of controller.

Very simple example of Fuzzy Logic in HVAC control is shown in paper [35]. Authors use Fuzzy controller to turn on and off HVAC units in four rooms of one building, in scenario where there is not enough energy to keep them all turned on. Fuzzy Controller must maintain the thermal comfort inside the house, while avoiding situation where HVAC power load is greater than available power (peak-load reduction). Authors implement their controller in laboratory conditions. Similar approach is used in [36]. Authors use two fuzzy controllers: one analyses building and active energy consumers to provide amount of available energy; and second distributes available energy so that temperature in every zone stays in comfort level.

Paper [37] also deals with Fuzzy Logic. Authors first give very extensive theoretical introduction to Fuzzy Logic Controllers (FLC): Knowledge Base, Interface System, Fuzzification Interface, Defuzzification Interface, which is shown in Fig. 3. Ability to handle multi-criteria control strategies is selected as one of most important properties of FLC. Second part of paper deals with Genetic Tuning of FLC, for which is also given an extensive description. Authors then concentrate on their own contribution in form of Weighted Multi-Criterion Steady-State Genetic Algorithm (WMC-SSGA) for tuning of FLC. This strategy is then applied on two different real-life test-sites, and one of them in different scenarios: summer-season model and mid-season model. Results of experiment are discussed with focus on energy efficiency improvements and system stability.

Similarly to previous paper, [38] describes combination of Fuzzy Logic Controller with Genetic Algorithms, which authors call Evolutionary Fuzzy Rule-Based models. List of rules is developed directly from data without previous model information. Authors focus their work on keeping the computational load (and complexity) at acceptable level, which they realize by use of indices of rules. Additional benefit is that with this method, physical interpretation of model is possible. Proposed method is tested by modeling control of natural-gas boiler.

Another combination of FLC and GA is given in paper [39], where FLC is used to control valves that regulate water and steam valves. Authors first give a detailed model of valves and Air Handling Unit (AHU), and produce a multi-criteria controller (temperature and humidity). This controller is also able to re-tune itself to match new conditions, so they call their controller Adaptive FLC (AFLC). They explain how GA is used to modify Fuzzy Rule Matrix (FRM) that will provide lowest possible RMS error. Results also show improvements in response (rise times and settling times). Testing is implemented in Matlab and Simulink.

A review of papers dealing with intelligent control techniques in HVAC systems is presented in paper [40], where by intelligent authors mean fuzzy-logic-based. First, a basic introduction to fuzzy control is given, after which authors continue with modified fuzzy techniques. They explain Neuro-Fuzzy Systems (NFS) where Artificial Neural Networks (ANN) are combined with FLC, and ANN is used to generate or modify the Rule Base of FLC. Second approach instead of ANN uses Genetic Algorithms (GA) for the same purposes, and it is called Genetic Fuzzy Systems (GFS). In second part of articles, a review of articles is given. Most of reviewed papers deal with control of HVAC systems in various forms, but part of them deal with improving of results of classical PID controllers (by developing methods for auto-tuning). Another review of fuzzy control strategies is given in paper [41], with over 80 reviewed articles. Authors give an introduction to Fuzzy Logic Control and continue to combination of FLC with other control strategies: Genetic Algorithms; Clustering; Model Predictive Control.

