A Case Study on Renewable Energy Management in an Eco-Village Community in Croatia – An Agent Based Approach

Igor Tomičić ‡*, Markus Schatten *

* *Artificial Intelligence Laboratory, Faculty of Organization and Informatics, University of Zagreb, Pavlinska 2, 42000 Varaždin, Croatia*
(tomicic.igor@gmail.com, markus.schatten@foi.hr)

‡ Igor Tomičić, Pavlinska 2, 42000 Varaždin, Croatia, Tel: +385 92 327 5547, tomicic.igor@gmail.com

Received: 13.06.2016 Accepted:30.07.2016

Abstract- An agent-based framework for modelling and simulation of resource management in self-sustainable human settlements is presented and tested on a realistic scenario including energy production with photovoltaic panels. The results of the simulation showed that the framework was able to prolong the self-sustainability of the observed settlement with regards to the overall energy production, storage and demands in the simulation environment. A detailed simulation analysis is provided, as well as system optimization using a number of heuristics. Specifically developed agent classes, behaviours and protocols are proposed that allow to model and simulate the dynamics of local resource production, storage and consumption in order to pursue and evaluate self-sustainability of a settlement at hand. The framework can be used by a modeler either to design and simulate a new self-sustainable system, or to evaluate and analyze an existing system. The presented framework enables considerable improvements in the design of a settlement and its resource production, consumption and storage elements, in regard to the context of self-sustainability.
Keywords: self-sustainability, renewable energy, resource management, agents, framework, modelling, simulation.

1. Introduction

The SSSHS (smart self-sustainable human settlements) is an agent based framework firstly introduced in [1] and [2]. Herein the framework is considerably extended with the possibility to simulate multiple resources simultaneously and with a more advanced bilateral negotiation algorithm. The updated framework is additionally applied on a realistic case scenario dealing with the energy production, storage and consumption by using photovoltaic panels as a renewable energy production technology in an observed self-sustainable eco village in Croatia.

In the following we provide a short clarification of the research context. A human settlement may exist in an environment which does not allow the use of central resource distribution systems such as national electrical grid or municipal water supply, where utilization of such systems is not feasible, or where it is not preferable by its inhabitants. In such a context, there is a need for managing resources that are being produced, stored, and consumed within the boundaries of such settlements, with the objective to maintain the self-sustainability in conditions that describe an intermittent nature of local resource production [3,4].

Resource production in a self-sustainable settlement is highly dependent on local environment features, and resource consumption is bound to various types of resource consumers, each of which have certain characteristics that directly influence the system's production and consumption dynamics (including but not limited to operating hours, capacities, modes of operation, possible deviations, priorities, user's comfort, etc.). The main goal of the SSSHS framework is to facilitate an infrastructure for smart resource allocation and management in order to cover overall needs of the system for a specific resource, in a defined period of time.

We consider a system to be self-sustainable for a given resource if its demands for that resource can be met with the resource quantities produced within its boundaries, and within a defined time period [1]. Such system won't require external resources, but exclusively those (restricted) resources which are produced or gathered within the same system, from available natural sources. If resource demands within a self-sustainable system can't be met with its existing production capacities, the system is considered non self-sustainable, and thus is unable to function properly off the grid. Note that energy sources for such settlements have to be renewable or at least constantly available in the observed period of time.

Advances in the areas such as the Internet of Things (IoT) [5], including the Environmental Internet of Things (EIoT) [6], smart cities [7] and smart residential buildings [8], are allowing us to design a model of mutually interconnected devices in an infrastructure which supports their dynamic networking, collaboration, and decision making in smart human settlements. These advances and their resultant technologies can provide feasible foundations for building real-time operational SSSHSs in the future, governed by the similar principles as described in this work.

Multiagent systems have been shown to be a natural methodology to approach such complex socio-cybernetic systems, in terms of both simulation and actual implementation [9]. We have developed a framework for the modeling and simulation of resources in SSSHS that provides a detailed analysis of such a system in terms of self-sustainability. Additionally, in order to test the framework, a number of test-case scenarios have been developed, one of which is analyzed in detail herein.

The rest of this paper is organized as follows: in section II we provide a short overview of related research. In section III we present the SSSHS framework's implementation. In section IV we present the implemented self-sustainability mechanisms, which allow for optimized use of resources. In section V we will show an example simulation scenario which has been modeled with the framework, and analyze the results in section VI. In the final, section VII, we draw our conclusions and give guidelines for future research.

2. Related Work

The Internet of Things (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 neighbors to reach common goals*" [5, p. 1]. Varying physical devices are included in the extension of the "thing" concept mentioned in this definition, amongst which are various kinds of sensors and actuators, mobile devices, TV sets, car/vehicle computers; but also non-ICT appliances (like dishwashers, microwave ovens, refrigerators etc.), electrical energy sources and building components [10].

An agent-based modeling approach shows to be adequate in approaching the Internet of Things [11], especially considering the possible interoperability issues induced by heterogeneous set of devices, different communication protocols and underlying networks.

Key application areas of IoT relevant to this research are smart cities [12], smart buildings [13], smart living solutions [11], and especially EIoT, which aims on leveraging IoT technology in a variety of environment related settings.

Intelligent buildings as defined in [14] use computer technology to autonomously operate the building environment for optimization of energy consumption, user comfort, safety and monitoring functions. Furthermore, intelligent building/houses/homes involve computer technology 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 [15]. Due to the complex, distributed and intelligent nature of such computing systems, multi-agent systems (MAS), provide a natural abstraction for representing and managing such systems. According to [8], intelligent buildings should not only be modeled as MAS, but should include learning capabilities to adapt to the user's need and changing preferences.

Authors in [16] argue that the environment of intelligent buildings is very complex: inaccessible, non-deterministic, non-episodic, dynamic and continuous, and it is further suggested that a feasible solution for controlling it would be to implement adequate multi-agent systems.

