REVIEW OF TECHNIQUES TO ENABLE COMMUNITY-SCALE DEMAND RESPONSE STRATEGY DESIGN

ABSTRACT

Incorporating demand side flexibility can aid in integrating intermittent renewable energy generation and reducing the electricity grid's operational costs. Buildings have the potential to provide demand response (DR) with minimal disruption to activities by leveraging the inherent energy storage in their heating ventilation and air conditioning (HVAC) systems. Harnessing this flexibility whilst minimising energy consumption and maintaining thermal comfort requires control strategies capable of incorporating these objectives, making model-predictive control (MPC) a promising framework. To elucidate the control techniques available to harness the HVAC flexibility of collections of buildings to participate in electricity markets, this paper reviews the current state of literature describing MPC techniques for community-scale control.

The reviewed studies were classified based the following characteristics: the general aim of the MPC approach, objective function, thermal response model, amount and type of buildings considered, DR type, control structure, solving tools and techniques, and the energy, cost savings or flexibility achieved. The review shows that MPC strategies can successfully provide many types of DR indicating the versatility of the control approach. Decentralised control approaches reduced the complexity of the large-scale control problem whilst providing more autonomy to individual users. However, compared to centralised approaches, decentralised control led to lower amounts of flexibility. Lastly, few studies validated the performance of their controller in either simulation or physical environments. Therefore, the review suggests further research is needed to study and validate the performance the of different MPC control structures considering various community types and concurrent participation in various DR schemes.

INTRODUCTION

As climate change caused by anthropogenic greenhouse gas (GHG) emissions continues to proceed, the urgency to find means of significantly reducing emissions is apparent (Rogelj *et al.*, 2016). In the UK, 19% of GHG emissions are produced directly at building sites, underlining the importance of decarbonising the sector's energy demand for reducing overall emissions (Committee on Climate Change, 2017). During the past decade renewable energy supply of the UK has substantially increased but more low-carbon electricity will be needed to meet the targets set by the Climate Change Act (Committee on Climate Change, 2017). This access to low-carbon electricity provides an opportunity of decarbonising the UK building sector heating demand by electrification, for example with heat pumps (BEIS, 2017). However, the increase of electricity demand due to electrification combined with the rise of distributed and intermittent renewable energy supply and storage technologies would put strain on the existing electricity grid infrastructure. For this reason, the use of demand flexibility has been recognised for its potential to increase overall system efficiency and avoid grid reinforcements. In the UK, utilising energy storage and demand response (DR) is estimated to save between £17-£40 billion in operation cost over the next 30 years (Carbon Trust, 2017). However, there is much uncertainty in the future capacity available for demand response (DR). Currently the majority of DR in the UK is provided by large industrial processes or through demand side generators. To increase the amount of low cost and low carbon DR, homes and workplaces will need to participate as well.

Demand flexibility in buildings can be incorporated into the electricity system through changes to the retail pricing structures or by acting as traditional generators to provide balancing services (Han *et al.*, 2008; Siano, 2013). In the former, individual buildings receive a time varying price for electricity that discourages use during periods of high demand. In the latter, buildings are actively changing their consumption in response to an external signal from the electricity grid operator. With current regulations and market structures, individual buildings are too small to participate directly in electricity markets. To counter this effect, the role of the aggregator was developed. An aggregator is responsible for coordinating the response of smaller entities to provide one aggregate response from the perspective of the grid operator (Siano, 2013). Therefore, active participation in balancing electricity markets from buildings will require coordination of individual building loads.

Building heating ventilation and air conditioning (HVAC) systems have the potential to provide demand response without affecting the level of service provided, i.e. thermal comfort. This contrasts with demand response by home appliances such as washing machines, lighting, or computers where a delay in use diminishes the level of service provided (Paetz, Dütschke and Fichtner, 2012). Buildings provide a significant source of flexibility due to their inherent capability to store heat, also referred to as the “thermal flywheel” (Haghighi, 2013). The challenge to overcome is to provide flexibility whilst minimising overall energy consumption and maintaining thermal comfort.