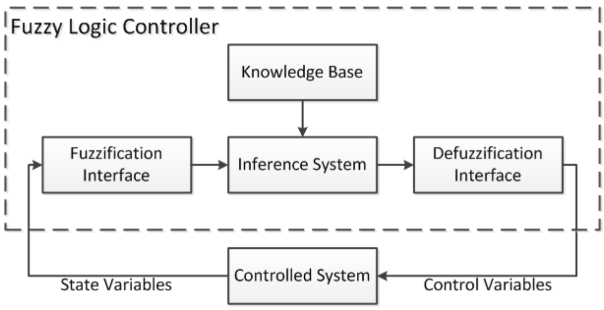

Fig. 3. Fuzzy Logic Controller and its elements

E. Other methods and general topic

Robust control is topic of paper [42]. Authors give only a short introduction to robust control, explaining how in this type of control uncertainties are assumed as part of system and controller. Experimental HVAC system is built to test performance, representing a typical HVAC system found in residential buildings. Authors compare a typical control system consisting of three separate SISO (Single Input Single Output) PI (Proportional Integral) controllers with one MIMO (Multiple Input Multiple Output) controller build on robust theory principles. Results demonstrate improvement in form of tracking times three times shorter that controlled by classical PI control, applied on the same actuators.

A novel approach to HVAC control is given in [43] where authors present a model-free control. Control is independent of model or sensor information, and control actions are decided upon votes of occupants. System is devised so that occupants use their smartphones to vote about their current thermal comfort (cold, neutral, hot), which triggers an action of HVAC system (heating or cooling). There are two possible approaches to voting: maximizing the number of comfortable people (where few people are maximally comfort, but some people are left very uncomfortable) or minimizing average thermal discomfort (where nobody is perfectly comfortable, but nobody is in discomfort). Additional energy save can be achieved by enabling "drift", which means that indoor temperature is let to drift to outdoor (inducing minimal thermal discomfort, but largely reducing energy consumption).

Paper [44] describes a control system based on adaptive feed-forward control strategy. Authors explain thermal modeling of building by Lumped Capacitance Method (resulting in graph mode of zones) and air-mass flow equations. Goal of control is to move the equilibrium of system closer to desired operating point, which is called Passivity Based Control. Uncertainty of inputs is also taken into consideration to achieve more robust control system. Method is tested on simulation of four-room building, where model is built by Computational Fluid Dynamics (CFD) software.

Paper [45] researches how to decentralize a control system. Authors first elaborate centralized and decentralized control systems – former can achieve optimal results, but are sensitive to model correctness and problems with communication and sensor failures; latter realize only suboptimal results, but can be more robust. When dealing with HVAC systems in buildings, decentralization is realized by splitting zones in such way that several zones are controlled by one decentralized controller. Usual approach to decentralizing is by heuristic methods, or designer's "feel". Authors propose a systematic method based on two factors: Coupling Loss Factor (CLF) which is connected to degree of clustering (few clusters is better); and Mean Cluster Size (MCS) which depends on average number of elements in clusters (smaller clusters are better). Authors explain how to divide zones in stages with use of combinatorial methods, how to calculate CLF and MCS factors for each stage, and how to select the optimal stage of clustering.

Paper [46] deals with general topic of comparison of different control strategies. Authors propose that experimental comparison can be misleading if conditions of experiment are not the same: either different outside temperature conditions; or not taking into consideration fundamental differences between control strategies. Additionally, properties of measuring system have to be taken into consideration, as separating influences of other system in the building have to be, too. Paper focuses on defining quantitative metrics for use of energy and for thermal comfort of occupants. Resulting methodology is tested on two different control strategies: classical control with Advanced Scheduling and Model Predictive Control.

III. COMPARISON OF CONTROL STRATEGIES

All reviewed papers (excluding books and papers about HVAC in general) can be seen in Table III. Papers are sorted by order of appearance.

