Wireless Sensor Network Routing for Energy Efficiency

Gad Hakim and Robin Braun

Abstract -
In this paper we present a new ABM model of Directed Diffusion using NetLogo that allows to study the impact of energy usage for various transmission activities. Furthermore we developed two new derivatives of of this model of Directed Diffusion that could lead to energy saving in practical applications. We call these Lazy Diffusion and Gradient Diffusion. We exercise the models to produce results that show significant reduction in energy consumption over Directed Diffusion. We conclude that Wireless Sensor Networks with their routing protocols are complex systems, which can yield to Agent Based Modelling.

1 Introduction

The paper begins with an introduction and motivation for using agent based modelling (ABM). It proceeds to describe a newly developed basic ABM of a standard Directed Diffusion routing scheme. In addition, it describes two new schemes we have called Lazy Diffusion and Gradient Diffusion. Neither are secure in the way that Directed Diffusion is, but both have the potential to reduce energy consumption.

Gad Hakim
School of Electrical and Data Engineering, University of Technology Sydney, e-mail: gad.hakim@student.uts.edu.au

Robin Braun
School of Electrical and Data Engineering, University of Technology Sydney, e-mail: robin.braun@uts.edu.au

1.1 Wireless Sensor Networks

Wireless Sensor Networks have become pervasive, particularly as they are integral to the Internet of Things (IoT).

1.1.1 What they are

A Wireless Sensor Networks (WSN) is a collection of sensing nodes with limited processing power, limited energy reserve that communicate by wireless with other neighbouring nodes. They are widely implemented in many areas of applications such as industry, the environment and healthcare. In recent years nodes/sensors have become smaller, less expensive, and more intelligent. They are now able to implement complex routing protocols to forward the data to a central location for analysis.

1.1.2 Problems

The main problem with WSN is the limited life of the network due to the limited battery life of the sensors. The energy is used in transmitting and receiving data, and computation. The biggest consumer is transmission. When a node uses up its energy it can no longer transmit its own sensor data. Neither can it forward the sensor data from other nodes. Thus, whole portions of the network can become isolated.

The way to extend the life of the network is by optimising the energy consumption of the routing protocols used to transmit and receive data from the sink (requesting data) to the source (data requested) and back.

In this paper, we determine the number of source data retrievals until the data can no longer reach the sink due to insufficient energy for transmission in nodes for particular protocols.

1.2 Purpose of the paper

The purpose of the paper is to describe the new agent based model of a data-centric protocol the Directed Diffusion protocol for Wireless Sensor Networks, and newly developed derivatives of the Directed Diffusion protocol. All models are exercised for longevity and energy efficiency. In future research all models will allow for energy harvesting.

Our models then exercises all three protocols to extract time to live statistics for various parameters. Changes to a number of aspects including the routing protocol, the ability of nodes to do energy harvesting, and the ability to enhance the energy of selected nodes are made for all models. The results of energy consumption and network longevity are plotted.

The modelling environment chosen is Netlogo[**?**]. To the best of our knowledge this has become the most widely used ABM integrated development environment. It has extensive capability described in the online documentation[**?**].

The paper concludes with a comparison of key performance indicators. These include number of messages transmitted and variable energy usage for data requests and transmission and retrieval of requested data.

Contribution of this paper

1. New models for design of energy efficient WSNs.
2. New methodologies for monitoring and varying energy usage for transmission and varying the energy usage for message retrieval in for analysis of protocols for WSN based on complexity theory.
3. Two new routing protocols for WSN based on Directed Diffusion.
4. A benchmark data-set for the analysis of energy efficiency of WSNs

1.3 What others have done in WSN energy efficiency

Substantial research has and is being conducted to optimise the lifetime of WSN[**?**]. Methods include allocating resources based on cross layer design, opportunistic transmission such as sleep-wake scheduling, routing and clustering, coverage, connectivity and optimal deployment, mobile relays and sinks, data gathering and network coding, data correlation, beam-forming and energy harvesting.

Other work includes ABM of WSN[**?**] which does not use NetLogo, instead utilising OMNeT++.

Hamzi[**?**] broadly categorized energy conservation schemes under the three main headings: duty cycling, data driven, and mobility driven techniques. Duty cycling is aimed at reducing idle listening when the node's radio waits in vain for frames and overhearing when nodes stay active listening to uninterested frames.

