Analysis of Configurations for Photovoltaic Solar Energy Production Using Agent-Based Simulation

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Abstract. To configure a photovoltaic solar energy production plant the circumstances of a site play an important role. A site usually consists a number of specific locations that can be considered ideal (no shadow, perfect southward position, optimal vertical angle). However, much more often locations in a site are not ideal, to an extent that both depends on time of the year and time of the day. An important issue for decision making then is how much loss in efficiency a specific location will entail. In this paper this is analysed by an agent-based simulation method. Here photovoltaic modules with micro-inverters are conceptualised as autonomous energy producing agents, which are monitored by a central monitoring agent which also interacts with a user via a local and a global Web-based interface agent. The presented approach provides an analysis of the different locations at a site by simulating the agents over one full year with time steps of half an hour per day. The outcome of such a simulation provides an overview of the loss of efficiency for each of the locations depending on its characteristics with respect to shadow, orientation and vertical angle.

1 Introduction

To increase the fraction of renewable energy with energy production, the production of solar energy by photovoltaic panels is becoming more and more successful; e.g., [6, 7]. Many sites for solar energy plants are considered, both for domestic and business situations. In a first phase the focus is mostly on sites with only ideal locations (e.g., no shadow, perfect southward position, optimal vertical angle of the panels). Indeed, to configure a photovoltaic solar energy production plant, the circumstances of a site play an important role. However, to increase the available area for solar energy production, in practice more and more often sites are considered for which the locations are not all that ideal, depending on time of the year and time of the day. For example, in the summer months May, June and July not much shadow may occur, but in the other months shadow may occur to an extent that depends on the specific day in the year and hour of the day. How much loss in efficiency would this entail over a year? To design a plant configuration on a site, decisions have to be made on which locations the solar modules are placed. An important issue for this decision making process is how much loss in efficiency a specific location will entail, compared to an ideal location. A trial and error approach would place the modules based on intuition or in an arbitrary manner, and after one year evaluate their results, after which reconfiguration of the site might take place; for example, see also [8]. In the current paper it is shown how this decision making process can supported by an agent-based simulation method. This analysis can take place before actually building up the site, which has advantages over a trial and error approach.

The presented approach considers a multi-agent system based on photovoltaic modules together with their own micro-inverter, which are conceptualised as autonomous energy producing agents. They are monitored by a central monitoring agent which also interacts with a user via a local and a global Web-based interface agent. The presented approach provides an analysis of the different locations at a site by simulating the agents over one full year with time steps of half an hour per day. The outcome of such a simulation provides an overview of the loss of efficiency over the whole year for each of the locations depending on its characteristics with respect to shadow, orientation and vertical angle. This information supports the decisions on where to place the modules at the site.

In the paper, in Section 2 an overview is given of how a plant can be conceptualised and formalised as a multi-agent systems, thereby using the concepts and formalisation of the agent system design method DESIRE; cf. [2, 3]. Section 3 discusses domain knowledge needed to make such agents realistic, and in Section 4 simulation results are discussed.

2 A Photovoltaic Energy Production Site as a Multi-Agent System

In this section it is described how a given photovoltaic solar energy production site can be conceptualised and formalised as a multi-agent system; for a picture, see Fig. 1. As a source of inspiration an actual real life PV-system has been used, in an abstracted form. This system is based on Power One Aurora microinverters, a central monitoring unit Aurora CDD and local and global Web-based interfaces; see [9]. The PV site is assumed to be based on microinverters, which means that each solar panel has its own (micro) inverter which

- controls the panel's DC voltage to obtain an optimal level of generated power for the panel for given circumstances (e.g., irradiation and temperature): maximum power point tracking (MPPT); often hill climbing methods are used for this optimisation such as 'perturb and observe'.
- inverts the low voltage DC current (e.g., around 30V) into a high voltage AC current (e.g., 230V).

Together the panel and microinverter can operate in an autonomous manner, in parallel with (and independent of) the other panel-inverter pairs. These autonomous entities are conceptualised as Solar Production Agents (SPA). The goal of each of these SPA agents is to provide optimal power for the given combination of circumstances at each point in time. Note that the panel itself is not considered an agent as it is fully controlled by the microinverter.

