

# Agent-based control of distributed electricity generation with micro combined heat and power—Cross-sectoral learning for process and infrastructure engineers<sup>☆</sup>

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## Abstract

For the distributed control of an electricity infrastructure incorporating clusters of residential combined heat and power units (micro-CHP or  $\mu$ CHP) a multi-agent system approach is considered. The network formed by households generating electricity with  $\mu$ CHP units and the facilitating energy supplier can be regarded as an electricity production system, analogous to a (flexible) manufacturing system. Next, the system boundary is extended by allowing the trade of electricity between networks of households and their supplier. A methodology for designing an agent-based system for manufacturing control is applied to both cases, resulting in a conceptual design for a control system for the energy infrastructure. Because of the analogy between production systems and infrastructures process systems engineering (PSE) approaches for optimisation and control can be applied to infrastructure system operations. At the same time we believe research on socio-technical infrastructure systems will be a valuable contribution to PSE management strategies.

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## 1. Introduction

Residential combined heat and power units based on Stirling engine technology at the domestic user level (micro-CHP, from now on referred to as  $\mu$ CHP) are expected to pervade the electricity infrastructure on a large-scale in the future. This will have an effect on the generation methods, transportation and supply of electricity. A  $\mu$ CHP unit produces heat from gas (like a traditional central heating unit common in most households), but next to heat it also produces electricity. De Jong, Bakker, Dam, and Van Wolferen (2006), Su (2005), Newborough (2004), Monasso (2005) and Microgen (2005), among others, describe the market diffusion potential and the technological characteristics of  $\mu$ CHP. A realistic estimate is that 50% of all households will install a  $\mu$ CHP in the coming two decades. The introduction

of distributed electricity generation technology on such scale changes the way electricity networks have to be controlled and the way control is researched (Chambers, Hamilton, & Schnoor, 2001; Jenkins, Allan, Crossley, Kirschen, & Strbac, 2000).

Decision making in a distributed system can be seen as local optimisation within a feasible region determined by other decision makers and it can be done in a hierarchical, coordinated or cooperative way (van Dam, Verwater-Lukszo, Ottjes, & Lodewijks, 2006a). The decisions made at a local level have an effect on the total behaviour of the system but it can be hard to predict the overall effect. Many local decision-making problems have been researched in great detail and these processes have been optimised. Optimisation of part of the problem does not mean that the overall process at system level is optimal, especially when local objectives are conflicting (Julka, Karimi, & Srinivasan, 2002). Studying and analyzing the dependencies between different levels of control is essential for improving control methods for the whole system.

Not only is this the case in the distributed electricity production systems discussed in this paper, but the same problem of how to control a distributed system is visible in chemical process

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systems and other manufacturing systems. Work on the control of an infrastructure system lead to the hypothesis that control approaches from the manufacturing domain are potentially also very useful and applicable outside their domain.

For the distributed control of  $\mu$ CHP units in the electricity sector a multi-agent system (MAS) approach (Wooldridge, 2002; Wooldridge & Jennings, 1995) is considered. Multi-agent systems closely resemble the structure of distributed systems: agents are autonomous, reactive to changes in their environment, they pro-actively pursuit their own goals and their social ability makes it possible for them to adapt to different organisational structures. Next to that, MAS are flexible, modular and they allow easy reuse of model components. The MAS approach has already successfully been used to control manufacturing systems aimed at the integration of planning, scheduling and processing in the process industry. The designing agent-based production control systems (DACS) methodology for designing an agent-based control system for manufacturing control (Bussmann, Jennings, & Wooldridge, 2004) is applied here to create a conceptual design for the control of an electricity infrastructure incorporating a large-scale use of  $\mu$ CHP units.

The hypothesis that control approaches from the manufacturing domain can be used for infrastructures was proved with

the application of DACS to an infrastructure control problem in van Dam, Houwing, Lukszo, and Bouwmans (2006b). That application is revisited in this paper. Here, the description of the process to be controlled is described in more detail and more realistically. The conceptual control model is adjusted accordingly.

Furthermore, in this paper it is shown that the approach is still applicable when the system is made more complex by adding multiple subsystems that interact and influence each other. When the distributed network not only contains the relationship between a supplier and a number of households, but also the relationship between several of these production systems, these subsystems can be controlled in a similar fashion. This leads to the new hypothesis that lessons learnt from the application of a process engineering methodology on an infrastructure can be useful again for the control of more complex production systems.

Fig. 1 shows the analogy between control tasks in an electricity infrastructure and a production process. Quadrants II and III (on the left) represent the distributed electricity infrastructure domain and quadrants I and IV (on the right) the domain of production processes. The arrow from I to II represents the analogy between the domains and the application of DACS on another

