TOWARDS AN AGENT BASED FRAMEWORK FOR MODELLING SMART SELF-SUSTAINABLE SYSTEMS

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ABSTRACT

Self-sustainability is a property of a system; a system is considered to be self-sustainable if it can sustain itself without external support in an observed period of time. If this property is mapped to a human settlement in context of resources (water, energy, food, etc.), it would describe a human settlement which is independent of external resources (like the national electrical grid or a central water distribution system), where such external resources are either not available, or not desirable.

This article contributes to presenting the state-of-the-art overview of self-sustainability-related research. While self-sustainability as in the above described form was not a direct subject of research, there are several fields which are either related to, or could be of significant value to the self-sustainability research in this context. The extensive literature overview also showed no frameworks for modeling self-sustainable systems in the context of human settlements. Herein a motivation for using agent-based modeling and simulation techniques will be given.

KEY WORDS

self-sustainability, sustainable development, multi-agent systems, agent-based modelling

CLASSIFICATION

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INTRODUCTION

Self-sustainability is a term which describes a property of a system. Any system that can sustain itself without the need of external support in an observed period of time can be labeled as self-sustainable. This kind of system could be used to describe self-sustainable human settlements, where this self-sustainability property could be measured. Such settlements might include remote/green villages/neighbourhoods/towns, but also underwater (deep sea) settlements, space settlements as well as manned space missions which need to be self-sustainable for the whole duration of flight.

While at he time of writing, there were no papers published dealing with self-sustainable systems in this specific context, fields of research that seem to be most related to certain aspects of self-sustainability, and which yield significant number of research papers, include sustainable development, intelligent building/houses, as well as, from a methodology standpoint, agent-based modeling and multi-agent systems. This paper will describe potentially useful concepts in the development of agent-based frameworks for modeling self-sustainable systems, like eco-feedback, load management, and some aspects of other research fields which are in a certain way related to multi-agent systems.

In the following a comprehensive literature overview of these connected fields will be presented and motivation for using agent-based modelling and simulation techniques will be provided.

SUSTAINABLE DEVELOPMENT AND SELF-SUSTAINABILITY

The term sustainable development was first articulated by the United Nations in 1987 in the report of the World Commission on Environment and Development (WCED) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1].

In 1994, John Elkington has proposed 3 aspects of sustainability: environmental, social and economic [2]. The main idea behind this 'triple bottom line' concept was that business activity can simultaneously deliver financial, social, and environmental benefits.

Many people have considered sustainability to be a synonym for energy-efficiency [3]. However, [4] argues that sustainability is not only about energy efficiency, but also about user's comfort, well-being and cost savings. When building a self-sustainable community, user comfort is indeed one of the key factors in maintaining the self-sustainability property.

Because many alternative and modified definitions have emerged since (more than 140 [5]), the term "sustainable development" has acquired a broad meaning with no formal or generally agreed definition, and often implies long-termed, strategic development, or organizing principle.

When summarized together, main focus of nearly all sustainability goals seem to be a fair distribution of resources [6].

More concisely, dictionary definitions, define the word "sustainable" as:

(a) "able to be used without being completely used up or destroyed",
(b) "involving methods that do not completely use up or destroy natural resources",
(c) "able to last or continue for a long time" [7],
(d) "able to continue over a period of time",
(e) "causing little or no damage to the environment and therefore able to continue for a long time" [8].

The term "self-sustaining" is defined as:

1. ”maintaining or able to maintain oneself or itself by independent effort ‘a *self–sustaining* community’ ” [9],
2. “Able to sustain oneself or itself independently” [10].

By reviewing these dictionary definitions, the distinction between those two terms is fairly obvious; the most evident factor is “independence”, present in the definition of “self-sustaining”, while absent in the definition of the word “sustaining”.

Self-sustainable communities imply a cyclical processes in terms of creating and using resources. Karl-Henrik Robèrt, founder of the Natural Step Initiative argues that “the only processes that we can rely on indefinitely are cyclical; all linear processes must eventually come to an end” [11]. He observes that our society is continuously processing natural resources in a linear direction, which in time reaches an end, thus being not sustainable.