The model predictive control (MPC) framework is currently the most promising control strategy for utilising the flexibility of buildings driven by the need to incorporate use of external information and the dynamic effects when making control-decisions (Killian and Kozek, 2016; Clauß *et al.*, 2017). In MPC, a model of the building combined with external data such as weather, grid status, occupancy or energy prices is used to make optimised control-decisions to reach varying objectives. MPC has in many studies been found to be successful in performing better than conventional rule-based control (Killian and Kozek, 2016). MPC thus provides the necessary features required from a control-perspective to both respond to price signals and provide incentive-based DR. However, it has been found that in MPC studies the consideration of flexibility has so far been limited (Clauß *et al.*, 2017). Further, the use of MPC for collections of buildings participating in “flexibility markets” has yet to be reviewed.

Therefore, the aim of this paper is to develop suggestions and recommendations for researchers and practitioners of how modelling and simulation can be used to design MPC based DR strategies for communities considering the recent literature. To achieve this the following objectives were determined:

1. Review recent research of MPC and how it has been utilised for DR in community-scale.
2. Integrate the review results to derive recommendations for designing community-scale DR strategies and prospects for further work.

The main contribution of this paper is a review of the current state of research on MPC of communities of buildings utilised for DR. Moreover, based on the review, recommendations of further work for the modelling and simulation community are developed. Structure of the paper is as follows: first the methodology used for reviews are presented which is followed by a summary of the review results. The paper is concluded with a discussion on prospects for further research.

METHODOLOGY

The methodology used was an integrative review of previously published literature (Torraco, 2005). The review was conducted between December 2017 and April 2018. For searching papers, two search engines were used, Google Scholar and Scopus. Reference lists of reviewed papers from previous reviews were also used. The requirements for review of the papers were that they were published in peer-reviewed journals, conference proceedings or as doctoral theses and that they used MPC to modify the collective response of buildings for DR. Papers were chosen for review based on their relevancy for the review’s topic which was determined by reading abstracts of the paper. If the paper was seen to fill the requirements, it was fully read and reviewed. Special focus was put on recently (post-2010) published literature given the high speed of development which is reflected by the increasing amount of publications within the last decade (Lindelöf *et al.*, 2015). The final set of papers were reviewed to highlight important aspects of MPC and community scale design of demand response techniques.

During the review aspects relevant for designing community-scale MPC strategies were investigated to differentiate between the studies. A key component in MPC design is defining the underlying model used by the controller to predict the building's thermal response to the HVAC system. Building thermal response models are typically classified by their level of physical representativeness. White-box models are detailed physics-based models requiring detailed knowledge of the underlying system, for example an EnergyPlus model. Grey-box models are simplified models based on the underlying physical interactions such as resistance-capacitance (RC) networks where parameters are typically determined by using measured data from the building. Black-box models like artificial neural networks are not based on physical characteristics and are purely reliant on the data and methods used when identifying the system (Li and Wen, 2014). Each of these techniques has different data requirements, either full knowledge of the physical characteristics or time-series data of building's thermal response, both of which have implications for community-scale modelling.

For understanding the scope and differences between different studies, the amount and type of buildings is relevant. For example, different DR schemes might be more suited for commercial buildings and others for residential buildings. Aggregators could also utilise the natural differences between buildings by utilising their occupancy patterns or differences in HVAC systems for example. Due to the interest in DR differentiation of different DR types is needed. Differentiation between different DR schemes can be made based on how the flexibility is delivered. In price-based DR participants are exposed to normally pre-known price-signals and then those willing and capable react to them by shifting consumption from high- to low-cost hours, i.e. energy arbitraging. This can be done with different pricing schemes, for example peak pricing, time of use tariffs or fully dynamic pricing. In incentive-based DR participants receive separate incentives for delivering DR. Incentive-based DR can be used to provide services important for maintaining grid reliability, typically referred to as ancillary services. DR required for these services ranges over different timescales, from controlling grid frequency requiring reactions within seconds to managing peak demand or imbalances where implementation can be done in minutes to hours. A third type of DR is demand bidding where participants are engaged in a bidding process by exchanging bids of compensation for delivering flexibility. The variance in DR types naturally poses requirements on the MPC design. This type of DR is also reflected in the objective function of the MPC optimisation formulation. (Han *et al.*, 2008; Siano, 2013)