TABLE III. COMPARISON OF REVIEWED PAPERS FOR HVAC CONTROL

Reference	Year	Classical Methods		Predict. Methods		Intelligent Methods			Other		Model type		Identification approach			Scope of control			Improvement
		On-Off	PID	General Predictive	MPC	Fuzzy	Genetic Alg.	ANN	General Topics	Other	Linear	Nonlinear	First-principles	Data-driven	Hybrid	Complete system	HVAC sys. or element	Zones model	
[5]	2012								x										
[6]	2010		x								x			x			x		40% improved tracking
[7]	2009		x								x		x				x		82% improved efficiency
[8]	2009		x								x			x			x		
[9]	2008		x									x			x	x			
[10]	2005		x								x		x			x			
[12]	2003				x				x										
[13]	2013				x				x										
[14]	2011				x						x				x			x	
[15]	2012				x							x			x	x			19% improved efficiency
[16]	2009				x							x			x	x			24.5% improved efficiency
[17]	2011				x							x	x			x			
[18]	2011				x							x			x	x			10.2% improved efficiency
[19]	2010				x							x						x	40% improved efficiency
[20]	2011				x						x		x				x		
[21]	2011				x						x		x					x	
[22]	2013				x						x	x	x					x	
[23]	2010				x						x			x		x			30% improved efficiency
[24]	2010				x						x			x		x			10% improved efficiency
[25]	2011				x				x		x				x	x			
[26]	2010				x						x			x				x	
[27]	2014				x														
[28]	2010				x						x				x		x		9-20% improved efficiency
[29]	2013				x				x		x				x			x	7.5% effic./50% track.
[31]	2012				x						x		x					x	99.9% reduced comp. cost
[32]	2011			x							x	x	x			x			
[33]	2007			x							x				x			x	30% reduced peaks
[34]	2011	x		x	x				x		x		x			x			8.21% improved efficiency
[35]	2012					x								x				x	
[36]	2009					x								x				x	
[37]	2003					x	x							x		x			30% improved efficiency
[38]	2000					x	x							x			x		
[39]	2013					x	x					x					x		
[40]	2010					x	x	x											
[41]	2006					x													
[42]	2008		x							x		x	x				x		300% improved efficiency
[43]	2013									x							x		50% improved efficiency
[44]	2013									x	x		x			x			16% improved efficiency
[45]	2011				x				x		x		x					x	
[46]	2012								x			x		x		x			
	40	1	6	3	21	7	4	1	8	3	20	11	12	10	9	14	9	11	

As explained before, regarding the control approach, papers are divided in four categories (grey part of table): Classical Control methods; Predictive Control Methods; Intelligent Control Methods; and other methods and general topics.

Classical approach comprises control methods that have been developed in past, e.g. On-Off and PID. These methods are still used in majority of applications, but their popularity as research subject is expectedly not strong anymore. Some possible developments are in combining these methods with variations of advanced approach.

Predictive methods present a major point of interest for new papers, especially Model Predictive Control. MPC in HVAC has been extensively researched in past (MPC as method exist since 1970s), but development and new application are still possible. Since efficiency of MPC depends on quality of thermal model, a lot of study is put into developing better models of buildings and HVAC systems. There are several drawback of MPC in regard to its implement. First, MPC is computationally intensive. Second, complex algorithm means more room of errors. And third, for complex systems as large commercial buildings, MPC has many parameters that have to be tuned, so commissioning is hard. This means that there is much effort to produce applications that can be used in commercial products.

Intelligent control methods are also interesting for research, especially those based on Fuzzy Logic Controllers, in combination with Genetic Algorithms or Artificial Neural Networks. They can give very good results and are relatively easy to implements. But, judging from lack of implementation in commercial products, there is still place for improvement and these methods are still looking for their place on the market.

Table III. also shows some information about type of model that is used to represent the system, where such information is stated in the paper. First category is model type, where models are divided as linear or nonlinear. HVAC systems are usually complex and nonlinear systems, but most papers either regard them as linear or use some kind of linearization methods on them.

Second division is based on type of approach that is used to acquire the model. First-principles approach uses knowledge of mathematics and physics to describe the systems dynamics, thermal processes and properties of buildings. Such approach enables useful insights in behavior of system, but it is usually complex and requires specialized knowledge about buildings. Data-driven approach uses numerical methods to produce the model from data only. It can yield very good results in short time, but it lacks interpretation of buildings interior behavior and physical interpretation. Hybrid approach presents a combination of previous two approaches, usually with use of first-principles methods to provide a structure of model and data-driven methods for parameter estimation.

