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Demand side flexibility coordination in office buildings: A framework and case study application

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ABSTRACT

The transition from the traditional electrical power grid to the smart grid calls for a paradigm shift to accommodate bi-directional flow of power, information and the use of available useful flexibility between consumers, their buildings, and the grid. As buildings are considered a potential source of demand side flexibility it therefore becomes paramount that measures be put in place to ensure the useful building flexibility is delivered to the smart grid. However, this should be done without compromising the traditional functionality of buildings, which includes safety, thermal comfort and maintaining an acceptable indoor air quality. In this paper, through a systematic review of relevant literature, requirements for coordinating the interaction between building’s useful energy flexibility and the grid are outlined. Secondly, based on performance analysis and measurements from an averaged sized test case office building, the useful flexibility for grid services is quantified. Thirdly, an autonomous coordination framework for leveraging the useful demand side flexibility from buildings is proposed.

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1. Introduction

In an effort to address the growing demand for energy in a sustainable and environment friendly manner, the last three decades has heralded a global increase in proliferation of renewable energy sources (IRENA, 2015) as well as increased effort to modernize the grid to a smarter and greener grid (Siano, 2014; Tuballa & Abundo, 2016). Smart grids are power networks that intelligently integrate connected entities (end-users, producers, prosumers) using comprehensive information and communication infrastructure (Andreotti et al., 2016; Tuballa & Abundo, 2016).

Specific advantages of the future smart grid include: ability to be greener as a result of renewable energy sources (RES) integration, increased quality of market interactions with connected infrastructure, reduced investments on grid reinforcement, accelerated power outage restoration and dynamic energy balancing to achieve operational efficiency (Farhangi, 2010; El-Hawary, 2014; Sloatweg, Member, & Morren, 2011). Demand side management (DSM) is one of the pivotal technologies in the development of smart grid and is particularly important for realization of end user energy efficiency, flexible load management and overall cost reduction (Macedo, Galo, Almeida, & Lima, 2015; Zhao & Tang, 2016). However, operation of DSM schemes are greatly affected by physical and informational uncertainties (Mathieu, 2015; Ruiz-Romero, Colsenar-Santos, Gil-Ortego, & Molina-Bonilla, 2013; Sankar, Raj Rajagopalan, Mohajer, & Vincent Poor, 2013). Therefore, the transition to the smart grid requires not only a two way flow of power and information, but also a two way flow of flexibility between the end user and utility supplier (Kolokotsa, 2015).

Power systems flexibility is the ability to continually balance electricity supply and demand with negligible disruption to service for connected loads often in response to variability in RES based generation (Ulbig & Andersson, 2015). Power systems flexibility can be derived from supply-side or demand-side resources (refer to Fig. 1).

Supply side power flexibility uses dedicated conventional power plants or supply side storage to balance mix-match in electricity production and demand within systems’ operations guidelines (Cochran et al., 2014). Sources of supply side flexibility include supply side energy storage, power transmission curtailment and dedicated power response plants (Lund, Juuso Lindgren, Mikkola, & Salpakari, 2015).

Demand side flexibility (DSF) refers to the use of demand side installations (such as storage after the traditional power meter and other connected loads) to intelligently balance power demand and available supply without diminishing design intended functionality (Lund et al., 2015; Ulbig & Andersson, 2015). DSF is currently under the spotlight due to two main benefits associated with it. First, the use of DSF is more cost effective as it forestalls investment in new standby power plants and limits operational expenses for existing ones by improving reliability (Mohagheghi, Stoupis, Wang, & Li, 2010; Xue, Wang, Yan, & Cui, 2015). Second, DSF is associated with resultant high energy sustainability as it allows for greater efficiency of available resources whilst also enabling use of RES (Labeodan, Aduda, Boxem, & Zeiler, 2015; Xue et al., 2015). The interest in DSF will continue to rise as more incidences of power flexibility requirement are expected with increased RES integration in electricity supply chain management (Kondziella & Bruckner, 2016; Lew et al., 2013).

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1.1. Importance of office buildings as a power flexibility resource

DSF can be derived from residential buildings, industrial buildings and non-residential buildings (including offices) as shown in Fig. 1. Whilst the flexibility from industrial is significant (Aslam, Soban, Akhtar, & Zaffar, 2015), it is misleading to assume that consumption from both sectors alone would translate proportionately to DSF potential. Realization of DSF from industrial sector must contend with two main challenges. First, industrial processes need continuous and reliable power supply to prevent heavy commercial losses and maintain safety (Noor, Thornhill, Fretheim, & Thorud, 2015); therefore, their co-option as DSF resource requires careful on-site management. Secondly, industrial processes are very complex; for example some occur on real time basis and at times produce energy as a by-product (Ding, Hong, & Li, 2014). Consequently, the use of industrial sector installations as DSF resources becomes equally complex.

The use of residential buildings for power flexibility is also hampered by requirement for elaborate information exchange infrastructure as a result of large number of load entities involved and their associated relatively small size (Hong et al., 2015a). As a result, DSF coordination for residential buildings becomes complicated taken that the process is hierarchically structured with stepwise aggregations from local energy contractors, distribution and transmission service operators (Siano, 2014).

The challenges associated with the industrial and residential sectors makes commercial office buildings seem relatively more viable as an alternative source of flexibility of power flexibility (Samad, Koch, & Stluka, 2016; Mathieu, Dyson, & Callaway, 2012). Consequently, with the right strategy non-residential buildings (including offices) appear to be best suited as DSF resources. There are 3 main reasons that make commercial office buildings an important focus for DSF studies. First, buildings in the European Union area and the United States of America account for up to 40% of total primary energy with a significant portion dedicated to heating, ventilation and air condition (HVAC) systems in commercial buildings (Cao, Dai, & Liu, 2016; Lin, Barooah, & Mathieu, 2015). HVAC systems in buildings are useful for DSF services with supply air fan for fast response services (Maasoumy, Rosenberg, Sangiovanni-Vincentelli, & Callaway, 2014) and chillers for both slow and fast response services (Maasoumy et al., 2014). Second, commercial buildings are mostly equipped with automation control systems which makes it easy for implementing additional control algorithms required for DSF actuation (Hao et al., 2014; Lin et al., 2015). Last, commercial buildings mostly have sign high thermal inertia that can be utilized as energy reservoir for short periods of time (Lin et al., 2015).

1.2. Contribution of this paper

The recent interest in office buildings as a power flexibility source (Samad et al., 2016; Mathieu et al., 2012) necessitates new ways of thinking in building operations and management. Specifically, the shift in thinking in building operations and management should be with respect to two main issues. First, it is no longer only sufficient to be energy efficient in operations but also important to dynamically synchronize operations between buildings (including occupants and installed systems) and power system domains to cooperatively gain
optimal energy and comfort performance (Lund et al., 2015; Palensky, Dietrich, & Senior Member, 2011; Bulut et al., 2016). Second, participation of buildings in grid support activities might at some point conflict with dedicated primary role towards their occupants thus requiring innovative tradeoffs in control actions (Shaikh et al., 2014; Shaikh, Mohd Nor, Nallagowdren, & Elamvazuthi, 2016). The mentioned trade-offs have to be dynamic and should ideally take into account both prevailing states and anticipatory future states of energy and comfort (Aduda et al., 2016).

As a consequence of the new thinking required in operations and management during use of buildings as power flexibility resources, innovative coordination of the ‘building’ and ‘power’ domains becomes of paramount importance. Implementation of DSF without concern for the primary function of associated resource may be complicated by underlying internal reliability issues (Shoreh et al., 2016). For office buildings, labour and productivity costs that are often higher than electrical energy costs (Alker, Malanca, & Pottinge, 2015). In addition, installed building services plants also have to adhere to manufacturer’s control specifications and operational guidelines (Wang & Martinez, 2014). To manage consequential challenges of using office buildings as DSF, this paper proposes a coordination framework that optimally balances building side performance and power grid support requirements.

There are two specific contributions of this study. First, utility function as the basis for coordinating transactional control for DSF activation without jeopardizing the primary role of the building is proposed. The proposal is important given that past studies have noted apparent inability of current building control systems for transactional interactions with the power markets (Labeodan et al., 2015; Mathieu et al., 2012; Xue et al., 2015). Requirements for building centric DSF coordination framework in office buildings are also outlined with the proposal. Building centricity takes into account building performance characteristics and parameters along with power demand and energy use characteristics during DSF coordination.

Specifically, thermal comfort, indoor air quality (IAQ), comfort recovery periods, availability periods, comfort response systems, power demand, power demand reduction or increase and energy delivered or energy used during DSF episodes are all considered. Consideration of identified building performance characteristics is instrumental in balancing local demand and power grid support requirements (Shaikh et al., 2016). This is an improvement from the trend whereby DSF coordination frameworks emphasize power grid performance at the expense of building performance as evident in Rajeev and Ashok (2015), Abdusalama et al. (2012), and Puchegger (2015). Second, using an averaged sized office building equipped as test bed, useful power flexibility available for grid support is quantified for duty cycling of operations of installed air supply fan and cooling system. Given the lack of empirical studies mentioned by Siano (2014) and Siano and Sarno (2016), this approach provides necessary knowledge base for calibration of building systems in event of their use as DSF resource.