For collections of buildings or other complex systems, structures of control schemes, i.e. how control decisions are made and relate to individual or collective control objectives, are important since they pose requirements to communication infrastructure and cyber-security. Consideration of control structure is especially important for aggregators as they need to manage distributed resources and ensure consumer satisfaction. Control structures can either be centralised, decentralised or hierarchical which here are used to refer to where and how the control decisions are made (Tindemans, Trovato and Strbac, 2015; Reynolds, Rezgui and Hippolyte, 2017). A structure where control decisions are made by a central party with knowledge of the states of sub-systems such as apartments or homes is considered centralised. The opposite is decentralised where control decisions are made by individual controllers with minimum communication of their states with other parties. Hierarchical structure refers a structure where decisions are made in different levels. For example, a higher party in the hierarchy defines the requirements or objectives which are then left for lower level controllers to fulfil according to strategies of their choosing.

In MPC, design simulation of the MPC together with the building response is often necessary to understand how a given MPC strategy would work within a building. This process of separately simulating the controller and the building is referred to as co-simulation, typically involving coupling different software, such as EnergyPlus and Matlab, with each other (Wetter *et al.*, 2014). In the example of EnergyPlus and Matlab, EnergyPlus model represents the real building response while Matlab is used to run the MPC operation and submit the EnergyPlus model the control inputs while receiving data from the building. This way the interaction between a controller and a building can be inspected. Another approach to design control strategies is to simulate operation of the controller without simulating response of the building. This approach is typical if research focus is on designing the control algorithm and ensuring the stability and efficiency of the controller. The goal of design naturally is the implementation of MPC strategies in real buildings for which experimental research is required.

Therefore, the reviewed studies were classified based the following characteristics: the general aim of the MPC approach, objective function, thermal response model, amount and type of buildings considered, DR type, the control structure, solving tools and techniques, and the energy, cost savings or flexibility achieved.

Table 1: Summary of reviewed publications on model-predictive control and demand response.