Data driven techniques use some parameters of the data themselves to make decisions to reduce energy consumption during communication while mobility schemes consider the mobility of the sink or relay nodes as a factor affecting the energy consumed in the network.

Energy conservation involves minimising the communication cost in nodes. As the radio is the biggest consumer of energy this can be achieved by energy efficient routing protocols. For example, there is a NetLogo model that investigates the energy efficiency of multi-hop routing in a decentralised wireless sensor network.

There is no similar model to the best of our knowledge in the literature to our ABM model. We also develop two new versions of Directed Diffusion which we have called Lazy Diffusion and Gradient Diffusion, which have the potential to reduce the energy usage, and provide us with a vehicle for investigating routing protocols.

1.4 Application areas

Significant applications are in such areas as home automation, security, environmental monitoring, and many more. This has seen increased research interest in WSNs. Although successful, gains in the adoption of WSNs, particularly in remote and inaccessible places where their use is most beneficial is affected by the major challenge of limited energy due to battery power being the dominant energy source. Currently, emphasis has been placed on energy harvesting, energy transfer, and energy conservation methods as the primary means of maintaining the network lifetime.

A generally accepted definition of lifetime is when the network degrades to a point when it is no longer able to perform its intended function. Energy consumption and optimisation models are available in the literature using energy consumption per payload. An energy consumption model for wireless sensor networks[**?**].

1.5 Modelling and simulation

Batool[**?**] describes effective modelling using Agent Based Models of Complex Adaptive Systems.

Commonly available simulators such as NS2[**?**], OPNET[**?**] and OMNET++[**?**] do not readily offer the flexibility to experiment with advanced complex connectivity scenarios.

Energy consumption models include node energy modelling[**?**], including the energy consumption of different node components in different operation modes and state transitions.

1.6 Data-centric protocols as the base of our work

There are seven major families of protocols[**?**]. Many are extensively reported in the literature. The most important to our work are Data-centric protocols including Directed Diffusion (DD)[**?**, **?**, **?**, **?**]. The main advantages of DD are that node addressing mechanisms are not needed and there is no need for global knowledge of network topology.

In *data-centric* protocols the data is sent from source sensors to the sink. In *address-centric* protocols, each source sensor that has the appropriate data responds by sending its data to the sink independently of all other sensors. However, in *data-centric* protocols, when the source sensors send their data to the sink, intermediate sensors can perform some form of aggregation on the data originating from multiple source sensors and send the aggregated data toward the sink. This process can result in energy savings because of less transmission required to send the data from the sources to the sink.

The Directed Diffusion protocol is extensively described in the literature[**?**]. We will only summarise it here.

In DD each node can only communicate with its direct neighbours. The sink node sends a request to its neighbouring nodes for specific data. Then the neighbours forward the request to their neighbours and so on. A source node contains the requested data. When the source node receives the request it transmits it back to the sink along the path the request came from, neighbour to neighbour. All nodes receive the request.

We will describe our two new derivatives of Directed Diffusion later in the paper.

Other routing protocols based on bio-mimetic paradigms, such as ant foraging behaviour have also been described, but as yet they do not consider energy exhaustion[**?**].

2 Wireless Sensor Network under consideration

The network under consideration is located in a 3 dimensional structure such as a building or a stack of shipping containers. Each node can be anywhere in that space. The communications network is a “mesh” where a node forwards information from other nodes.

The nodes are both a sensors and forwarders. When they have information they are called Sources. When they require information from other nodes, they are called Sinks. The network has at least one Sink and can have one or more Sources. The Sink acts as the forwarder to the external User Network. Several sinks or mobile sinks models can be investigated in future research with our models

Information collection is a 2 stage process initiated by the Sink.

1. A Sink needs some specified information, called an Interest. It initiates a diffusion into the network of requests for that Interest.
2. A Source that can satisfy a received Interest, starts a process of transmitting that Interest back to the Sink.

Each node can only communicate with its direct neighbours to squared energy consumption rule where the energy required for transmission is proportional to the square of the distance between the nodes.

Energy consumption is proportional to the length and repetition of the data packets. It is proportional to the square of the number of Interest packets propagated. We enhance our network through nodes replenishing their energy by energy harvesting.