The scope of this study is limited to spring and summertime operations of office buildings. Practical analysis in the study is with respect to duty cycling operations of installed air supply fan and cooling systems to take advantage of dead-band control area for energy performance improvements in line with Ghaemami et al. (2016) and Zhang and de Dear (2015). There are 5 further sections in the paper. Section 2 outlines literature survey results on DSF coordination in buildings. Section 3 reports on methodological approach in the study. Section 4 discusses results from case study monitoring and experiments. Details of proposed coordination framework and associated considerations for the case study application are presented in Section 5. Conclusions of the study are outlined in Section 6.

2. Literature survey

2.1. Survey methodology

Literature survey methodology for the study was motivated by approach in Ruparathna, Hewage, and Sadiq (2016). The survey methodology was based on the following:

1. Literature search on two major online databases (IEEE Xplorer and Science Direct) using the queries: control in demand side management, power flexibility control, demand side flexibility coordination in buildings. The search was restricted to articles published in the last 6 years.

2. Initial search on the IEEE Xplorer database yielded 4191 results. Inclusion for review was further restricted to studies by authors with at least 4 papers published in the database; this ensured better manageability, consistency and a measure of repeatability, and ensure a measure of repeatability and consistency. Next, filtering of literature search results was done using key words: buildings; electricity and energy; this yielded a total of 35 papers. The search in IEEE Xplorer database was restricted to the following conference proceedings and journals: IEEE Transactions on Power Systems; 2012 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies; IEEE Transactions on Smart Grid; IEEE Transactions on Sustainable Energy; IEEE Transactions on Engineering Management; 2013 4th IEEE/PES Innovative Smart Grid Technologies Europe and IEEE Transactions on Industrial Informatics and 2011 44th Hawaii International Conference on System Sciences.

3. Review of studies from Science Direct database was restricted to studies published in the following journals: Applied Energy, Buildings and Environment, Energy and Buildings, Energy, Renewable and Sustainable Energy Reviews, Sustainable Cities and Society, and The Electricity Journal. A total of 40 papers resulted after applying topical limitations to energy, building, energy consumption, renewable energy, energy system, energy management, smart, DSM, electricity and power.

4. Additional studies in DSF were included as long as they were considered to have milestone contributions.

5. After reading abstracts for the resulting studies, studies that did not directly focus on building control, load management, demand side management, demand side flexibility and power flexibility were excluded. Also excluded were studies with singular focus on building performance, energy policy and market issues, methodological techniques, renewable energy systems’ performance and environmental sustainability. Table 1 presents a summary of literature survey results.

6. To derive the themes presented in Table 1, papers with similar objectives or focus areas were classified according to domain of study in a first step; this yielded residential buildings versus those on industrial sectors and commercial buildings. Four dominant themes emerged, namely

(1) Demand side control,
(2) Approaches in demand side flexibility coordination,
(3) Pricing in demand side flexibility, and
(4) Utility value considerations for participating buildings.
Table 1 Overview of literature survey results for demand-side flexibility.

<table>
<thead>
<tr>
<th>Classification criteria</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>(Heussen et al., 2012; Koek et al., 2013; Wang &amp; Martínez, 2014)</td>
</tr>
<tr>
<td>Direct</td>
<td>(Aghaei et al., 2015; Ahmad Khan et al., 2016; Borsche, Oldewurtel, &amp; Andersson, 2013; Good, Karangelos, Navarro-Espinosa, &amp; Mancarelli, 2015; Heussen et al., 2012; Khan et al., 2015; Korkas et al., 2016; Koek et al., 2013; Li et al., 2013; Lu, Wang, &amp; Shan, 2015; Mekonnen et al., 2012; Moghaddam, Saniei, &amp; Mashour, 2016; Siano &amp; Sarno, 2016; Sando &amp; Sarno, 2016; Vivekananthan et al., 2014; Yamine et al., 2012)</td>
</tr>
<tr>
<td>Power</td>
<td>(Colak et al., 2016; Ding et al., 2015)</td>
</tr>
<tr>
<td>Control</td>
<td>(Ottesen, 2015)</td>
</tr>
<tr>
<td>Indirect</td>
<td>(Ahmad Khan et al., 2016; Badawy et al., 2013; Caraiscos, et al., 2014; Deheuvels, et al., 2011; Kofler et al., 2012; Kovacic &amp; Giampietro, 2013; Kofler et al., 2012; Korkas et al., 2016; Mekonnen et al., 2012; Safaei &amp; Rahimi-Kian, 2015; Safaei &amp; Rahimi-Kian, 2015; Siano, et al., 2013; Tsacikaraouglu et al., 2014; Theo et al., 2016)</td>
</tr>
<tr>
<td>Coordination</td>
<td>(Amputuzis, Nguyen, &amp; Kling, 2013; Asare-Bediako, Kling, &amp; Ribeiro, 2013; Badawy et al., 2013; Batla-Ozkan et al., 2013; Colak et al., 2016; Ding et al., 2014; Graditi et al., 2015; Kim &amp; Shcherbakova, 2011; Kohler et al., 2012; Kovic &amp; Giampietro, 2015; Markovic et al., 2013; Maruf et al., 2013; Siano, et al., 2014; Tascikaraouglu et al., 2014; Theo et al., 2016)</td>
</tr>
<tr>
<td>Pricing and demand side</td>
<td>(Ruparathna, Hewage, &amp; Sadiq, 2016; Aslam et al., 2015; Depoorter, Oró, &amp; Salom, 2015; Entrop, Brouwers, &amp; Reinders, 2010; Kohler, 2014; Rokach, 2010; Thakur &amp; Chakraborty, 2015)</td>
</tr>
<tr>
<td>flexibility</td>
<td>(Ciillé et al., 2007; Denguir et al., 2012; Kim, 2013; Ygge et al., 1999)</td>
</tr>
<tr>
<td>Utility value</td>
<td></td>
</tr>
<tr>
<td>consideration</td>
<td></td>
</tr>
</tbody>
</table>

Section 2.2–2.6 discuss results along the 4 themes mentioned.

2.2. Demand side control

Power systems network and the building domains both have independent control systems; these have to be coordinated to effectively deliver DSF.

Power grid control aims at ensuring continuous, safe and reliable connectivity to electricity supply with respect to contracted quality and established norms. For power systems, control of demand side is either direct or indirect. During direct control, operational instructions are issued by power network to demand side resources based on a prior contractual agreement (Ifland, Exner, & Westermann, 2011). Indirect control methods entails use of power systems generated signals to indirectly influence energy trajectory in buildings (Heussen et al., 2012); this approach ensures participating buildings in DSF schemes retain a measure of autonomy in decision making and local details are comprehensively considered. Direct control is mostly used for very fast DSF services whereas indirect control approaches tend to be dedicated for slow demand side flexibility requirements (Lund et al., 2015).

For modern commercial buildings, control is coordinated by a building management system (BMS). BMS ensure supervisory control and coordination of classical or intelligent local controllers to ensure optimal safety, comfort and sustainable energy use in buildings (Shaikh et al., 2014). The traditional objective of control in building is to achieve safety and climatic regulation of the building to maximizes comfort levels with realistic energy efficient operations (Dounis & Caraiscos, 2009). Even with participation in DSF activities, the traditional control objectives of the buildings have to be fulfilled. Therefore, effective coordination between the building control and power control is crucial as a way of synchronizing respective operational objectives of building and power systems domains during DSF events.

It is also observed that power systems domain sometimes require very fast control time response (seconds to one minute) during DSF episodes (Hao et al., 2014). On the other hand control response times for fans and cooling systems buildings are relatively slow (couple of seconds to several minutes) as indicated in Beil, Hiskens, and Backhaus (2016). Subsequently, effective DSF coordination strategies are needed to ensure that the slow response time characteristics of building systems are used to optimally support power grids without diminishing comfort performance.

2.3. Approaches in DSF coordination

DSF potentials from buildings can only be meaningful when aggregated from multiple buildings or within context of cooperative management (Alam, Ramchurn, & Rogers, 2013; Labeodan et al., 2015). Presently, guidelines for flexibility management are available for DSF coordination (CENELEC, 2014); however, the proposals largely ignore building performance issues and related local details that are important for successful coordination of DSF. At the same time, power flexibility in the wake of smart grid requires active participation at all levels; that is, from the user, building entities, multiple buildings and the power grid control. The participation of multiple entities and diversity in operations in DSF events is associated with various challenges (Kim & Shcherbakova, 2011): ignorance of end user on the operation of power markets, lack of technological application for real time performance monitoring and difficulties in informational flows amongst participants. An effective DSF coordination framework would alleviate some of these challenges.