Reference	Aim	Objective function	Building thermal response model	Nr. and type of buildings	DR Type	Control structure	Method, tools and solvers	Results and comments (energy savings+DR)
(Tang *et al.*, 2018)	To evaluate aggregate response capacity of load aggregators with varying populations of loads (electric vehicles, storage and appliances) and allocate respective balancing requirements to different load aggregators.	Low-level: minimise cost and comfort violations	Grey-box, low-order physical model	250 residential loads	Incentive-based, balancing service	Hierarchical	Control simulation	When considering thermal comfort, amount of flexibility declines as DR event lasts longer. Comfort bands and initial states have large effect on the flexibility.
(Corbin and Henze, 2017a)	To employ residential HVAC systems with MPC for grid management by utilising reference supply curves based on varying shares of renewables. To achieve this feeder-level models based on RC-models of buildings were utilized.	Minimise difference to a reference demand profile.	Grey-box, RC model	Three cases, with 1506, 1326 and 2146 residential buildings	Incentive-based, balancing service	Decentralised	Co-simulation, MPC and GridLAB-D, EnergyPlus, Particle Swarm Optimisation	Overall energy consumption increased with DR and MPC, however peak to valley ratio as well as ramping reduced in all cases. Absolute peak energy demand was reduced.
(Corbin and Henze, 2017b)	Evaluation and validation of distribution feeder models based on RC building models as residential loads. MPC used to reduce peak demand of feeders in the grid by changing set points of HVAC systems.	Minimise peak electricity demand	Grey-box, RC model	Three cases, with 1506, 1326 and 2146 residential buildings	Incentive-based, peak load management	Decentralised	Co-simulation, MPC + GridLAB-D, EnergyPlus, Particle Swarm Optimisation	Proposed distributed control scheme was able to reduce peak energy demand in all simulated cases. Even without communication between buildings the feeder and MPC show alignment with the objective.
(Nghiem and Jones, 2017)	To manage a collection of buildings for DR by determining their response to load tracking signals with a data-driven approach.	Minimise tracking error to the reference demand curve.	Data-driven, Gaussian regression model	3, commercial	Incentive-based, balancing service	Hierarchical	Co-simulation, Matlab + EnergyPlus, IPOPT	System successfully tracked reference demand - Flexibility increased as MPC horizon was increased.
(Perez, Baldea and Edgar, 2016)	Reduce peak load demand of a community by centralised control of community's HVAC and time-shiftable home appliances with MPC. MPC used for determining optimum HVAC set points and scheduling home appliances.	Minimise peak energy demand	Black-box, ARX a linear regression model	40, residential	Incentive-based, peak load management	Centralised	Control simulation, GAMS, CPLEX	Daily peak load reduced 25.5% on average by adjusting setpoints and scheduling appliances. Scheduling reduced load by 5.1% on average over a simulated week. HVAC provided 18.8 % of the reduction.
(Liu and Shi, 2014)	To design a MPC for population of thermostatic loads for ancillary services without violating comfort by operating within dead-bands. Two tracking signals differing in variability (hourly and minute by minute) compared.	Minimise tracking error while respecting comfort, weighed error function	Grey-box, RC model	1000 thermostatic loads	Incentive-based, balancing service / frequency response	Centralised load tracking	Control simulation, Matlab.	The proposed MPC followed the reference profile well. Lockout time increase compromises the tracking capability a bit. More significant negative effect observed if the dead-band is reduced.
(Tindemans, Trovato and Strbac, 2015)	To design a decentralised MPC structure for thermostatic loads for reacting to grid frequency changes while considering services with longer time-scales. Each load constructs individual reference power curves which are adjusted based on frequency.	Minimise tracking error to a reference power curve.	Black-box, First order linear model	100000 thermostatic loads	Incentive-based, balancing services / frequency response	Decentralised	Control simulation	The presented decentralised control scheme was introduced and shown to being capable of following a reference power curve enabling flexible delivery of DR in different time-scales.
(Cole, Morton and Edgar, 2014)	Designing an economic MPC within homes for reducing overall peak demand. To achieve the wanted response optimal individualised price signals for smoothing peak demand computed and employed.	Economic objective function to minimise community peak energy demand.	Black-box, ARX a linear regression model	900 residential	Dynamic pricing, peak pricing	Hierarchical	Simulation, MATLAB CLP algorithm in the OPTI toolbox	8.8 % peak reduction with centralised solution, increase in energy consumption 13.3 %. Decentralised solution achieved 7.7 % peak load reduction. Use of optimized pricing provides a good fit for the community compared to the centralised solution. More energy efficient homes were offered lower peak prices by the MPC.
(Khadgi, Bai and Evans, 2014)	MPC framework used for controlling air conditioning to model consumer behaviour under dynamic pricing. Dynamic prices determined based on ambient temperature and total consumption to simulate market operation.	Maximise utility functions of consumers.	Black-box, Linear regression model	25, residential	Dynamic pricing	Decentralised	Simulation, SIMIO	Focus on consumer behaviour, MPC only used to conceptualise this behaviour. Depending on the pricing structure as well as the weighed utility functions the different agents differed in response.
(Borsche, Oldewurtel and Andersson, 2014)	To control electric water heaters to provide demand response. Both day-ahead planning and intra-day adjusting of heater scheduling was made to track a reference demand and reduce cost. Scenarios used to account for uncertainties in forecasts.	Minimise cost of energy and deviation from reference demand	White-box, steady-state electric water heaters modelled.	2000 loads	Dynamic pricing and intraday trading	Hierarchical, centralised computation of schedules	Simulation	26 % cost saving with the scenario-based approach compared to only considering day-ahead schedules. Sensitivity of costs to scenarios can be observed but is limited.

