Intelligent multi-agent system for building heat distribution control with combined gas boilers and ground source heat pump

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ABSTRACT

Intelligent energy system refers to the use of *intelligent* control strategies with the energy system, which can help minimise energy waste and loss, optimise load control, increase and improve energy efficiency and/or maximise the benefits of *renewable* energy. *Renewable* energy and *intelligent* controls are inter-linked and correlated with each other. Without *intelligent* controls, the full benefits of *renewable* energy technologies may not be achievable, specifically the ground source heat pump (GSHP) technologies. This was observed, especially by the University of Central Lancashire (UCLan) that had incorporated a GSHP to one of its building. The GSHP is under performing due to the inefficient controls implemented with the GSHP. This paper proposes an *intelligent* multi-agent building management system (MAS BMS) that aims to tackle this issue. *Intelligence* is provided by an ARTMAP, a type of artificial neural network that provides incremental learning inspired by how human process memory. Simulation results show the proposed *intelligent* MAS BMS is able to maximise the use of the GSHP effectively by profiling, predicting and coordinating its usage with other energy resources. The proposed method has performed better than the existing control strategies for the GSHP.

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1. Introduction

The need for *intelligent* energy system arises due to technological innovations that has resulted in the increasing demand for more energy to accommodate improving lifestyles. This has caused significant detrimental impact on the environment, specifically environmental changes.

To date, the major sources of energy for the UK are from non-renewable carbon-based fuels, with almost 77% of electricity produced are from these sources [1]. High use of carbon-based fuels leads to high CO_2 gas emission, contributing to global warming [1,2]. Reducing the use of carbon-based fuels and substituting them with *renewable* energy sources may help reduce the CO_2 gas emission [1,2].

Intelligent systems are autonomous (or semi-autonomous) systems that have the ability to monitor their system behaviour and provide the necessary controls to increase efficiency. The use of *intelligent* controls may help optimise the use of *renewable* energy by (i) minimising energy waste and loss, (ii) optimising load control, and (iii) increasing and improving energy efficiency. This, in turn can maximise the use and benefits of *renewable* energy, which can help reduce the cost of energy usage as well as the CO_2 gas emission and its effect to the environment.

Intelligent controllers are required to ensure efficient *renewable* energy usage, particularly when the building incorporates slow response *renewable* technologies, such as the ground source heat pumps (GSHP) [3–6]. Furthermore, a number of reports [7–10] have indicated that the reductions in predicted efficiency and the under performance of such technologies are due to unsuitable control mechanisms, i.e. non-*intelligent* controls strategies.

The University of Central Lancashire (UCLan) has its own example. The Samuel Lindow Building (SLB) at UCLan WestLakes Campus in Cumbria is installed with a GSHP that operates in addition to the conventional gas central heating system [11]. Despite this, the controller used to manage this *renewable* energy is not *intelligent*. Investigations of the output from the GSHP at UCLan's SLB indicate that the GSHP is under performing. This may have resulted from the inefficient non-*intelligent* control strategies of the existing building management system (BMS).

The existing BMS uses a multi agent system (MAS) approach with the rule-based mechanism. The rule-based mechanism lacks adaptiveness and flexibility of controls, which may have resulted in the under performing of the GSHP. This paper proposes a new MAS with a new *intelligent* and adaptive control strategies to manage the different heat sources in SLB, including the GSHP. The new MAS incorporates a *computational intelligence* algorithm (artificial neural network) that aims to improve and maximise the use of the GSHP

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in providing heat for the building. This is achieved by profiling, predicting and coordinating its usage with other energy sources, and in accordance to the heat demand required (also profiled and predicted).

The paper introduces a MAS BMS with ARTMAP, a type of ANN that adds *intelligence* to the MAS. The paper is divided into eight sections. Section 2 provides a brief summary of the existing MAS used for BMS as well as a brief introduction to the proposed ARTMAP. Section 3 describes the UCLan WestLakes Samuel Lindow Building (SLB). Section 4 describes the existing MAS BMS that is currently in place and in use to provide heat to the SLB. Section 5 presents the method proposed to help maximise the use of the GSHP for the SLB. Section 6 presents and discusses the case studies used to test and analyse the proposed method presented in Section 5. Section 7 describes the results of the case studies and Section 8 concludes the paper.

2. Multi agent system

Multi-agent system (MAS) consists of two or more agents in an environment. Each agent has its own functions or goals, and interacts with each other in a peer-to-peer (decentralised or distributive) manner so as to achieve its collective goals or objectives. MAS is particularly suitable for the distributive control tasks in a building environment (MAS BMS) because of their distinctive advantages, such as modular structure, openness, self-capacities, self-organisation and high-level transparency [14,15]. For example, each room in the building will have its own individual room temperature and thermal comfort control that is independent of the boiler control system. Therefore, the room requires its own agent and the boiler system has another. Mutual agreement and decision making are achieved through communication between the agents in the building.

MAS alone, however, has low level on-line learning and adaptation capabilities. Recently, artificial neural network (ANN) and/or fuzzy techniques are incorporated to the agents of the MAS, with the goal of incorporating online learning and adaptation capabilities to the MAS and other performance improvements [15–17]. The examples of such incorporation are:

1. *Fuzzy MAS BMS:* Fuzzy logic is suitable for BMS because the objective of thermal comfort management may be referred to as the state of mind or *psycho-synthesis* of the occupants in a building environment that expresses satisfaction with the temperature in the building. This is fundamentally a fuzzy concept, which differs from people to people, and is dependent on the type of activities they are engaged in [18–22].
2. *ANN MAS BMS:* Liang [23] has developed a back-propagation ANN that is used to maintain the thermal comfort level within a desired range. However, due to the slow convergence of back-propagation, the controller may not be a feasible solution for large building environment.
3. *Neuro-fuzzy thermal comfort management:* Neuro-fuzzy systems combine ANN and fuzzy techniques. Yamaha et. al. [24] has developed a neuro-fuzzy BMS to predict weather parameters and the number of occupants in a building. This predictive information are then used to profile the energy flow for the building in order to minimise energy consumption and to maintain thermal comfort at an acceptable level.

2.1. Proposed algorithm: ARTMAP

This paper presents the use of ARTMAP to add *intelligence* and online learning to the MAS BMS. ARTMAP, which was developed by Carpenter et al. [27], is a supervised artificial neural network
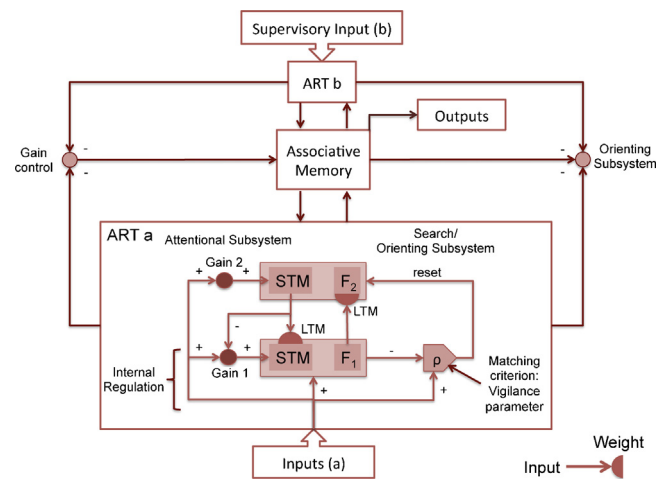

Fig. 1. ARTMAP structure [27,28].

(ANN) algorithm inspired by how human process memory, and is able to learn new information without necessarily forgetting previously learned information [27,28]. ARTMAP deals with the stability and plasticity issues by combining two adaptive resonance theory *ART* networks, i.e. *ART a* and *ART b*, as illustrated in Fig. 1, which have the ability to establish memory (the input-to-output correlations) within the two networks. A memory is created through the interconnection that transfers short term memory (STM) to and from long term memory (LTM) within each *ART* network [27,28]. ARTMAP performs both prediction and classification, and is an ideal tool for online learning and adaptation of an agent.