Various approaches have been proposed in past studies to deal with emerging challenges in DSF coordination. In Graditi et al. (2015), a control logic was used to achieve peak capping for a residential house below the contracted maximum value of 3 kW on a simulations platform. The system in Graditi et al. (2015) operated a decisions control logic prioritizing premium comfort, cheap energy purchasing contracts, load shifting and emergency curtailing of loads. Though focusing on residential sector, the study uniquely acknowledged different utilities and applicable time characteristics during DSF episodes (Graditi et al., 2015).

Another study (Ding et al., 2014), proposed power response schemes within DSM framework using industrial facilities. Proposal by Ding et al. (2014) used state task network (STN) and mixed integer linear programming (MILP); in the implementation, tasks and associated power were divided into non-schedulable tasks (NSTs) and schedulable tasks (STS). Implementation was based on the day ahead power market and employed a mix of load shifting and energy budgeting to realize facilities’ cost effectiveness and power reliability (Ding et al., 2014). Results in study Ding et al. (2014) demonstrated ability to shift demand from peak periods to off-peak periods with significant reduction in energy costs. However, the study indicated the need for real-scale DSF implementations.

Noor et al. (2015) successfully tested a methodology for leveraging DSF resources during industrial oil processing. In the study, actuators during DSF flexibility events were identified, appropriate point process model selected and safe power flexibility potential quantified before actuation using preset operation set-points (Noor et al., 2015). Most importantly, the methodology by Noor et al. (2015) ensures non-interruption of critical processes during DSF events using industrial plants.

Some studies have proposed multi agents system (MAS) based methodologies for DSF coordination. Though relatively at early stage
of development in building energy management application, MAS based coordination approach is favorable due to associated robustness and flexibility (Hommelberg et al., 2007; Hurtado, Nguyen, & Kling 2015). Also, the proposed MAS approach is relatively less costly as it leads to reduced information transfer loops; this is because distributed decisions at functional layers of facilities. Under MAS approaches each agent make respective own decisions and respective distributed decisions aggregated for effective exchange of flexibilities between buildings and the power grids (Hurtado et al., 2015).

Authors in Maruf, Munoz, Nguyen, Ferreira, & Kling (2013) presented a model for matching supply and demand in a residential building using game theoretic MAS optimization. Results incorporated user flexibility and was based on the Dutch day ahead power markets (Maruf et al., 2013). However, the proposed model did not consider randomness in end user behaviour and spatial related issues such as optimal points of connection to the grid for a feeder area.

In another study, a MAS based system was proposed to coordinate operations among different entities within the smart grid whilst taking into considerations both local and global needs (Badawy et al., 2013). The approach by Badawy et al. (2013) applied quantum evolutionary algorithm for energy management during peak demand periods on a multi-agent platform. However, the study by Badawy et al. (2013) did not directly consider building specific performance issues.

Kofler, Reinsch, and Kastner (2012), presented a web ontology language to manage challenges associated with balancing stakeholder needs during DSF activities in residential buildings. The approach by Kofler et al. (2012) was MAS based and emphasized in-depth knowledge management of energy characteristics for participating systems; however, it did not consider full details during DSF events.

Hurtado et al. (2015) present a MAS based approach for building control during power grid support activities that embraces distributed control to achieve dual management of comfort and energy efficiency. The study by Hurtado et al. (2015) successfully demonstrated grid level DSF control possibilities and potential achievable with MAS approach; however, it did not go far enough in terms of comfort considerations during the process.

Two hallmark studies practically implemented MAS based coordination of building and power system on real scale (Schaeffer et al., 2007; Ygge, Akkermans, Andersson, & Boertjes, 1999). In Ygge et al. (1999), business scenarios for energy management of an office building using computational market theory were simulated and tested in a field experiment. Results yielded peak hour cost reduction of approximately 33% with over 96% communication success (Ygge et al., 1999). Decentralised control using the powertachometer algorithm was applied to balance supply and demand for a community of buildings (Kamphuis, Kok, Wamer, & Hommelberg, 2007). Each device in the algorithm was represented by a control agent whose aim was to achieve optimal economic engagement in an electronic exchange market (Kamphuis et al., 2007).

As is evident in the foregoing, a number of solutions are available for DSF coordination. However, real scale field tests remain limited (Siano, 2014). Real scale field tests would be instrumental in addressing the following issues:

1. Informational exchange related problems such as lack of robust open platform and diverse vendors involved does not complement use of MAS based DSF coordination which favours distributed decisions and open platforms (Labedan et al., 2015).

2. Hierarchical nature of smart grid architecture as proposed for DSF coordination (CENELEC, 2014) does not favour distributed control approach taken in MAS approach. This calls for innovative approaches in forward aggregation of decisions at various functional levels: user, room, building and grid level.

3. Practical implementation of algorithms utilized in past studies (as evidenced in Badawy et al., 2013; Hurtado et al., 2015; Kofler et al., 2012) remains a challenge for real life scenarios. Implementations based on simple operational rules are thus preferable.

2.4. Pricing and demand side flexibility

Energy exchange between buildings and the power grid occur on the basis of connectivity contract outlining protocols, associated costs, energy and power quality guidelines. There are 5 main types of contract for energy exchange between buildings and power grids: (1) time of use (TOU) pricing, (2) dynamic pricing, (3) fixed load capping, (4) dynamic load capping, and (5) direct load control (He et al., 2013). Characteristics for respective energy exchange contracts are as summarized in Table 2.

Table 2 shows that pricing influences the speed and extent of participation DSF and must therefore be considered during DSF coordination. One observable fact not highlighted in Table 2 is that current power market prices are not differentiated enough to encourage load shifting, storage system viability and overall peak reduction (Kohler, 2014; Siano, 2014; Siano & Sarno, 2016).

Despite the lack of price differentiation evident with current electricity tariffs, existing studies continue to employ cost based coordination of buildings for DSF service. In cost based DSF coordination, buildings’ response aim at minimizing costs of operations (Rosso, Ma, Kirschen, & Ochoa, 2011; Zhao et al. 2015).

Cost based coordination for DSF service using office buildings is also hampered by associated low electricity costs and need for elaborate communication infrastructure. The need for elaborate communication infrastructure in cost based DSF coordination is achievable using smart metering infrastructure (SMI) (Aslam et al. 2015). However, the development of SMI continues to lag behind (Fröes, Alberto, & Ricardo, 2012; Siano, 2014). Subsequently, DSF coordination office buildings can be relatively easier to implement using non-mone tary incentives. As a result, utility value consideration for DSF coordination is proposed in Section 2.5.

<table>
<thead>
<tr>
<th>Contract Type</th>
<th>Autonomy/Privacy Loss</th>
<th>Financial Compensation</th>
<th>Applicable DSF Products (speed &amp; duration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOU</td>
<td>None</td>
<td>Limited</td>
<td>Slow &amp; long</td>
</tr>
<tr>
<td>Dynamic pricing</td>
<td>Limited</td>
<td>High Potential</td>
<td>Fast &amp; short</td>
</tr>
<tr>
<td>Fixed Load Capping</td>
<td>Limited</td>
<td>Limited</td>
<td>Slow &amp; short</td>
</tr>
<tr>
<td>Dynamic Load Capping</td>
<td>Limited</td>
<td>High Potential</td>
<td>Fast &amp; short or long</td>
</tr>
<tr>
<td>Direct Load Control</td>
<td>High</td>
<td>Limited/High Potential</td>
<td>Fast and very fast services &amp; short</td>
</tr>
</tbody>
</table>

Other characteristics for respective energy exchange contracts are as follows:

• TOU: uses seasonally or long interval based fixed tariffs.

• Dynamic pricing: uses hourly varying tariffs often depending on day ahead or intra-day power markets.

• Fixed load capping: fixes interval or seasonal based load floors.

• Dynamic load capping: fixes load floors on hourly basis depending on the day ahead or intra-day power market.

• Direct load control: places identified load at consumer’s premise under control of a third party and duty cycles it for flexibility service.
2.5. Utility value consideration

Utility value refers to usefulness associated with an action. During DSF events, utility considerations differ at building and power grid levels. For buildings, the utility consideration prioritize comfort, societal sustainability considerations, monetary gains, costs and direct penalties for participation and non-participation in DSF episodes (Kim, 2013). For the power grid, utility consideration emphasizes reliable connectivity to end users at pre-contracted quality and quantity (Rebours, Kirschen, Trotignon, & Rossignol, 2007; Rebours, Kirschen, Trotignon, and Rossignol, 2007). Consequently, a decision tool that ably balances indoor comfort, societal sustainability priorities and power flexibility service leverage from buildings is required. Balancing of indoor comfort, societal sustainability and power flexibility service priorities may be achieved using a weighting system (Clivillé, Berrah, & Mauris, 2007; Denguir et al. 2012). Under such a system, a unitary utility based decision continually finds an optimal balance between comfort and grid-wide energy management.

Ygge et al. (1999) used Eq. (1) to quantify utility considerations for peak power reduction at building level.

\[ u_{i(p,m)} = f_i(p_a) + m \]  

(1)

Where: \( u_{i(p,m)} \) is the utility function associated with demand reduction at a specific time, \( p_a \) is the active power demand reduction at a specific time and for a specific scenario, \( f_i(p_a) \) is the monetary equivalent of negative benefits (penalty) associated with \( p_a \), \( m \) is the direct monetary value for \( p_a \).