An introductory overview of an application of multi-agent system in hybrid systems (for example power control and optimization techniques) was presented in [17], putting more emphasis on agent communication, agent platform, and MAS architectures. Authors also argue that MAS based control systems "*are more effective in proper operation of hybrid system either in the form of microgrid or in islanding mode, i.e., autonomous mode*". The SSSHS framework operates exclusively in the islanding mode as presented in this work.

The paper [18] presented an application of multi-agent system for implementing smart grid functionalities in the control and management architecture of an integrated microgrid, and carried simulation studies that demonstrated the effectiveness of such application. The authors argue that a multi-agent system "*is a promising approach for smart grid operation*" [18, p. 20], that share key characteristics with the proposed SSSHS framework in the context of resource production, transmission, distribution and consumption, and that "*multi-agent system is a perfect platform for implementing the smart grid concepts*". [18, p. 20]

Optimizing consumption patterns is one of the implemented self-sustainable mechanisms in the proposed SSSHS framework, and also a focus of research of a group of authors [19], where a load shifting algorithm is presented, taking into account preferences of customers and electricity costs. The authors used multi-agent system based simulation studies and the simulation results showed that substantial load levelling is achieved by the proposed algorithm. This algorithm could be of potential interest for the SSSHS framework in advancing the optimization of consumers' consumption patterns within the framework.

The authors in [29] provide a detailed review of computer tools for analyzing integration of renewable energy into various energy systems, including a number of agent-based solutions. They state that identifying the potential of renewable energy has become a key area within energy planning and show that agent-based approaches in integrating renewable energy are suitable for simulating possible operational and economic impacts of various external events on the electricity sector in an energy-system.

An agent-based approach to micro-storage management has been presented in [30] and includes a game-theoretic analysis. It is stated that various storage devices can be used to compensate for the variability of typical renewable electricity generation, which allows for practical integration of such facilities into an existing grid. The developed agent based frameworks includes a storage strategy with an adaptive mechanism based on predicted market prices that is empirically shown to converge to Nash equilibrium. In [31] the same authors go further to develop a decentralized agent-based homeostatic control system for renewable energy in the smart grid. The developed software agents use various algorithms to optimize their owners' energy consumption, for example "*by storing electricity at times when it is inexpensive, thereby maximizing their individual utility and minimizing their carbon footprint*."

The term "smart city" (referred to also as the "intelligent city") is not formally defined, and can be referred to with various meanings. Nevertheless, smart cities are one of the important application areas of the Internet of Things [12], their main focus being "*applying the next-generation information technology to all walks of life, embedding sensors and equipment to hospitals, power grids, railways, bridges, tunnels, roads, buildings, water systems, dams, oil and gas pipelines and other objects in every corner of the world, and forming the 'Internet of Things' via the Internet.*" [20, pp. 1]. Although no unique definition has been given yet, one may state that a smart city is designed to make intelligent responses to various kinds of needs in the context of daily livelihood, environmental protection, public safety, city services, etc. [21].

The Environmental Internet of Things is a novel initiative which "*(...) provides the opportunity for (...) environmental scientists to have a seamless data stream from the field to the web.*" [6, p. 198]. The use of various IoT devices, most prominently environmental sensors and adequate sensor networks, allows for instant measurements of selected impacts various socio-cybernetic systems have on the environment. Connecting these devices to intelligent systems and consequently actuators, provides us with the opportunity to design and implement environmentally context-sensitive systems.

3. The SSSHS Framework

The development of the SSSHS framework was based on an adapted workflow described in the Multiagent Systems Engineering (MaSE) methodology [22]. Outputs of each section in the MaSE methodology are used as inputs for the next section; for example, identified goals are used for the creation of agent roles; agent roles are used for the definition of agent classes; etc. The methodology enables a linear progression of the system development, but is iterative across all phases.

The architecture of the proposed system is described with two layers. On the upper layer, a smart self-sustainable system is composed of individual dwelling units (labeled with "UNIT"), interconnected in a network infrastructure which allows both data and resource exchange (Fig. 1).