ARTMAP works by classifying and categorising the inputs presented to the network at *ART a* according to the desired categories (supervisory inputs) presented at *ART b* [27,28]. During supervised learning, *ART a* receives the inputs that needed to be classified, whilst *ART b* indicates how the provided inputs should be classified. The two *ART*s are linked by an associative memory, as illustrated in Fig. 1. The associative memory consists of an associative map and a controller, called map field, that prevents category proliferations within *ART a* [27].

The associative map does not directly associate inputs presented to *ART a* and *ART b*, but instead creates the association between the category activation produced by *ART a* and *ART b* [27]. The map field uses a *minimax learning rule* that automatically links predictive success (the category activation produced by *ART a*) that matches the category activation produced by *ART b*. The learning rule is executed on a trial-by-trial basis, by increasing the vigilance parameter of *ART a* (ρ_a) with the minimum amount needed to make the corrective predictive error at *ART b* [27]. The smaller the ρ_a value, the bigger the size of the category. This process is called *match tracking*, which sacrifices generalisation in order to ensure minimal predictive error [27]. If the predictive error persists, a new category will be created within *ART a*, which correlates the new input patterns presented to *ART a* to the input (category) information presented to *ART b*.

This architecture helps ARTMAP learn new data without forgetting its previously learnt information, as well as providing the ability to infer the adaptive output based on newly acquired memory [27,28].

3. UCLan Samuel Lindow Building

UCLan Samuel Lindow Building (SLB) uses gas fired boilers and a ground source heat pump (GSHP) as heat sources for the building. As indicated in Section 1, the SLB heat distribution is controlled by a rule-based multi agent building management system (MAS
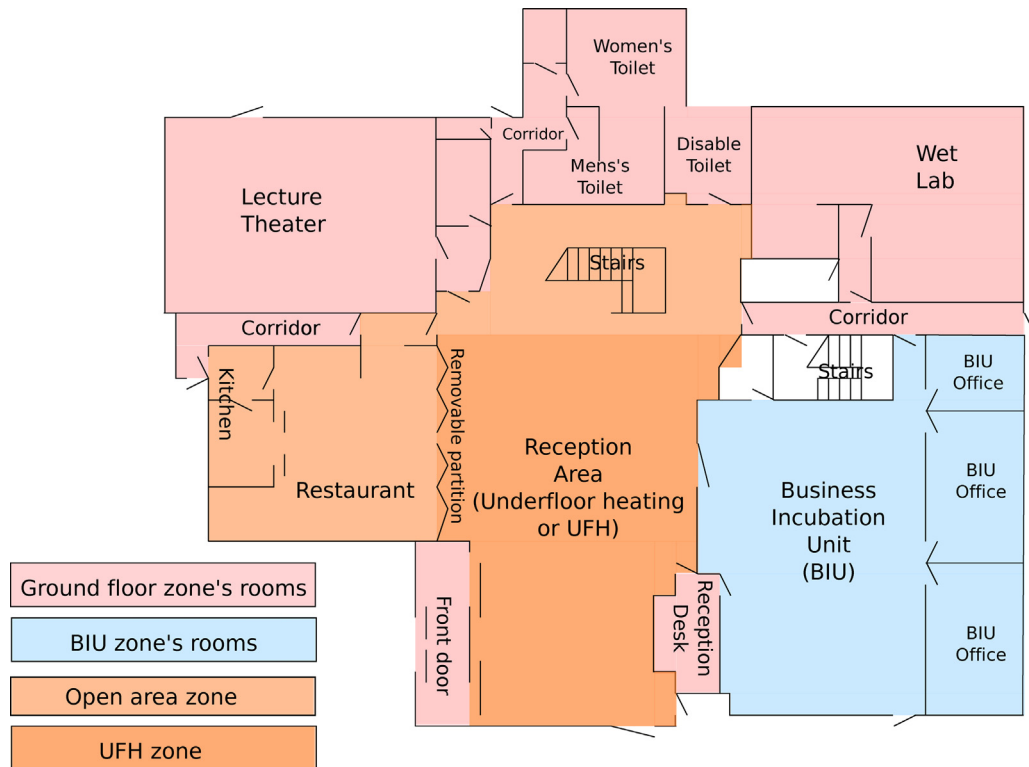
Fig. 2. The schematic of the ground floor of UCLan Samuel Lindow Building.

BMS) that aims to maintain the temperature of the building zones at $23 \pm 2\,°C$.

The current MAS BMS splits the building into 4 zones, with each zone controlled by an agent. The zones are:

1. Reception Zone: located on the ground floor and includes a cafe/restaurant area. The Reception Zone is shown in Fig. 2, which also includes the area labelled the open area zone.
2. BIU Zone: Business Incubation Unit (BIU) is also located on the ground floor and consists of one open work area and three small offices. BIU is shown in Fig. 2.
3. Ground Floor Zone: This is the remainder of ground floor area and consists of a lecture theatre and various rooms on the ground floor, as shown in Fig. 2.
4. First Floor Zone: consists of offices including a computer room, class rooms and a mezzanine/library floor.

The heat for Zones 2–4 are provided by radiator panel(s) in each room in the zones, with the gas boilers providing the heat to the radiators. The heat for Zone 1 is provided by:

1. Underfloor heating (UFH), with the heat provided by the GSHP.
2. Five radiator panels, with the heat provided by the boilers.

We are limiting our analysis of the MAS BMS and subsequent application of the newly proposed MAS BMS controls to Zone 1 only. Further information on other zones are described in [17].

3.1. Reception Zone

The Reception Zone (Zone 1) is divided into seven sub-zones. Each sub-zone has a temperature sensor. Five out of the seven sub-zone temperature sensors monitor the sub-zones heated by the radiator panels, one per each sub-zone. The UFH provides heat to the remaining two sub-zones, with a temperature sensor installed at each of the two sub-zones.

3.1.1. The under floor heating system (UFH)

The underfloor heating system or UFH is a sequence of nine loops of 40 mm plastic tubes arranged in parallel to cover the entire $165\,m^2$ floor space of the room. The tubes are set 150 mm apart. The loops are arranged so that heating is applied evenly throughout the room as warm water passes along the length of the pipe in each loop.

The heat (warm water) for the UFH heating system is provided by the Visemann Vitocell 300-B 500 l heat exchange vessel [12]. The exchange vessel uses two indirect coils to exchange heat via the water in the tank. The maximum heat output from the vessel is 15 kW, pumped at a rate of $0.39\,l\,s^{-1}$ by the UFH heating pump. Fig. 6 shows the recorded water temperature of the exchange vessel. Heat is supplied to the exchange vessel from the Visemann Vitocell 300 G ground source heat pump (GSHP) [13].

3.1.2. Ground source heat pump

The GSHP works by pumping a fluid along pipes buried underground. The heat that may be extracted from the ground is dependent on the temperature of the ground, the size of the evaporation chamber and the capability of the pump. Fig. 3 shows the relationship between the ground temperature and the heat that may be extracted (A), as well as the electrical power used by the heat pump to perform the evaporation, compression and condensing (C). The heat pump may be used for cooling, and this performance is shown by (B) in Fig. 3. The performance of the heat pump depends on the temperature the fluid is raised to.