The approach in Ygge et al. (1999) adopted a MAS based market perspective coordination of grid support activity by an office building. The advantage of such an approach is associated detailed consideration of all underlying utilities for principal components and actors during DSF episodes. The principal components of Eq. (1) are: penalty for participation in DSF events, direct monetary benefits and societal sustainability value. Detailed discussion of components Eq. (1) are detailed in Sections 2.5.1–2.5.3.

2.5.1. Penalty for participation in DSF

For office buildings, the penalty for participating in DSF service is taken to be equivalent to productivity loss. This is split into: productivity loss as a result of deterioration of thermal comfort (Kosonen & Tan, 2004a), and productivity loss as a result of deterioration of IAQ (Kosonen & Tan, 2004b).

For summertime operations, it is further assumed that between operative temperature 21 °C–25 °C productivity loss as a result of deterioration of thermal comfort is negligible. For operative temperature greater than 25 °C, productivity loss due to thermal comfort deterioration (Kosonen & Tan, 2004a) is given by Eqs. (2a) and (2b).

\[ P_{TR} = \alpha C_L \]  

(2a)

\[ \alpha = [2 \times (TR) - 50] \]  

(2b)

Where: \( P_{TR} \) is the penalty due to deterioration of thermal comfort, \( \alpha \) is the percent productivity loss as a result of deterioration in thermal comfort, assumes tasks are composed of 75% thinking and 25% typing type requirements, \( C_L \) is the labour cost (influenced by occupancy characteristics).

For office buildings, the penalty due to deterioration of indoor air quality as a result of participation in DSF service is given by Eqs. (2c), (2d) and (2e) (Clements-Croome, 2008; Kosonen & Tan, 2004b):

\[ PD_I = 395e^{(-3.25 C^{0.25})} \]  

(2c)

\[ \beta = 0.6PD_I \]  

(2d)

\[ P_I = \beta C_L \]  

(2e)

Where: \( PD_I \) is the percent of people dissatisfied with indoor air quality during DSF, \( C \) is the perceived indoor air quality in decipol, \( P_I \) is the penalty due to deterioration of indoor air quality, \( \beta \) is teh loss in productivity due to deterioration of indoor air quality, \( P_I \) assumes tasks are composed of 75% thinking and 25% typing type requirements.

2.5.2. Direct monetary benefits

Calculations of direct monetary benefits assume that the cost of power payable directly to the end user for demand reduction equals the current base tariff rate for offices without energy taxes, that is €/kWh 0.066 (Eurostat, 2016); for dynamic pricing contracts, this value continually changes.

2.5.3. Societal sustainability value

Societal Sustainability value is the intangible utility derived from demand reduction or using green power. It is built up by the following:

1. Level of CO₂ emission subsidies (in the European Union, the CO₂ emission subsidies amount to approximately €7.2 per ton (IEA, 2015)),
2. Value of sustainability branding,
3. Value derived from prevention of power grid reliability collapse, and
4. Value of delayed investments and cost saving for operation and maintenance of a supply side power plant to provide flexibility.

Due to lack of information on (ii), (iii) and (iv), their effects are ignored; societal sustainability value is as a result obtained by multiplying CO₂ emission rate with energy related emissions prevention value. In the Netherlands carbon dioxide emission rate per kWh of electricity production is 0.054 kg per kWh (RVO, 2015).

2.6. Literature survey conclusion

Three main conclusions are evident from the literature survey. First, autonomy in decision making for building is a priority as a way of ensuring that the traditional functions of buildings remain uncompromised during DSF activities. Consequently, comfort aligned performance parameters such as systems’ response times, indoor thermal comfort, IAQ, comfort recovery time, and availability period become a priority during DSF coordination. Second, DSF coordination approaches for office buildings need to integrate full utility value for both building and power systems domains; this entails considerations of all direct monetary benefits, penalties for participation of buildings in DSF events, forestalled investments and operational costs in power plants as a result of DSF and related emission reduction. Labour productivity and other non-monetary considerations outweigh direct
monetary benefits due to low and almost flat energy pricing regimes for office buildings. The participation of office buildings in DSF activities is as a result made difficult. Finally, DSF coordination requires use of simple algorithms for fast, easy and quick practical implementation. The use of simple algorithms for DSF coordination leads to avoidance of high costs of implementation whilst also ensuring robustness and pragmatism.

3. Methodology

The aim of the study was to propose an effective framework for DSF coordination that comprehensively considers building operational details, and indoor comfort. To achieve the aim, a four steps approach was undertaken as illustrated in Fig. 2.

First, literature survey was used to gain insights into requirements and considerations during DSF coordination for office buildings. Literature survey methodology and results are reported in Section 2. Next, a case study building was analysed to provide further inputs on DSF coordination requirements for real scenarios. Thereafter, a DSF coordination framework was proposed for cases whereby duty cycling of air supply fans and fixed cooling schedules in office buildings are used as power flexibility sources. Analysis of comfort and energy performance in the case study building was done with respect to the following parameters:

1. Operative temperature [°C]: is equivalent to the average of indoor mean radiant and air temperatures; for summer time conditions as the case here, an upper boundary of 27 °C is allowable.
2. Carbon dioxide concentration (CO2) [parts per million]: is used as a surrogate value for IAQ with levels of 695 ppm above prevailing outdoor concentration being the maximum allowable value.
3. PPD [%]: is the percent of people dissatisfied with indoor conditions in which they are present. The value is calculated based on PMV model (ASHRAE, 2013a, 2013b) and IAQ model (Clements-Croome, 2008). In this case, a surrogate value derived from voting of occupants was used.
4. Availability period [minutes]: is the time from commencement of DSF episode to its end.
5. Productivity loss [%]: is the loss in labour productivity as a result of displeasure with indoor comfort.
6. Comfort recovery [minutes]: is period from end of DSF episode to time when basic comfort is attained.
7. Demand reduction [kW]: refers to reduction in power consumption in unit time.

Further description on case study methodology are outlined in Sections 3.1 to 3.2.

3.1. The case study building

The case study building is dedicated for office use and has approximately 1500 m² total floor area. The building is equipped with a web based building management system (BMS), and a centralized heating, ventilation, and air conditioning (HVAC) system. Load configuration for the case study building is outlined in Fig. 3.

Additional details of the case study building including are available in Adada et al. (2016). During normal operational settings when building is active, indoor comfort is maintained within code acceptable bandwidth (that is, ASHARE 62-1/NEN 15251 (ASHRAE, 2013a, 2013b)) for IAQ, and ASHARE 55/NEN ISO 7730 for thermal comfort (ASHRAE, 2013a, 2013b). However, for spring and summer-time operation the rooms for the case study building are maintained at between 21 °C to 23 °C operative temperature with between 0.9 to 1 air change per hour when open for business as long as the building is open.

3.2. Measurements and experiments

The case study building was investigated using a 2 steps process. First, the comfort and energy profiles of the building were monitored throughout the spring and summer time; this provided performance benchmarks for energy and comfort performance in the building.

Monitoring was done with the aid of wireless sensor based instrumentation and energy metering connected to the Building Management System. Instrumentation layout is illustrated in Fig. 4. Indoor comfort parameters and respective accuracies were air temperature (±0.4 °C), radiant temperature (±0.3 °C), relative humidity (±0.5%), CO₂ concentration (±50 ppm) and supply duct air velocity (±0.2 m/s). Outdoor parameters monitored for the period of investigation with associated accuracies were air temperature (±0.4 °C), relative humidity (±0.5%) and solar irradiation (±1 W/m²). Also monitored were active power consumptions for all load groups in the building.

In the next step, short term performance characteristics were recorded during experiments emulating demand flexibility operational modes. Demand flexibility operational modes emulated were duty cyclic operations of the air supply fan between 60% and 80% Proportional-Integral-Derivative (PID) controller settings, and also fixed cooling duty schedules. Summaries of the protocols followed in the experiments are outlined in Sections 3.2.1 and 3.2.2.

3.2.1. Protocol for fixed cooling schedule duty cycling experiments

The chiller was operated to deliver cooling at fixed duty cycles instead of thermostatically controlled duty cycle. The aim was to identify optimal cycle time for DSF potential at different ambient temperatures. Two sets of experiments were run using the following protocol:

1. The chiller was first allowed to operate on normal thermostatic controlled on-off cycle till 0930 h.
2. After 0930 h, the chiller was switched ‘OFF’ for a period of 30 min and again ‘ON’ for 30 min; this pattern of on-off operation cycling was repeated till 1700 h. The same procedure was repeated for the second experiment with the ‘OFF’ duration adjusted to 60 min.
3. During experiment period, care was taken to ensure that operative room temperature remained within code defined bandwidth. At the same time, measurements were taken for power and comfort parameters. Occupants also recorded their dissatisfaction with indoor air quality on a scale of 1–5 (1 represented most satisfied and 5 representing most dissatisfied).
4. Performance results were then interpolated linearly to cover ambient temperature range of 23 °C to 27 °C; linear interpolation could yield fairly accurate results due to narrow temperature band.