Reference	Aim	Objective function	Building thermal response model	Nr. and type of buildings	DR Type	Control structure	Method, tools and solvers	Results and comments (energy savings+DR)
(Cole *et al.*, 2014)	MPC designed to adjust set points of HVAC to reduce peak demand. Different objective functions and effects of decentralisation considered. Community model created by utilising data from real homes.	Minimise electricity cost or peak energy demand	Black-box, reduced order linear model, ARX	900, residential	Dynamic pricing, peak load manageme nt	Decentralis ed + centralised	Control simulation, MATLAB, EnergyPlus+ BEOpt for model creation used	On average during summer the peak was reduced by 2.7%, total cost savings were 5-7%. Centralised controller reduced peak by 8.8%, decentralised by 5.7%. With penalty cost structures, the peak demand was reduced by 7.7 % by the decentralised controller.
(Vrettos *et al.*, 2013)	Minimise deviation of a balancing group from its obligation by employing centralised and decentralised MPC in buildings under the aggregator. Objective is to reduce added costs from balancing power.	Minimise costs from balancing power.	Black-box, linear regression model	32 office buildings with varying systems	Dynamic pricing	Centralised and decentralis ed	Control simulation	Centralised scheme provided 100 % reduction in balancing costs, decentralised 55 %. However, actual electricity costs increased in the decentralised scheme. In centralised control small electricity cost saving was achieved.
(Lu, 2012)	Direct load control of HVAC units to track reference demand curves constructed based on grid frequency or the load following signals. DR delivered by cascading on-off switching of units while operating within dead-band	Tracking of a reference demand within dead band	Grey-box, RC model	1000 thermostatic loads	Incentive-based, balancing service / frequency response	Centralised	Control simulation	1000 HVAC units were capable of tracking a reference load profile while respecting comfort. Ambient temperature could cause issues with comfort.

SUMMARY OF REVIEWED PAPERS

Table 1 summarizes results of the review of research on MPC and DR. In total 13 papers were included in the review assessed by using the methodology described. Papers in the table are arranged chronologically. The following sections summarise the findings within the observed characteristics found through the review shown in the table.

Among the reviewed studies the aims of using MPC varied. Some studies focussed on evaluating the aggregate flexibility capability for DR whereas some looked at designing the MPC strategies and algorithms. Approaches varied depending on the objective and DR type. Different exogenous streams of time-varying data such as pricing, weather forecasts and grid status were utilised depending on the control approach and objectives. Also, the controlled loads varied. For example, one of the studies looked into populations of loads with electric vehicles, air conditioning units and water-heaters while several control-oriented studies considered thermostatic loads in general (Tang *et al.*, 2018). Differing aims reflected on the models used and results presented. Specifically, Corbin and Henze, 2017a, 2017b, in their model considered the effects of power quality in grid-level operations while some others omitted such considerations.

Within the objective functions, the goal of minimising costs was most common, especially in DR based on dynamic pricing which seems natural. Cole, Morton and Edgar, 2014 examined also the question of how to create optimum price signals to manage peak load. In studies where incentive-based DR was considered, minimising cost or tracking error or a combination of these were used. The chosen objective function would reflect the general approach chosen to deliver DR, for example in DR requiring fast-response times tracking of a reference demand profile was prominent. Most MPC formulations took comfort into account either within the objective function or constraints of the optimisation problem. For example, Khadgi, Bai and Evans, 2014 used weighed utility functions to capture different goals of consumers by assigning weights on metrics such as energy cost and comfort.

With respect to the thermal modelling approach, most studies used linear grey-box or black-box models to allow effective optimisation and system identification. In studies that used grey-box RC models, it was suggested that they offered a reasonable way of compromising between white-box models requiring detailed knowledge about the building and black-box models needing large amount of operational data for identification. Existing tools and methods for creating and identifying RC-models further supports their use. In black-box models reduced order linear formulations were very popular, especially the auto-regressive model with exogenous inputs (ARX). In many of the studies uncertainties in predictions were omitted to simplify the demonstrations. However, the role of uncertainties has been acknowledged as scenario-based and probabilistic MPC formulations addressing uncertainty have been applied (Borsche, Oldewurtel and Andersson, 2014; Nghiem and Jones, 2017).