The system installed in the SLB is set to maximum $55\,°C$ (F), while better performance may be reached with lower temperatures $45\,°C$ (E) and $35\,°C$ (D). The maximum output from the GSHP is 29 kW for heating the brine to $55\,°C$ with very warm ground temperature (>$15\,°C$), but closer to 24.8 kW at a ground temperature at $\approx 8\,°C$. The
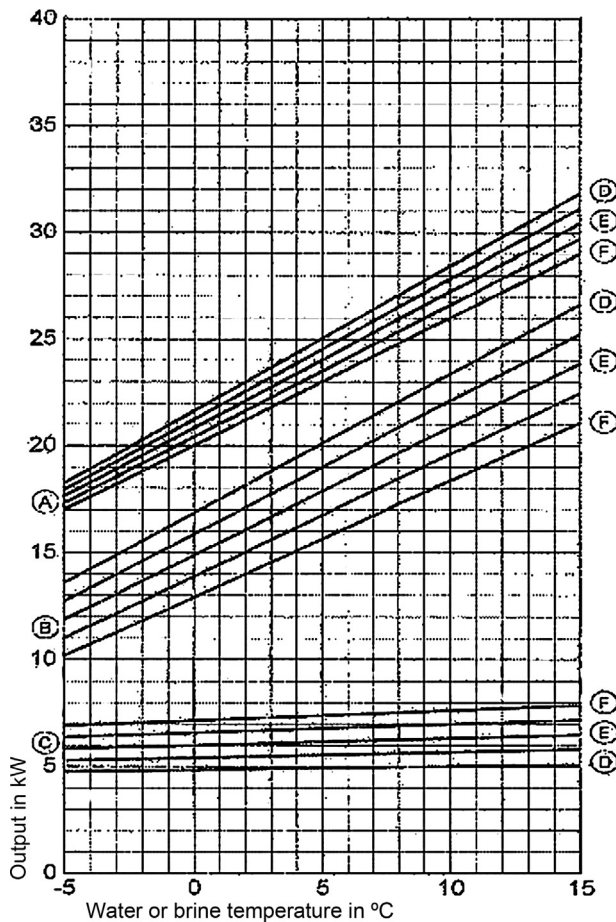
Fig. 3. Performance of the Vitocell 300G Heat Pump [13].

electrical power used to achieve this is ≈7.6 kW, giving a coefficient of performance (CoP) of 3.26. By comparison, the gas boilers may only be 85–92% efficient, therefore having far lower CoP values.

4. The existing multi agent building management system (MAS BMS)

As described in Section 1, the existing building management system (BMS) uses a multi-agent system (MAS) to manage its heat distribution. The existing MAS BMS, illustrated in Fig. 4, consists of User Agents and Source Agents. A User Agent is responsible for achieving and maintaining the desired temperature for each of its respective zone (Section 4.1). The Source Agent is responsible for describing how best to provide heat for the building (Section 4.2).

4.1. User Agents

In the existing BMS, the User Agents are incorporated with a set of rules (rule-based method) to ensure that the building is maintained within the desired temperature. The rules are:

If (zone temperature < desired temperature)
    Then open the hot water valve to the zone to allow the hot water to flow to the radiators in the zone and the water temperature in the radiators to increase to approximately (maximum of) 80 °C;
Else
    Then close the hot water valve and the water temperature in the radiators decreased and maintained at the decreased temperature until the zone temperature = (desired temperature - 2 °C);
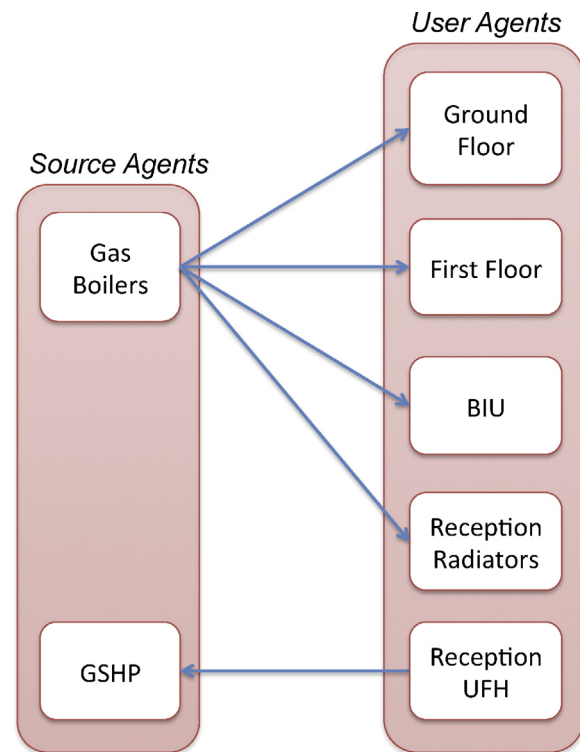

Fig. 4. The multi-agent system of the UCLan SLB multi agent building management system or MAS BMS.

The hot water temperature to a zone decreases by mixing hot water from the boilers with the return water from the radiators in the zone.
    The desired temperatures of the zone are:

If (during the weekdays)
    Then desired temperature ≈23 °C;
Else
    Then desired temperature ≈10 °C;

4.2. Source Agents

The Source Agent for the boiler system states that:

If during the weekdays *and* between 02:00 to 21:00 h
    Then the boilers are switched on *and* hot water temperature ≈80 °C;
Else
    Then the boilers are switched off *and* the water temperature from the boilers are cooled;

The Source Agent for the GSHP states that:

If (zone temperature < desired temperature)
    Then the GSHP is switched on;
Else
    Then the GSHP is switched off;

In the existing MAS BMS, there is only one-way communication between the Source Agent and the User Agents. The gas boilers Source Agent propagates the hot water temperature value to the User Agents, but no room temperature information is fed back to the gas boilers Source Agent from the User Agents. No communication is established between the two Source Agents, despite the two sources providing heat to the same zone (Reception Zone 1).
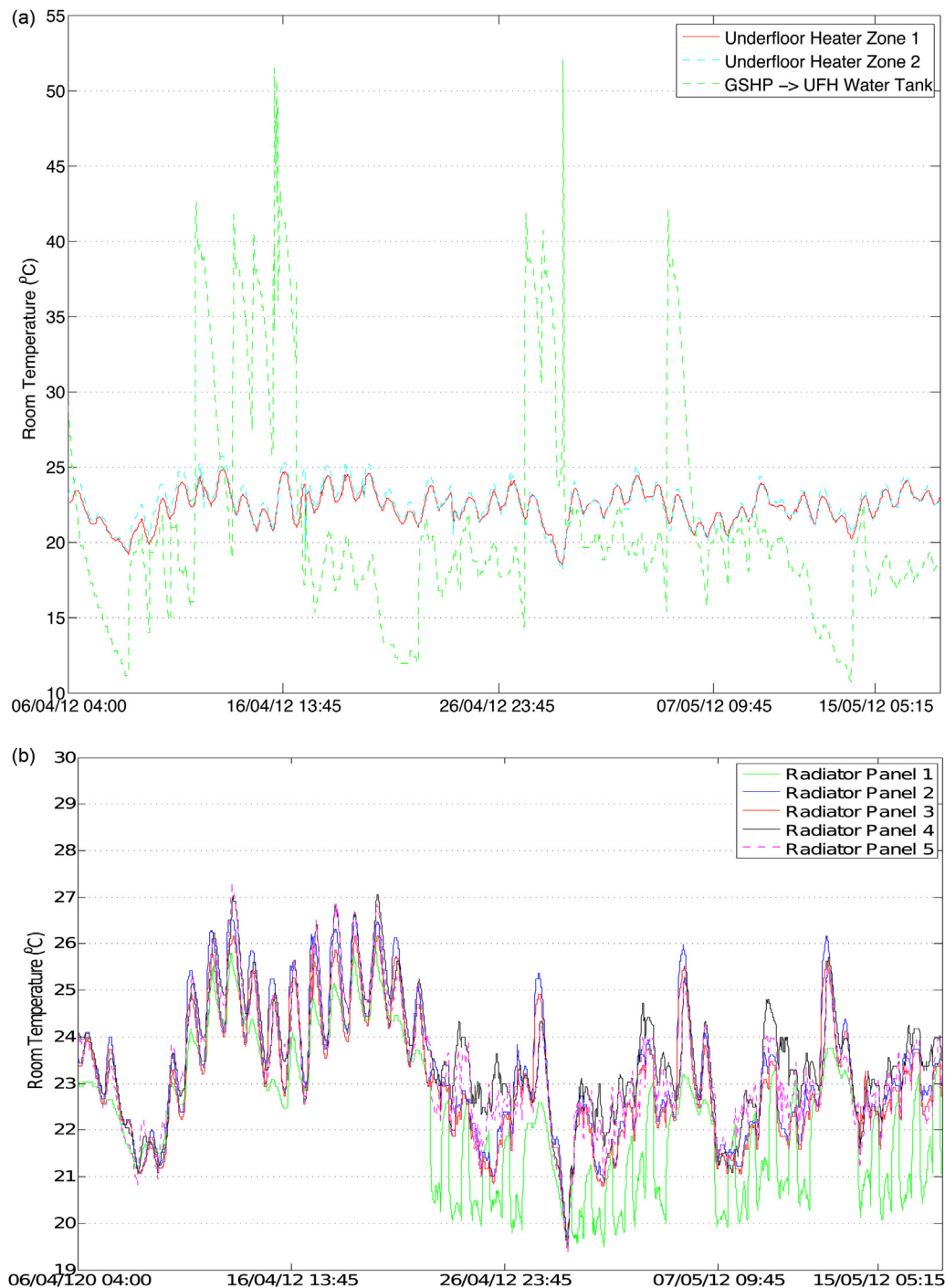
Fig. 5. The recorded room temperatures from the seven sensors installed in the Reception Zone (Zone 1) of the SLB shown in Fig. 2. (a) The reading from the two sub-zones temperature sensors heated by the underfloor heating (UFH) system. (b) The reading from the five sub zones temperature sensors, with each sub-zone is heated by a radiator and is within the area labelled the open area zone.