There are several clear advantages in using self-sustainable systems opposed to using linear consumeristic models:

- a self-sustainable system is not dependent on availability, capacity or price fluctuations of the central resource distribution system,
- a self-sustainable system minimizes resource loss due to transportation, considering the small physical scale and compact nature of the self-sustainable system, in comparison with resource transportation lengths from central distribution systems,
- it assumes the usage of local renewable resources, which itself has numerous advantages over using fossil fuels for example, being the root problem for global warming [12],
- a self-sustainable system supports the ideas of resilient communities, transition movement, localization and permaculture [13],
- self-sustainability could help low-income families to achieve economic independence [14, 15].

As far as current linear model trends in energy supply and consumption go, numerous established organizations have stated that such trends are unsustainable [16, 17]. These organizations include International Energy Agency [18] and European Union [19-21] for example.

Related to these trends, the rise of greenhouse gas emissions (mainly CO_2) is threatening the planet’s global climate and chemistry [22].

However, during recent years, using renewable energy sources gained significant interest. The final purpose of exploitation of renewable energy sources is to move towards increased energy sustainability, and eventually complete independence from fossil fuel energy [23].

SELF-SUSTAINABLE SETTLEMENTS

Self-sustainable neighborhoods/settlements are more feasible for implementing self-sustainable systems than it would be for individual houses alone. Resource production capacity for a house highly depends on numerous dynamic factors, for example the geographical position and orientation of individual houses, including a myriad of parameters of their local environment, and most importantly, on the complex behaviour of their residents.

For example, if a single person is living in a house, and he/she produces energy from “manually” burning biomass, the capacity of the house for this resource production is limited to times when the person is at home. However, in order to retain some defined comfort level, those resources might be needed before the person arrives. These resources could be transported from another unit/house per request. From such viewpoint, a network of resource production/consumption units could be realistically more feasible for implementing a self-sustainable system, than it would be for a single house. [24] notes that self-sufficiency can “hardly be achieved in a single household.”

Sustainable neighborhoods would achieve three broad sustainability goals: eco-efficiency, eco-equity and eco-effectiveness [25].

Interestingly, already in about 400 BCE, Aristotle referred several times to a self-sufficiency concept in his work titled Politics: "*For a household is more self-sufficient than an individual person is; and a community of a mass of people counts as a city only if it proves to be self-sufficient*". "*A city is the community of families and villages in a complete and self-sufficient life. This sort of life, as we say; is a happy and fine life; hence we should suppose that a city aims at fine actions, not 'merely' at living together*" [26].

AGENTS AND INTELLIGENT BUILDINGS

"An agent is a computer system that is situated in some environment, and is capable of independent (autonomous) action in this environment on behalf of its user or owner, in order to meet its delegated objectives." [27, 28].

An agent is independent in a sense that it can figure out for itself what it needs to do in order to satisfy its design goals, rather than being explicitly instructed about what action to follow in every possible case scenario.

A multi-agent system is one that consists of a number of agents which interact with one another; such a system can be observed as a system with multiple interacting components. In order to successfully interact, these components (agents) must cooperate, coordinate, and sometimes even compete, negotiate and argue with each other.

An essential ability of an agent must be its ability to learn from experience and hence adapt appropriately [29]. The authors of [29] further argue that this notion implies a system which can adapt and generate its own rules, instead of being restricted to simple automation. They define an intelligent building as one that uses computer technology to autonomously operate the building environment for optimization of energy consumption, user comfort, safety and monitoring functions.

Intelligent building/houses/homes involve certain computerized scheme (for example, multi-agent systems) which regulates building components, utilities, electrical circuits, and heating, ventilating and air-conditions systems in order to monitor building functions, security, energy consumption, and provide a comfortable environment to users [30]. Furthermore, [31] argues that intelligent buildings should not only be modeled as multi-agent systems (MAS), but should include learning capabilities to adapt to the user's need and changing preferences.

The [32] proposes the development of a new subfield of IS called energy informatics, which recognizes the role that information technologies could play in reducing energy consumption (resulting as well in reducing CO_2 emissions) and they present their core idea with the following illustrative expression:

$$\text{Energy} + \text{Information} < \text{Energy}.$$

As noted in [33], the environment of intelligent buildings is very complex: inaccessible, non-deterministic, non-episodic, dynamic and continuous, and it is suggested that a feasible solution for controlling it would be to implement adequate multi-agent systems [34]. Further, it is suggested that if a problem domain is "particularly large, complex, or unpredictable, then the only way it can reasonably be addressed is to develop a number of functionally specific and (nearly) modular components (agents) that are specialized at solving a particular problem aspect" [35].

