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Integrated optimization of energy supply systems in horticulture using genetic algorithms

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Abstract

Although simulation models are most suitable to examine real world systems, they would not be used enough for optimization programs. Genetic algorithms are now offering a good way to integrate simulation models in optimization tools. The search for optimized energy supply systems in horticulture serves as an example for this assumption: The design tools HORTSI and HORTOS were developed to support the efforts for a resource and environmentally friendly energy supply in horticulture. The simulation tool HORTSI integrates the simulation of selected energy supply systems whereby total costs, primary energy demands and carbon dioxide emissions are calculated. HORTSI covers the heat and power demand that is calculated by the tool HORTEX (T. Rath, 1992. Dissertation, Universität Hannover). The optimization tool HORTOS is based on HORTSI: the aim is to cover the heat, power and carbon dioxide demands with optimized supply systems. The designer can optimize the energy supply system for a given horticultural enterprise by hand or can automatically generate optimal solutions with the available optimization tool, where a genetic algorithm achieves and offers several optimal solutions. The tool optimizes the system as a whole, thereby taking into account interrelations between the supply components. All the tools are embedded in an integrated planning system called HORTEV, which runs under Windows 95 or Windows NT 4.0. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Agriculture; Computer-aided engineering; Energy control; Genetic algorithms; Optimization problems; Simulation

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1. Introduction

To optimize the primary energy input in horticulture, especially for protected cultivation, there are several starting-points (Fig. 1). Structural measures outside and inside the greenhouse and suitable climate controls can decrease the energy demands. An optimized energy supply system can influence the primary energy input, as well as utilizing the ratio of primary energy and the carbon dioxide emissions.

Computer-based plannning tools can be one part of a comprehensive concept for an optimized design of energy supply systems. Until now, the available tools are restricted to the design of single components. With HORTEX (Rath, 1992) the heat demand of greenhouses and the power demand of artificial lighting could be calculated. Additionally, the program selects the energy source for the enterprise and the heat transport system. To date, an integrated approach has been missing.

Tools simulation models are often successfully used to examine systems under designer analysis. By changing the input values, the designer can directly calculate selected simulation variants. In spite of this, the designer often works under pressure and so the number of calculated variants is limited. With the now introduced planning modules HORTSI and HORTOS, tools are constructed that allow the integrated design of the energy supply in horticulture. Components shall be considered as a complete set, not in isolation, thereby taking into account the interrelations between the different components. Particularly when cogeneration units or thermal heat storage systems are used, the design of these components depends on the design of other components.

The simulation tool HORTSI calculates the total costs involved, primary energy demands and carbon dioxide emissions of energy supply systems. Based on auto-

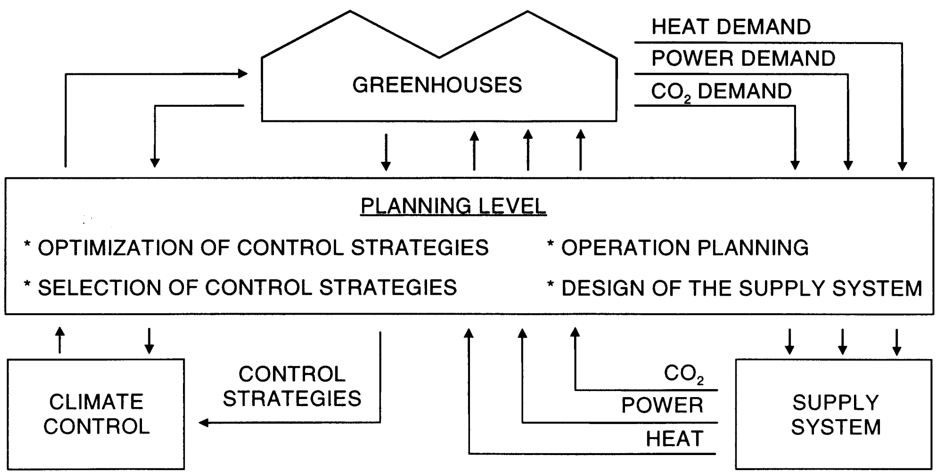

Fig. 1. Starting points for the optimization of the energy supply system in horticulture.