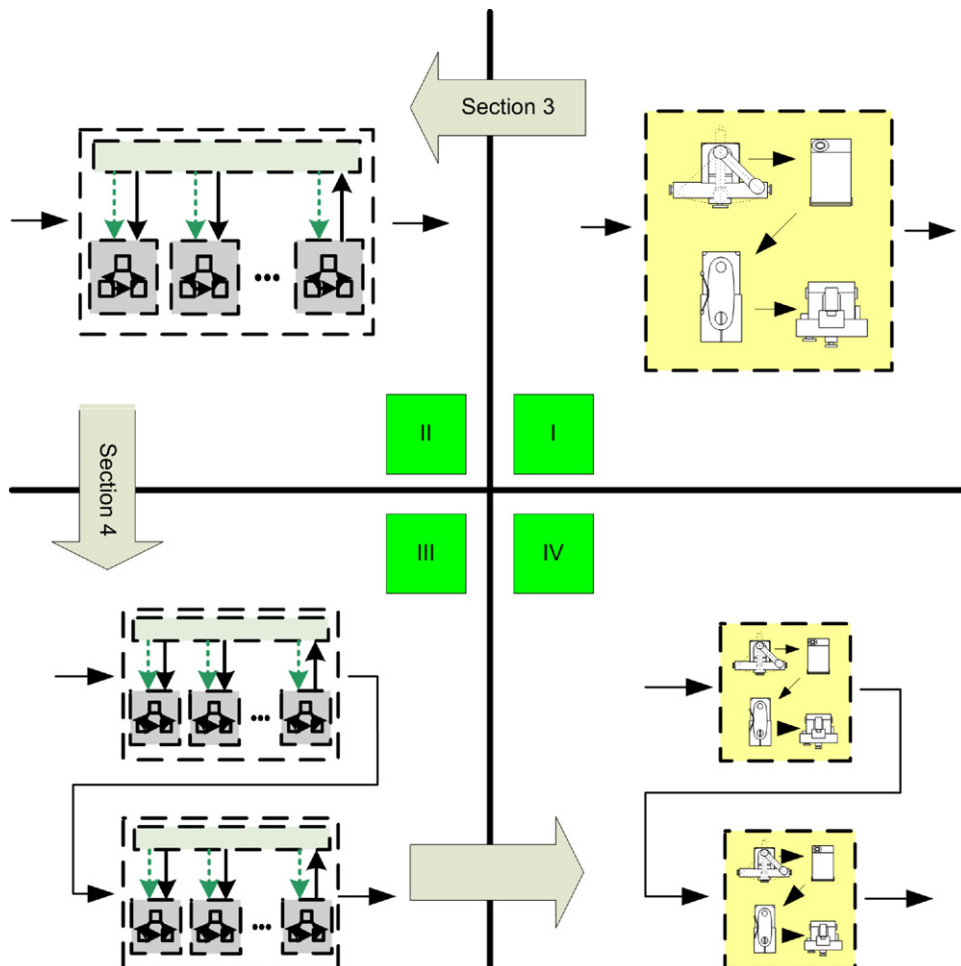


Fig. 1. Analogy between control tasks in an electricity infrastructure (II and III, on the left) and a production process (I and IV, on the right) and link between systems (I and II, on top) and networks of systems (III and IV, at the bottom).

domain. Moving from II to III adds a new level of complexity, for which we can find an analogy again in IV.

The rest of this paper is structured following this line of thinking. Section 2 contains an introduction to agent-based control in process systems engineering and a summary of the DACS approach. In Section 3, this approach is applied to a different domain, namely the distributed generation of electricity by  $\mu$ CHP technology. Section 4 shows how the approach is still valid when applied after a new level of complexity is added. Section 5 deals with implementation and performance issues. Finally, Section 6 discusses how engineers working on manufacturing control and infrastructure control can learn from each other.

## 2. Agent-based control and the DACS methodology

There are many similarities between manufacturing control and the control of infrastructures. Production control is the process of choosing, initiating and monitoring actions in production systems to optimise the system performance (Dean & Wellman, 1991). The same can be said about the control of electricity infrastructures. Networked industrial systems can be compared with infrastructural systems, seen as complex networked systems operated by a multitude of actors in a setting of decentralised decision making (Lukszo, Weijnen, Negenborn, & De Schutter, 2006). For both manufacturing and electricity domains the classical control approach is hierarchical and schedule driven while the new approach is more goal-driven and distributed, promising to be more robust, flexible, and reconfigurable, resulting in agile performance.

### 2.1. Applicability and benefits of agent-based control

Parunak (1999) lists a number of system characteristics that have to be met before an agent-based approach can be considered: Systems have to be modular, decentralized, changeable, ill-structured and complex. The electricity infrastructure presented here has all these properties. Moreover, the decision makers in this system can be characterised by autonomy, social ability and pro-activeness. These system characteristics show a natural fit with the agent characteristics (Wooldridge, 2002). Also, these properties make agents suitable for a bottom-up approach in which a system is described by making models of small parts of the system.

The main advantage of building agent-based controllers in such a bottom-up approach is that it creates a very flexible system that can deal well with changes in the configuration. By describing components rather than the entire system, the structure of the control system is not pre-defined. Because agents can communicate with other agents without having to program the direct relations between them, different networks of agents can be formed. Reconfigurations in the system to be controlled become easier and the control system is more robust.

Mathematical models, combined with traditional optimization techniques, can be used to describe and control the same system for which an agent-based controller can be designed. Application of agents is not a matter of not being able to

use another approach. It should be stressed that the outcomes of existing optimisation-based technologies can be exactly the same as the outcome of an agent-based formalism. In fact, the agent-based approach can contain precisely the same optimization routine as the behaviour of one or more agents. Which formalism to use depends on the desired results of the application.

### 2.2. DACS methodology

The designing agent-based production control systems (DACS) methodology, developed by Bussmann et al. (2004) is a new methodology designed specifically for the control of manufacturing systems, but it can also be applied to other domains in which a physical process is controlled by discrete decisions. It was our hypothesis that it can also be applied to infrastructures. Can a methodology developed for the control of production systems can be used for control of an electricity infrastructure which is based on the large-scale incorporation of  $\mu$ CHP technology?

We consider the DACS approach to be especially interesting because Jennings and Wooldridge are renowned experts of agent-based modelling (see Wooldridge & Jennings, 1995). The use of MAS in process engineering is relatively new and it is different from traditional methodologies (Grossmann, 2004). There are other approaches for the use of MAS in process engineering (e.g., Siirola, Huan, & Westerberg (2003), Aldea et al. (2004) and a large overview of other applications in Shen, Hao, Yoon, & Norrie (2006)) but to our knowledge there is no other published step-by-step methodology specifically for the design of agent-based control systems.

Bussmann et al. demonstrate in their book (2004) that neither data-oriented (focus on input/output) nor structured (focus on functions) methodologies work well for the new coordinated control. Object-oriented methodologies are not applicable to the design of MAS either and cannot be used to model the new cooperative production control method because objects are passive and they lack support for structuring organisations. Existing manufacturing control design methodologies (based on discrete event systems or Petri-nets, for example) as well as traditional methodologies for agent design (e.g., CommonKADS Brazier, Dunin-Keplicz, Jennings, & Treur, 1996) also are not sufficient, mostly because they lack focus. DACS is a promising new approach because it incorporates the appropriate and descriptive requirements for the production control domain and it allows for re-use of interaction protocols.

The input for the DACS approach is a specification of the production control problem (Section 2.3). The major steps are analysis of control decisions (Section 2.4), followed by identification of agents (Section 2.5) and finally the selection of the interaction protocols (Section 2.6). The output after following these steps is an agent-based design of a controller that can then be implemented and executed (Section 2.7). The DACS methodology and the work by Bussmann et al. (2004) is summarised below.