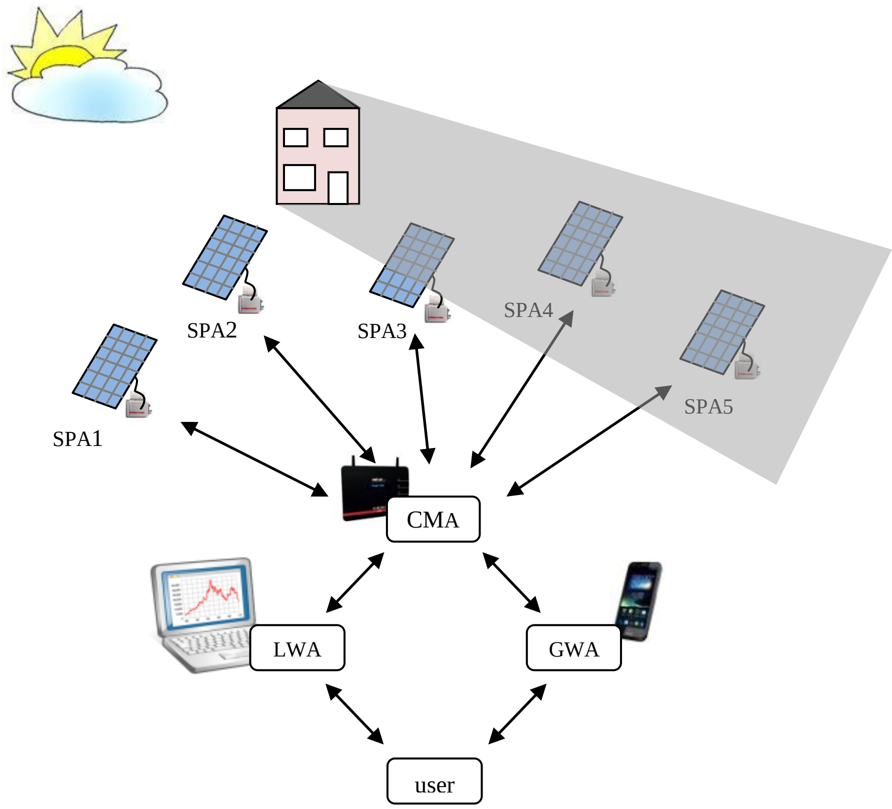

Fig. 1 Overview of the multi-agent system

The autonomy of the Solar Production Agents makes that they can easily adapt to the environmental circumstances, for example, of irradiation and temperature, in manner independent of each other. This is in contrast with the also often used string-based approach, where a number of solar panels are combined in a serial manner into a string which gets only one inverter for the whole string. This makes the panels dependent in their responses on the environment; in particular, if only one panel of a string is in the shadow, then the whole string will have a very low production, also the panels that have no shadow. The approach based on micro-inverters considered here can adapt to environmental circumstances in a much more sensitive manner: a panel in the shadow will produce less, but this does not affect the production of the other panels which are not in the shadow.

To be able to get an overview of the whole plant, usually a Central Monitoring Agent (CMA) is used (in the example PV system the Aurora CDD unit). This is a device that communicates with each of the micro-inverters (wireless, by radio signals, for example, or by using specific wirings) and gets information from each of them. This information is obtained by the Solar Production Agents by observing their own energy production processes in the (physical) World. The Central Monitoring Agent pro-actively gathers and maintains up to date information from of the SPA agents, by initiating a communication with them, for example each minute.

For an overview of the interactions within the multi-agent system, see Table 1. Note that the energy producing actions are initiated within the Solar Production Agents, but their execution takes place in the (physical) World component (after they were transferred to this component, from the initiating agent). This entails determining the effects (e.g., provided power P_{out}) of the action within World. In return observation information on these effects flows from World to the Solar Production Agents. Note that World is a system component here representing the physical world, but this component is not considered an agent. The agents interact with this component but this interaction concerns observation and action execution, not communication.

Table 1 Interaction structure for the multi-agent system

to from	World	SPA	CMA	LWA	GWA	user
World	-	Observation info	-	-	-	-
SPA	Action info	-	Observation info	-	-	-
CMA	-	Request info	-	Monitoring info	Monitoring info	Wifi or LAN info request
LWA	-	-	Request info	-	-	Observation info
GWA	-	-	Request info	-	-	Observation info
user	-	-	Wifi or LAN info	Request info	Request info	-

In addition the Central Monitoring Agent communicates with Local and Global Web-based interface Agents (LWA and GWA); this communication takes place locally through a local area or Wifi network and globally via Internet. These Web-based interface agents communicate with the user. The idea is that the Local Web-based interface Agent can be used within a local area network at home, for example at a PC or laptop, and that the Global Web-based interface Agent can be used via Internet anywhere, for example at a smartphone, as is the case for the Power One Aurora example considered.