4.3. Recorded temperatures

The GSHP was installed to help reduce the energy bill for the building. Figs. 5 and 6 show the recorded room temperature sensors from the seven sensors installed within the Reception Zone of the SLB and the recorded water temperature in the exchange vessel for the UFH.

Fig. 5a demonstrates how the GSHP is under performing in providing heat to the Reception Zone 1, whereby the figure shows that for long periods of time, the temperature of the room is greater than the water temperature in the UFH tank. This is because during these periods, heat is provided by the five radiators connected to the gas central heating system. The existing MAS BMS allows heat to be provided by the gas boilers without considering the heat provided by the GSHP. This resulted in the heating system with faster response to provide the bulk of heat to the zone during the office hours. In Fig. 5a, the GSHP is switched on when the water temperature values of the UFH system, labelled GSHP → UFH Water Tank in the figure, is greater than the zone temperature (approximately >25 °C).

Fig. 6. The recorded (hot) water temperature in the exchange vessel heated by the GSHP.

As can be seen in Fig. 5b, the sub-zones temperatures with the radiators remain higher than the desired room temperature. This demonstrates that the gas boilers are the dominant heat source to the zone, when compared against the lower temperatures of the UFH system. This is because the radiators in the zone can draw heat faster from the gas boilers than from the GSHP; with their hot water constantly maintained at ≈80 °C. The gas boilers have provided a faster response to the heat demand from the zone.

In contrast, the water temperature of the exchange vessel to the UFH system is not maintained at a high temperature by the GSHP. The water temperature in the tank is only limited to ≈55 °C, once the system is switched on. The system is only switched on when there is a demand for heat from the zone. As a result, there is a far slower response from the GSHP to provide hot water for the UFH system. This is evident because, only at weekends that the UFH system is providing heat to the zone, i.e. providing heat when the gas boilers are programmed to be switched off. This is shown in Fig. 6. The UFH system is indicated to provide heat to the zone when the water temperature provided to the UFH (indicated by GSHP → UFH Water Tank in Fig. 6) is greater than the zone temperature. This indicates that the existing MAS BMS does not use the capabilities of the GSHP effectively.

Therefore, a new control approach is required to ensure the full utilisation of the GSHP. This may prevent the under performing of the GSHP and allows the building to achieve its initial objective of reducing its energy (gas) bills.

5. The need for new *intelligent* control strategies

Qiao et. al. [16] presents a MAS incorporating Mediator Agents as intermediary agents that acknowledge and mitigate the transfer of information between User Agents and Source Agents. The incorporation of Mediator Agents to our MAS BMS can help maximise the use of the GSHP and reduce the demand of energy from the gas boilers. The Mediator Agents can categorise the two heat sources for Reception Zone 1 into (i) *primary* energy demand provided by GHSP and (ii) *secondary* provided by the gas boilers. The Mediator

Agents can mediate when additional heat required by the Reception Zone is indicated and is to be provided by the *secondary* gas boilers.

Fig. 7 illustrates the proposed MAS BMS that incorporates the Mediator Agents. This proposed MAS BMS is an extension to the BMS system for SLB described in [17]. The new BMS allows bi-directional communication between the Source Agents and the users agents in the building, mediated by the Mediator Agents. In the figure, Mediator Agent(ii) informs Mediator Agent(iii) when its respective User Agent(s) can participate with the heat management performed by the boiler's Source Agent.

Results presented in [17] show that the bi-directional communication between the two agents as well as the incorporation of ARTMAP to the agents can increase the energy efficiency of the
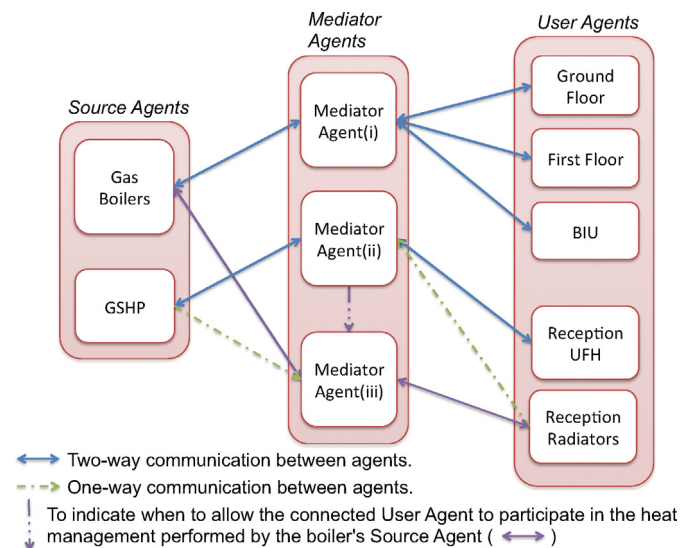

Fig. 7. The proposed infrastructure of the MAS BMS with the Reception Zone (Zone 1) heat management performed by its respective User Agents.

building.[1] The control strategies required for the gas boilers and the radiators are dependent on the information provided by both the Source Agents and User Agents.

5.1. The need for Mediator Agents

The Mediator Agent(ii) is required to help categorise the two heat sources into the two categories: (i) *primary* and (ii) *secondary* heat sources. This is as illustrated in Fig. 7, which categorises the Reception Radiators User Agent as a passive system. The reception radiators User Agent does not propagate and influence the heat demand from the boilers, unless allowed by Mediator Agent(ii). The transfer of heat demand information from the Reception Radiators User Agent to the gas boilers Source Agent is via the mitigation of the Mediator Agent(iii).

Because of this arrangement, the GSHP will be the main heat provider to this zone, with Mediator Agent(ii) as the main communication link between the heat sources (gas boilers and GSHP) and the heat users (Reception Zone). Mediator Agent(iii) will allow the Reception Zone Radiators User Agents to be active, similar to the other zones in the building, only when fault occurs to the GSHP and/or when additional heat is required by the zone.