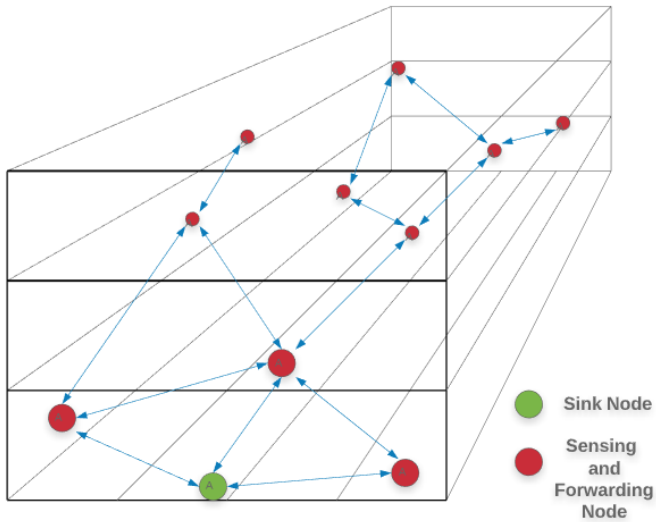

Fig. 1 Overall picture of the Sensor Field rfig:shipping$_{c}ontainers$

2.1 Key limitations of the network

The network is a collection of autonomous nodes. There is no global knowledge about the network. There is no central controller that has visibility of the network. The only knowledge that nodes have is the Interest being sought, their own neighbours, their own stored energy and the information they have collected.

A key criterion for WSN is to minimise the likelihood that any part of the network is unable to send its information to the Sink. This happens if one or more nodes exhaust their energy leading to a portion of the network being isolated from the rest.

The network is made up of nodes (agents) that perform tasks autonomously based on both their own dynamic environment, and the behaviour of other nodes that are similarly autonomous with their own dynamic environments. In essence, the nodes are performing autonomous actions to minimise the likelihood of failure anywhere in the network, *while still only having local knowledge*. Such scenarios are found extensively in nature[**?**]. An example is an ant colony. These examples are Complex Systems needing modelling tools like ABMs[**?**].

A simple ABM can exhibit complex behaviour providing valuable information about the dynamics of the system it models. Agents are capable of evolving, allowing unanticipated behaviours to emerge.

2.2 Our Approach

We use Complex System Theory (CST)[**?**], with Agent Based Models (ABM) to model routing algorithms that minimise energy consumption.

Complex System Theory

We refer to the excellent work of Willensky[**?**]. Complex systems are composed of multiple individual elements that interact with each other. However the aggregate behaviour or properties are not predictable from the elements. These interactions of multiple distributed elements lead to emergent phenomenon. One definition of emergence is "the arising of novel and coherent structures, patterns and properties through the interactions of multiple distributed elements". Important features of emergence include the global pattern's spontaneously arising from the interaction of elements, and the absence of an orchestrator or centralized coordinator. The system "self-organizes."

CST uses principles and tools for making sense of the world's complexity. One such tool is ABM. In this paper we use the NETLogo ABM tool. This includes modelling energy harvesting, and adaptive routing.

Agent-based models have been shown to successfully model Complex communications networks[**?**]. This includes ad-hoc, P2P and other types of networks[**?**, **?**].

Traditional network simulators such as NS2, OPNET and OMNET++ do not easily allow modelling of advanced complex connectivity scenarios, which ABMs do[**?**].

2.3 Building and exercising the NetLogo Models

The base WSN routing protocols selected for this paper is Directed Diffusion (DD). We will be modelling it using NetLogo. (Note that there is a Directed Network model in the NetLogo model library, but it refers to to a different scenario. Another model refers to virus spreading.)

We also demonstrate the Lazy and Gradient Diffusion models, which are adaptations of the previously described Directed Diffusion Model.

The models developed here have energy usage parameters, and adaptive routing strategies.

2.4 Our Models

Here we describe our models and the way we have implemented them.

2.4.1 Directed Diffusion

Directed diffusion model were previously developed but not as agent based models with energy monitoring. In this model, we have grid of patches we call nodes. The number of nodes can be modified.

Each node is given a selected amount of energy for transmission.

We create a fixed sink that requests information. The request is transmitted as interest packets to neighbouring nodes from the sink by diffusion to all the nodes. Each transmission costs energy

We create a random source that has the information. When the interest packet reaches the source it transmits the message back to the sink following the path/route that the interest packets took to reach the source. This transmission also costs energy to return message. We can repeat the process until there is insufficient energy to send or receive the source data. See Figure **??**.