Papers are then divided according to the scope or target of control. Part of authors tries to target complete HVAC systems, including the behavior of thermal conditions in building (e.g. temperatures in each zone). Rest of authors tries to focus on smaller scope: either only on HVAC system or its elements (e.g. production of heat, control of boilers, etc.), where they dismiss how produced energy will be distributed in building; or on zones model (control of climate conditions inside the building), presuming that necessary energy is available.

Lastly, Table III. gives some quantitative data about improvements that resulted from implementation of these control methods. These numbers must be taken with caution and usually cannot be compared directly – context and previous conditions of buildings and HVAC systems, and scope of control must be regarded.

IV. CONCLUSION

As explained in introduction, as standard of living is growing, so does the amount of energy used for heating, ventilation and air conditioning. This signifies that methods for efficient control of HVAC systems will only be more important in future.

Classical approaches, especially PID controllers, are still ubiquitous in most applications, whether domestic or commercial. Advanced approaches, marked mostly by predictive and intelligent control methods show very good results when it comes to energy efficiency. Trivial problems of advanced methods have been mostly solved. Next steps of advanced control methods in HVAC should be finding ways to make application commercially available and easier to implement in different settings.

REFERENCES

[1] J. D. Kelso, "Building Energy Data Book 2011," 2012.

[2] L. Perez-Lombard, J. Ortizb, and C. Pout, "A review on buildings energy consumption information," *Energy Build.*, vol. 40, no. 3, pp. 394–398, Jan. 2008.

[3] V. Vakiloroaya, B. Samali, A. Fakhar, and K. Pishghadam, "A review of different strategies for HVAC energy saving," *Energy Convers. Manag.*, vol. 77, no. 1, pp. 738–754, Jan. 2014.

[4] R. McDowall, *Fundamentals of HVAC Systems*, 1st ed., vol. 40, no. 6. Elsevier, 2007.

[5] S. Kozak, "Advanced control engineering methods in modern technological applications," in *Proceedings of the 13th International Carpathian Control Conference (ICCC)*, 2012, pp. 392–397.

[6] N. Jain, R. J. Otten, and A. G. Alleyne, "Decoupled Feedforward Control for an Air-Conditioning and Refrigeration System," in *American Control Conference (ACC)*, 2010, pp. 5904–5909.

[7] M. Komareji, J. Stoustrup, H. Rasmussen, N. Bidstrup, P. Svendsen, and F. Nielsen, "Simplified optimal control in HVAC systems," in *2009 IEEE International Conference on Control Applications*, 2009, pp. 1033–1038.

[8] J. Liu, W. Cai, and G. Zhang, "Design and application of handheld auto-tuning pid instrument used in HVAC," in *2009 4th IEEE Conference on Industrial Electronics and Applications*, 2009, pp. 1695–1698.

[9] J. Wang, C. Zhang, and Y. Jing, "Application of an intelligent PID control in heating ventilating and air-conditioning system," in *2008 7th World Congress on Intelligent Control and Automation*, 2008, pp. 4371–4376.

[10] B. Tashtoush, M. Molhim, and M. Al-Rousan, "Dynamic model of an HVAC system for control analysis," *Energy*, vol. 30, no. 10, pp. 1729–1745, Jul. 2005.

[11] D. Bao-Cang, *Modern Predictive Control*. CRC Press, 2009.

[12] S. J. Qina, T. a. Badgwell, S. J. Qin, and T. a. Badgwell, "A survey of industrial model predictive control technology," *Control Eng. Pract.*, vol. 11, no. 7, pp. 733–764, Jul. 2003.

[13] R. Kwadzogah, M. Zhou, and S. Li, "Model predictive control for HVAC systems — A review," in *2013 IEEE International Conference on Automation Science and Engineering (CASE)*, 2013, pp. 442–447.

[14] S. Bengea, V. Adetola, K. Kang, M. J. Liba, D. Vrabie, R. Bitmead, and S. Narayanan, "Parameter estimation of a building system model and impact of estimation error on closed-loop performance," in *IEEE Conference on Decision and Control and European Control Conference*, 2011, pp. 5137–5143.

