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CONTROL SYSTEMS FOR GEOTHERMAL GREENHOUSES IN TUNISIA - A STUDY BASED ON DYNAMIC SIMULATION

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ABSTRACT

This paper describes the design and simulation of a complete typical geothermal project in Tunisia, including well, tank, water distribution, greenhouse and connection with oasis irrigation. It presents a design study based on dynamic simulation focussing on the development of control systems for a geothermal utility installation for a greenhouse heating and cooling and oasis irrigation project. The hierarchical and interconnected features of the process are first discussed, leading to appropriate problem formulation. The aspects of modelling, simulation and development of a control system for interconnected large-scale greenhouse projects are then presented in a methodological form. Thereafter, the technical subsystems, namely, geothermal water production and distribution, greenhouse heating and climate controls, are described. The report demonstrates that simulating the geothermal installation and its computer control systems is a realistic and useful step in a pre-feasibility and management study for a project of this kind. One key finding of the simulation work is that the greenhouse area can potentially be doubled through the addition of a buffer tank and suitable control equipment.

1. INTRODUCTION

Tunisia, a Mediterranean and North African country, has rapidly developed mainly tomato and melon production in greenhouses heated and irrigated with geothermal water. The development of this sector has been going on under adverse climatic conditions in the southern part of the country in arid and desert regions known for their lack of rain. Deep wells were drilled by the government for irrigation purposes in oases where ventilated cascade towers are used for cooling. Creating geothermally heated greenhouses close to an oasis system is complicated and needs careful planning and studies based on many aspects such as the choice of the appropriate site, the organization and arrangement of the greenhouses, temperature regulation in the greenhouses and flow regulation of the geothermal water (Said, 1997). Water demand, needed for heating greenhouses and irrigation purposes in oasis and greenhouses, has gradually increased due to the extension of the greenhouse projects and increased oasis agricultural renovation. In order to avoid waste of water resources which are considered non-renewable and very expensive in these regions, a considerable effort is needed to optimise geothermal water direct use. The development of geothermal greenhouses in the southern part of Tunisia is the result of several historical and technical steps. Late in the seventies and during the eighties, a large amount of low-enthalpy water from artesian geothermal wells was identified. These wells were drilled mainly for irrigation purposes by the Government. Due to the lack of rain in the southern part of the country, this area is considered an arid zone with a natural water deficiency too low to ensure normal crop development. However, the Government drilled many deep wells to exploit these geothermal resources for complementary irrigation in oases where the date palm is the most dominant crop. The geothermal water used for irrigation is generally cooled by ventilated atmospheric cooling towers. As in most sub-Mediterranean countries, obtaining early production and good quality of products needed for export was very difficult without heating, because of too low night temperatures during the winter when the minimum air temperatures were mostly below 7°C and, particularly, lower than 5°C in the desert regions. Therefore, the idea was accepted to use geothermal water in the southern regions (Tozeur, Gabes, Kébili) for heating greenhouses and to raise the air temperature inside greenhouses about 7-8°C in order to maintain a minimum temperature of 12°C. Several experiments have been carried out since 1983 by the National Agronomic Institute of Tunis. In 1985, the United Nations Development Project was created (UNDP-TUN/85/004) with the object of promoting production in greenhouses for export by using geothermal resources for heating and irrigation. At present (1998), about 85 ha of plastic greenhouses heated by geothermal water are in production. This area places Tunisia third in the world after the United States and Hungary.

The government and the private sector are both involved in the capital investment of the projects. Each has a role and responsibility to ensure sufficient and better use of geothermal resources in the country. However, accurate analysis and technical solutions should be envisaged for creating more geothermal greenhouse projects in cascade with oasis irrigation. This study, is a contribution in developing an optimal control technique for the whole system from the production well to the use of water. This paper is structured in six chapters. First is an introduction covering the direct use of geothermal water in agriculture in Tunisia. The second chapter deals with a preliminary study of the whole project control connections analysis, the management aspects and the situation of the state of the art of greenhouse control systems. The third chapter concerns the dynamic modelling of the different subsystems of the project. The fourth chapter describes a design study of the proposed control systems of the geothermal project. The control system algorithms and the dynamic simulation methods constitute the subject of the fifth chapter. Some results are depicted to illustrate the simulation runs presented and discussed in chapter six. A general conclusion is given in the seventh chapter to focus on the main points of this study and to offer some recommendations. Useful details, for understanding the report text, are kept in two appendices.