We monitor the average energy of the nodes and number of transmissions. After each transmission, the energy of each node is recorded in the node.

2.4.2 Lazy Diffusion

The same principle as above in directed diffusion is used. However, we developed a Lazy Diffusion model where the diffusion is going to one randomly selected neighbour only at a time not all the neighbours. Hence energy can be saved as not all the nodes use energy.

In this model if a node previously sighted the interest pack it rejects the message occasionally this may stops the transmission and following a specified action or time the request is sent again. However, when the interest packet reaches the source of information requested it transmits the message back to the sink following the path/route that the interest packets took to reach the source. See Figure **??**.

We compared the average energy per node in this model to directed diffusion.

In future research, we propose to modify this model to allow transmission to a node that has not previously been visited.

2.4.3 Gradient Diffusion

This is another modification of a combination of the above models.

The interest packet can visit the same node multiple times until it reaches the source.

In this model, a gradient is developed from the sink to determine the distance of each node from the sink or order to achieve energy saving in returning the message based on distance from the sink rather than the random path it took to reach the source as in the other two models We compared the average energy per node in this model to directed diffusion.

2.5 Algorithms for the NetLogo Models

We use the same base NetLogo model for Directed Diffusion (DD), Lazy Diffusion (LD) and Gradient Diffusion (GD).

- We use a 2 dimensional model to reflect our sensor field. (Netlogo supports 3 dimensional models, but we do not see a benefit to using it.)
- We set the dimensions of the World to reflect the number of Nodes.
- The Patches in the World are used as the Nodes of the network. (Patches and Turtles are Agents in Netlogo)
- We create breeds of Turtles which will act as the packets that move information around the network. They are used to convey Interests, and the Events that the interests indicate. They are also used for housekeeping work such as Gradient creation.
- We designate the bottom left hand side Node as the Sink.
- We randomly choose any other Node as being the Source of the Event that satisfies the Interest

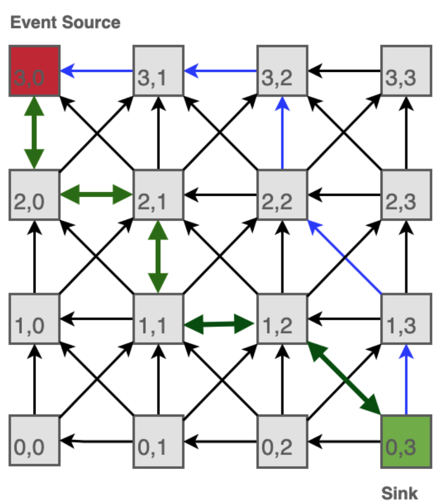

Fig. 2 Pictorial view of Directed Diffusion showing the Interest and Event paths
rfig:DD

2.6 General notes

- As the messages are created and diffuse through the network they use energy *cost to diffuse*.

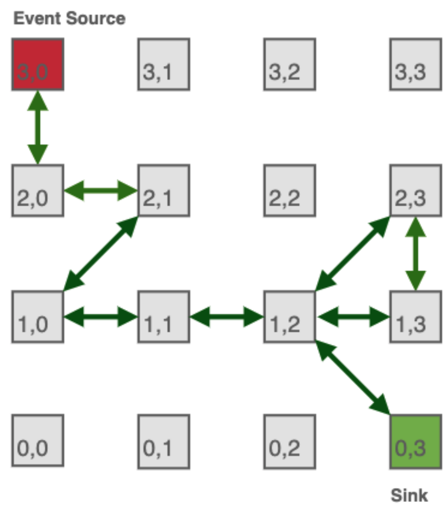

Fig. 3 Pictorial view of Lazy Diffusion showing the Interest and Event paths
rfig:LD

Algorithm 1: Setting up the World - common for all the models

Input: Number of Nodes (NumNodes)
Result: $size = \sqrt{NumNodes}$
$Xdim \leftarrow size, Ydim \leftarrow size$;
`/* Assume a square World */`
while *Not any Sink* **do**
  Designate Node 0 0 as Sink;
end
while *Not any Source* **do**
  $X \leftarrow randomInt(0; size), Y \leftarrow randomInt(0; size)$;
  Designate Node X Y as Sink ;
  Load Event into Node X Y
end
while *Not any Node Energy* **do**
  $NodeEnergy \leftarrow MaxEnergy)$;
end
if *GD* **then**
  repeat
    $Gradient \leftarrow 0$;
  until *all nodes have gradient*;
end

- As time progresses, Nodes harvest energy from the environment. Set this set to *energy harvested*.
- When the interest is found, it sets a *path-to-sink*. When the message passes along this path it uses energy *Energy-cost-to-return-event*
- When Nodes forward packets, their energy is depleted until they can no longer forward. We set an energy level below which messages cannot be transmitted from a node to *minimum-energy*

2.7 Ramifications of the specific protocols

The different protocols affect energy consumption differently for a number of reasons.