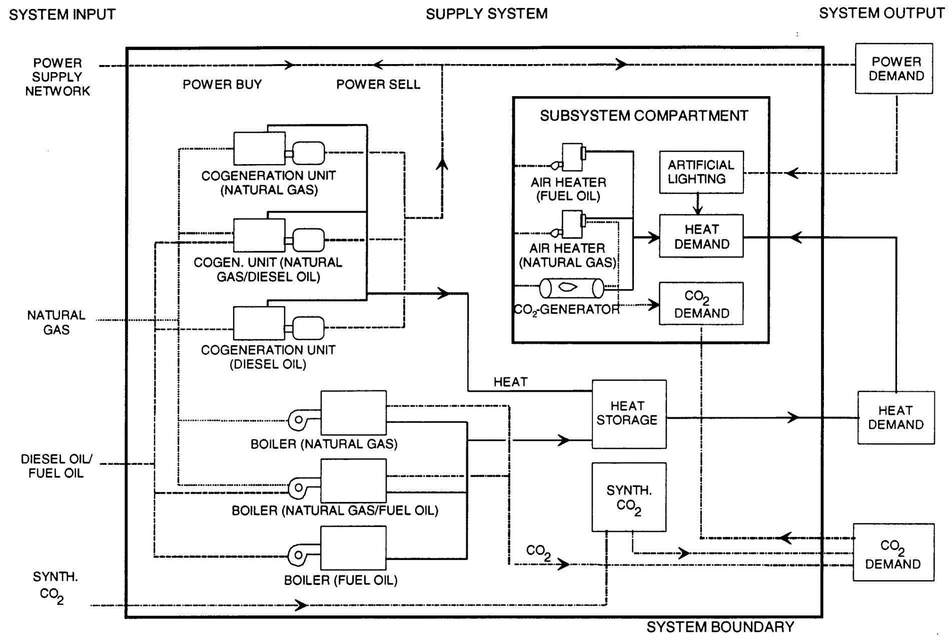

Fig. 2. Used model of an integrated supply system for heat, electrical power and CO_2 in horticulture.

matically triggered simulations, HORTOS optimizes the design of energy supply systems, using a genetic algorithm. The designer can optimize the energy supply system for a given horticultural enterprise by hand with HORTSI or automatically with HORTOS.

In this paper, the methodical approach to module development will be described. First, results will be presented and then, in the discussion, the possibilities of a simulation-based optimization approach will be considered.

2. Materials and methods

The heat and power demands of an entire horticultural enterprise must be provided by the energy supply system (Fig. 2). The supply components can be subdivided into centralized and decentralized components. Centralized supply components can be used to cover the demands of all greenhouses. Decentralized components can only cover the demands of the greenhouse in which they are installed. Boilers, cogeneration units and thermal heat storage systems make up the centralized components, and direct fire air heaters and carbon dioxide burners are considered to be the decentralized components. Carbon dioxide demands in a greenhouse are met by exhaust gas from the combustion of natural gas. Apart from this, the use of poor carbon dioxide for the carbon dioxide enrichment is considered as an additional supply component. The input values of the system are the flow of fuel oil, natural gas, electrical power energy and poor carbon dioxide. The amount of heat, power and carbon dioxide produced covers the total demand.

Greenhouse hourly heating demands and the hourly power demands needed for an artificial lighting system, can be simulated with the tool HORTEX (Rath, 1992). The carbon dioxide demand structure will be separately fixed. This demand structure serves as the base for the simulation with the tool HORTSI.