### 2.3. Specification of the production control problem

The input to the DACS design methodology, or any suitable methodology for that matter, is a specification of the production

control problem under investigation. The specification of the control problem consists of three parts:

1. A description of the physical production process to be controlled and the available interfaces with mechanical components.
2. A specification of the operation conditions (input, output, possible changes and disturbances).
3. A set of goals and requirements for the production system, such as high productivity or high throughput.

The *specification of the physical production process* lists the mechanical components in the system and their specifications and behaviour. For a description of the behaviour of a component any suitable modelling approach can be used. A schematic overview of the layout of the system and a detailed description of the full process are essential parts of this specification.

The *operating conditions* are defined as a list of allowed inputs and a specification of the outputs. Changes (things that can be modified by for example the owner of a process) and disturbances (variations of the normal conditioning of the system that are unintended) that may effect the process are often hard to identify, but the specification should contain at least those that the controller is expected to deal with automatically.

Finally, the set of *goals and requirements* determine how the process is optimised, to what performance criteria and within which constraints. Together, the specification of the production control problem provides a document of the problem to which a solution is developed in the next steps. This solution is a control system that is able to control components of the production process given a set of specifications and optimised for a given goal.

#### 2.4. Analysis of control

In this step the control problem is analysed and decomposed into a decision model. This is done in two phases:

1. Identification of decisions;
2. Identification of decision dependencies.

First, *decision tasks* that can be taken to run the process under certain constraints and that have an effect on the physical aspects of the system are identified. The tasks are described without specifying how a decision is made and what the result is, it is simply a list of individual (physical) actions that can be taken and in which a controller has to choose between alternative actions. For each of these decision tasks the *triggers* (i.e., when a decision is needed), *decision space* (a set of possible actions) and *local decision rules* (rules used to choose from the possible actions which one has the best effect) are described. Also the parameters and control interface should be part of the description of every task. The analysis of control can be documented in a table that included all attributes and a short description of their

value. [Bussmann et al. \(2004\)](#) give extensive examples of these tables.

Next the *dependencies between the tasks* are identified. Decision tasks are classified as being dependent on one another when one task sets constraints for other tasks or when their effects are linked. It is not enough to look only at the individual tasks but the relationship with the other tasks has to be taken into account to reach an optimal solution at the system level. When one task has an affect on another task, it is important to analyse these effects and possibly include them in the controller.

#### 2.5. Identification of agents

The control tasks are executed by agents, but often it is beneficial to give multiple tasks to one agent instead of designing a separate control agent for each control task. When dependencies between tasks are ignored this might result in sub-optimal performance. There are three *clustering rules* that can be applied. Multiple decision tasks can be executed by the same agent if tasks can be clustered based on *interface cohesion* (i.e., if the task has an effect on the same physical device through a control interface), *state cohesion* (i.e., if the task has an effect on the state of a device) or *interactive coupling* (i.e., if the task can only be solved after having also solved another task). When it is difficult to distribute tasks among agents, an attempt can be made to *split* up the task in smaller subtasks, thus creating new decision tasks. The clustering and redefining of the decision tasks is an iterative process. The result of this step is a list of all control agents and their responsibilities.

#### 2.6. Interaction protocols

Agents that are made responsible for tasks that are dependent will have to communicate with one another. For this interaction a library of protocols is available. DACS provides a set of standard interaction protocols (that can also be customised), but an alternative to what is described in the DACS methodology is to use a communication language based on an ontology. An ontology is a formalised specification of concepts ([Gruber, 1993](#)) used by the agents to communicate at a semantic level. [van Dam, Nikolic, Lukszo, and Dijkema \(2006c\)](#) and [Nikolic, Beers, and Dijkema \(2007\)](#) describe a process decomposition method that results in such a formal domain description. The use of a shared ontology makes it possible to extend the system and re-use agents in other models ([van Dam & Lukszo, 2006](#)).

#### 2.7. Output

The output of the DACS methodology is a conceptual design of an agent-based controller for the system that was analysed. After looking at the decision tasks, selecting agents and choosing a way for the agents to communicate, the controller can be implemented in an agent platform. The design is modular, which means that the agents can now be implemented individually.

In the next two sections, these steps will be repeated for two case studies.

### 3. Conceptual model of agent-based control of a cluster of $\mu$ CHP

In this section, the DACS methodology is used to design an agent-based controller for a distributed electricity generation system based on  $\mu$ CHP technology. Houwing, Heijnen, and Bouwmans (2006) and Houwing and Bouwmans (2006) explain the main principles of residential  $\mu$ CHP systems based on Stirling technology. In Houwing et al. (2006) a conceptual framework to study the impact of residential power generation, storage and exchange is presented. The impacts for households themselves, as well as for electricity suppliers and network managers are discussed. In Houwing and Bouwmans (2006) simulation results are presented showing aggregated energy flows and associated costs and CO<sub>2</sub> emissions levels for clusters of households using fuel cell and Stirling  $\mu$ CHP units to fulfil their energy needs.

Here, we focus on groups of households interacting with their energy supplier in electricity sales. We view this system in a novel way, namely as a *production process*. We extend the energy hub concept of Geidl and Andersson (2005) and define a household as being part of a network of hubs contractually connected to their supplier. Multiple households and their energy supply company are considered and the total system is regarded as one production process, more precisely as a *virtual power plant*. The situation which is sketched here can be regarded as a realistic scenario for the future of electricity generation. We will first briefly introduce  $\mu$ CHP operation, the configuration of the Dutch electricity sector, and different trading arrangements of residentially generated power. Then the different steps of the DACS methodology are applied to the production control problem under study.

#### 3.1. $\mu$ CHP and intelligent metering

Fig. 2 shows how the  $\mu$ CHP unit supplies heat to a central hot water storage from which hot water for space heating as

well as sanitation is obtained. The Stirling engine of the  $\mu$ CHP unit produces heat and electricity at a fixed ratio and at a fixed power level. An auxiliary burner, also inside the  $\mu$ CHP unit, can deliver extra thermal power at a variable power level. The produced electricity can be used in the household. Power which is generated in excess of residential load could be sold to an external party. When the self-generated power is insufficient to meet all demands, additional power can be bought from the external grid via the electricity supplier.