The multi-agent system and its agents have been specified using the component-based agent design method DESIRE [1, 2, 3], and in particular the generic agent model GAM [4]. In each cell in Table 1 the name of an information type [3] is indicated. These information types include generic concepts for communication, observation and action performance from GAM; see [4]. In addition, for this specific instantiation of GAM they include domain-specific elements as shown in Table 2. Note that in the information type Action info the energy production action is specified. In the World the effect of this action has certain parameters, for example, the power P_{out} delivered. This action effect will depend on the circumstances in the environment of the Solar Production Agent (e.g., the available irradiation) and the agent's physical characteristics such as the Watt peak $P_{panelpeak}$ and efficiency ρ_{panel} of its panel, the maximal input power $P_{invpeak}$ and the efficiency ρ_{inv} of the micro-inverter, and the angle and orientation of the panel (in Self info). This is specified also as part of World.

Table 2 Information types and their domain-specific information

Information type	*Domain-specific information included*	*Used in Agent*
Observation info	• P_{in} incoming power (W) • V_{in} incoming voltage (V) • processing temperature (°C) • P_{out} outgoing power (W) • V_{out} outgoing voltage (V) • I_{out} outgoing current (A) • frequency (Hz) • alarm and warning states (e.g., ground leakage, communication faults)	SPA World
Action info	• energy production action • shutting down (power off) • resetting (power off and restart) • production action effect (characteristics I_{out}, P_{out}, V_{out})	SPA World
Request info	Observation info with an extra label indicating that the information is requested	CMA, SPA, LWA, GWA
Monitoring info	Observation info with an extra label indicating a specific SPA agent name to which the info relates	CMA, LWA, GWA, user
Self info	• $P_{panelpeak}$ Watt peak of panel (W) • ρ_{panel} efficiency of the panel • $P_{invpeak}$ max power of inverter (W) • ρ_{inv} efficiency of the inverter • Vertical angle of panel (°) • Horizontal orientation of panel (°) • Serial numbers, MAC addresses • Software version information	SPA
Agent info	Self info with an extra label indicating the agent to which the info relates	World, SPA, LWA, GWA, user
Collective info	Information on collective achievements: • P_{tot} total power produced by the plant (kW) • E_{tot} total energy produced over time by the plant (kWh)	SMA, LWA, GWA, user

What has been presented up till now is an agent-external perspective on the multi-agent system, abstracting from what happens in agents internally. In addition to this external view, the component-based method DESIRE offers means to specify the agents from an internal perspective in a component-based manner. In particular the Generic Agent Model GAM [4] is composed of a number of standard components. In this agent model the component *World Interaction Management* (WIM) takes care of interaction with the world, the component *Agent Interaction Management* (AIM) takes care of communication with other agents. Moreover, the component *Maintenance of World Information* (MWI) maintains information about the world, and the component *Maintenance of Agent Information* (MAI) maintains information about other agents. The processes involved in controlling the agent (e.g., determining, monitoring and evaluating its own goals and plans) but also the processes of maintaining a self model are the task of the component *Own Process Control* (OPC). In the component *Agent Specific Task* (AST) tasks specific for the agent can be modelled. For situations in which cooperation with other agents plays a role (such as in this case where the different Solar Production Agents together achieve the total production), in addition also a Cooperation Management (CM) component is included; cf. [1]. This model has been instantiated for each of the agents in the multi-agent system. As an example, in Table 3 it is shown which information types are used by the different components within the Central Monitoring Agent CMA. Note that in CMA the component World Interaction Management (WIM) is not used as this agent only communicates and has no own interaction with the world. In contrast, Table 4 shows the same for a Solar Production Agent SPA.

Table 3 Overview of the components within the agent CMA and the information types used

Internal agent concepts	CMA	Component
World Model	Monitoring information	MWI
Agent Models	Monitoring info Agent identification info	MAI
Collective Model	Collective info	CM
Communication initiation	Monitoring info Request info	AIM
Processing of received communication	Monitoring info	AIM

Table 4 Overview of the components within an agent SPA and the information types used

Internal agent concepts	SPA	Component
World Model	Monitoring information	MWI
Self Model	Self info	OPC
Action initiation	Action info	WIM
Communication initiation	Monitoring info	AIM
Processing of received observation results	Monitoring info	WIM
Processing of received communication	Request info	AIM

Here the component World Interaction Management is used for observation and for performing the action energy production, but not the components Cooperation Management (CM) and Maintenance of Agent Information (MAI).