As the components and their operation strategies are well known, it is possible to simulate the operation of the supply system. Depending on the demand structure itself, single components can be switched on or off hourly, influencing the primary energy flow. Interactions between the components are calculated hourly. HORTSI calculates the total costs of the supply system (eq. 1) for 1 year, with a sampling time interval of 1 h:

$$C_{\text{energy supply system}} = \sum_{k=1}^{K} \left(\sum_{i=1}^{N_{\text{TE,NG}}} C_{k,j}^{\text{TE,NG}} + \sum_{j=1}^{N_{\text{TE,FU}}} C_{k,j}^{\text{TE,FU}} + \sum_{m=1}^{N_{\text{TE,BI}}} C_{k,m}^{\text{TE,BI}} + \sum_{n=1}^{N_{\text{E,NG}}} C_{k,n}^{\text{B,NG}} + \sum_{o=1}^{N_{\text{E,FU}}} C_{k,p}^{\text{B,FU}} + \sum_{p=1}^{N_{\text{E,BU}}} C_{k,p}^{\text{B,BI}} + C_k^{\text{HST}} + C_k^{\text{TC2}} + \sum_{q=1}^{N_{\text{Sec}}} C_{k,q}^{\text{AH,NG}} + \sum_{r=1}^{N_{\text{Sec}}} C_{k,r}^{\text{AH,FU}} + \sum_{s=1}^{N_{SEC}} C_{k,s}^{\text{C2G,NG}} \right) + C^{\text{P,BUY}} - V^{\text{P,SELL}} + C^{\text{FU}} + C^{\text{ECO2}} \quad (1)$$

$$\sum_{i=1}^{N_{\text{TE}}} P_{k,i}^{\text{TE}} + P_k^{\text{EVU,BUY}} - P_k^{\text{EVU,SELL}} = \text{PD}_k - \text{NCPD}_k \quad (2)$$

$$\sum_{j=1}^{N_{\text{E}}} H_{k,j}^{\text{B}} + \sum_{i=1}^{N_{\text{TE}}} H_{k,i}^{\text{TE}} + H_k^{\text{HST,OUT}} - H_k^{\text{HST,IN}} + \sum_{m=1}^{N_{\text{Sec}}} (H_{k,m}^{\text{AH}} + H_{k,m}^{\text{C2G}}) = \text{HD}_k - \text{NCHD}_k \quad (3)$$

$$\sum_{\text{n}=1}^{N_{\text{E,NG}}} \text{CO2}_{k,n}^{\text{B,NG}} + \sum_{m=1}^{N_{\text{Sec}}} (\text{CO2}_{k,m}^{\text{AH,NG}} + \text{CO2}_{k,m}^{\text{C2G}}) + \text{CO2}_k^{\text{T2C}} = \text{CD}_k - \text{NCCD}_k \quad (4)$$

$$\text{Target function} \quad \min\{\text{total } C_{\text{optimized supply system}}\} \quad (5)$$

$$C_{\text{optimized supply system}} = C_{\text{energy supply system}} + \text{PC}^{\text{NHCD}} + \text{PC}^{\text{NCPD}} + \text{PC}^{\text{NCCL}} \quad (6)$$

Several optimization methods can be used to automate the design process of energy supply systems. But until now, only a few approaches existed for optimizing the design of some energy supply system components (Braun, 1992; Kretschmer, 1995). When using optimization methods for optimizing complex systems, there are a few handicaps to be overcome. The main tasks are the formulation of the problem, the resolvability, and the computing time and the storage requirements. For many complex problems, the required computer time grows exponentially and simplified methods have to be found.

The Genetic Algorithms (GA), first devised by Holland (1975), are such a simplified and efficient optimization method. GA are stochastically navigated, using a single-minded search method that mimics the metaphor of natural biological evolution. Beginning with randomly determined start solutions, GA find increasingly better solutions. The system always converges more or less quickly to reach a local optimum. The disadvantage of this method is that the designer never knows exactly if the global optimum has been reached, or how large is the distance between the best found solution and the global optimum. The big advantage of GA is that it performs a global search that is parallel in nature. This reduces the risks associated with local optima. One further advantage is that the calculation of the objective function can be placed in a black box. A GA only has to know the combination of the input values and the resulting function value. With this knowledge, the algorithm is able to search for optimized input values. In such a black box, the objective function can be a function like $y = f(x)$ but also a simulation package.

The following describes the use of GA for the optimization of the energy supply in horticulture with the tool HORTOS. The general methodical approach will first be explained, and then selected parts of the method will be described in more detail. The target function is defined to minimize the total costs (eq. 5). To force the system to cover the demand, penalty costs are introduced (eq. 6).