Together with the application of  $\mu$ CHP technology, intelligent metering is expected to pervade the sector on a large-scale in the future. Intelligent meters could communicate price levels and energy consumption data between households and suppliers, even real-time if needed. Currently 13% of all 230 million meters installed within the European Union support Automated Meter Reading (AMR) (Energy Magazine, 2006). More intelligent meters are now being installed, for example in the Netherlands where all 2.7 million customers of the Dutch network operator *Continuon* will have an intelligent meter by 2011 (Energie Nederland, 2006) and in France where all 30 million meters will support AMR by 2020 (Fens, 2005). Next generation intelligent meters could even incorporate computational capabilities (e.g., possibilities for optimisation of the  $\mu$ CHP unit and other devices in the household).

#### 3.2. Introduction to the Dutch electricity sector

In the Dutch electricity infrastructure the network management activities are separated from the commercial activities of power generation, trade and supply. Suppliers in the Dutch system have so called *program responsibility*. This means that programs handed in to the system operator, the day before, should be met as good as possible in the moment of realisation. The program contains the planned transactions that are expected to take place the next day, detailed for slots of 15 min each. Via the imbalance market having imbalance between prediction and realization is disincentivised for suppliers because this leads to

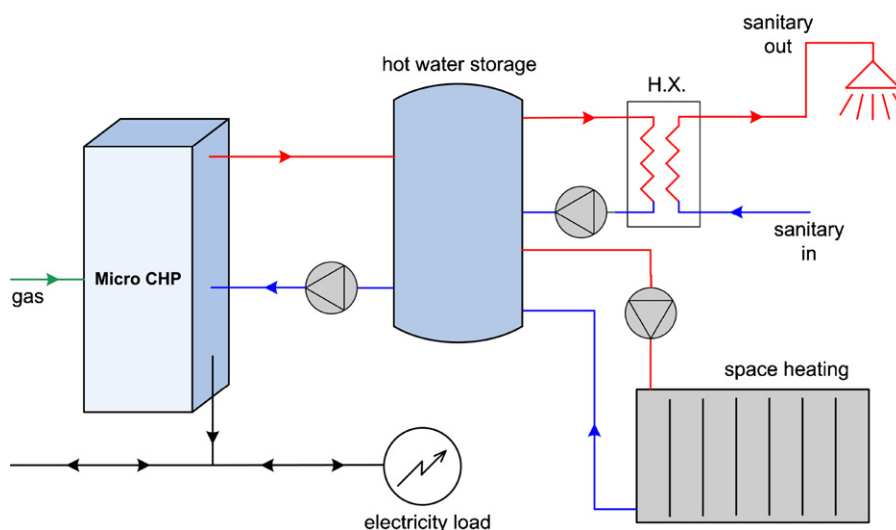


Fig. 2. Configuration of a residential  $\mu$ CHP system and its balance of plant equipment. Note the two-way exchange of electricity with the external grid. HX = heat exchanger. (Houwing & Bouwmans, 2006).

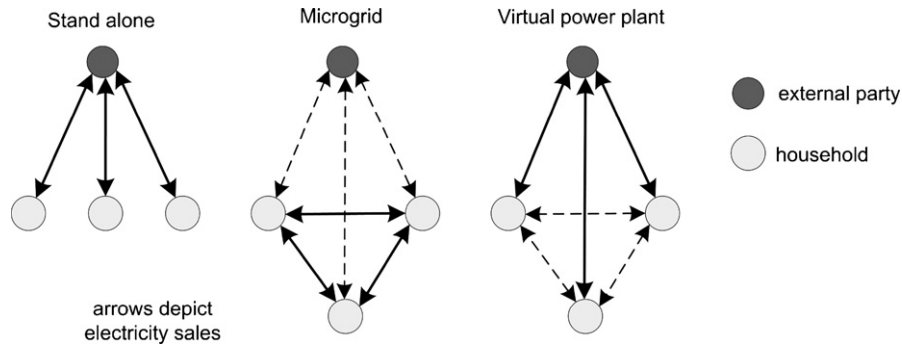


Fig. 3. Different trading arrangements between a supplier and a number of households. Dotted lines represent contractual sales which are possible, but less significant in that specific arrangement (Houwing & Bouwmans, 2006).

imbalance costs. Imbalance can be either positive or negative, but both have to be avoided as, in general, there are penalties attached to buying or selling electricity on the imbalance market.

### 3.3. Trading arrangements

Households are physically connected to their network manager and contractually interact with their supplier. With residential power generation and intelligent metering possibilities, parties in the electricity infrastructure obtain an additional option to organise their power generation and supply activities. Household generators could be controlled by an external party and residential load patterns could be influenced.

In this paper, we focus on the household-supplier interaction. Fig. 3 shows different trading arrangements between households and their supplier (or other external party). Residential power generators could be operated *stand alone*. Another option, called *microgrid*, is that households fulfil their energy demands solely by physical and contractual interactions amongst each other.

A third option is that an external party coordinates the electricity flows of residential generators. This is called the *virtual power plant* concept. A supplier can then trade residentially generated power to optimise overall economic performance. Within the virtual power plant concept two additional possibilities can be discerned; electricity trade between the households could be

possible or not. In this paper, we focus on the virtual power plant trading arrangement in which households cannot trade electricity amongst themselves. The next section specifies the production control problem further.

### 3.4. Specification of the production control problem

In Fig. 4 a conceptual model of the virtual power plant system under study is presented. A group of households and their supplier interact. The physical interactions within household 1 are shown in detail. Conversion 1 represents the Stirling engine and conversion 2 the auxiliary burner. Each household in the system has the same technology, but storage capacities and demand profiles differ between the households. The symbols of all the energy flows depicted in household 1 of Fig. 4 and their accompanying prices are shown in Table 1. The process is as follows:

The supplier sells gas for fuelling the  $\mu$ CHP ( $f$ ) and additional electricity for households ( $i$ ). Furthermore, the supplier buys any electricity that is produced by the household but not consumed by them ( $e$ ). For the full control problem, the objective function and the system constraints we refer to Houwing and Negenborn (2007). Here, we just state that the decision variables for the household, given external prices, to maximise profits are  $f$ ,  $s_o$  or  $s_i$  (electricity is either imported or exported). The control problem translates to setting the power levels of the conversion technologies in the  $\mu$ CHP unit and deciding how much electric-