3 Modelling Situational Efficiency of the Solar Production Agents

To be able to perform agent-based simulation experiments, knowledge has been modelled about how at any point in time, the efficiency of the energy production action of a Solar Production Agent depends on circumstances. In general, the action effect of the energy production action of a Solar Production Agent (as determined in the World component) on provided power P_{out} can be described as a function of:

- used irradiation, which itself depends on
  - the efficiency ρ_a due to angle and orientation of the panel
  - the efficiency $\rho_s(t)$ due to shadow at time t
  - the available irradiation $irr(t)$ at time t
- the maximal power $P_{panelpeak}$ of the panel (Watt peak)
- the efficiency ρ_{panel} of the panel
- the maximal power $P_{inverterpeak}$ of the micro-inverter
- the efficiency ρ_{inv} of the micro-inverter.

The following relations are assumed:

- Provided power P_{panel} by panel: $\min(P_{panelpeak}, \rho_a \, \rho_s(t) \; irr(t)) \, \rho_{panel}$
- Provided power P_{out} by inverter: $\min(P_{inverterpeak}, P_{panel}) \, \rho_{inv}$

In the model the World component receives the energy production actions from the Solar Production Agents, and determines the action effects P_{out} for each of these Solar Production Agents based on the above formula. In turn the Solar Production Agents receive (as observation) this effect of their own action (e.g., P_{out}) from the World component and communicate this to the Central Monitoring Agent CMA. Note that ρ_{panel}, ρ_{inv}, $P_{panelpeak}$, and $P_{inverterpeak}$ are given characteristics of the Solar Production Agent, represented as Self info in each Solar Production Agent and as Agent info for all Solar Production Agents in the World component. The other three $\rho_s(t)$, ρ_a, and $irr(t)$ are variables that can be manipulated or depend on time of the day and year; they will be discussed in more detail in this section.

3.1 Modelling shadow effects on the energy production: the variable $\rho_s(t)$

As a first step it has been modelled how shadow affects the results of the energy production action (the variable $\rho_s(t)$). As shadows directly relate to obstacles on the one hand, and positions of the sun on the other hand, they vary much with the sun positions at different times of the day and at different days of the year. The position of the sun (seen from the earth) is characterised by two angles (see also Christensen and Barker, 2001):

- The vertical angle above the horizon
- The horizontal angle with the direction of North

The *vertical sun angle* dynamics as seen from the earth has been modelled (as an approximation) by

$$vsa(t, d) = 23.4\cos(360(d-172)/365.26) + (90-nl)\cos(360(t-t0)/24))$$

when this is positive and $vsa(t, d) = 0$ otherwise

Here

$vsa(t, d)$ = vertical sun angle at time t of day d
t = time on the day
d = day of the year
nl = northern lattitude (= 52.7 in the simulation)
el = easter longitude (= 4.7 in the simulation)
$t0 = round(2*(13-el/15);0)/2 = 12.5$ (= time of maximal vertical sun angle)

The first term in this formula varies from -23.4 (on December 21, day 355) to 23.4 (on June 21, day 172) over the year. The second term is for $t = t0$ always $90\text{-}nb$. Therefore for $nb = 52.7$ the maximal vertical sun angle varies from 14 (on Dec. 21, day 355) to 61 (on June 21, day 172), which indeed is empirically valid for the given site. For $t = t0\text{-}6$ and $t = t0+6$ the second term is 0. The *horizontal sun angle* depends in a linear manner on the time *t* of the day:

$has(t)$ = horizontal sun angle (with North) = $180 + (t\text{-}t0)*15$

Given this model for the sun's dynamics, as a next step it has been modelled how for a given obstacle (assumed here to be a rectangle with a certain position, height and direction) this results in a certain *shadow length* $sl(t, d)$:

$$
\begin{aligned}
sl(t, d) &= oh\,\sin(sao(t, d))/\tan(vsa(t, d)) && \text{if } vsa(t, d) > 0 \text{ and } \sin(sao(t))/\tan(vsa(t, d)) > 0\\
&= 0 && \text{if } vsa(t, d) > 0 \text{ and } \sin(sao(t))/\tan(vsa(t, d)) \leq 0\\
&= maxs && \text{if } vsa(t, d) = 0
\end{aligned}
$$