2.7.1 Directed Diffusion

In this protocol, the Interest is propagated to all nodes using energy in all nodes. As there is no global information available to the Nodes, the one that has the Event is unable to signal to the other nodes that the Event has been found. The other nodes simply continue diffusing the Interest until all nodes have been reached.

This results in a general depletion of energy, when that is not needed.

2.7.2 Lazy Diffusion

In this case, there is only one Interest Packet "lazily" randomly meandering around the network. When it reaches the Event, it stops. There is no need to signal other Nodes to stop diffusing Interests to their neighbours as they do not have Interest Packets to diffuse.

Statistically this saves up to 50% of the energy used in the diffusion process.

2.7.3 Gradient Diffusion

In this case, energy is used at the start of the process to install a Gradient in each node. This is effectively the hop distance from the Sink. This helps to save energy in the LD protocol by obviating the need to send the Event back by the same meandering route that the Interest followed to get to the Source.

3 Results

We have collected the results obtained from our models into three graphs.

Algorithm 2: Interest and Gradient Diffusion

```
if No Interest yet then
    Create Interest packet in Node 0 0;
    if GD then
        Create Gradient packet in Node 0 0;
        HopCount ← 0;
    end
end
/* Then all nodes on every tick                                    */
if DD then
    repeat
        for all nodes and all neighbours do
            if not any Interest there then
                Create new Interest packet;
                Forward Interest to that neighbour
            end
        end
    until all nodes have the Interest;
end
if LD then
    repeat
        if Interest packet here then
            Forward Interest to one random neighbour
        end
    until node with the Event receives the Interest packet;
end
if GD then
    repeat
        for all nodes and all neighbours do
            if not any Gradient there then
                Create new Gradient packet;
                HopCount ← HopCount + 1;
                Forward Gradient to that neighbour;
                Gradient ← HopCount;
            end
        end
    until all nodes have the Gradient;
    repeat
        for all nodes and all neighbours do
            if not any Interest there then
                Create new Interest packet;
                Forward Interest to that neighbour
            end
        end
    until all nodes have the Interest;
end
```