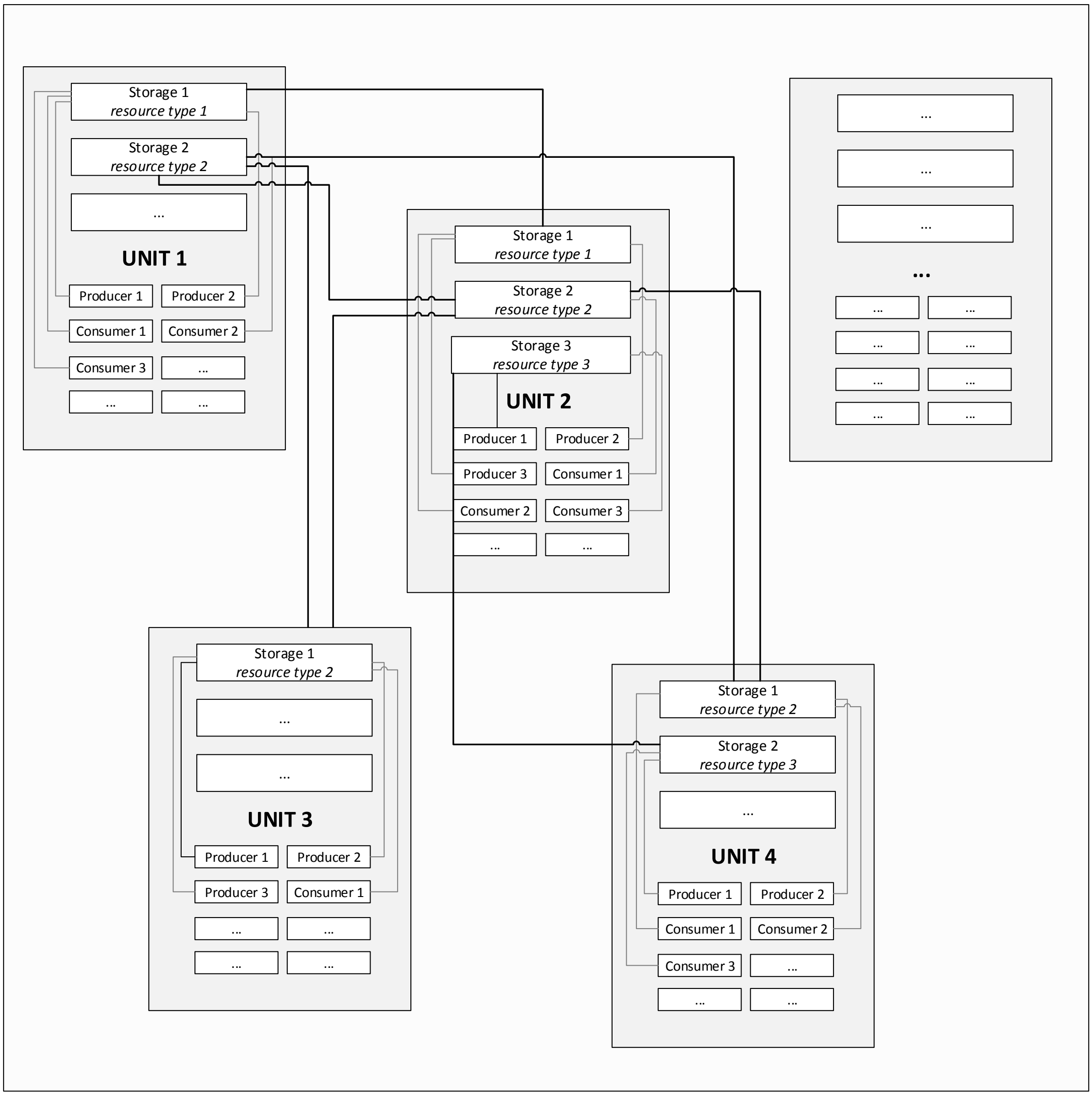

Fig. 1. The SSSHS framework architecture

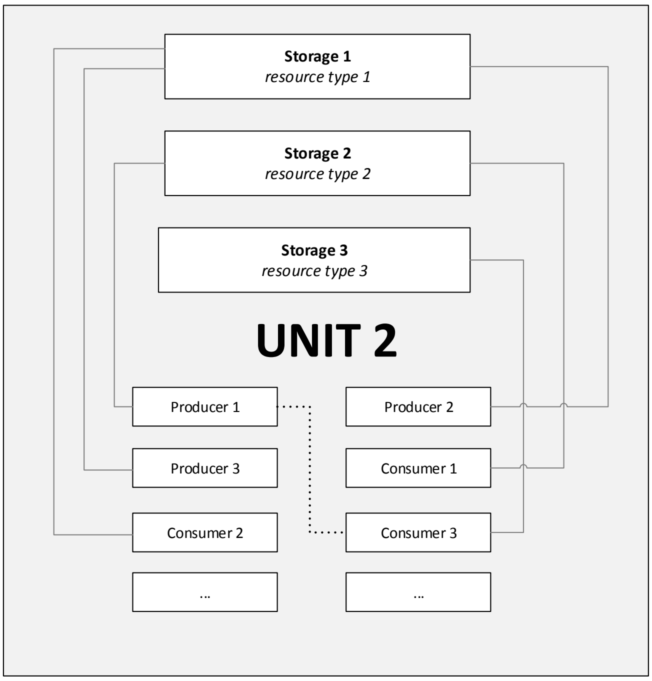

Fig. 2. Single dwelling unit

Individual dwelling units initiate a communication and resource transfer negotiation between themselves only upon triggering the predefined resource depletion alerts within their own subsystems. The proposed network topology of this model is an ideal fully connected network topology. Since this topology ensures that all the dwelling units are connected to each other both by data and resource infrastructure networks, it is possible to connect and transfer resources from any and to every other dwelling in the settlement system, between storages that process the same resource type.

In the lower layer shown on Fig. 2, each dwelling unit is composed of agent classes, which include a producer class, a consumer class, and a storage class. As such, individual dwelling units are able to produce, store and consume resources autonomously.

Each agent class has its own parameters and methods which have the ability to change the inner state of the agent, i.e. to change specific parameter values of the instantiated agent class. Individual dwelling units can implement one or more storage units, each dealing with different resource types. This facilitates the ability of the SSSHS framework to simulate more than one resource type at a simulation run, describing for example scenarios where the production of one resource type requires the consumption of another resource type (or more than one resource types). Communications and resource transfers between individual dwelling units is possible through storage units which process the same resource type.

4. Self-Sustainability Mechanisms

The SSSHS framework uses several mechanisms that facilitate the self-sustainability of resource management in the settlement. The basic mechanisms are confined to their subsystems (individual dwelling units), and include an economical working mode, manipulation of operating times (advancing or postponing the operation, dependent on the resource levels), and restoring default operation modes. Should these mechanisms fail to maintain the self-sustainability of their sub-system, inter-dwellings mechanisms are triggered by the framework. The resource negotiation mechanism calculates the value of needed resources which would bring the sub-system's resource level above the lower threshold zone, reducing the risk of the system to become non self-sustainable. According to the service-oriented negotiation paradigm, an agent (the client) requires a service to be performed (a resource transfer) from other agents (servers). The client presents its request to the server according to the calculated value of critically needed resources, and in respect to the server's own resource levels. The server then calculates its own capacities based on the most current parameter values stored in its inner state, and decides on the counter-offer it is willing to give to the client. If the counter-offer is greater than zero and resource transfer costs are acceptable, the negotiation thread is initiated. If the resource transfer costs are not acceptable, or the agreement is achieved but the counter-offer does not provide sufficient resource quantity, the client sends further requests to other agents, sequentially, until its resource levels are above the defined threshold. The client negotiation perspective is depicted in Fig. 3 in the form of a finite state machine.