Here

$sl(t, d)$ = shadow length at time t of day d
oh = obstacle height
$sao(t)$ = sun angle with obstacle
$sao(t)$ = has(t) - 90 - ao
ao = angle obstacle with East-West direction (= 25 in the simulation)
$maxs$ = max length shadow

Given this, the irradiation loss due to shadow has been modelled. Note that the potential irradiation/hour is given by

$$
\begin{aligned}
pr(t) = \text{potential radiation /hour} &= \sin(vsa(t)) && \text{if } vsa(t) > 0\\
&= 0 && \text{otherwise}
\end{aligned}
$$

The irradiation loss due to shadow can be modelled in different manners, for example, by identifying shadow areas of obstacles using, their dimensions and distances, or by determining the vertical angles of the contours of the horizon in all directions. For the simulations it has been modelled in the first manner:

$$rl(t, d) = \begin{cases} sin(vsa(t, d))\ (sl(t, d)\text{-}cd)/(fd\text{-}cd) & \text{if } cd < sl(t, d) < fd \\ sin(vsa(t, d)) & \text{if } sl(t, d) \geq fd \\ 0 & \text{otherwise} \end{cases}$$

Here

$rl(t, d)$ = irradiation loss at t and d

cd = closest distance of location from obstacle

fd = farrest distance of location from obstacle

The distribution over a day has been aggregated to a day loss and month loss as follows:

$drl(d)$ = day irradiation loss = $\int_0^{24} rl(t,d)dt$

$dpr(d)$ = day potential irradiation = $\int_0^{24} pr(t,d)dt$

$mrl(m)$ = month irradiation loss = $\int_0^{30x24} rl(t,m)dt$

$mpr(m)$ = *month potential irradiation* = $\int_0^{30x24} pr(t,m)dt$

$dlf(d)$ = day irradiation loss / day potential irradiation = $drl(d) / dpr(d)$

$mlf(m)$ = month loss fraction = $mrl(m) / mpr(m)$

These models provide a way to keep track in simulations of the overall effects in loss of efficiency due to shadow.

3.2 Modelling the effects of panel orientation and angle on the energy production: the variable ρ_a

A next circumstance addressed is the orientation and angle under which the panel of a Solar Production Agent is positioned (the variable ρ_a). For example, at [10] a schematic overview is shown of how efficiency relates to the vertical and horizontal angle of a panel, taken over a year. This has been modelled here as an approximation

$$\rho_a(\alpha) = \gamma\ sin(90 + \alpha - \alpha_{opt}) + \eta$$

with α the vertical angle and α_{opt} the optimal vertical angle. When $35°$ is the optimum, as approximately is the case in middle European areas, it follows that

$$\rho_a(\alpha) = \gamma\ sin(\alpha + 55) + \eta$$

The other parameters can be determined depending on the horizontal orientation, for example:

Orientation to south: $\rho_{a,S}(\alpha) = 0.65\ sin(\alpha + 55) + 0.35$

Orientation to south south west: $\rho_{a,SSW}(\alpha) = 0.58\ sin(\alpha + 55) + 0.39$

The latter was used in the example plant simulation, which has an orientation south south west.

3.3 Modelling the effects of available irradiation on the energy production: the variable *irr(t)*

For input on irradiation for different times in a year, realistic empirical data were acquired (from the Dutch Meteorological Institute KNMI). These data show the distribution of irradiation over different months of the year, indicated as $irr(m)$ with m a month. Note that such information for Europe can also be obtained at [11]. From these irradiation figures the relative distribution of *irradiation fractions* has been made (total sum = *1*), indicated by $irrf(m)$ with m a month:

$$irrf(m) = irr(m) \,/\, \textstyle\sum_{m'=1}^{12} irr(m')$$

To get an impression of the different periods of the year, the diagram shown in Fig. 2 has been made. As can be seen there, the months May, June and July provide *45%* of the year (red numbers) irradiation. From March to September *85%* is provided. This has a strong relation with the maximal vertical sun peak angles (black numbers). This overview is of some help in interpreting the results from the simulations.