At the beginning of an optimization run, the tool HORTOS randomly generates a set of potential energy supply systems (Fig. 3). These supply systems are more or less suitable to cover the energy demands of the viewed enterprise. This first set of solutions is called the initial population and represents the first generation of the optimization run. The variety in the initial population fundamentally determines the course for optimization.

When the actual population is complete, each supply system or individual of the actual population can be evaluated. In HORTOS, the evaluation is based on the simulation of the energy supply with HORTSI. The result of each simulation

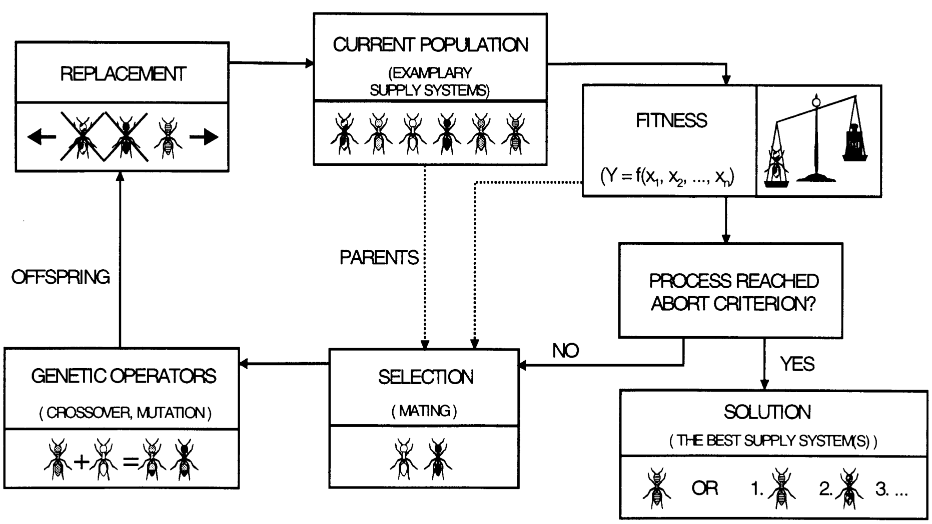

Fig. 3. Genetic algorithms as a tool to optimize the energy input in horticulture.

consists of several different values, e.g. like the total costs and the CO_2 emissions. These values are then compressed into one definite fitness value. This fitness value is used by the GA to compare and classify the supply systems.

If the optimization criteria are not met, the creation of a new generation starts. Two individuals or supply systems are selected for the production of offspring (Fig. 3). Random selection occurs, but individuals with a higher fitness will be selected with higher probability. The crossover operator mixes the characteristics of the individuals, in such a way that good parts from one parent can be combined with other good parts from the other parent, so the search can converge to improve supply systems. After recombination, the mutation operator changes the offspring with a certain probability. The mutation prevents the algorithm from prematurely converging to a local optima. Once the offspring has been produced, the fitness of the offspring may be determined and they have to be reinserted into the actual old population to build up a new population. This is done by a reinsertion scheme that determines which individuals are to exist in the new population and which individuals of the old population have to leave the population.

The cycle of searching for new supply systems is repeated until the optimization criteria are reached. This can be, for example, a set computing time or a set number of generations. At a later date, the designer can use the best individual or selects an individual from the group of best individuals. Specifically, when the optimization results from good individuals have very different characteristics from each other, the designer can take other preferences into account or take the whole amount of good solutions as an information base.

Because the GA use a binary code for the supply systems, these components have to be converted into a coded description. The characteristics of the components are described by genes. The combined genes of all used components represent a supply system, the individual. The number of genes has a substantial influence on the efficiency of the GA. In order to reduce the number of genes, the optimization system describes the components only with a few genes, although the complete component descriptions for the simulation are more complex (Fig. 4).

With the shaping of the genes and the assigned databases, which include further object characteristics, the system generates complete component descriptions (Fig. 5). The data expansion function uses standard database files, but certain components need more than one database file: These components can be described by data classes (Fig. 6).