Negotiation in the SSSHS framework is a one-to-one negotiation based on Raiffa's model for bilateral negotiation [23], and it proceeds in a series of iterations, with every agent making a proposal at every iteration. Upon reaching the agreement, negotiation terminates with the agreement deal, which is referring to the last counter-offer.

Raiffa's model f is defined as follows: Let i ($i \in \{a, b\}$) represent agents involved in the negotiation process, j ($j \in \{1, \ldots, n\}$) represent elements of offer, and $x_j \in [min_j , max_j]$ represent a possible set of values for the element of offer j. Every agent implements a usefulness function $V_j^i : [min_j , max_j] \rightarrow [0, 1]$ which assigns value to the individual elements of the offer. The relative weight which the agent i assigns to the offer element j is labeled with w_j^i.

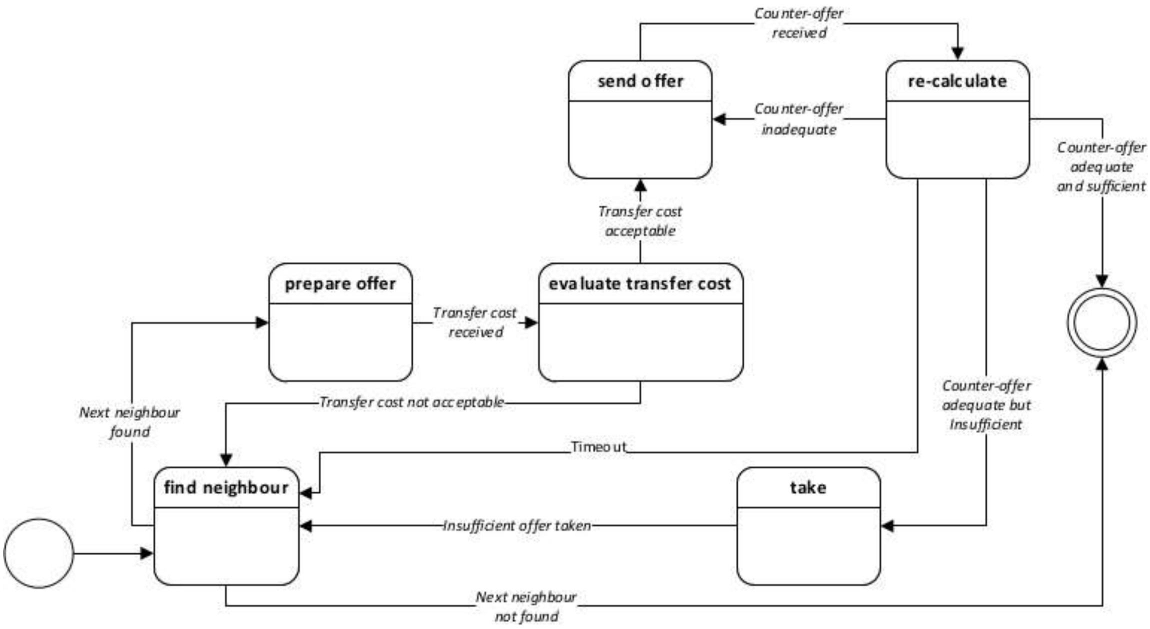

Fig. 3. A finite state machine of the negotiating client

The usefulness function of the agent i for an offer x = (x_1, …, x_n) is defined as follows:

$$V^i(x) = \sum_{1\le j\le n} w_j^i V_j^i(x_j) \qquad (1)$$

The SSSHS framework implements two elements of the offer, "quantity" and "worth". Quantity refers to the amount of resources being negotiated. "Worth" can refer to monetary value, quality of offer, or other factor, decided upon by the modeler. The results of the negotiation process depend on the defined timeout, and the interpretation of the offer. For example, let $a, b \in A$ represent agents in the negotiation process. Agent *a* has a usefulness function V_a. The interpretation of the offer $x_{b\to a}^t$ of the agent a in time $t'(t < t')$ is defined as following:

$$I^a(t', x_{b\to a}^t) = \begin{cases} refuse\ if\ t' > t_{max}^a \\ accept\ if\ V^a(x_{b\to a}^t) \ge V^a(x_{a\to b}^{t'}) \\ else: x_{a\to b}^{t'} \end{cases} \qquad (2)$$

- $x_{a\to b}^{t'}$ is an offer which the agent a would send to the agent b in time t'
- t_{max}^a is the latest time in which the agent a has to end the negotiations

Therefore, the acceptance of the offer is determined by the interpretations of both received and prepared offers, and their mutual comparison.

The other important inter-dwelling mechanism deals with the surplus of generated resources at individual dwelling units, preventing the resources from being irrecoverably lost because of the generated overflow. This surplus is recursively offered to other dwelling units, with the priority queue that is generated with regard to other unit's resource levels at the time.

Within the SSSHS framework, communication between agents is initiated within specific agent's methods. According to [24], "*the most basic communication method of agents is a procedure call, where the message is encoded within the parameters and the answer is the return value of the procedure*." [24, p. 18]. Although this communication method is bound to relatively simple communications, it provides adequate grounds for the SSSHS framework's designed functionality.

SSSHS framework can be used by the modeler to model, simulate, and analyze the self-sustainable system. The simulation can be terminated in two ways:

1) Simulation ends according to the predefined runtime schedule set by the modeler. In this case, the simulated system is considered self-sustainable. The framework notifies the modeler of the possible resource losses that took place because of the insufficient storage capacities, and of the number of system interventions that took place in order to avoid the loss of resources.

2) Simulation ends because of the critical resource deficit, with every self-sustainable mechanism exhausted. The system is proclaimed as being non self-sustainable, and the modeler is notified of the critical limitations of the modelled system which prevent it from being self-sustainable.

Should the simulation terminate early in the simulation runtime due to the depletion of resources, an architectural change in the modeled system would be typically recommended. Failures that occur near the end of the simulation runtime could be rectified by model's parameter re-configuration. In any case, a detailed analysis should be performed based on the SSSHS framework's reporting variables in order to obtain an important insight into the modeled system.