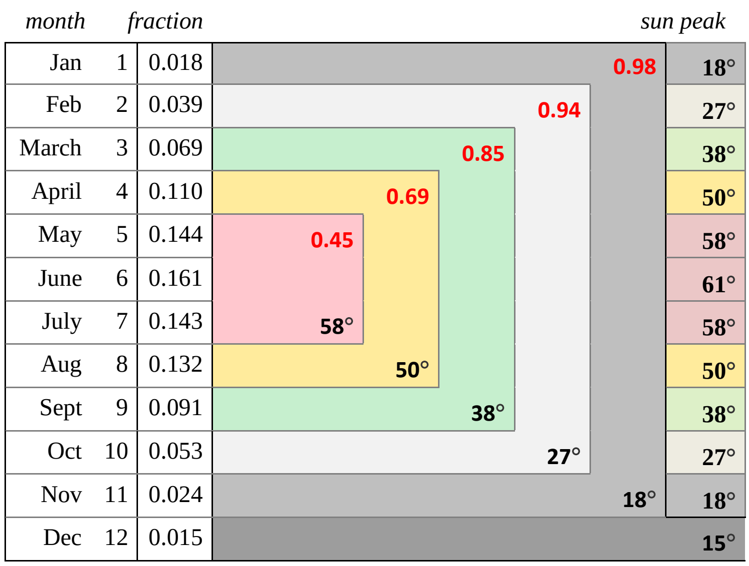

Fig. 2. Relative contribution of irradiation of different time periods in the year.

4 Simulation Experiments

The agent-based models described in Sections 2 and 3 enable to simulate a designed plant configuration, for example, for one year, before the plant is to be realised. A period of one, or even multiple years is needed as the circumstances are different at different times of the year, and even between different years. Moreover, within each day simulation took place with time steps of half an hour, in order to deal with different circumstances during the day. Given the obtained empirical data on irradiation per month (see Fig. 2), the decision was made to run simulations by taking one day for each month. More specifically, as an approximation, *12* days $d_1, .., d_{12}$ in a year were simulated, representing the *12* months (taken at the *21*-th of each month); the month loss fraction for month m is based on the day loss fraction (see Section 3) of the day d_m representing this month:

$$mlf(m) = dlf(d_m)$$

From this the year loss fraction was determined, using the irradiation fraction:

$$\text{year loss fraction} = \sum_{m=1}^{12} mlf(m)irrf(m) = \sum_{m=1}^{12} dlf(d_m)irrf(m)$$

Simulation results for an example site are shown in subsequent Figures 3 and further. Note that the figures shown focus on loss fractions, as these are most relevant for the decision making. The example site consists of four locations with different shadow circumstances, with the following characteristics.

Location 1	shelter in the garden with an almost flat roof oriented south south west with shadow from the house with height 5.00 meter at a distance of 6.00 to 10.00 meter south east
Location 2	garage with a flat roof oriented south south west with shadow from the house with height 5.00 meter at a distance of 2.85 to 4.50 meter south east
Location 3	flat roof at top of a dormer oriented south south west with shadow from a row of trees east south east at a distance of 8.50 to 15.50 meter and height 5.50 meter and from the rooftop south south west at a distance of 0.85 to 3.00 meter with height 0.50 meter
Location 4	sloped roof oriented south south west with shadow shadows from a row of trees east south east at a distance of 8.50 to 15.50 meter and height 5.50 meter

First the panels are assumed under the ideal angles. In Fig. 3 the month loss fractions *mlf(m)* are shown for the different locations.

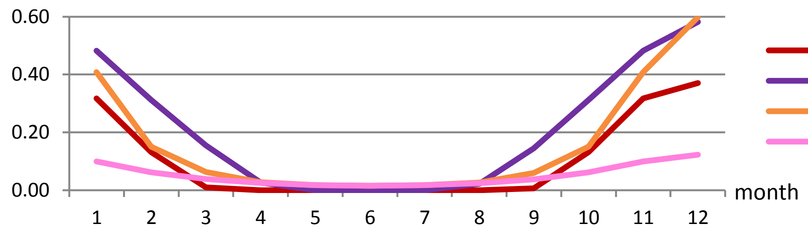

Fig. 3. Month loss fractions over months for the different Solar Production Agents

It can be seen that in the summer months the loss fraction of all locations is practically *0* (almost no shadows). But in other times of the year (from September to April) there are differences up to *500%*. In Fig. 4 the losses are related to the year instead of the month by multiplying the month loss fraction with the month irradiation fraction: *mlf(m) irrf(m).* Also here it can be seen that in the months from September to April large differences occur.