To enable the GA to generate suitable supply systems, the designer declares an orientation frame (Fig. 7). Within the orientation frame, the designer releases the components for optimization, e.g. the designer fixes the maximum number of boilers and the possible minimum and maximum rating of the boilers. Furthermore, in the orientation frame, other existing components could be taken into account. In Fig. 6, the designer releases two boilers for an optimization. The first boiler is an existing one and is completely described over the file 'FIRST.-HK'. The second boiler is released for optimization. This component can be determined from the system until reaching a maximum thermal rating of 2000 kW. When the system sets the rating at 0 kW, the boiler will not be considered. In spite of the thermal rating, the boilers have genes to describe the used energy source.

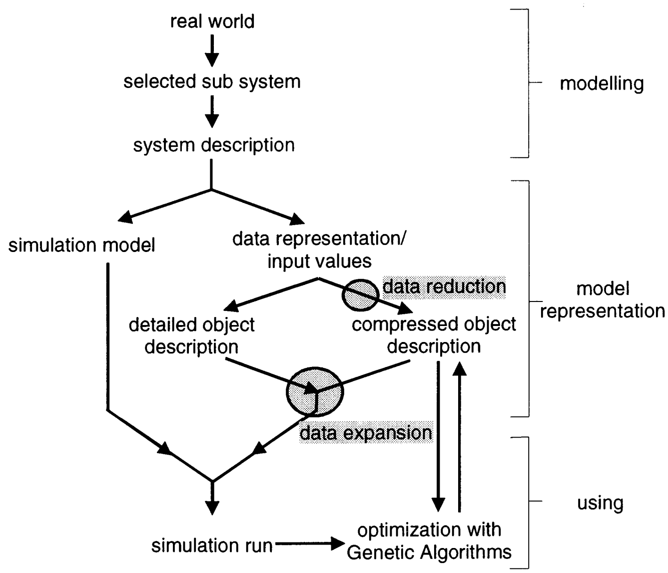

Fig. 4. Principle of data reduction and expansion.

3. Results

The following shall describe the optimization course for a selected greenhouse enterprise with given heat and power demands. The enterprise produces cut flowers in an area of 24 000 m^2. The whole production area will be illuminated. The lighting system reaches an operation time of up to nearly 5000 h per year.

The aim is to find an optimal energy supply system for this enterprise with the tool HORTOS. The orientation frame allows two boilers, a thermal heat storage system and three cogeneration units. The maximum permitted thermal rating for the boilers is set to 4400 kW, and the maximum power rating for each cogeneration unit is set to 1000 kW. The maximum permitted storage volume is 500 m^3. As energy sources, the system considers fuel oil and natural gas. The power demand can be covered by the cogeneration units or by the power supply network.

Fig. 8 shows the optimization course for the presented example. The fitness of the best and mean solution in every generation is plotted. The fitness values represent the total annual costs for the energy supply of this enterprise. The optimization runs over 60 generations, whereby every generation has 30 individuals. In the beginning, the randomly generated supply systems have very different fitness values, which is shown by the bad mean fitness. In the loop of the optimization run, the results converge to an optimal result. In this example, the GA already reaches a good solution after ten generations.

On closer examination of the curves for single components (Figs. 9–11), the search for optimal solutions can be closely investigated and the interplay of the different components can be seen. The course of the search for optimal boilers shows the changing role of the two released components. At the beginning, the first boiler is greater than the other. Later on, the second boiler is the bigger one. The optimization source of the thermal storage system is not so clear. Apparently, the selection pressure is not so high as for other components. This effect of selection pressure can also be seen at the optimization of the cogeneration units. The system finds good solutions quickly, but it seems to be very hard for the GA to reduce the power rating of the cogeneration units 2 and 3 to a value of 0 kW. As the use of such small cogeneration units is probably unfavourable, the optimization system must be supplied with some rules to filter the solutions.