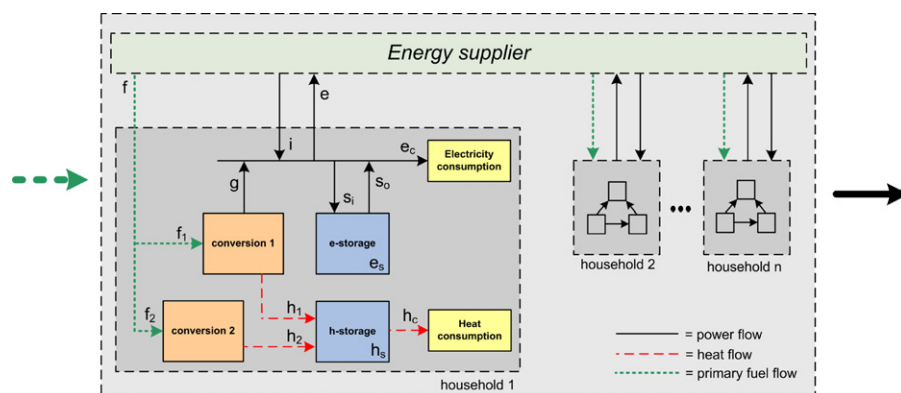


Fig. 4. Conceptual model of the relationship between an energy supplier and a number of households. Detailed version of quadrant II from Fig. 1. Based on Houwing and Negenborn (2007).

Table 1  
System variables for energy flows and prices to, from and within households

$g, p_g$	Generation electricity from own $\mu$ CHP generator (kWh), (€/kWh)
$f, p_f$	Total primary fuel for total $\mu$ CHP system (kWh), (€/kWh)
$f_1, p_{f1}$	Primary fuel for Stirling engine in $\mu$ CHP (kWh), (€/kWh)
$f_2, p_{f2}$	Primary fuel for auxiliary burner in $\mu$ CHP unit (kWh), (€/kWh)
$s_o$	Storage outflow of electricity (kWh)
$s_i$	Storage inflow of electricity (kWh)
$e, p_e$	Export electricity flow to environment (distribution network/energy supplier) (kWh), (€/kWh)
$i, p_i$	Import electricity flow from environment (distribution network/energy supplier) (kWh), (€/kWh)
$e_c$	Consumed electricity (kWh)
$e_s$	Electricity in storage (kWh)
$h_c$	Consumed heat (kWh)
$h_1$	Heat delivered by Stirling engine (kWh)
$h_2$	Heat delivered by auxiliary burner (kWh)
$h_3$	Conceptual heat flow between heat storage 1 and 2 (kWh)
$h_s$	Heat in storage (kWh)

ity to import or export. Important to note is that the supplier can influence household behaviour by adjusting the price level for the exported electricity (decision variable  $p_e$ ).

By setting the export tariff such that it becomes economically beneficial for households to generate more electricity than needed by themselves, the supplier can obtain power from its customer households. The supplier now has the extra option to purchase electricity from its households to minimise positive imbalance (when actual use of electricity is higher than predicted the day before) as an alternative to buying additional electricity on the imbalance market. Negative imbalance can be solved via households by adjusting the export tariff, provided that this is allowed in the contractual arrangement. Another option to minimise imbalance costs is to trade directly with other clusters, which will be discussed in Section 4. Important to note here is that the supplier has to have some sort of forecast model to set the value of its decision variable  $p_e$ . This model should predict the response of households on a price setting with a certain degree of accuracy.

The most important assumptions regarding the electricity market that play a role in the electricity production system are listed below:

- There are no technical constraints in physical network;
- There is a hybrid electricity infrastructure (central as well as distributed generation co-exist);
- Intelligent metering is present at the household level. These meters have computational capabilities;
- Import price of electricity and primary fuel are fixed;
- Energy supplier has authority to adjust electricity export tariff for households.

Assumptions regarding the  $\mu$ CHP unit and technical household equipment:

- The Stirling engine in  $\mu$ CHP unit only operates on full load or is turned off;

- Part-load operation of auxiliary burner is possible (until 30% of the maximum capacity);
- Households have technology present for hot water storage and for electricity storage;
- Effects of heat loss from hot water storage can be neglected;
- Heat dump is impossible;
- Load shifts are not possible (i.e., values for  $e_c$  and  $h_c$  are fixed).

The *physical production* process is the process of generating heat and power from a primary fuel (e.g., natural gas) by the use of a  $\mu$ CHP system (Stirling engine and an auxiliary burner) with the least costs. Therefore, the decision variables  $f$ ,  $e$  or  $i$  are optimally set by the households. Heat can be stored in a hot water storage and electricity in some form of electricity storage (e.g., lithium-ion batteries). The temperature of the water in the heat storage should be kept between certain minimum and maximum levels. Future residential energy demand and external prices could be forecasted and via the storage capabilities anticipated values for control parameters can result in minimal operational costs for households. This so called Model Predictive Control is outside the scope of this paper, see for details Houwing and Negenborn (2007).

The physical component that has to be controlled in this system is the  $\mu$ CHP unit and the energy storages. Regarding the *operating conditions* it can be stated that the input to the total supplier-household production system is primary fuel and electricity. Output of the system is electricity. So, analogous to Bussmann et al. (2004) we define inputs (electricity and gas), outputs (electricity), changes (predicted electricity and heat demand patterns) and disturbances (e.g., abrupt price changes) of our production process. Besides physical processes there are also non-physical processes to be controlled in this system, as energy supply is mainly an administrative business.

The *goals and requirements* of the total system are to minimise total operational costs. These are mainly primary fuel and electricity costs/revenues. Households set their decision variables and the supplier sets the price level of the electricity exported by households. Suppliers should therefore make a relatively realistic prediction of the situation present in households when setting the price level of exported electricity. Suppliers benefit from the presence of intelligent metering which ensures a high degree of information availability regarding household energy use and technology settings and conditions.