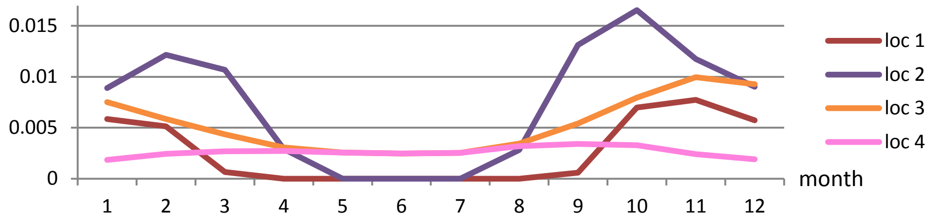

Fig. 4. Year loss fractions over months for the different Solar Production Agents

In Fig. 5 the total irradiation used for the different locations is shown, still assuming an ideal angle of the panels. It can be seen that in the summer months the used irradiation is practically the same for all locations (almost no shadows). But in other times of the year there are differences. However, in these times the overall available irradiation is less, so although the loss is a high fraction, in absolute terms the differences are more modest.

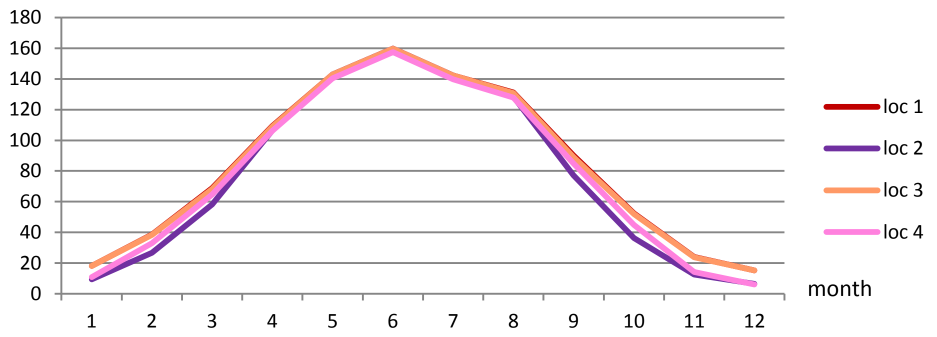

Fig 5. Irradiation used at each location in each month

In Fig. 6 the overall loss fractions for the year as a whole are shown. The four locations differ in losses from *3%* to almost *9%*. Such differences are worthwhile to consider in deciding where to place the Solar Production Agents.

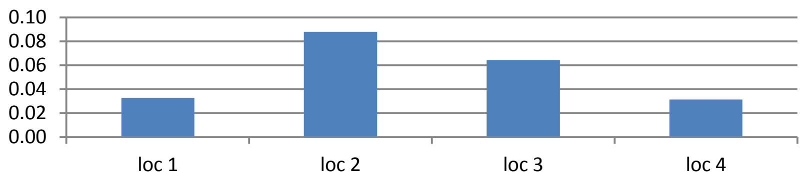

Fig. 6. Year loss fractions for the different locations for equal, ideal angle of the panels

In Fig. 7 results are shown for a different simulation in which for each location there is a different vertical angle of the panel. Due to the less optimal angle year losses become more in this case, up to *16%*, and the distribution changes as well. For example, location 3 becomes much worse due to a less ideal angle of *5°*.

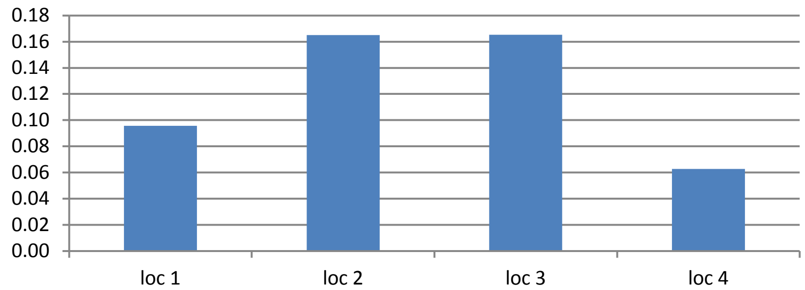

Fig. 7. Year loss fractions for the different locations for different angles: loc 1: *15°* loc 2: *10°* loc 3: *5°* loc 4: *30°*