Within studies focussing on control design and grid-scale implications, the use of MPC on hundreds or even thousands of individual loads of varying kind have been simulated. These studies typically focussed on the control algorithm design without considering the response of the building. Co-simulations or experimental studies of collections of buildings utilising MPC are limited in numbers. Only one co-simulation study looking into response of a collection of three residential buildings considered incentive-based DR (Nghiem and Jones, 2017). Price-based DR was considered in two papers studying grid-level impacts by using RC models in a decentralised MPC scheme (Corbin and Henze, 2017b, 2017a). No studies experimenting or simulating the response of communities consisting of collections of buildings of different use-types, like residential and commercial, were found.

All reviewed papers looked into either incentive or price-based DR. None of the studies investigated demand bidding i.e. engaging in a system with bids of flexibility, most probably reflecting the types of DR schemes used in energy markets currently. Within price-based approaches different kinds of pricing schemes were utilised, for example critical peak pricing, more traditional time of use tariffs or hourly dynamic pricing similar to wholesale markets. In MPC formulations created for price-based DR, the time-scales of the control horizon were typically longer since price signals varied hourly and day-ahead prices were used. This allows MPC aiming to reduce cost to implement pre-cooling or heating strategies before high cost hours (Cole *et al.*, 2014). One study considered a scheme where an aggregator faced dynamic spot pricing and balancing costs simultaneously, here classified as price-based DR (Vrettos *et al.*, 2013). In incentive-based DR schemes, it was typical to introduce a more direct approach of load control where controllers aimed to follow a reference demand and allow reactions within minutes or seconds. However, one of the studies considered the aspect that reference demand profiles could be created by also considering for example hourly energy prices (Tindemans, Trovato and Strbac, 2015). Studies explicitly simulating communities participation simultaneously in price- and incentive-based DR were lacking.

Only two studies investigated how varying the structure of the control problem affected the outcome. Decentralisation or decoupling of the control problem was found to reduce the total performance in terms of DR but was still able to deliver benefits while maintaining numerical tractability (Cole, Morton and Edgar, 2014). However, in another study it was found that a decentralised control structure increased the balancing electricity costs compared to a centralised controller (Vrettos *et al.*, 2013). The motivation for designing hierarchical or decentralised control structures were driven by reduced need for communicating data to a central party and potential to effectively control varying types of loads (Tindemans, Trovato and Strbac, 2015). To allow pursuing targets relevant for parties like utilities and aggregators such as reducing peak demand of a community, hierarchical or centralised structures were still popular, although this would require gathering and storing relevant data for the operating the centralised MPC.

Most of the studies looked only into simulating the control operation and did not test the building's response to the controls. Only one of the studies performed co-simulation with a dynamic building energy simulation software EnergyPlus and Matlab (Nghiem and Jones, 2017). Also, co-simulation studies with grid simulation software GridLAB-D has been made (Corbin and Henze, 2017a, 2017b). Overall, Matlab was a common tool but also GAMS and SIMIO have been applied. For model creation, BEOpt together with EnergyPlus was used in one of the papers (Cole *et al.*, 2014). Some of the studies did not explicitly mention software or optimisation methods used. In the reviewed research, particle swarm optimisation, interior point optimiser (IPOPT), CPLEX and CLP were used to solve the optimisation problems. Their use depended on the mathematical nature, e.g. linear, nonlinear, mixed integer, of the system of equations to be solved. No experimental studies conducted on studying collections of buildings operated together were found, reflecting on the general difficulty and high costs of such experiments.