The tools HORTEX, HORTOS and HORTSI are embedded inside an integrated planning system, called HORTEV. This program was developed for Windows 95 and Windows NT. The user describes the greenhouse system with a computer-aided design-like construction tool and, afterwards, can work with the different planning tools. In addition to the online help system, there is an information system with a fundamental knowledge base for the energy supply in horticulture.

SENSIBLE HEAT THERMAL ENERGY STORAGE SYSTEM	
SYSTEM PARAMETER (read only): ...	
OBJECT CHARACTERISTICS (variable):	
density of the storage medium	$[kg*dm^{-3}]$
specific heat capacity	$[Wh*kg^{-1}*K^{-1}]$
STORAGE VOLUME (GEN)	$[m^3]$
adjusted maximum storage temperature	[°C]
adjusted minimum discharge temperature	[°C]
air temperature	[°C]
loading period	[h]
power consumption	[%]
heat loss	$[\%*d^{-1}]$
alternative description of costs:	
a: assigned specific capital costs	$[DM*m^{-3}]$
assigned specific power costs	$[DM*m^{-3}*h]$
b: structure of specific capital costs [	$DM*m^{-3}]$
structure of specific power costs	$[DM*m^{-3}*h]$
RATING (simulated): ...	

Fig. 5. Component description example described for the thermal heat storage system.

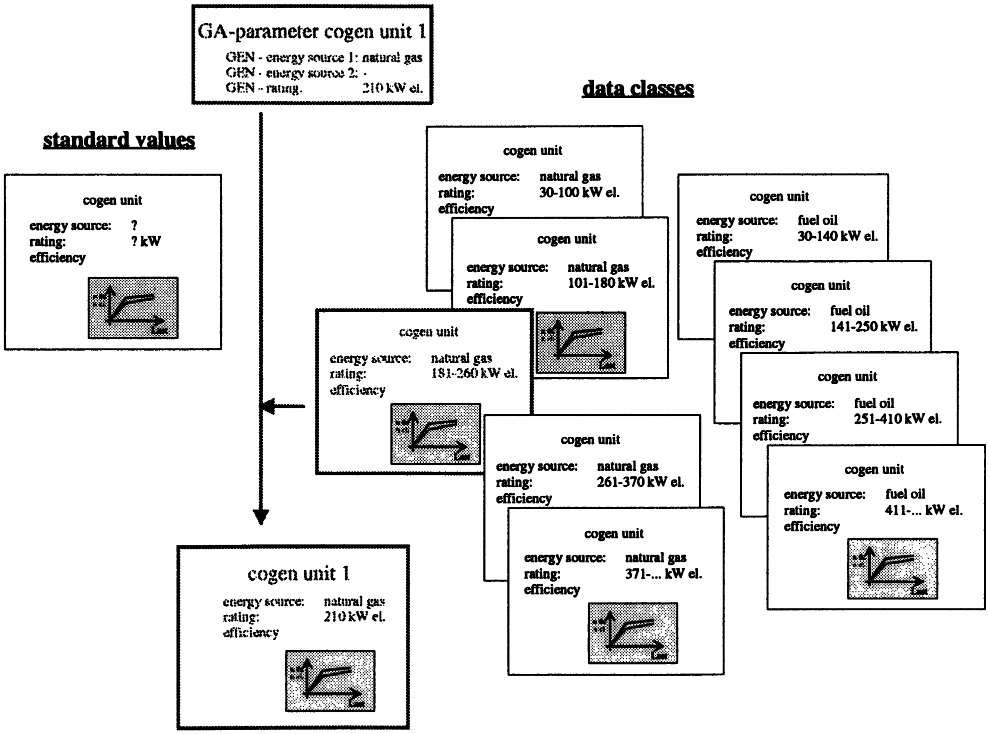

Fig. 6. Database for the data expansion function.

4. Conclusion

The aim of the development for the planning and optimization tool HORTOS is to optimize the energy supply in horticulture. By providing several good or almost optimal solutions as an information base, the designer is helped to realize a resource and environmentally friendly energy supply for horticulture. Based on the optimization results, the designer can estimate the ecological and the economical consequences of using different energy supply systems.