5 Discussion

Usually the performance of photovoltaic solar energy production plants (e.g., [6, 7]) are analysed during their operation (e.g., [8]). A plant is distributed over a number of locations within the site. Such locations in a site are not always ideal, and may entail loss of efficiency due to effects of shadow and/or to nonoptimal orientations and angles for the panels (which may, for example, depend on slopes and orientation of available roofs). It is not easy to estimate the effects of such circumstances at forehand, as they vary with time of the day and day of the year. Therefore, evaluation of performance of an operational plant makes most sense after at least one year, but even then the weather circumstances in that year may not be representative for other years. From such evaluations afterwards it may be found that the configuration of the plant can better be changed by moving panels from apparently less favourable locations to more favourable locations, but in the meantime more than a year was lost.

In this paper a different approach was followed: the expected performance of possible configurations of a plant are analysed at forehand by an agent-based simulation method. Using the outcomes of such a what-if analysis, there is a better chance that the configuration of a plant uses the best locations right from the start. The photovoltaic modules with micro-inverters were conceptualised as autonomous energy producing agents, interacting with a central monitoring agent, which in turn interacts with a user via a local and a global Web-based interface agent. The presented approach has been shown to provide an analysis of the different locations at a site by simulating the agents over one full year with time steps of half an hour per day, which easily can be refined, for example, to smaller time steps of, for example, 5 minutes. Based on this analysis a decision can be made about the most optimal locations for the modules.

The aim of the work presented here was to bring together knowledge from two different disciplines. On the one hand this concerns knowledge about modelling parallel processes in a conceptual and formal agent-based framework. On the other hand detailed domain knowledge was considered about photovoltaic solar energy production and all kinds of practical factors affecting the efficiency of it. Such domain knowledge is often hidden in tools used in practice. For example, see [12] for an overview of such tools, and [13] for one specific tool: Solar Pathfinder. Although the details are not revealed, it seems that in the latter tool the role of shadow is determined based on the contours of the horizon. As also mentioned in Section 3.1 above, the method used in the work presented here takes a different approach, not based on contours, but on the dimensions and distances of the obstacles. In the paper it is shown how the agents considered as conceptual entities to model the parallel processes can be provided with such very detailed domain knowledge in order to obtain a level of detail needed for realistic simulations of real world situations.

References

1. Brazier, F.M.T., Cornelissen, F., Jonker, C.M., Treur, J: Compositional Specification of a Reusable Co-operative Agent Model *International Journal of Cooperative Information Systems* 9, 171-207 (2000)
2. Brazier, F.M.T., Dunin Keplicz, B., Jennings, N., Treur, J.: DESIRE: Modelling Multi-Agent Systems in a Compositional Formal Framework. International Journal of Cooperative Information Systems 6, 67-94 (1997)
3. Brazier, F.M.T., Jonker, C.M., Treur, J.: Principles of Component-Based Design of Intelligent Agents. Data and Knowledge Engineering 41, 1-28 (2002)
4. Brazier, F.M.T., Jonker, C.M., Treur, J.: Compositional Design and Reuse of a Generic Agent Model. Applied Artificial Intelligence Journal 14, 491-538 (2000)
5. Christensen, C.B., Barker, G.M.: Effects of Tilt and Azimuth on Annual Incident Solar Radiation for United States Locations. In: Proc. of Solar Forum 2001 - Solar Energy: The Power to Choose. April 21-25, 2001, Washington, DC.
6. Eltawil, M.A., Zhao, Z.: Grid-connected photovoltaic power systems: Technical and potential problems—A review. Renewable and Sustainable Energy Reviews 14, 112–129 (2010)
7. Parida, B., S. Iniyan, S., Goic, R.: A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews 15, 1625–1636 (2011)
8. Sharma, V., Chandel, S.S.: Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India. Energy 1-10. Doi 10.1016/j.energy.2013.03.075 (2013)
9. URL Power One Aurora http://www.power-one.com/renewable-energy/products/solar/string-inverters/panel-products/aurora-micro/series-0.
10. URL The effect of vertical angle and horizontal orientation over the year http://www.enpower.be/finance/home/enpower_en.php?lnk=zon&page=techniek_zon
11. URL Irradation data http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.
12. URL Overview of available tools http://www.builditsolar.com/References/SunChartRS.htm
13. URL Solar Pathfinder http://www.solarpathfinder.com