The reviewed studies show a consensus in the potential and flexibility of MPC to provide energy savings and different DR services ranging from price- to incentive-based. Benchmarking was typically done against a Proportional-Integrative (PI) or some other rule-based controller. In general, when DR was delivered, total energy consumption increased. Most studies reported some form of positive cost savings too. However, comparisons are rather difficult due to the differing underlying assumptions and conditions between the studies. Also, metrics in the delivered DR varied depending on the DR scheme chosen. For example, some considered metrics such as peak demand or error to a reference profile while other studies focussed on cost savings. Aspects like building thermal characteristics were found to have impact to the deliverable DR and cost savings (Cole, Morton and Edgar, 2014). Also, uncertainty in external data and predictions done by MPC affected the results (Borsche, Oldewurtel and Andersson, 2014).

Overall, the review provided interesting insights on the current state of community-scale MPC and DR research. For MPC to become widely used there is a need to further test MPC strategies in real buildings as the amount of experimental research is still low. Control-oriented research seems to provide algorithms and strategies designed for collections of thermostatic loads but without simulating the response of buildings to develop understanding of their effects on physical conditions and aspects like thermal comfort. To investigate these co-simulation or experimental work would be more suitable. The variety in MPC formulations demonstrates versatility of the framework, necessary for implementing different DR schemes in buildings. However, the use of MPC in collections of buildings to deliver incentive-based DR while subjected to dynamic pricing as well as studying the implication on varying control structures has not been studied extensively. Also, studies with comparisons of communities with varying structures, residential, commercial or mixed, were not found.

DISCUSSION

Reviewed research provides a picture of the current state of MPC research and how it is applied to solve different kinds of problems. Two lines of research in MPC emerged, one being research focussing on control algorithms while the other looking into the implications of MPC for grid operators and aggregators. In general, the research demonstrates that if well-designed MPC can be used effectively to enable flexibility provision within communities for DR. However, as the results show, DR programmes might conflict with local energy savings and thermal comfort objectives. An important consideration for implementation and pursuing community-wide objectives is the control structure and its effects on the communication and data gathering. Decentralised control approaches reduced the need for communicating data but were also found to reduce the control performance compared to a centralised control structure. However, the research has so far not considered co-operative decentralised approaches but rather decomposing a centralised optimisation problem into independent controllers.

Furthermore, the review demonstrates that testing of the performance of community-scale DR strategies through co-simulation or experimental studies are lacking. To understand effects of community-wide implementation of MPC strategies, dynamic simulations of communities would allow to build understanding of how varying types of communities could be utilised together and what implications that might have within the buildings. Of the studies that did perform co-simulation strategies, no automated methods for parameter identification of grey- or black-box models were used. This is an important aspect of MPC design as the identification of the underlying thermal response model must be performed repeatedly and systematically. Further, as many energy service providers are aiming to shift towards dynamic pricing, future research should consider how incentive-based DR would be affected under such constraints. Comparing control structures also requires also attention to understand their impact on the communities and capability to deliver different types of DR. Filling these gaps in knowledge would support future community-scale experimental research which was not found within the literature reviewed.

From the review, it is recommended that further research on community-scale DR strategies utilising co-simulation is made for understanding dynamic effects of implementation of MPC strategies for DR within buildings. Co-simulation could also be used to develop automated methods for creating effective methods for creating and identifying MPC models. Research of utilisation of communities for DR in the UK context could be used to demonstrate capabilities of novel centralised and decentralised MPC techniques allowing community participation in incentive-based DR via aggregators while improving comfort and energy efficiency.

CONCLUSION

In this paper an integrative review of recent MPC literature focussing on DR was made to develop recommendations for future research of community-scale DR strategy design. The review of MPC and DR research showed that further community-scale simulation studies are required to understand how communities would respond to implementation of MPC strategies for DR. Research on aspects relevant for community-scale control design such as how different control structures differ in delivering DR as well as combining price- and incentive-based DR schemes together are also lacking.

Furthermore, research on how the structure of the community affects the potential flexibility for DR is needed. It is recommended that co-simulation of communities is used to design new MPC strategies to study interplay of different control structures, community type, service level and participation in different types of DR.

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