Relating to above mentioned modular components, it would prove beneficial for a modeled self-sustainable system to have the possibility to be open-ended and extensible, as there might be a need for adding new resource sources, or removing existing loads at any time, without having an impact on the overall operation of the system.

In [29], authors have defined a set of behaviours for an agent responsible for autonomously governing the building environment:

- safety behaviour (for example, light levels are always at safe levels),
- efficiency behaviour (for example, it should turn off the lights when there is no presence in the room, or if there is sufficient natural light present),
- emergency behaviour (controls resources in an emergency situations),
- manual behaviour (complete control of the user, and it reacts to any orders the occupant gives it),
- self-taught behaviour (adapts to different users and environments).

The agents in the mentioned paper do not contain complex modelling or reasoning capabilities, because these might be very processor-intensive. Whilst limited, this approach ensures that the system is able to respond in real time on any situation or event.

Similarly, [36] decomposes agent behaviours into 4 behaviour subsets, and defines hierarchy amongst them: Safety behaviour has the top priority, following by Emergency, Efficiency, and Comfort behaviours. However, their architecture is not limited to these pre-defined behaviours, but it also “has the ability to learn new behaviours dynamically, based on actions taken by occupants within the room.” Learning mechanism is derived from the CASE based learning, a branch of traditional AI work [37].

MavHome (Managing an Intelligent Versatile Home) is a project supported by National Science Foundation which is focused on creating a home that acts as an intelligent agent [38]. Authors introduce the MavHome architecture, discuss the role of prediction algorithms, and present a meta-predictor “which combines the strengths of multiple approaches to inhabitant action prediction.” Authors define the need for a number of capabilities for their smart home scenario and its integration: machine learning, mobile computing, robotics, databases and multimedia computing.

Article [24] raises the question “Can we make smart home sustainable or sustainable homes smart?”, and discusses current trends and challenges arising with these questions. Along with illustrative examples of some real-life efforts of designing sustainable homes, authors elaborate critiques and problems regarding smart homes, like increased energy consumption, electronic waste [39], user frustration and cognitive overload [40], and similar, which need to be addressed in order to make smart home sustainable.

Authors of [34] found 72 literature sources identified to have potential significance on some aspect of agent technology in intelligent buildings domain.

ECO-FEEDBACK

Indeed, it has been researched that supplying consumers with information about their energy usage can lead to changes in usage patterns, and decrease in overall consumption [41, 42].

The [43] claims that the use of real-time feedback can decrease energy consumption by 10 % - 20 %.

The [44] found 133 papers (89 papers from environmental psychology and 44 papers from the human computer interaction and ubiquitous computing literature) that report about eco-feedback. It shows that the monitoring of energy consumption has the potential to make users aware of the hidden details of their current behaviour, as well as about how he compares to other community members.

When receiving this eco-feedback, users can clearly see their consumption footprint, and they become more able to control their energy usage. At the same time, eco-feedback is informing them about usage of other users, which provides increased social awareness in the household [45-47].

The [47] presents a study where a minimal in-home energy consumption display encourages users to identify high-power devices in their home, and to reduce energy consumption.

Article [48] designed, implemented and evaluated an interactive visualization that allowed users to engage with and understand their consumption data. Validation of this design included 12 participants who installed meters in their homes and used the system for a period of two weeks. Results were that the users started to relate energy consumption to activities, rather than just appliances, and were able to discover that some appliances consume more than they expected. The results also indicates that there is a "potential for interactive eco-feedback technology that engages users with their data beyond mere presentation".

LOAD MANAGEMENT

Load management mechanisms are presented in [49], according to distribution control described in [50]. These mechanisms allow time adjustments of certain services/appliances in order for them to operate in time periods when global resource consumption is lower, and/or resource price is lower. To achieve this, a load management system designer must observe that some services/appliances can be delayed, some can be reduced, some services programmed to run according to the weather forecast, energy could in some cases be accumulated for later use, etc.

Demand side management is a method designed to coordinate the activities of energy consumers and energy providers. This method seeks to avoid so called peaks of energy consumption [50].

This method could be significantly valuable to the modeling of self-sustainable systems, because it could prevent consumption peak times which have the capacity to deny the system of the self-sustainability property (extremely high resource demand in the short time interval). The main idea is to smooth the energy consumption by using intelligent domestic appliances that communicate and coordinate with each other.