5. The Scenario and the Simulation

The scenario developed in this paper was designed with the significant help of the consultant Loren Amelang, an expert in self-sustainable systems, and with partial reference to the observations registered at the existing eco-village setup, located in Sisak-Moslavina County, Croatia, Central Europe and Southeastern Europe, with rough coordinates of 45° N, 15° E. According to [28] Croatia has an enormous potential for using renewable energy and in particular solar energy. The village consists of a 3 infrastructurally independent dwelling units (from now on referred to as "Units"). The scenario-relevant data was obtained from three sources: (1) on-site, by personally visiting and analyzing the site parameters; (2) by informal interviews of the site residents via email correspondence; (3) by the MeteoNorm 7.1 station data [25]. The scenario context consists of the electrical energy production process by using photovoltaic solar panels and an auxiliary propane generator, battery packs as energy storage units, and a set of consumer units. The initial model parameterization was done in the context of stand-alone (off-grid) system pre-sizing project by using PVsyst, a "*software package for the study, sizing and data analysis of complete PV systems*" [26].

The initial parameters included specifications of consumers and their load values, computed nominal power value of solar panel array, global system properties (panel tilt, azimuth, geographical coordinates, monthly meteorological data such as global irradiation, diffuse, temperature, etc.), specifications of the battery configurations, power input, etc. The solar irradiance input was obtained by MeteoNorm 7.1 station on geographical coordinates of 45° N, 15° E, and altitude 128 m above sea level, for month January (see table I).

Table 1. Monthly meteorological values at Lat. 45.8°N, long. 16.0°E, alt. 128m, Source: [25]

	Global Irrad. kWh/m².day	Diffuse kWh/m².day	Temper. °C	Wind Vel. m/s
January	1.02	0.56	1.1	1.50
February	1.98	1.16	3.7	1.70
March	2.94	1.55	8.1	1.99
April	4.03	2.19	12.8	1.90
May	5.53	2.46	18.5	1.80
June	5.83	2.54	21.2	1.70
July	5.85	3.03	23.0	1.60
August	5.03	2.35	22.5	1.49
September	3.27	1.66	16.5	1.48
October	2.19	1.36	12.6	1.40
November	1.11	0.67	7.5	1.40
December	0.76	0.54	2.3	1.49
Year	**3.30**	**1.68**	**12.5**	**1.6**

Monthly meteorological values (global irradiation, diffuse, temperature and wind velocity) and solar paths were used by the PVsyst software to obtain relevant values for the simulation's setup.

Dwelling units are using photovoltaic solar panels as the main electrical energy source and propane generators as auxiliary energy source. The energy storage systems are implemented via solar battery packs. Units used in the scenario and in the SSSHS environment are watt-hours (Wh) for energy, liters (l) for propane quantities, ampere hours (Ah) for electric charge, and watt-peak (Wp) for the nominal power of the photovoltaic solar array[1]. The term "photovoltaic" will be referred to with an abbreviation "PV" in most of the current section.

The initial system setup for all three units was designed and optimized with the help of PVsyst software for the planned and regular total load of the settlement units presented in the following table. It is important to note that the cloth-washer at Unit 1 was added subsequently according to the scenario development described later in the section. According to the PVsyst software documentation, "*The evaluation of the available irradiance on the collector plane uses the Monthly Meteo tool algorithms, which calculate irradiation's monthly averages on the basis of instantaneous data for one day per month. This is not sufficient to manage the storage balance evolution from day to day, and the effective use of solar incident energy. Therefore the program generates a random sequence of 365 days, according to the algorithms of Collares-Pereira, renormalised to the monthly sums, and calculates the daily battery balance for three intervals in a day (morning, day and evening).* " [26]

The energy production involving propane generator included nominal production values from a case study, and is calculated according to the following formula:

$$Aux = P \times 1.2 \times 1000 \tag{3}$$

where *Aux* represents energy quantity generated from an auxiliary propane generator (Wh), *P* represents propane quantity in liters, *1.2* is used as a nominal production coefficient, and *1000* is used for conversion from kWh to Wh. Losses deriving from equipment inefficiencies are considered within the conversion coefficient derived from the case study.

Table 2. Stationary consumers at Units 1, 2 and 3

UNIT 1 / UNIT 2 / UNIT 3				
	illumination	consumer electronics	fridge	cloth-washer / hydronic pump
power (W)	20/18/18	65/60/70	*N/A*	*N/A/20/N/A*
No.	3/5/2	3/2/1	*N/A*	*N/A/1/ N/A*
approx daily use (h)	3/3/2	3/2/2	*N/A*	*N/A/2,5/N/A*
energy per cycle (Wh)	*N/A*	*N/A*	740/740/0	1100/N/A/0
daily energy (Wh)	180/270/72	585/240/140	740/740/0	1100/50/0
total (Wh)	**2605/1300/212**			

[1] The term "watt-peak" is used in colloquial language in the context of domestic photovoltaic installations, because the International System of Units prohibits the use of suffixes [27]

Unit 2 uses hydronic pump, but does not utilize a cloth-washer during the observed time period. Unit 3 has the lowest initial load, thus the lowest requirements for solar photovoltaic array and solar battery pack. The solar collector plane orientation was set with tilt of 45 degrees and azimuth of 0 degrees.

According to these values, the solar panel array nominal power for the Unit 1 was set to 1026 Wp, and the battery pack capacity to 295 Ah, which corresponds to 7080 Wh with 24 V battery/system voltage. Required autonomy was set to 4 days. Unit 2 was allocated with the nominal solar array power of 849 Wp, battery pack capacity of 255 Ah at voltage of 24 V (6120 Wh), with considering the required autonomy of 4 days. Unit 3 has a nominal solar array power of 141 Wp, battery pack capacity of 42 Ah, which translates to 1008 Wh by using the 24V system voltage, and is considered with the required autonomy of 4 days.

The analysis of the static resource allocation per dwelling unit was performed in spreadsheets. For the purposes of a more thorough insight into the resource allocation processes, factors such as production overflow on the battery pack were purposefully omitted in the static allocation analysis.