5.2. Adding intelligence

To allow the full utilisation of *renewable* energy technologies, the *intelligent* mechanism is also required. *Intelligence* includes, but is not limited to, predictive and regulative capabilities in describing its required functionalities. The *intelligent* mechanism will be installed to a microprocessor for each agent. Communication is proposed via the power line communication.

The following section describes how *intelligence* are incorporated with the proposed MAS BMS illustrated in Fig. 7.

6. Case study: simulation of the SLB and the proposed building management system

To test the proposed MAS BMS shown in Fig. 7, a model of the heating systems of the SLB, initially presented in [17], is used. The model is modified to include heating of the Reception Zone. This model will be simulated with three scenarios:

1. *Scenario 1:* using the recorded (actual) hot water temperature as the heat source for all the zones (to omit the boiler controls simulation) and with the inclusion of the GSHP as another heat source to Zone 1. Heat management of the building is provided by the existing MAS BMS control strategies described in Section 4.
2. *Scenario 2:* Reception Radiator User Agent as a passive agent, and the gas boilers Source Agent is incorporated with new boiler controls. More information on the new boiler controls is described in Section 6.1.1. The new boiler controls, initially presented in [17], use the demand information only from Zones 2–4 provided by the Mediator Agent(i). This is as indicated in Fig. 7,
3. *Scenario 3:* the proposed MAS BMS using the infrastructure illustrated in Fig. 7.

Each MAS BMS is simulated to manage the heat distribution of the SLB. Further description of Scenarios 2 and 3 are described in Sections 6.1 and 6.2 respectively. The results of these simulations are presented in Section 7.

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[1] In [17], we omitted the Reception Zone in our analysis. This is valid with the assumption that there is no heat transfer between the zones.

6.1. Scenario 2: new boiler controls and the Reception Radiators User Agent as passive agent

In Scenario 2, new boiler controls are provided by the ARTMAP (added to the gas boilers Source Agent – Section 6.1.1). This arrangement is made to test the capabilities of the ARTMAP to provide new and improve boiler controls according to the dynamic heat demand from Zones 2–4 (the hot water is heated to ≈80 °C only when Zones 2–4 demand the heat).

In this scenario, no heat demand information from the five radiators in the Reception Zone 1 are included in the decision making process of the gas boilers Source Agent. This forces the Reception Radiators User Agent to become a passive agent. Reception radiators User Agent is a passive agent to help overcome the under performing of the GSHP and to encourage its usage. As a passive agent, the Reception Radiators are not allowed to demand for more heat from the gas boilers. This is illustrated in Fig. 7.

Scenario 2 is also created to indicate how much heat is required from only the Reception Zone. Results from Scenario 2 are compared against our previous work described in [17] that omits the Reception Zone from its simulation. The differences show how much heat can be saved if such heat was to be provided by the GSHP instead. This in turn helps in the energy saving of the building.

The User Agents use the rule-based mechanism that is currently in use within the existing MAS BMS (Section 4).

6.1.1. New boiler controls

At present, the gas boilers are not controlled by the dynamic heat demand of the building. This is as indicated in Section 4.2. The new gas boiler controls provided by the ARTMAP can help reduce energy wasted due to the unnecessary heating of the boilers when there is no heat demand from the building and/or excess heat generation. The Source Agent uses the information provided by the User Agents under the mitigation of Mediator Agent(i), to provide the best operation of the boilers. The inputs to the Source Agent are:

1. Current date and time.
2. $O_T(t)$, $O_T(t-1)$, $O_T(t-2)$, $O_T(t-3)$, $O_T(t-4)$:
   $O_T(t)$ is the current outdoor temperature.
   $O_T(t-x)$ is the outdoor temperature at the previous x sample.
3. $I_y(t)$, $I_y(t-1)$, $I_y(t-2)$, $I_y(t-3)$, $I_y(t-4)$:
   $I_y(t)$ is the current average building temperature.
   $I_y(t-x)$ is the average building temperature at the previous x sample.
   Average building y temperature is calculated by averaging the measured temperature values of all zones in the building.
4. $W_O(t)$, $W_O(t-1)$, $W_O(t-2)$, $W_O(t-3)$, $W_O(t-4)$:
   $W_O(t)$ is the current average return water temperature from the radiators.
   $W_O(t-x)$ is the average return water temperature from the radiators at the previous x sample
5. $W_I(t)$, $W_I(t-1)$, $W_I(t-2)$, $W_I(t-3)$, $W_I(t-4)$:
   $W_I(t)$ is the current water temperature from the boiler.
   $W_I(t-x)$ is the input water temperature from the boiler at the previous x sample

(1)–(3) are the inputs indicating the energy demand. (4) and (5) are the inputs indicating the energy resource.

The outputs from the ARTMAP are:

1. '0' - boiler is switched off or '1' – boiler is switched on (labeled as mARTMAP1 in Fig. 8 [17]).
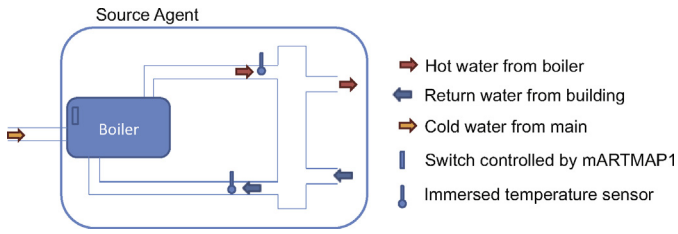
Fig. 8. The Gas boilers Source Agent responsible for the boiler management.

2. The *learned* ideal hot water temperature to be maintained (and boiled) by the boilers.
3. The *learned* desired building temperature to be maintained.

The Source Agents (the gas boilers and the GSHP) provide their outputs every 15 min.

6.2. Scenario 3: the proposed MAS BMS

The MAS BMS presented in [17] aim to achieve energy efficiency by minimising energy loss and energy bills of the building. The presented MAS helps increased energy efficiency through the:

1. Bi-directional communication between the User Agents and Source Agents.
2. New gas boiler controls provided by its Source Agent (as described in Section 6.1.1), which utilises demand information from the User Agents in its decision making strategies.

6.2.1. Mediator Agents
The two additional Mediator Agents (Mediator Agent(ii) and Mediator Agent(iii)) allow an indication of when the Reception Radiator's User Agents should become active and provide hot water to the five radiator panels in the zone. This allows the GSHP to become the primary heat provider to the zone. The mitigation of controls are managed through the communication between the two Mediator Agents.

To decide when the Reception Radiators User Agent should become active, Mediator Agent(ii) will utilise the following input information from the GSHP:

1. Is there hot water flowing from the GSHP.
2. The water temperature from the boilers.

These sensors are installed and currently under-used by the existing MAS BMS of the building.

Inputs to the Mediator Agent(ii) are:

1. Current date and time.
2. $O_T(t)$, $O_T(t-1)$, $O_T(t-2)$, $O_T(t-3)$, $O_T(t-4)$.
3. $I_T(t)$, $I_T(t-1)$, $I_T(t-2)$, $I_T(t-3)$, $I_T(t-4)$.
4. $W_I(t)$, $W_I(t-1)$, $W_I(t-2)$, $W_I(t-3)$, $W_I(t-4)$.
5. $W_O(t)$, $W_O(t-1)$, $W_O(t-2)$, $W_O(t-3)$, $W_O(t-4)$.
6. $W_{GSHP}(t)$, $W_{GSHP}(t-1)$, $W_{GSHP}(t-2)$, $W_{GSHP}(t-3)$, $W_{GSHP}(t-4)$:
   $W_{GSHP}(t)$ is the current water temperature to the UFH.
   $W_{GSHP}(t-x)$ is the water temperature to the UFH at the previous x sample.

(1)–(5) are the inputs indicating energy demand and (6) indicating the energy resource.