### 3.5. Analysis of control

In Table 2 the operational decision tasks that can be distinguished in the production process are presented together with parameters influencing the decisions, control interfaces, decision space and local decision rules. The names of the decision makers are not added to Table 2 to stay close to the DACS methodology, even though tasks 1, 2 and 3 are made within the household domain while tasks 4 and 5 are in the domain of the energy supplier. Still, all decision-making tasks are viewed as part of the same system that is to be controlled and only in

Table 2  
Operational decision tasks

Task name	Parameters	Control interface	Decision space	Local decision
(1) Set $\mu$ CHP power level	See price and energy flow parameters in Table 1.	$\mu$ CHP unit	Power level max or off	Choose level to meet energy consumption for lowest price
(2) Set auxiliary burner power level	See price and energy flow parameters in Table 1.	$\mu$ CHP unit	Flame height between 30% and 100% of max.	Choose level to meet energy consumption for lowest price
(3) Set electricity flow to or from storage	See price and energy flow parameters in Table 1.	e-Storage	Min. and max. storage capacities	Choose values to meet energy consumption for lowest price
(4) Electricity export price setting	Predicted imbalance volume and prices, predicted energy flows to and from households	Intelligent meter	Regulated tariffs or higher (euro/kWh)	Profit optimisation
(5) Set electricity import from imbalance market	Predicted imbalance volume and prices, predicted energy flows to and from households	System operator	National reserve capacity (kWh)	Profit optimisation

the *identification of agents* step (Section 3.4) these tasks are to be assigned to specific agents.

All listed decision tasks are triggered every 15 min as this coincides with the trade periods in the Dutch electricity market. The energy flows in a household (gas, heat and electricity) are connected via mathematical energy balances. On top of that, tasks 1 and 2 have the same interface. Therefore, decision tasks 1, 2 and 3 are fully dependent.

In the case of a positive imbalance for the supplier, a choice has to be made to either obtain electricity from the households or from the imbalance market. A prediction of the imbalance market prices, while difficult, is needed for this. Tasks 4 and 5 are dependent because they share the same parameters.

### 3.6. Identification of agents

For each cluster of highly coupled decision tasks an agent is created that is responsible for executing these decision tasks. Following the clustering guidelines and the dependencies addressed above, we arrive at a MAS with one agent responsible for decision tasks 1, 2 and 3 (household agent) and one agent responsible for tasks 4 and 5 (supplier agent). It is important to keep in mind that there is a large number of households in the system so there are multiple agents of the first type, each with their own goals and values for decision variables (different comfort levels), but based on the same decision tasks.

### 3.7. Interaction protocols

Agents that have dependent control decision tasks have to communicate to exchange information about these tasks. In this case, the household agent and the supplier agent have to communicate about prices and flows. The control agents also have to communicate with the interfaces of the processes they control. An ontology has been developed to create a communication language for these agents (van Dam & Lukszo, 2006).

### 3.8. Output: conceptual design

The result of following the design steps is a conceptual design of a control system for the production process consisting of a

supplier and a number of households. The model is implemented using the Repast agent modelling toolkit (North, Collier, & Vos, 2006). As already shown in van Dam et al. (2006b), the DACS methodology for manufacturing control can also be applied to infrastructure operations. The control problem described in this section is more realistic and up-to-date and the conclusion that the methodology is applicable still holds.

Next we will look at a different configuration in which an extra level is added, creating a more complex system.

## 4. Conceptual model of agent-based control of a network of production clusters

The previous section described the case study of a single cluster in which one supplier has a connection with a number of households, forming a single production system that can produce electricity from gas. Here, the connection between two of these clusters is discussed.

### 4.1. Cluster of clusters

When there is unused capacity in a cluster this capacity can potentially be utilised to produce electricity that can be sold outside the cluster. We talk about unused capacity when there are  $\mu$ CHP units not running at full capacity, for example when there is no local heat and electricity demand or when electricity import is cheaper than self-generation. The electricity produced by the households can then be sold to other parties via the supplier, see Fig. 4. A supplier who knows (with information communicated via the intelligent meters) there is unused capacity in its network can try to look for another party to buy electricity. Parts of these revenues are then used to pay its clients (i.e., the households) for using their  $\mu$ CHP electricity generation capacity.

In the Dutch electricity market it is possible to buy and sell electricity *bilaterally* within the day itself, a certain amount of time before actual realisation and delivery. This allows players to anticipate on possible imbalance volumes arising between the forecasted demand (the day before, when the majority of electricity is bought and when programs are set with the system operator) and the demand they later predict on a shorter notice (e.g., 1 h). One cluster can then buy electricity directly from a



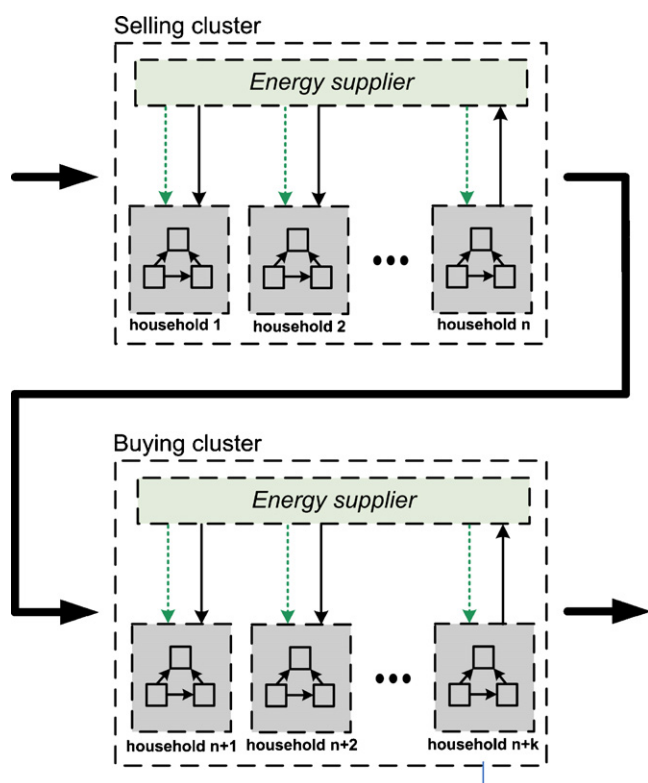


Fig. 5. A network of production clusters, where excess electricity produced by households in one cluster is sold bilaterally to another cluster. The electricity is transported to another cluster via the suppliers (contractually) and the distribution network (physically).

cluster that is willing to sell. The cluster buying electricity might contain fewer households with a  $\mu$ CHP unit or perhaps none at all. For example, while in one region a  $\mu$ CHP unit can be heavily subsidised, another region might not especially encourage this investment. These potential differences between regions make it more interesting to do research on the interactions between them.