3.2.2. Protocol for experiments using duty cycling operation of the air supply fan

In this experiment, air supply fan was operated at the following PID controller settings: 57%, 64%, 71% and 80%; this corresponded to airflow pressure after the fan of 156 Pa, 161 Pa, 200 Pa and 250 Pa

---

1. A PID controller sets the operational capacity of the air supply fan. In this case the PID controller determines the output of the fan based on the desired maximum pressure of 250 Pa and the measured pressure; the system works to continually ensure that a continued positive pressure is realized in the ducting.
respectively. The results of this experiments were initially reported in (Aduda et al. 2016); the experiment was done for 3 days using the following protocol:

i. An each of the PID controller settings (that is, at 57%, 64%, 71% and 80%), operation was allowed for at least 1.5 h before changing to the next setting and corresponding observations for the following: indoor temperature, CO$_2$ concentration and relative humidity at room level and duct air flow velocity at the respective ventilation zones, and total fan power consumption.

ii. Between 0700–0900 h and before changing PID controller settings during the day, the air supply fan is operated at between 80% to 100% nominal setting for a minimum of 1.5 h to allow adequate indoor air quality recovery.

iii. During the experiment occupants also recorded their dissatisfaction with indoor air quality on a scale of 1–5 (1 represented most satisfied and 5 representing most dissatisfied).

iv. Comfort and power performance characteristics realized for settings in the initial study were curve fitted using regression analysis to find interpolated performance at 60% and 80%, PID settings.

Interpolated supply fan performance was based on regression analysis of performance data at the following PID controller settings: 57%, 64%, 71% and 80%. Regression equations used for interpolation are shown in (3) and (4).

\[ s = 0.458p_{fan}^{0.302} \]  \hspace{1cm} (3)

\[ s = 0.309e^{0.005t} \]  \hspace{1cm} (4)

Where: $s$ is the PID setting of the air supply fan, $t$ is the availability period and $p_{fan}$ is the maximum power demand of the air supply fan.

Field study results are available in Section 4.

4. Results and discussions

The aim of the field study was to tease out important DSF characteristics and consideration for their coordination when using the following strategies in an average sized office building:

- Fixed cooling duty schedules
- Duty cycling operation of air supply fan

Important findings of the case study analysis are thematically summarized in Table 3.

4.1. Load characteristics for normal operations at the case study building

Table 4 outlines load characteristics at the case study building when actively in operation for spring and summertime in 2015 calendar period. The building is considered actively in operation when open for business or when air supply fan is operational. Presentation in Table 4 should be interpreted with respect to prevailing total load for the building during spring and summer time.

During spring time, 25% of total load during active sessions remained less than 8.0 kW; median, 75 and 100 percentile values for the same were 17.0 kW, 19.0 kW and 25.0W respectively. The total load registered by the building at summer time during active sessions of the building was 12.5 kW, 17.0 kW, 19.0 kW and 27.5 kW at 25 percentile, median, 75 percentile and 100% distribution range respectively.

For the entire period of activity on a normal day, average indoor operative temperature remained 23°C and the indoor CO$_2$ concentration 469 ppm when building was operating at normal active.

The chiller characteristics for the entire year may be divided into 3: light, medium and heavy cooling requirements (details are presented in Table 5 and Fig. 5). Occurrence of light, medium and heavy cooling requirements coincide with spring, summer and extreme summer weather conditions.
Fig. 5 provides additional illustration of cooling load characteristics during active operational duty 6. In Fig. 5, the plots are made from the period the building opens at 0630 h to 1630 h when it closes for business. The fan load for the building remains constant with the a notable average value of 4.01 kW during spring time compared to 4.69 kW during summer. The actual consumption is dependent on PID controller setting and typical power profile is illustrated in Fig. 6.

4.2. Demand side flexibility characteristics during field experiments

Resulting DSF characteristics for the 2 sets of field experiments using cooling and air supply fan loads are presented in Sections 4.2.1 and 4.2.2.

4.2.1. Demand side flexibility characteristics for fixed cooling schedule duty cycling

Table 6 presents some important DSF characteristics when using fixed cooling duty schedule in the case study building. In the reported results prevailing operative temperature in the room, comfort recovery period, availability period and demand reduction possibility are outlined for various ambient outdoor temperature ranges.

Another important result reported is the load profile during fixed cooling duty cycling experiment (refer to Fig. 7). It is observed that on restarting the cooling system after one hour of shutdown, cooling demand resurges by an additional 10 kW.

During the tests, recorded voting for occupants dissatisfaction with the tests registered a maximum of 12%; this occurred during the heavy duty cooling demand.

4.2.2. Demand side flexibility characteristics for duty cycling operation of the air supply fan

DSF characteristics associated with duty cyclic operation of air supply fan load (with PID controller setting at 60%, 80% and 100%) are outlined in Table 7. The focus of the DSF experiment using the air supply fan was its operation as curtailable reducible load through alternate duty cycling between 80% and 60% PID controller settings. Results of CO₂ concentration and availability are based on readings and interpolation at the worst performing room at the end of the availability period. In addition, CO₂ concentration measurements used were those between 0930 h to 1700 h when the levels are stable. Measurements of CO₂ concentration levels remained below the maximum recommended threshold of 1000 ppm as per ASHRAE 62 standard (ASHRAE, 2013a, 2013b). Based on occupants votes, dissatis-
Table 3
Summary of results at the case study building.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Observed results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed schedule cooling duty cycle operation</td>
<td>Duty cycling air supply fan between 60% to 80% PID setting</td>
</tr>
<tr>
<td>Size of demand reduction</td>
<td>1. Potential: 7 kW (with respect to delayed demand).</td>
</tr>
<tr>
<td></td>
<td>2. Value to grid: Negligible unless aggregated in a framework.</td>
</tr>
<tr>
<td>Availability period for service</td>
<td>1. Available for use for less than 60% when the cooling system is operational; the resource cannot be used during heavy cooling requirements.</td>
</tr>
<tr>
<td>Response time</td>
<td>Short: less than 20 minutes</td>
</tr>
<tr>
<td>Duration of DSF service</td>
<td>Fast (less than 5 minutes).</td>
</tr>
<tr>
<td>Recovery time</td>
<td>Long: up to the whole</td>
</tr>
<tr>
<td></td>
<td>20 minutes to 40 minutes (depending on prevailing ambient outdoor weather conditions and occupancy).</td>
</tr>
<tr>
<td></td>
<td>30 minutes (with respect to exploitation for 60 minutes; recovery time for the room depends also on occupancy).</td>
</tr>
<tr>
<td>Acceptance</td>
<td>6% to 12% (depending on prevailing ambient outdoor weather conditions and occupancy).</td>
</tr>
<tr>
<td></td>
<td>6% to 12% (depending on the prevailing ambient conditions and occupancy)</td>
</tr>
</tbody>
</table>

The details of the results are discussed in Section 4.1 to 4.3.

Table 4
Basic statistics of connected loads at the case study building for 2015 calendar year during active operational period.

<table>
<thead>
<tr>
<th>Season</th>
<th>Statistical Characteristics</th>
<th>Load Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative Energy consumption(kWh)</td>
<td>Cooling</td>
</tr>
<tr>
<td>Spring</td>
<td>316</td>
<td>7.29</td>
</tr>
<tr>
<td></td>
<td>Average (kW)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Minimum(kW)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Maximum(kW)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Median(kW)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Mode(kW)</td>
<td>7</td>
</tr>
<tr>
<td>Summer</td>
<td>1244</td>
<td>7.54</td>
</tr>
<tr>
<td></td>
<td>Average (kW)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Minimum(kW)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Maximum(kW)</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Median(kW)</td>
<td>7</td>
</tr>
</tbody>
</table>

fication with indoor air quality remained below 6% for the first 60 min of all tests; the value changed to 12% after 90 min for the 60% PID setting.

4.3. Discussions

4.3.1. Size of demand reduction
Demand reduction potential for the 2 sets of experiments seem promising with respect to the total installed load in the building (at 3.6 kW and 7 kW reduction potential). However, the demand reduction realized are insignificant at power grid level when considered individual basis as larger power margins (in the tune of MW) are needed to realize desired results. Aggregation of loads from respective connection is therefore needed to make an impact. Infor-
mation exchange between different buildings and devices participating in DSF schemes is therefore important to coordinate the aggregation.

4.3.2. Availability period and seasonality of participating load
It is also revealed that unlike duty cycling operations using air supply fan, use of fixed cooling duty schedule as DSF resource is subject to the prevailing outdoor weather conditions. In the case study building cooling system is not operational during fall, winter and is only partially operational in spring and summer. This make it unavailable as DSF resource in periods where it is out of service. Also, the use of cooling system as a DSF resource during extreme summer is impossible as cooling demand is heavy then and associated systems barely cope. Dynamic information on outdoor weather conditions and equipment operational status is therefore crucial in the coordination of DSF resources.