Outputs from the Mediator Agent(ii) are:

1. Either '0' for no hot water flow or '1' for full hot water flow to the radiators.
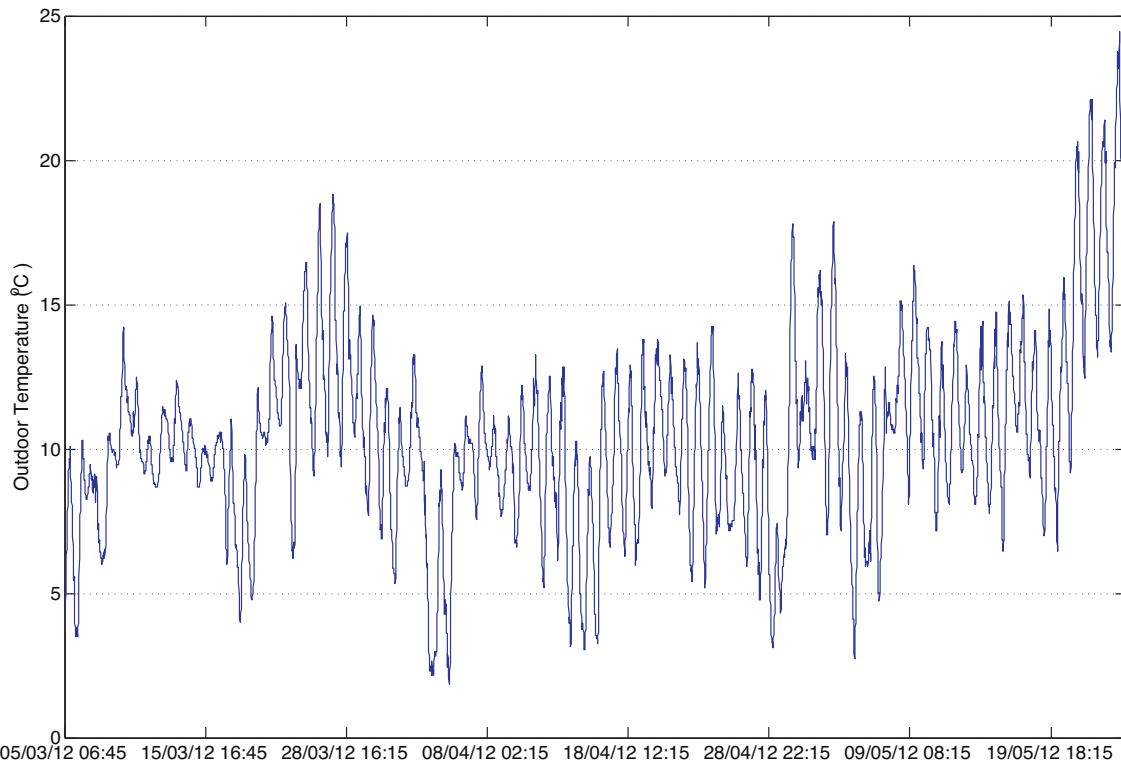2. The *learned* desired temperature setting for the Reception Zone.

Fig. 9. The recorded outdoor temperature between 5th March 2012 to 25th May 2012, omitting the hours of 22nd March 2012 09:00 to 24th March 2012 22:24. No data were collected during these times.
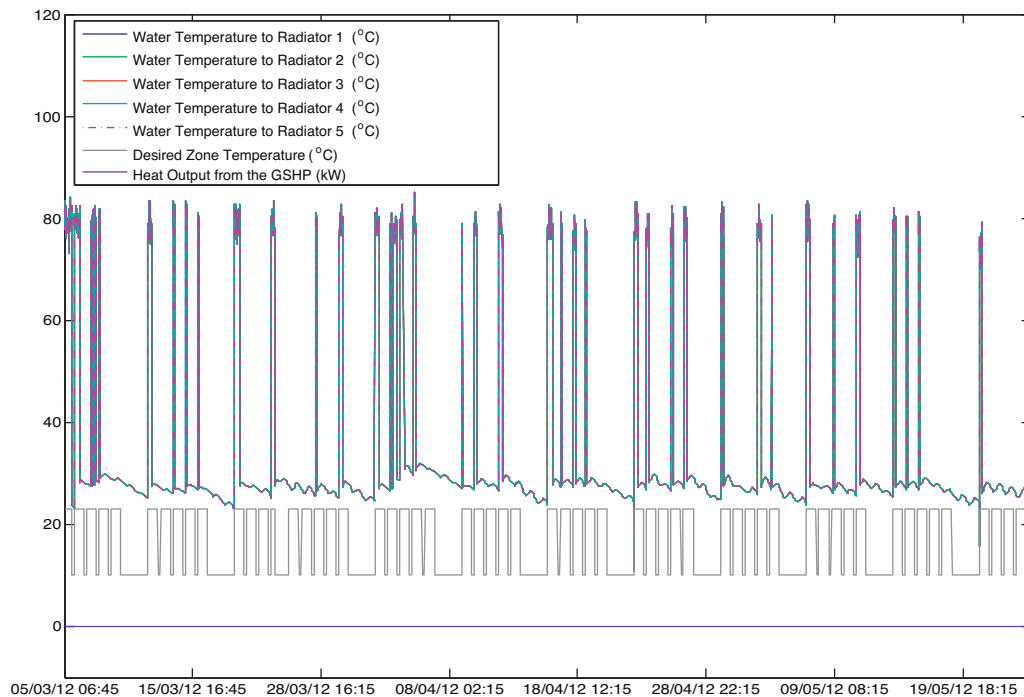
Fig. 10. The water temperature provided to the five radiators in Reception Zone, the desired zone temperature and the GSHP heat output from Scenario 1.

Similar to the Source Agent described in Scenario 2 and the agents presented in [17], the Mediator Agent(ii) provides its outputs every 15 min. The above information is forwarded to the Mediator Agent(iii) to indicate when the Reception Zone User Agents can propagate its demand information to the Source Agent gas boilers.

6.2.2. Adding the intelligent capabilities

The proposed MAS BMS incorporates the ARTMAP, described in Section 2.1, to provide *intelligence* to its active agents.

7. Results

As listed in Section 6, three sets of simulations conducted are:

1. *Scenario 1: Existing BMS (Section 7.1)*: Scenario 1 uses the recorded (actual) hot water temperature as the heat source for all the zones. This is to omit the boiler controls simulations. Heat management of the Reception Zone 1 is provided by the existing rule-based MAS BMS control strategies indicated in Section 4.1.
2. *Scenario 2: new boiler controls and the Reception Radiators User Agent as passive agent (Section 7.2)*: reception radiators utilise the hot water provided by the gas boilers Source Agent new boiler controls presented in Section 6.1.1, without the reception radiators User Agent be part of the decision making process of the boiler controls.
3. *Scenario 3: proposed MAS BMS (Section 7.4)*: the proposed MAS BMS described in Section 6.2.

All these scenarios are simulated with the recorded outdoor temperature indicated in Fig. 9. The outdoor temperature is between 5th March 2012 to 25th May 2012, omitting the values between 22nd March 2012 09:00 to 24th March 2012 22:25. This is because no data was collected during these times.