During the construction of HORTOS, it was confirmed that the combination of a simulation package like HORTSI and the optimization with GA is a powerful tool for investigating complex systems. The simulation supports the modelling of complex systems and the GA supports the search for optimal system conditions. One great advantage of such an optimization system is that, at the end, there is not only one solution, but several good solutions provided.

Although a designer never exactly knows the distance between the optimized results and the global optimum, the quality of the solutions can still be estimated. Contrary to that, a mathematically calculated global optimum can be the best solution but it is also uncertain if the exactness is only an ostensible or a real exactness. Because the models are often very simplified reproductions of reality, several good solutions can provide more information content than one optimum solution. Even when taking into account the disadvantages associated with the tool HORTOS, HORTOS can still be considered as one step forward in optimizing energy supply systems in horticulture.

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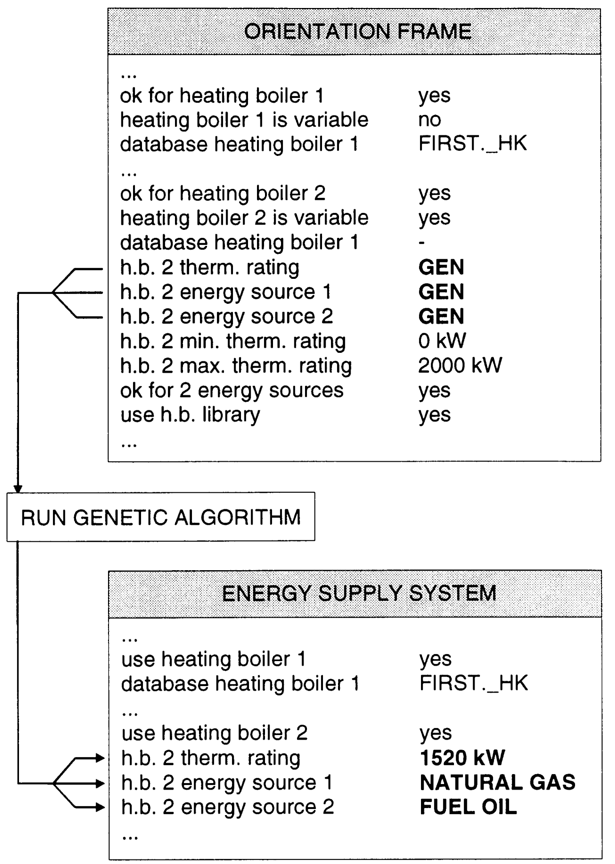

Fig. 7. Orientation-frame-based generating of new energy supply systems.

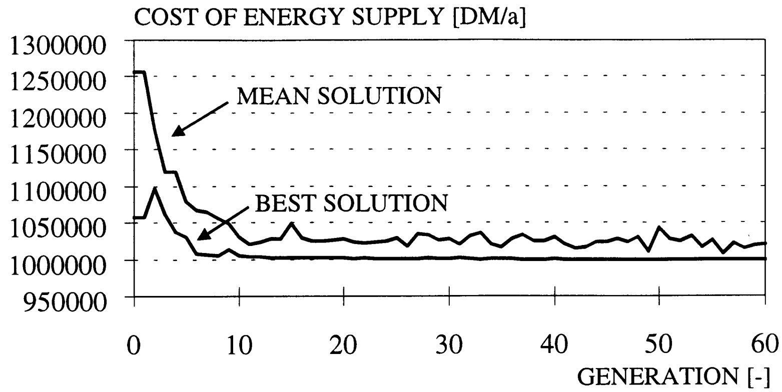

Fig. 8. Course of an example optimization run.

The authors wish to thank H.-D. Corsten and H.-J. Kruzek from the Ruhrgas AG, Essen, for their support and encouragement.