The three dwelling units were initialized with battery levels 5700 Wh, 4200 Wh, and 680 Wh, respectively. These values were calculated into the day one in both the individual static analysis, and in the SSSHS simulation environment.

The battery levels are calculated according to the following formula:

$$BL(t) = BL(t-1) + P(t) - C(t) \tag{4}$$

where BL(t) represents battery level in time unit t, BL(t-1) battery level in previous time unit, P(t) total energy production in time t, and C(t) total energy consumption in time t.

It is evident that the Unit 3 has the lowest load requirements, but still occasionally uses auxiliary power generators to complement the insufficient energy production from the photovoltaic panels – in this case, a propane generator is utilized in time units 13, 14, and 23.

The following three figures illustrate the production of electricity by using both the photovoltaic modules ("PV") and auxiliary propane generators ("AUX" - if available) in Units 1, 2, and 3, against the battery pack energy levels ("battery"). All three variables are presented in Wh units.

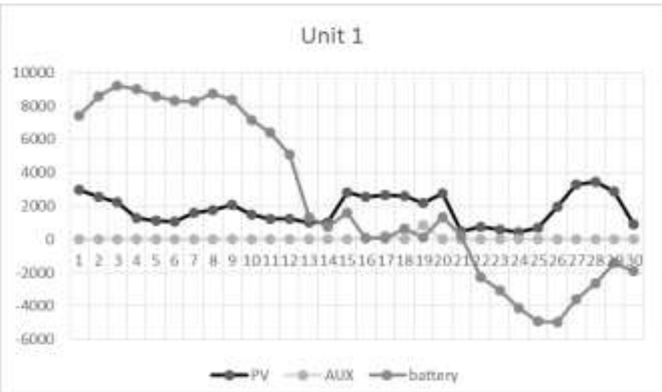

Fig. 4. Electricity production by using PV modules and propane generators at Unit 1

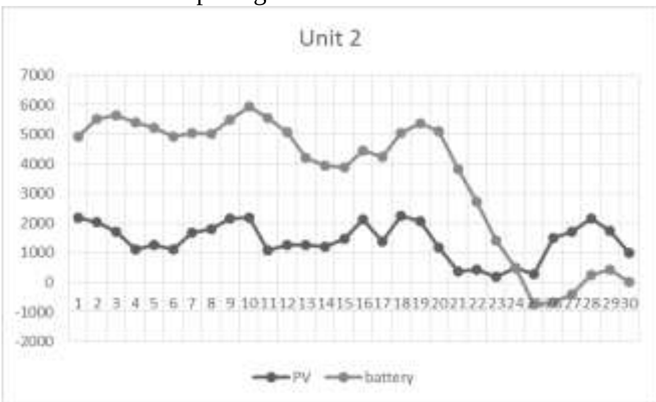

Fig. 5. Electricity production by using PV modules and propane generators at Unit 2

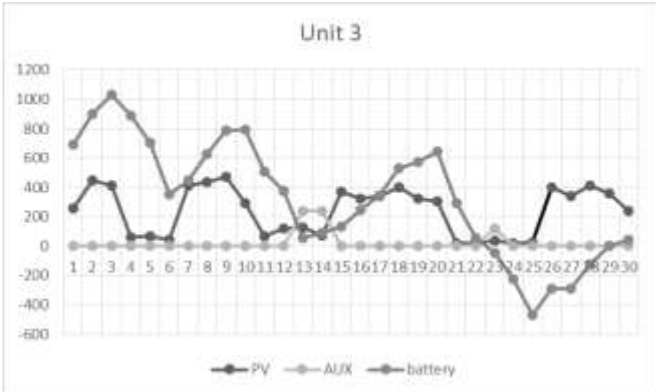

Fig. 6. Electricity production by using PV modules and propane generators at Unit 3

Fig. 4 and Fig. 6 illustrate a significant deferment of the energy reserves depletion by the use of auxiliary propane generators. Unit 1 had the reserves of 1 l, and unit 3 reserves of 0.5 l of propane available for electricity production. Both units depleted their propane reserves in the developed scenarios.

The main event that rendered system specification at Unit 1 inefficient were unexpected difficulties with the house infrastructure that required immediate attention of the residents. Because of these new circumstances occurring on day 15, two additional residents moved in to Unit 1, and workings within and around the house intensified. The growing need for clothes washing, and a lack of time to do it manually, compelled the residents to obtain a washing machine, which presented a significant new load on the existing energy production infrastructure. In a similar way, refrigerator load, illumination, electronics', tools' and machines' consumptions increased. In order to mitigate the overall load on solar PV panel array, the residents used the propane generator for additional power production, but the energy reserves were completely depleted by the time unit 22.

Similarly, energy reserves were depleted at dwelling unit 2 at 25th day. The unit 3 managed to postpone the depletion of the energy reserves by using the propane fuel from day 13, but at the end depleted all the reserves at 23rd day.

6. Simulation Results

The SSSHS framework was set to simulate two different types of resources simultaneously: the electrical energy obtained directly from the PV modules, and the propane fuel used to produce the electrical energy as an auxiliary source. Within the SSSHS framework, the simulation runtime was set to 30 time units, which corresponds to days observed in the analysis of the individual static resource allocation scenario. All the parameters were initialized according to the observed static resource allocation data.

A total of five storage units reported at the end of the simulation run; three of them representing the photovoltaic system, and two of them representing the auxiliary propane system. According to the simulation output, a total of 163 system interventions executed during the simulation runtime, with similar number of triggering the upper (24) and lower (26) threshold alerts. Unit 3 had the lowest overall load of the three dwelling units, which reflected on its overall battery pack levels which showed above 50% capacity in most of the simulated time units. Units 1 and 2 were using below 50% of battery capacity about half of the simulation runtime, which should be checked against the used battery technology in the real-world implementation, where a possible destructive patterns of battery usage should be considered. The following three figures illustrate the differences between battery pack levels with and without using the SSSHS mechanisms.