7.1. Scenario 1: existing BMS

Fig. 10 shows the heat demand from the gas boilers reaches and maintains the desired temperature at the Reception Zone, given the outdoor temperature indicated in Fig. 9. No heat output from the GSHP is shown, which resulted from the inefficiency of the existing MAS BMS in utilising the GSHP to meet the demand of heat from the zone. The GSHP is not providing any heat to the zone because the five radiators in the zone are the *primary* heat provider to the zone. This finding corroborates with the actual system shown in Fig. 6.
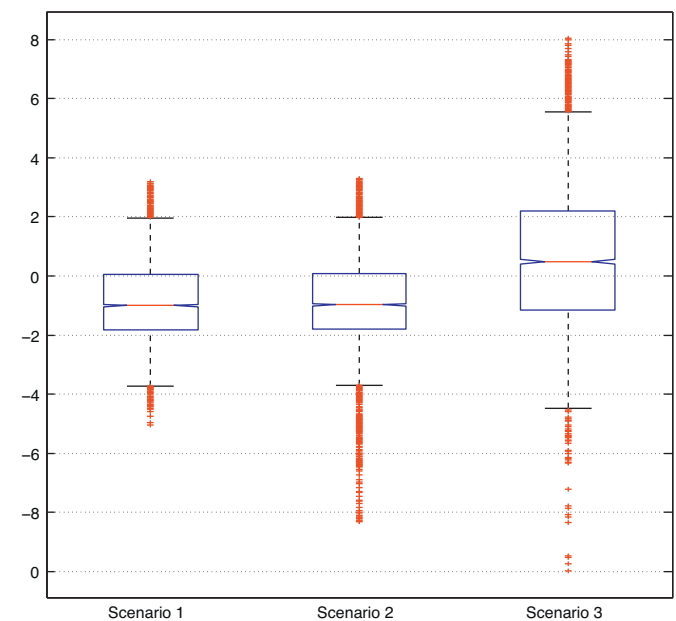

Fig. 11. The distribution (box plot) of the average Reception Zone 1 temperature minus the desired temperature for Scenarios 1–3.

The existing MAS BMS control strategies resulted in the five radiators in this zone to be the main heat provider to the zone (as shown in Fig. 10). This causes the under performing of the GSHP. The intake of the hot water, demanded by the five radiators, should have been provided by the GSHP; which was the main purpose for the GSHP installation.

7.2. Scenario 2: Reception Radiators User Agent as passive agent

Fig. 11 shows the distribution (box plot) of the simulated sub-zone temperatures minus the desired zone temperature when the Reception Radiators User Agent is a passive agent and the new boiler controls described in Section 6.1.1 are used. Similar

Table 1
Comparing the energy usage with new boiler controls.

	Energy used (MWh)
Existing BMS[a]	55.009[b]
With new boiler controls (Section 6.1.1) without the Reception Zone	27.0839[b],[c]
With new boiler controls with the Reception Zone	39.1618[c]
Heat required by the Reception Zone	39.1618 −27.0839 = 12.0779

[a] The actual energy used by the building between 1st March to 25th May 2012. Information is estimated based on the information provided by the energy provider *e.on* and the installed BMS.

[b] Data collected from [17].

[c] *Energy used* is measured using the temperature differences between the provided hot water to the zone and its return water temperature.
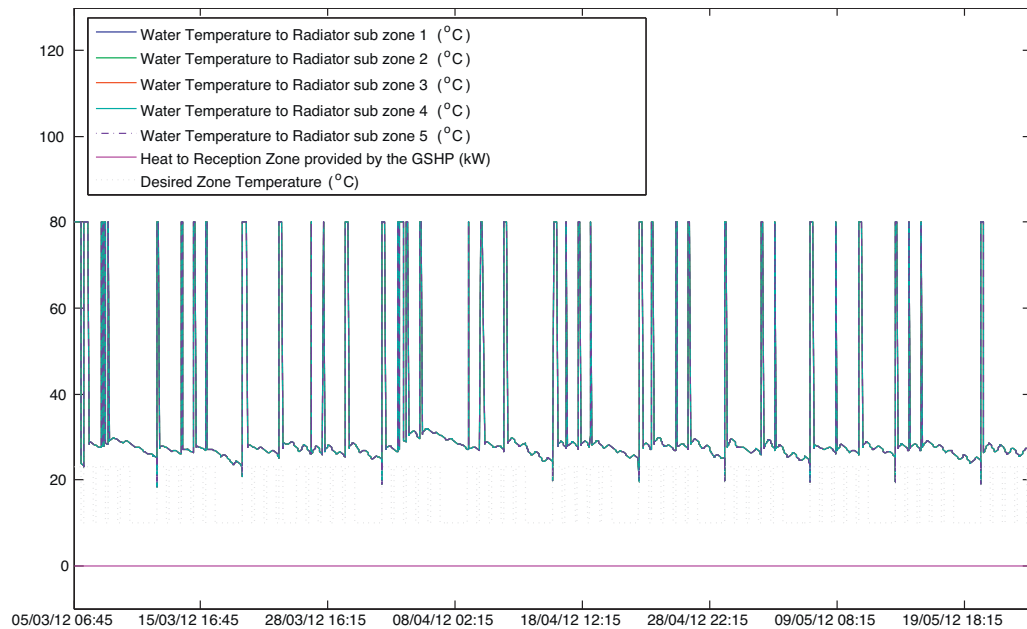

Fig. 12. The water temperature provided to the radiators in Reception Zone, the desired zone temperature and the GSHP heat output to the zone from Scenario 2.
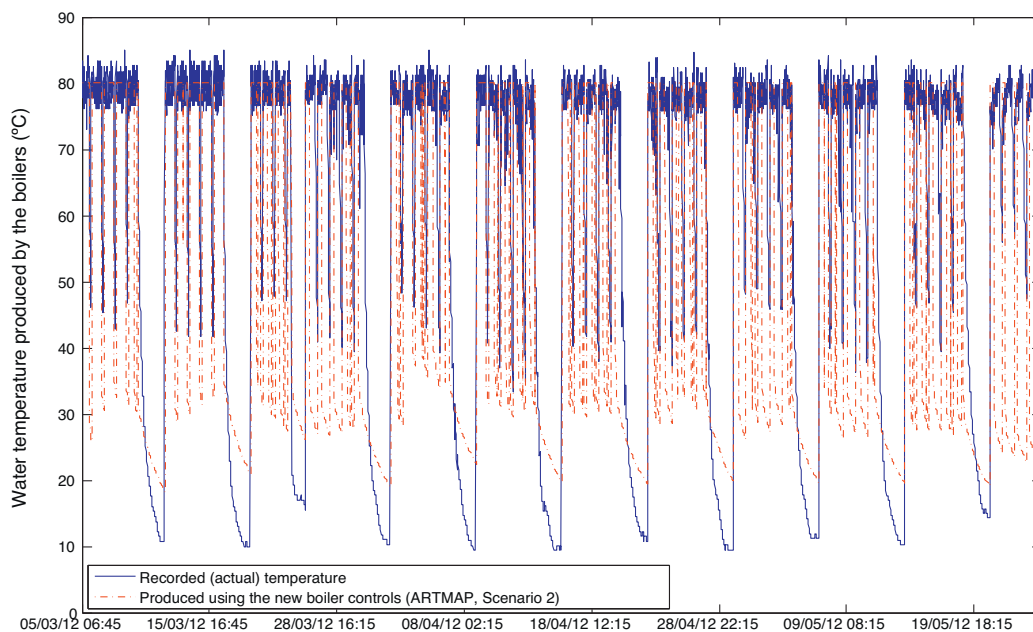