4.3.3. Availability period and seasonality of participating load
The response time for installed cooling system during DSF events are comparatively slower than those of air supply fan. This makes cooling system unsuitable for fast and very fast power flexibility requirement (refer to Table 3). Use of cooling systems in office buildings with direct load control and dynamic pricing type of contracts becomes difficult. Instead, cooling systems are more suited for slow speed power flexibility products that extend for a long period of time. On the other hand, duty cycling operations of air supply fan loads have fast response time and make a good fit for dynamic pricing environment and fast response requirements. An effective DSF coordination strategy may however be used to combine the advantages derived from both duty cycling operations of the air supply fan and fixed scheduled cooling. For example, in case of requirement for a continuous fast service of more than 45 min, a DSF response sequence may be to engage duty cycling operations of air supply fan from 80% PID controller setting to 60% controller setting for 30 min followed by switching off the cooling system for the remainder of the term as long as later is online.

4.3.4. Comfort recovery period
Results also indicate that comfort recovery periods for the 2 sets of experiments are influenced by occupancy and prevailing outdoor weather conditions. This makes it pertinent that during DSF events, dynamic update of outdoor weather states and occupancy information is crucial for successful service delivery to the grid without compromising to the traditional function of the building. Care should also be taken to ensure staggered recovery of participating buildings in a manner that ensures compliance to power flexibility delivery contracts.

In relations to this, duty cycle periods should be optimally designed to ensure that the length comfort recovery periods are taken into account and rebound requirements by systems as seen in Fig. 7 are avoided. Rebound requirements after DSF events may be counter-productive to the objective of power grid support by building. Consequently, effective DSF coordination strategy is needed to optimally balance equipment settings, recovery time, comfort demand, outdoor weather conditions and occupancy dynamics to avoid such eventualiy. These may require close coordination of various use conditions to clearly map out comfort recovery periods, availability periods and actual cycle times.

4.3.5. Acceptance
Based on voting, it is observed that satisfaction with both indoor air quality and thermal comfort remain less than 12% for a 60 min
Table 5
Daily run time, associated ambient weather conditions and chiller load characteristics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Duty</td>
<td>120</td>
<td>18.3</td>
<td>8.3</td>
<td>13.6</td>
<td>641.6</td>
<td>176.7</td>
<td>13% of active building session</td>
<td>2% of active building session</td>
</tr>
<tr>
<td>Medium Duty</td>
<td>255</td>
<td>21.1</td>
<td>9.5</td>
<td>15.4</td>
<td>612.2</td>
<td>180.2</td>
<td>25% of building active session</td>
<td>5% of building active session</td>
</tr>
<tr>
<td>Heavy Duty</td>
<td>460</td>
<td>22.9</td>
<td>12.0</td>
<td>17.9</td>
<td>780.9</td>
<td>248.2</td>
<td>45% of building active session</td>
<td>20% of building active session</td>
</tr>
<tr>
<td>680</td>
<td></td>
<td>26.4</td>
<td>15.3</td>
<td>21.0</td>
<td>799.7</td>
<td>249.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>740</td>
<td></td>
<td>28.0</td>
<td>16.2</td>
<td>22.3</td>
<td>813.2</td>
<td>277.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;740</td>
<td></td>
<td>28.2</td>
<td>17.8</td>
<td>22.9</td>
<td>768.4</td>
<td>255.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Chiller load demand characteristics at the test building.

Fig. 6. Air supply load characteristics at 71% PID controller setting, the demand changes to 6 kW, 3 kW and 2 kW respectively for 80%, 64% and 57% PID controller setting.

period of the two DSF duty cycling strategies investigated. For, thermal comfort this conforms to the basic limit of dissatisfaction with indoor conditions specified in ASHRAE 55 (ASHRAE, 2013a, 2013b). This confirms existing potential for using duty cycling operations of the air supply fans and cooling systems as sources of DSF in office buildings. Despite apparent insignificance of acceptability in these experiments, active user feedback is still needed to monitor acceptance during DSF coordination.

4.3.6. Summary
In the overall, effective information flow from the user, devices, indoor spaces and outdoor environment is critical for successful coordination of DSF. The information flow has to be undertaken in a
Table 6
Building performance during fixed schedule cooling duty cycling.

<table>
<thead>
<tr>
<th>Ta (°C)</th>
<th>P_{av} [kW]</th>
<th>Operative Temperature ~ 24 °C</th>
<th>Operative Temperature ~ 25 °C</th>
<th>Operative Temperature ~ 26 °C</th>
<th>Operative Temperature ~ 27 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>availT</td>
<td>recovT</td>
<td>availT</td>
<td>recovT</td>
<td>availT</td>
</tr>
<tr>
<td>30 °C–32 °C</td>
<td>7</td>
<td>46</td>
<td>36</td>
<td>48</td>
<td>38</td>
</tr>
<tr>
<td>28 °C–30 °C</td>
<td>7</td>
<td>50</td>
<td>33</td>
<td>52</td>
<td>34</td>
</tr>
<tr>
<td>25 °C–28 °C</td>
<td>7</td>
<td>54</td>
<td>31</td>
<td>56</td>
<td>32</td>
</tr>
<tr>
<td>23 °C–25 °C</td>
<td>7</td>
<td>60</td>
<td>27</td>
<td>63</td>
<td>28</td>
</tr>
<tr>
<td>20 °C–23 °C</td>
<td>7</td>
<td>69</td>
<td>24</td>
<td>72</td>
<td>25</td>
</tr>
</tbody>
</table>

Note: Ta: Ambient temperature; P_{av}: Demand Reduction for cooling set-point increase strategy [kW]; availT: Availability Period [Minutes]; recovT: Comfort recovery Period [Minutes]; ON period – comfort recovery; OFF period – availability period.

Table 7
Power consumption, demand reduction potential and availability period for various air supply fan PID settings.

<table>
<thead>
<tr>
<th>Performance characteristics during DSF events</th>
<th>PID Controller settings for the air supply fan 's'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Setting in desired output pressure (pa)</td>
<td>250</td>
</tr>
<tr>
<td>CO₂ concentration (ppm)</td>
<td>–</td>
</tr>
<tr>
<td>Demand [in kW]</td>
<td>12.2</td>
</tr>
<tr>
<td>Demand Reduction 'd,' [in kW]</td>
<td>0</td>
</tr>
<tr>
<td>Availability Period 't' [in Minutes]</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 7. Chiller power characteristics during 1/2 h ON–1 h OFF fixed schedule cooling duty cycling.

manner that is timely to ensure even matching of time characteristics of the building and power grid service requirements. In view of this, a DSF coordination framework that builds from previous ones discussed in Section 2.4 is herein proposed; the proposed framework adds value along the following lines:

1. It is based on interpretation long term and short term empirical data from real scale office building. This ensures additional details are captured to enrich simulation based frameworks.
2. The algorithm used relies on operational rules actuated for utility sensitive period and considers actual building performance parameters such occupants productivity, demand reduction, operative temperature, availability period and comfort recovery time. This algorithm is easily implementable as compared to earlier DSF presentations discussed in Section 2.3.

Section 5 discusses the proposed DSF coordination framework in details.

5. Demand side flexibility coordination framework

To ensure well-coordinated decision-making framework that ensure continued autonomy of buildings whilst still offering support for the power systems network, a MAS based coordination framework is proposed. Details associated architecture, information flow and operational algorithm for the DSF coordination framework are discussed in Sections 5.1–5.5.

5.1. Architecture

The approach is composed of 3 control layers at building level. The first layer is composed of local controllers with interconnection to sensors and users. The first this layer ensures that service equipment are operated according to defined set points, sensor derived information and within equipment derived operational boundaries. The BMS forms the second layer, it is charged with supervisory control of all local controllers and database management for safety, indoor comfort and building energy management. With respect to this case study, a web based BMS is used. The third layer is a MAS based virtual control. The MAS layer is tasked with balancing comfort and power performance requirements to attain optimal user satisfaction, work productivity in the building, social welfare considerations and facility cost effectiveness during DSF. This is achievable using a combination of operational rules and unitary utility decision approach mentioned in Section 2.4. Under the MAS approach each agent is able to make respective own decision; all distributed decisions are then aggregated for effective DSF coordination. The architecture of the framework is depicted in Fig. 8.

Taking cue from (Labedan et al., 2015), five categories of agents suggested for the MAS approach: user, device, room, building, and grid side agent. Details of the agents and their respective a roles outlined below:

1. User agent actively manage use profiles, occupants’ preferences, occupants counts and related energy flows; it takes into account activities in the building that are directly associated with various users. The user agent communicates with relevant sensors to obtain information on occupancy count, expected occupancy, preferred comfort and associated utility to the relevant room agent. User presence and acceptance are particularly important for controlling curtailable loads.
2. Device agents compiles dynamic energy profiles for respective appliances, centralized equipment and on site energy production;
HVAC agents fall under this category. Device agents actively communicate information on device operational state, its flexibility potential and associated utility to the room or building agent depending on whether it is room dedicated or centralized. This is accomplished in line with classification along the following lines (El-Hawary, 2014):

- Storable loads: can used to store energy for future use.
- Shiftable loads: must be satisfied but start up can be postponed to a later time without compromising utility to occupants.
- Curtailable reducible loads: may be reduced to a certain level without being replaced and without switching off with possible loss of utility for the user (example is dimming light).
- Curtailable disconnectable: may switched off without replacement with possible loss of some utility for the user.
- Inflexible loads: must be met at all circumstances; example include baseload for server use.