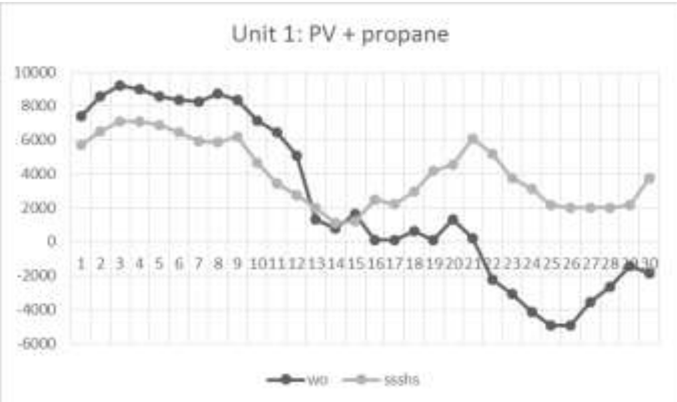

Fig. 7. Battery pack levels with and without using the SSSHS framework at Unit 1

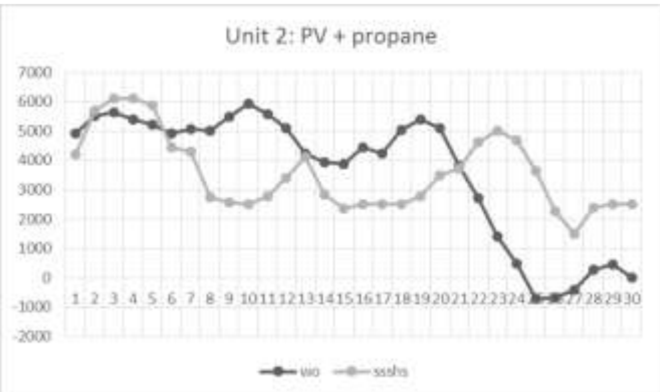

Fig. 8. Battery pack levels with and without using the SSSHS framework at Unit 2

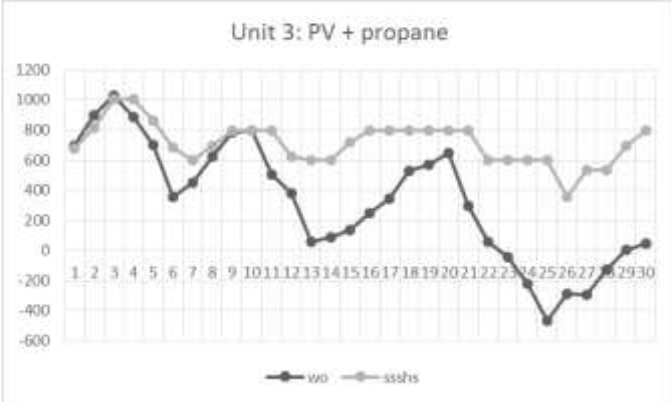

Fig. 9. Battery pack levels with and without using the SSSHS framework at Unit 3

Fig. 7 (Unit 1) shows a decreased drop of battery levels with using the SSSHS mechanisms and maintaining the overall energy levels above zero until the end of the simulation runtime. Fig. 8 (Unit 2) demonstrates the dynamics of resource allocation at Unit 2, with the SSSHS mechanisms maintaining the energy levels of the battery pack until the end of the simulation runtime. Fig. 9 (Unit 3) demonstrates the additional potential of the framework to manipulate battery usage patterns. These fluctuations can be additionally configured by the framework's parameters, particularly on the storage level.

The analysis of the static resource allocation observed in worksheets showed that the settlement failed to preserve the self-sustainability of electrical energy production. The energy reserves were depleted in time units 22 for dwelling unit 1, time unit 25 for a dwelling unit 2 and in time unit 23 for the dwelling unit 3. With the use of the SSSHS framework's self-sustainability mechanisms, the time interval of self-sustainability of the settlement was prolonged until the end of the simulation run, e.g. until the end of the observable period, with using identical input data.

7. Conclusion & Future Research

In this paper we have presented a significant improvement of the SSSHS agent-based modelling and simulation framework by allowing it to simulate multiple resources simultaneously. Additionally, we have developed and analyzed a specific real-world case scenario of an eco-village in Croatia on which the framework has been tested. This developed test-bed scenario allowed for a detailed evaluation of the SSSHS framework with reference to actual needs and available renewable energy resources. An energy production process using photovoltaic solar modules and auxiliary propane generators presented a complex ground for developing a scenario with the possibility to simultaneously simulate multiple resources, and consequently, multiple storage types per dwelling unit (energy stored as watt-hours, and propane stored in liters). Because of the specific, existing technologies involved in this scenario, an expert in the domain of off-grid power producing was consulted. The results of the simulated scenario within the SSSHS framework environment showed that the framework was able to prolong the self-sustainability of the settlement in comparing the results to the static resource allocation analysis. The framework also showed a potential to manipulate the battery usage patterns, which requires further analysis and experimentations.

The implemented test-bed scenario is limited in terms of small numbers of dwelling units and correspondingly small number of energy producers and consumers. The SSSHS framework allows for modelling arbitrary numbers of dwelling units, various consuming and producing devices as well as various numbers of resources limited only by the available computing facilities.

In our future work we will try to address more complicated test-bed scenarios by using larger numbers of variables and agents (e.g. dwelling units, consumers, producers, resources etc.), by including human agents into the framework that might act unpredictably and selfishly, since the framework currently assumes benevolent agents in a cooperative problem solving.

Acknowledgments

This work has been supported in full by the Croatian Science Foundation under the project number 8537.

References

[1] I. Tomičić, M. Schatten, “Towards an Agent Based Framework for Modelling Smart Self-Sustainable Systems”. Interdisciplinary Description of Complex Systems, 13(1), 57-70., 2015.