Fig. 13. The hot water temperature produced by the gas boilers when utilising the MAS BMS control strategies described in Section 6.1 (Scenario 2) and the actual hot water temperature.
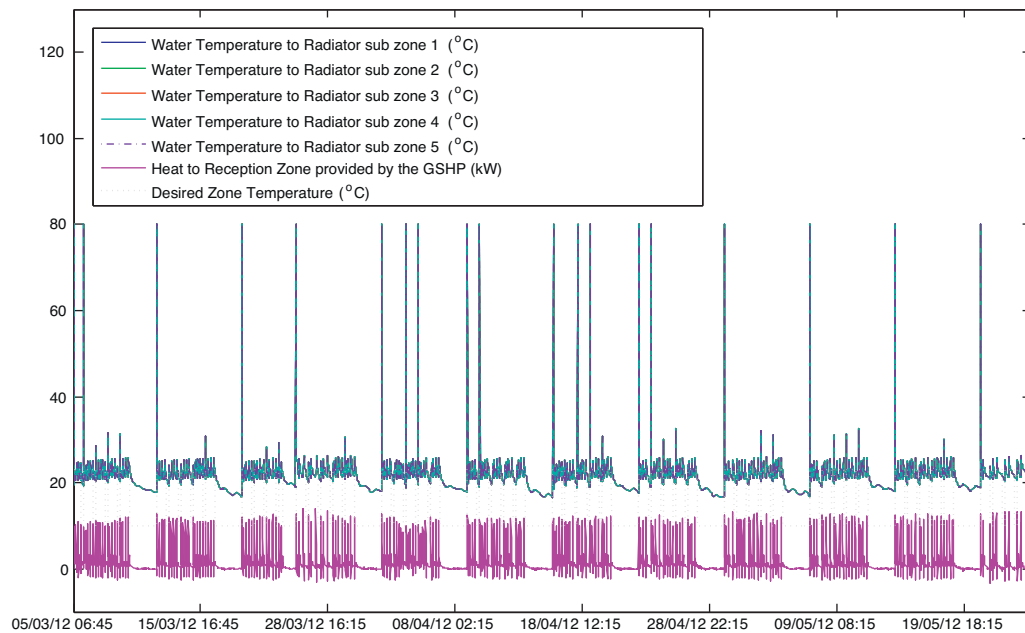
Fig. 14. The energy for the Reception Zone when utilising the proposed MAS BMS Scenario 3. Figure shows the GSHP is the main heat provider to the zone.

simulated zone temperature values were recorded when compared against the two MAS BMS strategies: Scenarios 1 and 2.

Despite treating the Reception Radiators User Agent as a passive agent, the results demonstrate that the heat provided can achieve and maintain the desired zone temperature, with less gas used and energy produced by the gas boilers. Heat is provided by the hot water produced by the new boiler controls. This is in comparison to actual energy (heat) consumption of the building, as indicated in Table 1. The difference between the actual boiler temperature and the boiler temperature resulting from dynamic heat demand from the building with new boiler controls is illustrated in Fig. 13. Similar observation was described in [17].

7.3. Summarising the results from Scenarios 1 and 2

Figs. 10 and 12 show that because of the slow response time of the GSHP, the GSHP is not acting as the *primary* heat source to the

Reception Zone; even with the Reception Radiators User Agent as passive agent (Scenario 2). No heat is provided by the GSHP because the five radiators in the zone are providing the required heat for the zone.

This indicates the need for the new MAS BMS strategies required to force the GSHP to become the primary heat provider for the zone. The new MAS BMS is presented in Section 6.2 and illustrated in Fig. 7. Results from the new BMS *Intelligent* control strategies are presented in the following section.

7.4. Scenario 3: the proposed MAS BMS

The new proposed BMS strategies adds *intelligence* (ARTMAP) to all the active User Agents and to its gas boilers Source Agent in the MAS BMS. This is because these agents are easily replaceable from the existing BMS. Fig. 14 shows the distributions of the simulated sub-zone temperatures for the Reception Zone when
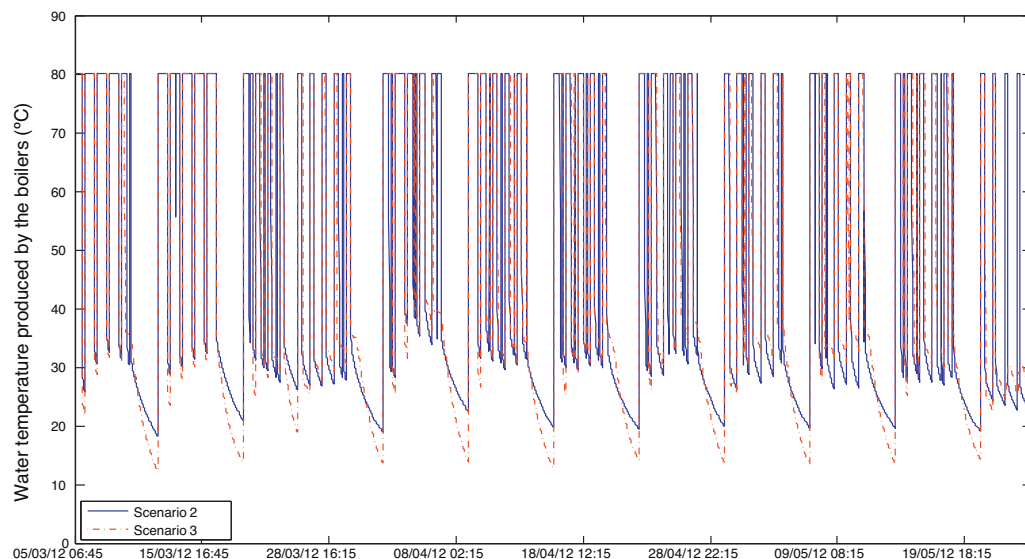

Fig. 15. The hot water produced by the gas boilers for Scenarios 2 and 3; resulted in the small energy saving indicated in Table 2.

Table 2
Comparing the energy usage with the proposed MAS BMS

	Energy used (MWh)
Existing BMS	55.0090
With the proposed MAS BMS	38.6796[a]
Electricity used by the GSHP	3.36409

[a] *Energy used* is measured using the temperature differences between the provided hot water to the zone and its return water temperature.

its heat is managed by the proposed MAS BMS illustrated in Fig. 7.

Fig. 14 shows *Intelligence*, provided by the ARTMAP, added to the GSHP User Agent helps ensure that the GSHP is the *primary* heat provider to the Reception Zone. The GSHP has produced part of the required 12.0779 MWh heat required by the zone. This is as indicated in Table 1. The GSHP has provided the heat output of $\approx$11.7660 MWh, which is equivalent to 97.5% of the energy required to heat the Reception Zone. In doing so, the GSHP used 3.36 MWh of electrical energy. This demonstrates a system efficiency of $\geq$349% (Fig. 15).

The greater use of the GSHP with the improved boiler controls have resulted in a 23% reduction in the building's gas consumption. This can lead to lower carbon emissions and greater energy cost savings. Increased revenues may be achieved with the addition of Renewable Heat Incentive payments from UK government [31].

The performance of the GSHP means that the carbon cost of the grid electricity used to power the heat pump is less than that equivalent heat energy from the gas supply. This further contribute to the lowering of the carbon emissions (Table 2).

8. Summary and conclusion

The existing multi agent building management system (MAS BMS) at the UCLan Samuel Lindow Building (SLB) shows that without the *intelligent* control strategies, the advantages of incorporating its ground source heat pump (GSHP) energy technology are not manifested.

This can be addressed by adding *intelligence* to the MAS BMS. ARTMAP, a type of artificial neural network (ANN), was introduced to address this issue. The ARTMAP provides the *intelligent* capabilities to User Agents and the Source Agents of the MAS BMS. This is to allow heat sources to provide heat based on the dynamic heat demand of the building.

Simulation results presented in this paper show how a MAS BMS with *intelligence* incorporated to its User Agents and Source Agents can help maximise the advantage of incorporating the GSHP energy technology, which in turn helps in the reduction of energy costs and the lowering of CO_2 gas emissions.

The implementation of the ARTMAP-MAS BMS is currently underway within the university, beginning with the implementation of the User Agents to the rooms in the building. The work then continues with the implementation of the Source Agents to the gas boilers and the GSHP; where issues in integrating the Source Agents with the existing control systems of the boilers and the GSHP are envisaged. Future work includes: investigating potential limitations of the integration and finding solutions to the identified limitations, as well as investigating the suitability of the proposed MAS to provide cost effective integration of multiple types of renewable electric generators to the building.

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