#### 4.2. Specification of the production control problem

The physical process to be controlled is presented in Fig. 5. Both clusters work like the one shown in Fig. 4. The electricity is transported from one cluster to another via the national grid, controlled by transmission and distribution system operators. These actors are not part of the control problem presented here, however. The *physical components* of the system, their specifications and behaviours are the same as in Section 3.2. The

same applies to the inputs, outputs and possible changes and the other *operating conditions* and the *goal* is again the cost efficient generation of electricity.

When considering both clusters together as one production system, the input of the system is natural gas and electricity, while the output of the system can again be electricity even when most of the electricity generated is consumed by the households themselves.

#### 4.3. Analysis of control

Table 3 shows the control tasks that have to be executed in this production process. Tasks 1–5 remain the same as in Table 2 and we refer to Section 3 for their description. Compared to Table 2, tasks 6 and 7 are added that deal with contracts between a buying and selling supplier. These are non-physical processes to be controlled, but cannot be omitted. As concluded in van Dam et al. (2006b), also decisions that do not have a direct effect on the physical state of the system (e.g., decisions about contracts) have to be included in the production process.

#### 4.4. Identification of agents

Equivalent to case of the network of one supplier with its households, one agent is needed to control the operations in each household. Tasks 4 and 5 are dependent on each other and can therefore be performed by the same agent. Furthermore, an agent is required for offering and comparing contracts (Tasks 6 and 7). Information asymmetry plays a big role in this setup. One actor may know things the other actor does not know, so their decisions cannot be taken by the same agent. Clusters have to be able to perform both buying and selling tasks, because their role can change depending on their current situation. A cluster that sells electricity at one point of time might need to buy extra electricity at a later point. The identification of agents phase results in a setup of the control system again consisting of two classes of agents: household agents (multiple instances of the same class of agent) and supplier agents (one instance for each cluster).

#### 4.5. Interaction protocols

For the interaction protocols in this system an extension to the ontology mentioned in Section 3.5 is needed that deals with the non-physical interactions between two suppliers. This extended ontology includes the concept of a contract between two actors for the physical flow between two nodes.

Table 3  
Additional operational decision tasks

Task name	Parameters	Control interface	Decision space	Local decision
(6) Find offer from other cluster	Predicted imbalance volume and prices, predicted energy flows to and from households	Supplier	Yes or no	Profit optimisation
(7) Make offer to other clusters	Predicted imbalance volume and prices, predicted energy flows to and from households	Supplier	Electricity price (euro/kWh)	Profit optimisation

#### 4.6. Output: conceptual design

The conceptual design resulting from following these steps has not yet been implemented. However, the bottom-up approach in MAS makes it possible to reuse the agents for the household control in an extended system where clusters trade electricity with one another. The supplier agents have to be adjusted to deal with the extra decision tasks, but the control decisions for the households themselves have not changed.

After we showed that DACS can be applied to the control of one cluster, we now showed that this still holds when the sales of electricity between clusters is taken into account.

### 5. Implementation and performance

The output of the DACS methodology is a conceptual design for an agent-based control system. While the focus of this paper is on the development process and the fact that a methodology from the process industry is applicable on infrastructure operations, this section deals with implementation and performance of agent-based controllers of which the conceptual design has been presented in Sections 3 and 4. First the implementation of agent-based controllers is discussed (Section 5.1), with a focus on the use of ontologies, before addressing performance issues (Section 5.2) related to the application of the agent-based controller.

#### 5.1. Implementation

As mentioned above, the Java-based Repast agent modelling toolkit (North et al., 2006) is used to build the agent controllers. The ontology, used as formal description of the domain concepts and as the communication language between the agents, is built in the Protégé knowledge acquisition tool (Gennari et al., 2003). Fig. 6 shows a small fragment of this ontology, dedicated to describing the physical part of the network. The figure does not contain all properties, as some have been left out to improve readability. *Physical node* is the main class representing element of the technical system and *physical connections* are the links that connect two physical system. Physical connections enable *physical flows*, which are actual transfers of mass or energy. The way a physical system works is described with *operational configurations*, a formal way to specify input and output *component tuples*. *Agents* are the owners and/or controllers of the technologies.

Next, the knowledge base is filled by creating instances of the ontology classes; specific descriptions of the objects (such as actors and technologies) with their properties that play a role in the system. A *knowledge base reader*, designed in a generic way to deal with any domain formalised in an ontology in Protégé, reads all instances from the ontology and creates the right Java objects that work with the Repast toolkit. This way the computer model is instantiated directly from the ontology. This process is described in more detail in van Dam and Lukszo (2006).

The behaviour of the agents, namely to control the operation of the technology as presented in the conceptual designs in Sections 3 and 4, can then be implemented. For this mathematical optimization techniques are used, wrapped

in the agent-paradigm. This makes it possible to use the advantages of strong and proven optimization algorithms together with the flexibility and modularity of the agent-based approach.

#### 5.2. Performance

Mostly, large-scale complex systems provide a difficult control challenges because of spatial distribution, nonlinearity and containing discrete and continuous elements. As already mentioned, multi-agent system models have many properties that make them attractive for the supervision of large, complex systems (i.e., systems characterised by modularity, scalability, and self-regulation). It should be mentioned, that the multi-agent system has been designed for the supervisory control, taking into account the time scale of the physical system. For regulatory control, which should take place on a very short-time basis traditional controllers can be used.

However, the stability of the multi-agent system cannot be guaranteed. Multi-agent systems represent a different way to develop control systems for large complex and especially distributed systems, complementary to the hybrid control approach by El-Farra and Christofides (2003) and El-Farra, Gani, and Christofides (2003, 2005), for example. By not addressing stability in a traditional way, the multi-agent approach helps to reduce the emergence of dysfunctional behaviour by stimulating the desired behaviour while punishing the undesirable by performing different simulation experiments and making adjustments to the cooperation protocols and the model if needed (Lukszo et al., 2006).