As an illustrative example, there could be software agents embedded in the appliances, which can negotiate about which of them needs to be temporarily interrupted in the case of unscheduled events like resource shortage, or unforeseen resource consumption (this is called "intelligent load shedding"). Each of the agents can permanently monitor satisfaction levels of its services, and take appropriate actions according those levels.

The article [50] presents a system for power consumption distribution in private homes uniformly over time, where logical relation between devices is established, and energy consumption policy is coordinated between them. All this is taking place in a distributed, autonomous infrastructure. Figure 1 illustrates the short-term power management of appliances, where energy consumption peak is avoided [50].

Shift of energy usage load for avoiding peak times for reducing the need for high production capacities has been identified as one of the keys for energy efficiency [51].

Similarly, objective of the study in [49] was to "design a building electric energy management system able to determine the best energy assignment plan, according to given criteria".

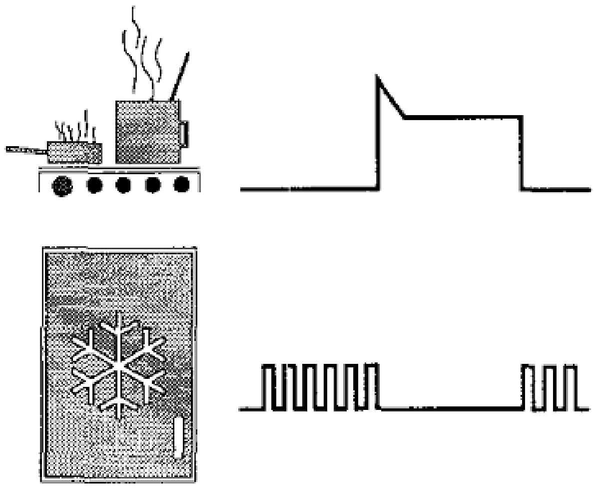

Figure 1. Short-term power management of appliances for avoiding peak consumption – illustrative example [50].

Based on a large literature overview and documented cases, [52] concludes that the "main operational benefits of installing intelligent building components include:

(i) energy efficiency and higher environmental sustainability;
(ii) increased user comfort and productivity;
(iii) improved safety and reliability;
(iv) improved operational effectiveness; and
(v) enhanced cost effectiveness."

Authors also suggest that the input that environment gives to agents cannot be specified in advance. They gave an illustrative example: "something happens to one system (e.g. reducing light level) may cause a person to change behaviour (e.g. sit down) which in turn may result in them effecting another systems (e.g. needing more heat); and people are essentially non-deterministic." Since there is a myriad of home appliances which consume resources, they have proposed grouping all these operations of different appliances into the term "service". This "service" transforms energy in order to meet a user's need via one or several appliances, and could be qualified as permanent, or temporary, depending on its usage of energy.

Second important notion from the same paper is the "satisfaction function", which defines "user comfort" in terms of delivered service regarding the user's feelings, which is close to the notion of personal satisfaction from [53].

OTHER RELATED FIELDS

The field of distributed/concurrent systems has been investigating properties of systems with multiple interacting components, and there are theories, programming languages and tools developed in order to explain, model and develop such systems [54-56].

In order to distinguish concurrent systems from agents, we can argue that agents are assumed to be autonomous, and their mechanisms allow them to coordinate their activities at run time, instead of being hard-wired at design time. Moreover, agents are presumed to be self-interested entities, whereas in a classical distributed/concurrent system, all the components of a system share the common goal.

Game theory is a mathematical theory that studies interactions among self-interested agents [57], which plays a major part in use for the analysis of multi-agent systems as the predominant theoretical tool. However, many of the solution concepts developed in game theory "were developed as descriptive concepts, without a view to computation" [27]. Multi-agent systems research allow the use of tools of computer science such as computational complexity theory [58, 59].

Artificial intelligence is mainly concerned with the components of intelligence, and agents are entities that integrate these components. For this reason, AI could be perceived as part of the construction of agents [27].

Expert systems deal with detailed knowledge in a defined domain, and are able to solve problems or give advices in the context of that domain [60]. Although some expert systems might resemble agents, there are several key distinctions: expert systems are usually not connected directly to any environment; they are generally not equipped with social abilities; nor they are generally capable of proactive behaviour.

The Internet of Thing (IoT) is a novel field defined as "a variety of things or objects (...) which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbours to reach common goals" [61]. These things include numerous different devices including but not limited to sensors and actuators of various kinds, mobile devices, TV sets, car/vehicle computers; but also non-ICT appliances (dishwashers, microwave ovens, refrigerators), electrical energy sources and building components [62].