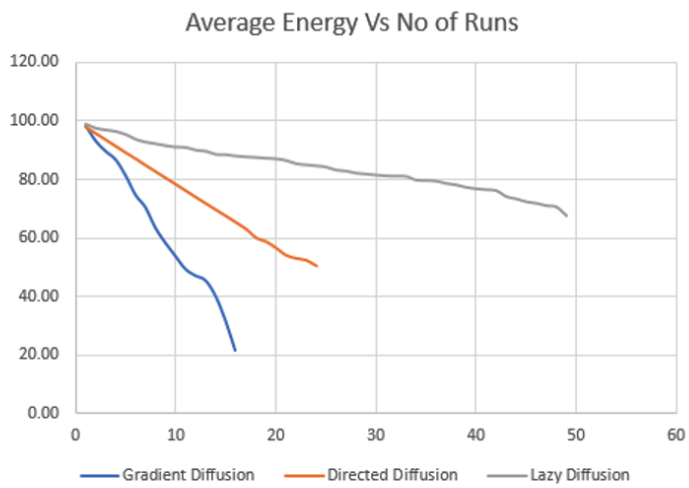

Fig. 4 Average Energy vs No of Runs for DD, LD and GD All Runs
rfig:Num

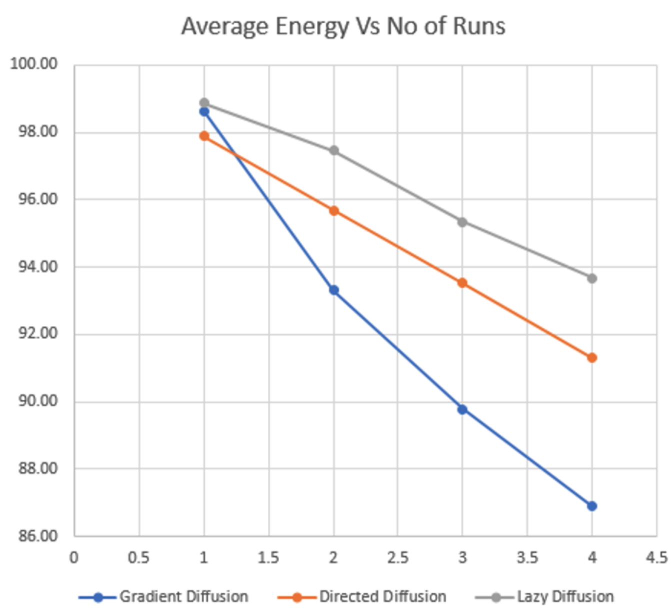

Fig. 5 Average Energy vs No of Runs for DD, LD and GD for 4 runs
rfig:Num4Runs

Algorithm 3: Returning the Event to the Sink

if *Interest reached Source with the Event* **then**
  if *DD and LD* **then**
    Return the Event to the Sink using the route followed by the Interest packet to reach the Source
  end
  if *GD* **then**
    Return the Event to the Sink using the Gradient values of each Node. The Event effectively "rolls" downhill to the Sink
  end
end

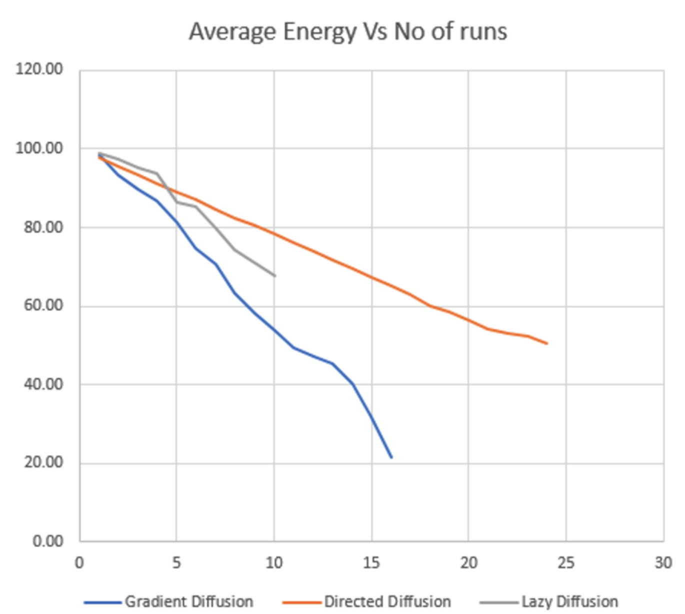

Fig. 6 Average Energy vs No of Runs for DD, LD and GD Successful
rfig:Num4RunsSuccessful

In each case, we are plotting the number of Event retrievals before too many nodes have depleted their energy to such an extent that a new retrieval is impossible. Our graphs also show the average energy remaining in the nodes after the Event retrievals

As can be seen, after a single retrieval, in all cases, the average energy remaining is much the same. However, as the number of retrievals grows, the energy depletion is very different for the three protocols.

Figure **??** shows that the new proposed lazy diffusion and gradient diffusion could be more energy efficient. On the first 4 runs see Figure **??**. Lazy Diffusion performed better than Directed Diffusion. Gradient Diffusion performed better on the first run.

The performance of LD and GD is dependent on the likelihood of reaching the source as the route is randomly selected

4 Conclusion

In this paper, we have shown that we can use Agent Based Modelling with the NetLogo tool, to analyse complex routing protocols, and extract meaningful results.

The network we have used as a base exhibits all the characteristics of complex systems such as an ant colony. It is composed of multiple agents (nodes and packets) with very low individual intelligence, but having the ability to work together to produce significant emergent properties.

While it is certainly possible to create equation based models of these protocols, they would require a deep knowledge of areas of mathematics such as Markov Modelling, and would only produce results in the aggregate. On the other hand, constructing Agent Based Models only requires the ability to imagine the behaviour of simple agents with respect to each other.

Having built and exercised the models, we can clearly show that given the identical infrastructure, we can find far more effective ways of operation that very much improve the energy efficiency of our system.

The work is part of an ongoing industrial application.

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