Moreover, it should be added that the framework and the ontology described here have also successfully been applied to other case studies, for example to model CO<sub>2</sub> emission trading and the impact that has on the portfolio development of electricity producers (Chappin & Dijkema, 2007; Chappin, van Dam, Dijkema, & Lukszo, 2007) as well as in a study to analyse industrial clusters and their growth and development (Nikolic, Dijkema, & van Dam, in press). These applications show that the agent-based framework is suitable to describe the problem in a flexible, modular and transparent way, addressing both social and technical aspects that would be more difficult to describe with traditional mathematical models.

New applications may mean that an extension of the agent-based framework is needed (e.g., extra components in the ontology, updated functionality of the generic source code). The development of the framework is an iterative process. It is always done in a generic way so the results are also useful again in other case studies (van Dam & Lukszo, 2006).

### 6. Final remarks

The network formed by households generating electricity with  $\mu$ CHP units and the facilitating energy supplier can be regarded as an electricity production system. When households act as a *virtual power plant*, the system can be an efficient alternative for central generation. Application of the DACS methodology to this system resulted in a conceptual design of

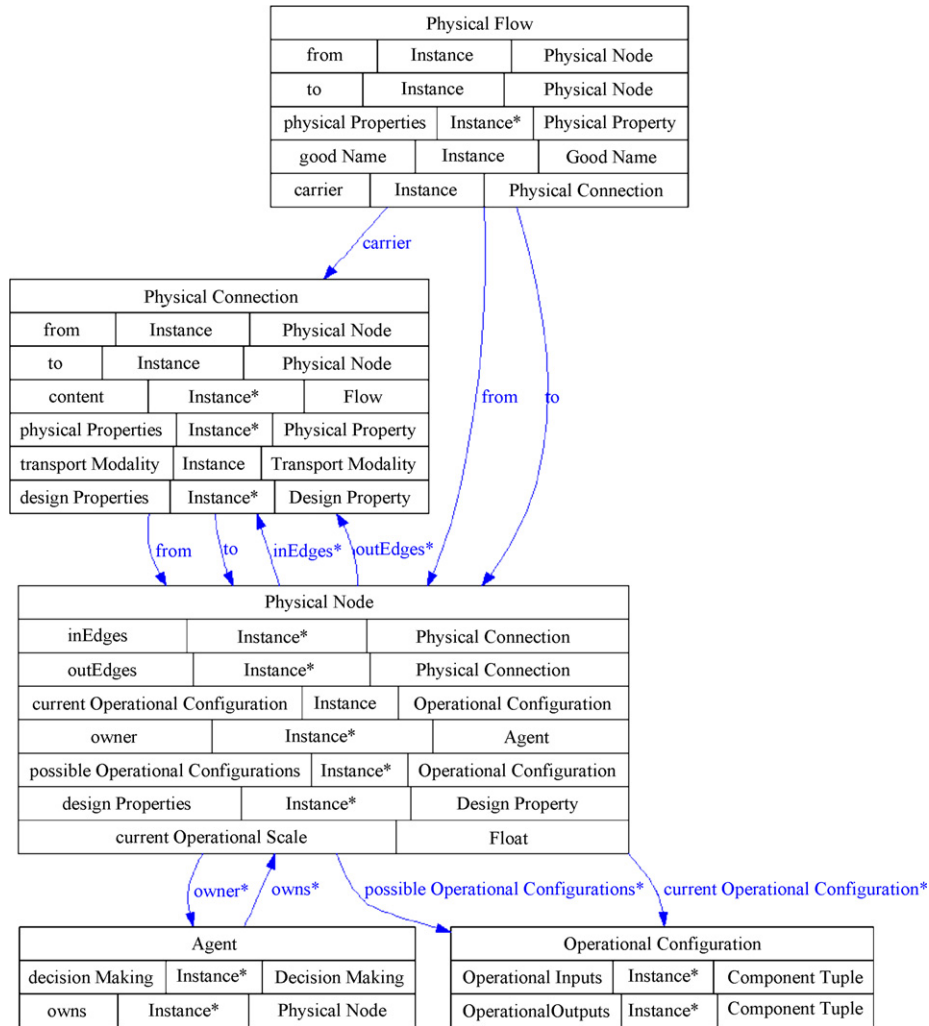


Fig. 6. Fragment of the generic ontology for socio-technical networked systems. The part shown describes the physical nodes and physical links of the system. Physical nodes are owned by agents who make decisions to control the physical system.

an agent-based controller for an electricity infrastructure incorporating a large share of  $\mu$ CHP units.

The aim of the designed agent-based controller is to support operational decision-making regarding cost minimisation and profit optimisation. The design of the control system is being implemented so that experiments with different control strategies, in particular within households, can be carried out. An agent-based model is an excellent way to experiment with different control strategies, because it is developed in a bottom-up way. The structure and the interactions between the components in the controller design are not rigid. This means, for example, that the household controller described in Section 3 can be reused for the system introduced in Section 4. Such a controller can even continue doing its job when direct links between households are introduced, as long as new control tasks and dependencies between them are also taken into account.

It was shown that a design methodology for manufacturing control can be applied to a socio-technical infrastructure if the control of non-physical processes is included. This is a new application that goes beyond the type of systems intended by

the developers of DACS. Furthermore, when the system boundary is extended by allowing the trade of electricity between networks of households and their supplier, the DACS methodology can be used to make a conceptual design of the control agents.

At the start of the paper, the electricity infrastructure with  $\mu$ CHP units was compared with a production process. The fact that a methodology from the manufacturing control domain could be applied strengthens this comparison. Our new hypothesis was that lessons learnt from the application to complex infrastructures can, in turn, be applied to manufacturing systems consisting of subsystems. In infrastructures research the physical aspects that need to be controlled are dealt with. Moreover, the non-physical links between actors are taken into account.

At the level of individual plants and at the level of industrial enterprises, chemical process systems can be represented as networked systems. Because of the analogy with infrastructures, process systems engineering (PSE) approaches for optimisation and control can be applied to infrastructure system operations.

Techniques developed in the PSE community, such as multi-level optimisation and multi-agent Model Predictive Control techniques, can be applied to infrastructure system operations. This poses a challenge, but the results are promising. In addition, communication and collaboration between actors in a complex socio-technical system of infrastructures may at first appear to be beyond the world of PSE, but this paper indicates there are parallels with production systems. We believe research on socio-technical systems will be a valuable contribution to PSE management strategies.

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