3. Device agents operate concertedly with the user agents as occupants’ related information determines respective utility for operational setting.

4. The room agents collate information from sensors and instrumentation system, devices, users and related databases to determine dynamic actual power flexibility parameters associated with the zones and spaces in the building; this is dynamically updated to the building agent. In addition, the room agents’ compile comprehensive active register for all use profiles, cases and room based devices associated. In cases whereby the room or zone is dependent on a centralized device, the room agent dynamically calculates the room level effect of operation at respective settings.

5. The building agent is responsible for oversight decision making involving installed centralized systems, aggregation of power flexibility possibilities in the building and evaluation of requests for grid support and associated offers including communication for actualization. It also evaluates facility cost effectiveness at various energy profiles together with associated social welfare values. The building agent dynamically communicates to the power network aggregator agent information on whole building peak demand reduction, energy in peak, increase in demand, energy in valleys and potential shifts is required.

6. The grid side agent is tasked with power flexibility requirement (in terms of quality and quantity) and associated unit pricing (such as dynamic tariff and flexibility service pricing) for support services; this is made possible through interfacing with smart power metering infrastructure.

Fig. 9 outline algorithmic details followed by some main agents in the framework.

5.2. Informational aggregation

The proposed DSF coordination framework relies on ‘push type’ strategy in which only essential information is aggregated and transmitted upwards from users, workplaces, zones, building and power grid. It addition, distributed decisions are ensured thereby reducing latency. Fig. 10 illustrates informational aggregation details in the proposed DSF coordination framework. For example, the building agent only communicates flexibility offer and acceptance terms to the power network aggregator agent. On the other hand the device agents and room agents in the building continually update the building agent with information on available power flexibility, respective state of operations, energy consumption and comfort points where relevant. The room agents deciphers available power flexibility based on comprehensive user information obtained from multiple interactions with users, sensors and instrumentation databases and equipment operation.
5.3. DSF operational policy and rules

A set of operational policies and rules are proposed for smooth DSF coordination. These are defined in a stepwise manner in sub-sections 5.3.1–5.3.4.

5.3.1. Step 1-choice of operational mode

In the first step an operation mode for the building is selected based on the following considerations:

i. Calendar characteristics: this classifies a day according to whether the prevailing day and the next one is a work day or not. A workday and non-workday imply that the building is open and closed respectively, hence differing occupancy and operational profiles.

ii. Season of the year: This determines appropriate selection of seasonally varying loads during operations.

iii. Occupancy: this includes the occupancy count and location in building. DSF strategies are matched with occupancy information to ensure maximum utility derivation for both building and the power grid domains.

iv. Prevailing weather characteristics considered are prevailing outdoor air temperature, prevailing outdoor absolute humidity, expected average daily minimum/maximum temperatures, expected daily minimum and maximum global solar radiation.

v. State of the power grid/DSF requirements: This registers the criticality of power flexibility requirement. Consideration of DSF requirements is based on quality and quantity of power flexibility requirement, associated advance warning for requirement and pricing.

5.3.2. Step 2-demand side resource classification

The second step classifies demand side resources as storable, shiftable, curtailable, reducible or disconnect-able as explained in Section 5.1. It is assumed that at any defined operational period, there is finite control possibilities for the demand resources. The aim of DSF control and coordination is to continually achieve optimal power state whilst taking into account actual settings of installed local controllers, code acceptable comfort requirements, prevailing weather conditions, cost effectiveness and DSF possibilities. This step sets the stage for defining control actuation during DSF event.

5.3.3. Step 3-control rules implementation

In the third step control rules are implemented based on operational modes selected in the first step and the demand resource classification of target load in step 2. This step addresses the specifics on actuation of DSF coordination. These rules consider available options in equipment control and utility value as well as the states of the building and power systems, detailed considerations and rules are as follows:

i. Storable loads: key issue to consider is when to charge or discharge stored energy for optimal utility realization. Ideal charging op-
eration occurs when there is no competing demand for energy in the building as occupant related uses such as comfort and office appliances needs are minimal and energy price low; discharge of storable loads occur when the building becomes operational, occupancy is regular and power grid requires demand side support. For the case study building, charging of storage is recommended as long as Eqs. (5a) and (5b) hold, the building is closed.

$$\text{SoC} \leq \text{SoC}_m$$ \hspace{2cm} (5a)

$$\text{EC} \leq \text{EC}_m$$ \hspace{2cm} (5b)

Where: SoC is the prevailing state of charge of the storable load [%], SoCm is the minimum allowable state of charge of the storable load [%], EC is teh prevailing electricity cost [€/kWh], ECM is the minimum allowable electricity cost for storage charging [€/kWh].

Discharge of storable load occurs as long as the building is actively operational and Eqs. (6a), (6b) and when total building load exceeds contracted peak operational value.

$$\text{SoC} > \text{SoCM}$$ \hspace{2cm} (6a)

$$\text{EC} > \text{ECM}$$ \hspace{2cm} (6b)

Where: SoC and EC are as defined in Eqs. (5a) and (5b), SoCM is teh maximum attainable state of charge of the storable load [%], ECM is the minimum allowable electricity cost for storable load charging [€/kWh].

ii. Curtable loads: The total utility value during load curtailment must always be greater than that at full load operations as given in Eq. (7).

$$\left\{ \sum_{t=1}^{h} (u_{t1}) \right\} \right\} > \left\{ \sum_{t=1}^{h} (u_{t2}) \right\} \right\}$$

Where: $(u_{t1})$ is the utility value for curtable load at a time $t_1$ [€/kWh], $(u_{t2})$ is the utility value for the curtable load at time $t_2$ [€/kWh], $(P_{cm1})$ is the average power consumption of curtable load at time $t_1$, $(P_{cm2})$ is the average power consumption of curtable load at time $t_2$, $(P_{cm12})$ has a value equal to 0 for curtable disconnect-able load, $(P_{cm2})$ has a value $c > 0$ for curtable reducible load.
For the case study, air supply fan is the main curtailable load; its operation for power grid friendliness can be on 3 PID settings: 80%, 60% and 0%. Based on results obtained in the field studies, operational conditions applicable for respective air supply fan settings are as follows:

* **Air supply fan at 80% PID setting**
  a. There is no requirement of DSF or DSF requirement cannot be accommodated,
  b. Occupancy > 0,
  c. The building is open for business,
  d. Prevailing ambient outdoor temperature > 25 °C,
  e. Room operative temperature > 25 °C,

* **Air supply fan at 60% PID setting**
  a. There is some requirement or high requirement for DSF, occupancy > 0,
  b. The building is open for business and it is after 09:30 h,
  d. Prevailing ambient outdoor temperature < 25 °C,
  e. Allowed recovery period < 60 min,

* **Air supply fan at 0% PID setting (OFF state)**
  a. Occupancy equals 0 and,
  b. No night ventilation or early start operation is required;
  c. The converse is true for ON state.

**iii. Shiftable loads**: The guiding principle for load shifting in buildings is that utility value of the shift must be greater than prevailing one. For summer time operations and where dedicated thermal storage capacity is not available as in the case study building, pre-cooling becomes equivalent to thermal inertia. There are 2 categories for shiftable load operations evident in the case study building; these are fixed duty cycling and thermostatic set point temperature reset.

**5.3.4. Step 4-Evaluation of power flexibility offer for usefulness**

The last step in DSF coordination at building level entails evaluation of power flexibility offer for usefulness with respect to the period of requirement and states of both the building and the power grid. It is desired that the power flexibility offer stays within the bandwidth defined by Eq. (8) at all times.

\[
P_{th} = \{P_{MaxCom} - P_{MinCom}\}
\]

Where: \(P_{th}\) is power flexibility offer from the building at all times, \(P_{MaxCom}\) is power dedicated to provision of maximum comfort in the building, \(P_{MaxCom}\) changes dynamically depending on the considerations in step 1. \(P_{MinCom}\) is power dedicated to provision of code minimum comfort in the building, \(P_{MinCom}\) changes dynamically depending on the considerations in step 1.

Usefulness of power flexibility offer by building is achieved with utility considerations. DSF coordination has to continually balance the utility considerations between building and power grid domains to be reachable trade-offs in attempt to fully integrate demand side resources in power systems management.

The following specify utility considerations during DSF coordination with respect to the proposal:

1. State of the grid: 3 categories of decisions may be made according to the following states:
   - High requirement for DSF: during this time power grid is moving towards reliability failure. At this point of operations, more priority is given to energy utility value at building level,
   - Some requirement for DSF: this is the period in which there is no great danger to power grid reliability; however, some amount of DSF service is required to ensure that the energy system complies with set standards for sustainability. At this point, there is a bias towards maintaining comfort and productivity overrides all other decisions in the building.
   - No requirement for DSF: in this case, the building and power grid are all operating optimally and the price payable to the former is minimal. At this operational point, comfort utility over-rides power utility.