Some of the key application areas of IoT are smart cities [63], smart power grids [64], smart health [65], smart transport [66], as well as smart buildings [67] which includes smart living solutions [68].

Most of these publications can and should be considered when dealing with smart self-sustainable communities, since they deal with detailed theoretical and practical models of implementing smart solutions for residential facilities.

TOWARDS AN AGENT-BASED FRAMEWORK

From the previous contemplation it becomes obvious that smart self-sustainable settlements are complex, socio-technical systems which are hard to plan, model, implement and sustain. There a currently no adequate solutions for modeling and simulation of such systems which is why herein we propose to take an agent-based approach.

Agent-based modeling is a natural methodology to analyze and build such systems, given the large number of non-deterministically interacting components (agents) including but not limited to humans, various sensor and actuator equipment as well as environmental influences. The various possible interaction models like automated negotiation protocols, argumentation, resource allocation (possibly implemented using auction protocols) as well as different machine learning and artificial intelligence techniques for interaction with the environment and human behavior, induce this complexity to an even higher level. Such systems of greater magnitude cannot be simulated efficiently using traditional simulation techniques.

The potential benefits of using an agent-based modeling approach are threefold:

1. it allows us to determine if and for how long a settlement will be self-sustainable through simulation,
2. it allows us to experiment with different configurations of various equipment and environmental influences before actually building a settlement,
3. it allows us to analyze existing settlements and provide solutions to enable/enhance self-sustainability.

In order to use agent-based modeling a framework that establishes a common ontology of the field has to be established. This ontology has to include available knowledge from all the above mentioned fields of research but also go further and formalize important terms and metrics dealing with self-sustainability.

CONCLUSION

In this paper an overview of available literature in the field of self-sustainability, and related fields was given. Most important concepts such as sustainable development, intelligent buildings, eco-feedback, load management, user satisfaction function, etc. were identified. While there were no significant research papers found on the subject of self-sustainability of human settlements, there is a large number of papers published in the related fields of sustainable development and intelligent buildings, which describe certain aspects and tools that have the capacity to be used in the research of self-sustainable human settlements.

A clear distinction has been made between two at-first similar concepts "self-sustainability" and "sustainable (development)". Self-sustainability refers to the property of a system, whilst sustainable development encompasses a broader meaning, a strategic development, or organizing principle, which strives to "smarter" use of natural resources.

Self-sustainable settlements can be viewed and modeled as self-sustainable systems, where all the needed resources for the settlement are produced locally, without the need to transfer the resources from external sources. The main challenge of such settlement is the answer to the question: when taking into account all the relevant parameters (resource production capacities, residents, etc.), can this settlement be self-sustainable for some defined time period?

The authors suggests to design a framework which uses agents for modeling such self-sustainable systems, and which will enable a direct answer to this question. The framework should be able to determine if the transit to a resource-independent community, which would use local, renewable energy sources, is possible (for a specific case-study), but should also be able to design such a resource-independent community, providing all the parameters needed to achieve the self-sustainability property.

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RAZVOJ AGENTNOG OKVIRA ZA MODELIRANJE PAMETNIH SAMO-ODRŽIVIH SUSTAVA

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SAŽETAK

Samo-održivost je svojstvo sustava; sustav smatramo samo-održivim ako je u stanju sam sebe održati bez pomoći iz okoline u promatranom vremenskom razdoblju. Ako ovo svojstvo primijenimo na ljudska naselja u kontekstu resursa (vode, energije, hrane itd.), ono opisuje ljudsko naselje koje je neovisno o vanjskim izvorima (poput nacionalne elektroenergetske mreže ili centralnog vodovoda), pri čemu takvi vanjski resursi nisu dostupni ili nisu poželjni. U članku daje se pregled najrecentnijih istraživanja vezanih uz samo-održivost. I dok tako definirana samo-održivost nije bila izravno predmet istraživanja, postoji nekoliko područja koja su vezana uz samo-održivost ili su od signifikantne važnosti za istraživanja u ovom kontekstu. Obuhvatni pregled literature također je pokazao da ne postoji okvir za modeliranje samo-održivih sustava posebice u kontekstu ljudskih naselja. U skladu s time, daje se motivacija za korištenje agentnih metoda za modeliranje i simulaciju u ovom području.

KLJUČNE RIJEČI

samo-održivost, održivi razvoj, višeagentni sustavi, agentno modeliranje