[2] I. Tomičić, M. Schatten, “Agent-based framework for modeling and simulation of resources in self-sustainable human settlements: a case study on water management in an eco-village community in Croatia”. International Journal of Sustainable Development & World Ecology, 1-10., 2016.

[3] P. Moriarty, D. Honnery, “Intermittent renewable energy: The only future source of hydrogen?”. International Journal of Hydrogen Energy, 32(12), 1616-1624., 2007.

[4] M. Ni, D.Y. Leung, M.K. Leung, “A review on reforming bio-ethanol for hydro-gen production”. International Journal of Hydrogen Energy, 32(15), 3238-3247., 2007.

[5] L. Atzori, A. Iera, G. Morabito, “The internet of things: A survey”. Computer networks, 54(15), 2787-2805, 2010.

[6] J.K. Hart, K. Martinez, “Toward an environmental Internet of Things”. Earth and Space Science, 2(5), 194-200, 2015.

[7] A. Caragliu, C. Del Bo, P. Nijkamp, “Smart cities in Europe”. Journal of urban technology, 18(2), 65-82., 2011.

[8] M. Schatten, “Smart Residential Buildings as Learning Agent Organizations in the Internet of Things”. Business Systems Research Journal, 5(1), 34-46., 2014.

[9] M. Schatten, J. Ševa, I. Tomičić, “A Roadmap for Scalable Agent Organizations in the Internet of Everything”. Journal of Systems and Software, in press, 2016.

[10] Z. Hu, S. Frénot, B. Tourancheau, G. Privat, “Iterative model-based identification of building components and appliances by means of sensor-actuator networks”. In Segovia, R., Zarli, A., Fies, B. (Eds.), Proceedings of the 2nd Workshop organised by the EEB Data Models Community “EEBuilding Data Models”, 26-28 October 2011, Sophia Antipolis, France, Publications Office of the European Union: Luxembourg, pp. 216-226., 2011.

[11] I. Ayala, M. Amor, L. Fuentes, “An agent platform for self-configuring agents in the internet of things”. Third International Workshop on Infrastructures and Tools for Multiagent Systems, ITMAS, pp. 65-78., 2012.

[12] P. Vlacheas, R. Giaffreda, V. Stavroulaki, D. Kelaidonis, V. Foteinos, G. Pouli-os, P. Demestichas, A. Somov, A.R. Biswas, K. Moessner, “Enabling smart cities through a cognitive management framework for the internet of things.” Communica-tions Magazine, IEEE, 51(6), 102-111., 2013.

[13] E. Welbourne, L. Battle, G. Cole, K. Gould, K. Rector, S. Raymer, M. Balazinska, G. Borriello, “Building the internet of things using RFID: the RFID ecosystem experience”. Internet Computing, IEEE, 13(3), 48-55., 2009.

[14] S. Sharples, V. Callaghan, G. Clarke, “A multi-agent architecture for intelligent building sensing and control”. Sensor Review, 19(2), 135-140., 1999.

[15] R. Giladi, “Heterogeneous building automation and IP networks management”. Distributed Computing Systems Workshops, 2004. Proceedings. 24th International Conference on. IEEE, pp. 636-641., 2004.

[16] U. Rutishauser, A. Schafer, “Adaptive Building Automation. A multi-agent approach”. Research project, 7(20), 02., 2002.

[17] A.R. Khare, B.Y. Kumar, “Multiagent structures in hybrid renewable power system: A review”. Journal of Renewable and Sustainable Energy, 7(6), 063101., 2015.

[18] T. Logenthiran, D. Srinivasan, “Multi-agent system for the operation of an integrated microgrid”. Journal of Renewable and Sustainable Energy, 4(1), 013116., 2012.

[19] T. Logenthiran, D. Srinivasan, K.W.M. Vanessa, “Demand side management of smart grid: Load shifting and incentives”. Journal of Renewable and Sustainable Energy, 6(3), 033136., 2014.

[20] K. Su, J. Li, H. Fu, “Smart city and the applications”. Electronics, Communications and Control (ICECC), 2011 International Conference on. IEEE, pp. 1028-1031., 2011.

[21] H. Qin, H. Li, X. Zhao, “Development status of domestic and foreign smart city”. Global Presence, 9, 50-52., 2010.

[22] M.F. Wood, S.A. DeLoach, “An overview of the multiagent systems engineering methodology”. Agent-Oriented Software Engineering. Springer Berlin Heidel-berg, pp. 207-221., 2001.

[23] H. Raiffa, “The art and science of negotiation”. Harvard University Press, 1982.

[24] R. Dumke, S. Mencke, C. Wille, “Quality Assurance of Agent-Based and Self-Managed Systems”. CRC Press, 2009.

[25] Meteonorm: Irradiation data for every place on Earth. Retrieved October 10, 2015 from: http://meteonorm.com/

[26] PVsyst Photovoltaic Software. Retrieved March 01, 2016 from: http://www.pvsyst.com/en/

[27] Wikipedia contributors. “Nominal power (photovoltaic)”. Wikipedia, the Free Encyclopedia. Retrieved November 02, 2015 from: https://en.wikipedia.org/wiki/Nominal_power_(photovoltaic)

[28] L. Runko Luttenberger. “The barriers to renewable energy use in Croatia”, Renewable and Sustainable Energy Reviews, 46, 646-654, 2015.

[29] D. Connolly, H. Lund, B. Vad Mathiesen, M. Leahy. "A review of computer tools for analysing the integration of renewable energy into various energy systems." Applied Energy 87(4), 1059-1082, 2010.

[30] P. Vytelingum, T. D. Voice, S. D. Ramchurn, A. Rogers, N. R. Jennings. "Agent-based micro-storage management for the smart grid." In Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems, 39-46. International Foundation for Autonomous Agents and Multiagent Systems, 2010.

[31] S. D. Ramchurn, P. Vytelingum, A. Rogers, N. R. Jennings. "Agent-based homeostatic control for green energy in the smart grid." ACM Transactions on Intelligent Systems and Technology (TIST) 2(4), 35, 2011.