2. State of thermal comfort and IAQ in the building: depending on how the conditions for the occupants are, decision on DSF services are made. If there is no requirement for DSF, the building would tend to operate at premium comfort. On the other hand, during periods of high requirement for DSF, the air supply fan and cooling systems are set to provide basic comfort. For air supply fan, the operational settings would be alternately changed from 60% PID setting (for up to 30 min) to 80% PID setting (for 60 min) from 09:30 h to 17:00 h.

- Likelihood of rebound cooling demand: high rebound cooling demand after the off period should be avoided or compensated for by an optimally sized electrical storage system.
- Cycle time and size of cooling plant: the cycle time has to be chosen in such a way that the cooling plant can cope with rebound cooling demand.
- Occupancy count and internal heat load: depending on occupancy count, a longer off period may be chosen without grave consequences to thermal comfort.

During periods of high requirement for DSF, the building could participate in grid support with acceptable penalties in terms of discomfort (leading to loss in productivity) as long as the monetary benefits and acceptable and code limitations are adhered to. The above may be implemented by embedding them in the utility function detailed in the literature review section. Section 5.4 details implementation results using field study results from Section 2.5.

**5.4. Scenario implementation of the proposed DSF coordination framework**

To illustrate the working of the proposed DSF coordination framework a utility based evaluation for 4 scenarios at the case study building is implemented. The scenarios in the implementation are:

i. Operation of air supply fan at 70% PID setting, denoted ‘Air supply Fan @ 70%’.
ii. Operation of air supply fan at 60% PID setting, denoted ‘Air supply Fan @ 60%’.
iii. Operation of the cooling system with an 30 min ON and 30 min OFF duty cycle, denoted ‘30/30 duty cycle’.
iv. Operation of the cooling system with an 30 min ON and 60 min OFF duty cycle, denoted ‘30/60 duty cycle’.

The following assumptions are made in the implementation:
- Contract: the building has a contract with the power system balancing responsible party to supply flexibility matching the following profile to provide peak reduction service for a period of 30–60 min. Calculations on energy offers are done in separately for every min of operation.
- Utility value parameters are assumed as follows; the values adopted are in line with Section 2.5:
  - Energy Price for demand reduction: €/kWh 0.066;
• CO₂ emission rate per kWh of electricity production: 0.054 kg per kWh;
• CO₂ emission subsidies amount to approximately €7.2 per ton.
- Occupancy count is 22.
- An initial operative temperature of 24 °C is assumed to uniformly hold throughout the building, thereafter it increases progressively till allowable maximum boundary. Initial value for dissatisfaction with indoor air quality is 5%.
- The event commences at 14:00 h on a summer day with ambient temperature remaining between 25 °C to 28 °C; this is used to derive operational values in Table 7.
- A flat labour cost of €15 per man-hour holds.

The results of utility based evaluation for respective DSF implementation scenarios are presented in Table 1 with additional illustrations in Fig. 11. Resultant utility values associated with DSF scenarios for an hour’s period are revealed to be extremely low ranging from a maximum of €2 to € (–27). This is due to two reasons. First, currently there is low compensation for CO₂ emissions hence equally low societal sustainability value in utility consideration. Second, utility value calculation did not take into account some benefits of DSF such as probable loss of service as a result of grid collapse or reliability loss and forestalled capital investment in establishment, and or associated operations of standby power plants.

It is important therefore to increase direct monetary gains for DSF coordination to match the loss of comfort penalties; this buttresses the suggestion in (Kohler 2014) for greater price differentiation to encourage DSF leverage. Based on the implementation results, it is realized that use of the air supply fan has the least utility compared to

![Fig. 11. Utility values and comfort loss penalties for scenarios of DSF using air supply fan setting reduction and fixed cooling schedules duty cycles.](image)

![Fig. 12. Prevailing operative temperatures in the building and resultant power use reduction during DSF events using air supply fan setting reduction and fixed schedules cooling duty cycles.](image)
Table 8
Implementation results for utility value calculation in proposed DSF coordination framework.

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>DSF strategy option</th>
<th>Utility characteristics per PTU (1 PTU = 15 minutes interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14:00 to 14:15</td>
<td>14:15 to 14:30</td>
</tr>
<tr>
<td>Tr (°C)</td>
<td>Air supply Fan @ 70%</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Air supply Fan @ 60%</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Cooling system at 30/30 duty cycle</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Cooling system at 30/60 duty cycle</td>
<td>24</td>
</tr>
<tr>
<td>Power Supply Reduction (kW)</td>
<td>Air supply Fan @ 70%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Air supply Fan @ 60%</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cooling system at 30/30 duty cycle</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Cooling system at 30/60 duty cycle</td>
<td>0</td>
</tr>
<tr>
<td>Comfort loss penalty($)</td>
<td>Air supply Fan @ 70%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Air supply Fan @ 60%</td>
<td>0.00</td>
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<tr>
<td></td>
<td>Cooling system at 30/30 duty cycle</td>
<td>0.00</td>
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<tr>
<td></td>
<td>Cooling system at 30/60 duty cycle</td>
<td>0.00</td>
</tr>
<tr>
<td>Direct monetary gains($)</td>
<td>Air supply Fan @ 70%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Air supply Fan @ 60%</td>
<td>0.00</td>
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<tr>
<td></td>
<td>Cooling system at 30/30 duty cycle</td>
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<tr>
<td></td>
<td>Cooling system at 30/60 duty cycle</td>
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<tr>
<td>Utility value ($)</td>
<td>Air supply Fan @ 70%</td>
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<tr>
<td></td>
<td>Air supply Fan @ 60%</td>
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<td></td>
<td>Cooling system at 30/30 duty cycle</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Cooling system at 30/60 duty cycle</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Note: 1. All values in brackets are negative. 2. Other performance values such as response time, recovery period, availability period, state conditions of equipment (fan & cooling), CO2 measurements and state of grid has to be taken into account. 3. The value used above are for worst performing rooms in the building, coordination with respective room agents may be essential to integrate these with respective occupancy values.

cooling system as a result of the potential for load reduction as shown in Fig. 12.

However, use of cooling system may not be possible if the service is to be deployed fast; the cooling system is only deployable in 5–15 min time whereas the air supply fan is deployable within 1 min (see Table 8). Also, the use of cooling system results to comparatively longer recovery time especially when cycle times are increased; this makes air supply fans more suited for short term peak reduction duties. Consequently, innovative coordination is need with the power grid side agent to integrate the aspect of DSF time characteristic requirements and pricing.

5.5. Limitation of the study

There are 3 main limitations with respect to the proposals for DSF coordination. These are:

1. The field study is based on average sized office buildings with centralized air supply fan, cooling system and predictably stable occupancy. Results for large offices with multiple fans or cooling systems and highly variable occupancy may be different. In addition, analysis is with respect to using duty cycling operations of the air supply fan and cooling systems to provide DSF service during spring and summertime operations. Interpretations of results must therefore be taken within the context of the case study.

2. Underlying analysis in the is based on static scenarios. This is not fully representative of the real scenario whereby dynamics change very fast and multiple weather conditions and details of occupancy and use conditions of the building and power grid may be experienced all at once.

3. In addition, analysis used is with respect to single building control; this does not fully demonstrate practical implications within the context of multiple buildings control. Further work is therefore needed to practically implement the analysis on dynamic mode and using multiple buildings.

6. Conclusion

This study has confirmed effective information flow between participating actors, devices and spaces as critical for DSF coordination. This is partly driven by the need to ensure that office buildings continue to provide comfortable, safe and productive environment even when participating in DSF events. Specific information exchanged pertains to prevailing and future operational states of devices, comfort conditions, weather conditions, energy prices, power system and comprehensive occupancy. The exchanged information has to be aggregated upwards from the lower levels (user environment) of operations to the upper levels (building and grid controls).

Even though cost based coordination for DSF are most dominant; their application is not practical for office buildings due to associated difficulty in achieving tasks’ shift-ability and lack of significant price differentiation between off peak and peak periods. Also, electricity cost for commercial sector is comparatively low and no match to cost of occupants productivity losses; this makes utility considerations an idea approach to incorporating building considerations during DSF coordination in office buildings. Consequently, a utility based coordination framework using simple operational rules and cognizant of characteristics of existing service installations is proposed. This framework is adaptable for use in DSF services demanding fast, slow and very slow response requirements.

In line with limitations highlighted, the following are outlined as prime areas for future research:

1. Buildings with other types of HVAC installations (concrete core cooling, use of multiple chillers with synchronous drive motors, heat pumps and radiant heaters amongst others). Also different sizes of the building should be incorporated in future empirical
studies to capture associated equally different building use dynamics.

2. Empirical studies involving multiple buildings should be organized with the cooperation of distribution service operators. This would capture real scale performance and implications during actual DSF events.

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References