Appendix A. Nomenclature

AH	direct fired air heater
B	boiler
BI	bivalent use of natural gas and fuel oil (parallel or alternative)
BUY	power energy purchased
C	costs
C2G	CO_2 burner

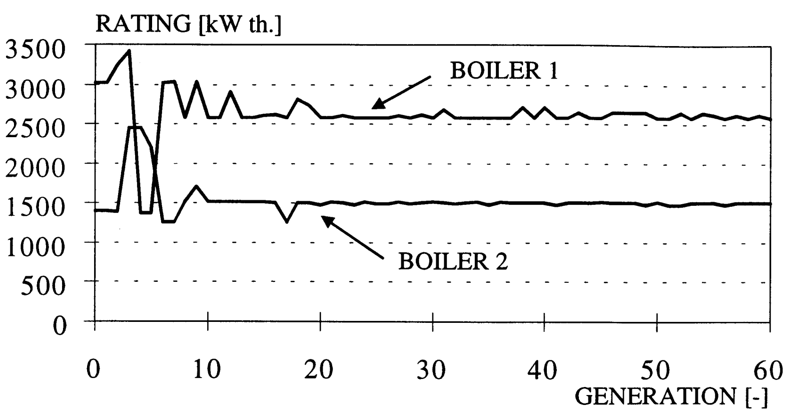

Fig. 9. Course of optimization for the boilers (best solutions).

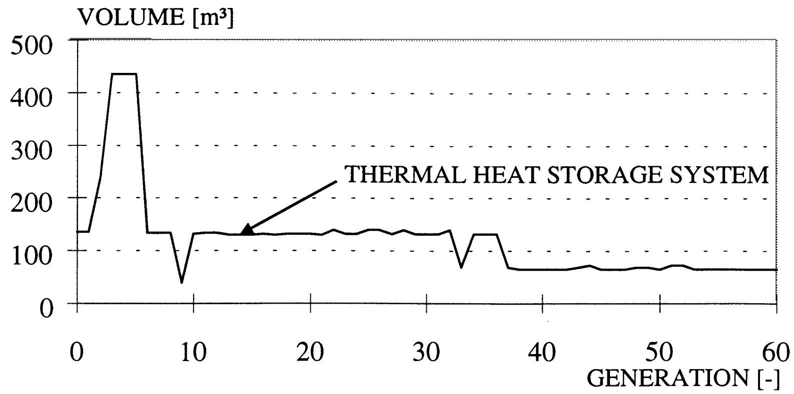

Fig. 10. Course of optimization for the heat storage (best solutions).

CD	CO_2 demand
CO2	CO_2 for CO_2 enrichment
ECO2	CO_2 emissions
EVU	electricity supply company
FU	fuel oil (monovalent)
H	heat flow
HD	heat demand
HST	heat storage system
IN	inlet of heat into thermal storage tank
K	total number of sampling time intervals
k	index for each sampling time
N	number of equipment installed, number of section
NCCD	non-covered CO demand

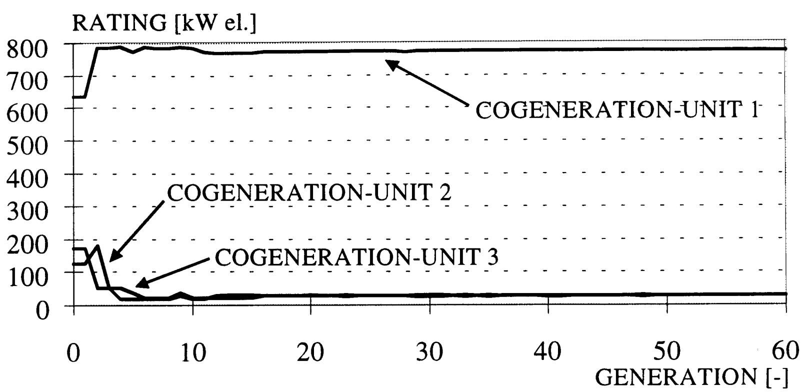

Fig. 11. Course of optimization for the cogeneration units (best solutions).

NCHD	non-covered heat demand
NCPD	non-covered power demand
NG	natural gas (monovalent)
OUT	outlet of heat from thermal storage tank
P	electric power
PC	penalty costs
I’D	power demand
Sec	greenhouse section
SELL	power energy sold
T2C	technical carbon dioxide
TE	cogeneration unit
v	allowance
k	index for sampling time
j, m, n, o, p, q, r, s	index of equipment installed

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