[15] Y. Ma, A. Kelman, A. Daly, and F. Borrelli, "Predictive Control for Energy Efficient Buildings with Thermal Storage," *IEEE Control Syst.*, vol. 32, no. January, pp. 44–64, Feb. 2012.

[16] Y. Ma, F. Borrelli, B. Hencey, A. Packard, and S. Bortoff, "Model Predictive Control of thermal energy storage in building cooling systems," in *Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference*, 2009, pp. 392–397.

[17] A. Kelman and F. Borrelli, "Bilinear Model Predictive Control of a HVAC System Using Sequential Quadratic Programming," in *International Federation of Automatic Control World Congress*, 2011, pp. 9869–9874.

[18] Y. Ma, G. Anderson, and F. Borrelli, "A Distributed Predictive Control Approach to Building Temperature Regulation," in *American Control Conference*, 2011, pp. 2089–2094.

[19] F. Oldewurtel, A. Parisio, C. N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, and K. Wirth, "Energy efficient building climate control using Stochastic Model Predictive Control and weather predictions," in *American Control Conference (ACC), 2010*, 2010, pp. 5100–5105.

[20] J. Rehrl and M. Horn, "Temperature control for HVAC systems based on exact linearization and model predictive control," in *2011 IEEE International Conference on Control Applications (CCA)*, 2011, pp. 1119–1124.

[21] M. Vašak, A. Starčić, and A. Martinčević, "Model predictive control of heating and cooling in a family house," in *Proceedings of the 34th International Convention MIPRO, 2011*, 2011, pp. 739–743.

[22] M. Vašak and A. Starčić, "Model Predictive Control of a Heating, Ventilation and Air Conditioning System," in *36th International Convention on Information & Communication Technology Electronics & Microelectronics (MIPRO)*, 2013, pp. 913–918.

[23] J. Cigler and S. Privara, "Subspace identification and model predictive control for buildings," in *2010 11th International Conference on Control Automation Robotics & Vision*, 2010, no. December, pp. 750–755.

[24] L. Ferkl, J. Siroky, S. Privara, and J. Sirok, "Model predictive control of buildings: The efficient way of heating," in *2010 IEEE International Conference on Control Applications*, 2010, pp. 1922–1926.

[25] L. Ferkl, C. Verhelst, L. Helsen, A. Ciller, D. Komarkova, and D. Kom, "Energy savings potential of a model-based controller for heating: A feasibility study," in *2011 IEEE International Conference on Control Applications (CCA)*, 2011, pp. 871–876.

[26] P.-D. Morosan, R. Bourdais, D. Dumur, J. Buisson, and P. Moros, "Distributed model predictive control for building temperature regulation," in *American Control Conference (ACC), 2010*, 2010, pp. 3174–3179.

[27] R. R. Negenborn and J. M. Maestre, "Distributed Model Predictive Control: An Overview and Roadmap of Future Research Opportunities," *IEEE Control Syst.*, vol. 34, no. August, pp. 87–97, 2014.

[28] Z. Liao and A. L. Dexter, "An Inferential Model-Based Predictive Control Scheme for Optimizing the Operation of Boilers in Building Space-Heating Systems," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 5, pp. 1092–1102, Sep. 2010.

[29] P. Radecki and B. Hencey, "Online thermal estimation, control, and self-excitation of buildings," in *52nd IEEE Conference on Decision and Control*, 2013, pp. 4802–4807.

[30] P. Radecki and B. Hencey, "Online Building Thermal Parameter Estimation via Unscented Kalman Filtering," in *American Control Conference (ACC), 2012*, 2012, pp. 3056–3062.

[31] D. I. Mendoza-Serrano and D. J. Chmielewski, "HVAC control using infinite-horizon economic MPC," in *Proceedings of the IEEE Conference on Decision and Control*, 2012, no. 3, pp. 6963–6968.

[32] P. Kret, K. J. Burnham, T. Larkowski, and L. Koszalka, "Control Optimisation of a Domestic Heating System," in *2011 21st International Conference on Systems Engineering*, 2011, pp. 55–58.

[33] K. Lee and J. E. Braun, "Reducing Peak Cooling Loads through Model-Based Control of Zone Temperature Setpoints," in *2007 American Control Conference*, 2007, pp. 5070–5075.

[34] K. Chinnakani, A. Krishnamurthy, J. Moyne, A. Arbor, and F. Gu, "Comparison of energy consumption in HVAC systems using simple ON-OFF, intelligent ON-OFF and optimal controllers," in *2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–6.

[35] A. R. Al-Ali, N. A. Tubaiz, A. Al-Radaideh, J. A. Al-Dmour, and L. Murugan, "Smart grid controller for optimizing HVAC energy consumption," in *2012 International Conference on Computer Systems and Industrial Informatics*, 2012, pp. 1–4.

[36] J. R. Villar, E. D. La Cal, and J. Sedano, "A fuzzy logic based efficient energy saving approach for domestic heating systems," *Integr. Comput. Aided. Eng.*, vol. 16, no. 2, pp. 151–163, Jul. 2009.

[37] R. Alcalá, J. M. Benítez, J. Casillas, O. Cordón, and R. Pérez, "Fuzzy Control of HVAC Systems Optimized by Genetic Algorithms," *Appl. Intell.*, vol. 18, no. 2, pp. 155–177, 2003.

[38] P. P. Angelov, R. a. Buswell, V. I. Hanby, and J. a. Wright, "A methodology for modeling HVAC components using evolving fuzzy rules," in *2000 26th Annual Conference of the IEEE Industrial Electronics Society. IECON 2000. 2000 IEEE International Conference on Industrial Electronics, Control and Instrumentation. 21st Century Technologies and Industrial Opportunities (Cat. No.00CH37141)*, 2000, vol. 1, pp. 247–252.

[39] M. W. Khan, M. A. Choudhry, and M. Zeeshan, "An efficient design of genetic algorithm based Adaptive Fuzzy Logic Controller for multivariable control of HVAC systems," in *2013 5th Computer Science and Electronic Engineering Conference (CEEC)*, 2013, pp. 1–6.

[40] H. Mirinejad, K. C. Welch, and L. Spicer, "A Review of Intelligent Control Techniques in HVAC Systems," *IEEE Int. Netw. Infrastruct. Digit. Content*, pp. 1–5, 2010.

[41] J. Singh, N. Singh, and J. K. Sharma, "Fuzzy modeling and control of HVAC systems – A review," *J. Sci. Ind. Res.*, vol. 65, no. June, pp. 470–476, 2006.

[42] M. Anderson, M. Buehner, P. Young, D. Hittle, C. Anderson, and D. Hodgson, "MIMO Robust Control for HVAC Systems," *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 3, pp. 475–483, May 2008.

[43] S. Purdon, B. Kusy, R. Jurdak, and G. Challen, "Model-free HVAC control using occupant feedback," in *38th Annual IEEE Conference on Local Computer Networks - Workshops*, 2013, pp. 84–92.

[44] J. T. Wen, S. Mishra, S. Mukherjee, N. Tantisujjatham, and M. Minakais, "Building temperature control with adaptive feedforward," in *52nd IEEE Conference on Decision and Control*, 2013, vol. 1, no. 5, pp. 4827–4832.

[45] V. Chandan and A. G. Alleyne, "Optimal Control Architecture Selection for Thermal Control of Buildings," in *American Control Conference*, 2011, pp. 2071–2076.

[46] A. Aswani, N. Master, J. Taneja, A. Krioukov, D. Culler, and C. Tomlin, "Quantitative Methods for Comparing Different HVAC Control Schemes," in *Proceedings of the 6th International Conference on Performance Evaluation Methodologies and Tools*, 2012, pp. 326–332.