1.1 Objectives

Process controls and system automation of greenhouse geothermal installations fall within the span of techniques and technologies for direct application of geothermal energy. To envisage the range of problems addressed here, one should have in mind the actual object of control and management as a whole. A closer schematic overview, as will be presented in Chapter 2, would easily show how composite and complex the large-scale system is.

It should be pointed out that system complexity is by no means less when considered solely from the control point of view, even when having all conventional and advanced control system structures, control algorithms and a whole selection of technical equipment (sensors, transmitters, actuators, signal and information processing units, computer controllers, etc.) available. For long term goals, an integrated control and management system yielding inter-dependent optimized evolution of both technological and business processes should be developed.

Here we confine ourselves to the technological control horizon and existing modelling, simulation and design problems of characteristic controls pertinent to the use of a low-temperature geothermal resource in agriculture applications in Tunisia. Yet, even if tackled this way, the problem is rather large and complex, influenced by various disciplines ranging from engineering thermodynamics, through biology and to signal and information processing. As will be seen, all the composite parts of the geothermal project are studied in process modelling and control simulation.

In this study it is indispensable to begin with a discussion aimed at an organised structure of the problems to be dealt with, keeping in mind that the controlled object is an interconnected and/or interactive subsystem. This presentation concentrates on the modelling, simulation and control of interconnected multi variable process systems. Thereafter, three specific technical control cases for geothermal projects are considered more closely, namely, those of controlling the hot water flow, greenhouse-climate and cooling tower-oasis irrigation.

The ultimate aim of using the geothermal resources is to achieve an optimal load operating scheme over any exploitation time period. The whole project inherently has multi-level control problems, each of which is supposed to control processes of considerably different time scales. There is the technological plant and process of extracting the geothermal resource in a way convenient to the whole utility installation. Optimally, this could be partially achieved by controlling the buffer storage tank level and the well level draw down by controlling the well output flow. In addition, there should exist a facility for the overall coordination control of the entire utility. Here, we limit our contribution to the simulation of the operational control systems part. A brief description of the whole system and management of decisions level steps is presented. An important feature is the transmission subsystem of the liquid flow-transporting pipes. Here, there is needed a two-level control structure: automatic protection and monitoring, and resource flow regulation. A facility for overall coordination is also needed.

Such a control system is quite a composite technical task, even if we adopt a simplified approximation of the controls. Extensive modelling and experimental identification studies are required in developing models (of dynamic control characteristics) of processes to be controlled and optimized. Developing control system structures and algorithms, and designing a range of controls require a number of alternatives and their simulations to establish the most appropriate control system with quality performance in both transient and steady state. Implementing such a system, would require the use of both analogue devices and digital controls in a distributed computerized control system. A supervisory control custom made for the actual utility installation may also be needed.

1.2 Overview of geothermal resources and greenhouse direct use in Tunisia

Ben Dhia and Bouri (1995) described the geothermal resources in Tunisia by dividing the country into five geothermal areas. This division is based on the geological, structural and hydro-geological features of the different regions. The northwest region (Province I) is greatly affected by the overthrust of the alpine napes, dated as upper Miocene, and thick deposits of sandy layers "Numidian formations". This region is geologically related to the Tuscan Italian province, and so is expected to be a potentially high energy zone. Provinces II and III constitute the "Atlas domain", and are separated from Province I by the "Diapers zone". Rocks represent both marine and continental sedimentary facies and are relatively well known either by surface or subsurface surveys. Province IV, representing the "Chotts province", is structurally known as "Tebaga anticline". This most important structure in Tunisia constitutes a transition between the Atlas and the Sahara domains. Sedimentary, Jurassic and Cretaceous rocks represent the most particular occurring layers constituting the extreme northern part of the most important aquifer of the whole north African Sahara. The southern province (Province V) contains the biggest sedimentary basin in Tunisia, with the thickest and widest deep aquifer system. It is located in the northern part of the stable Sahara platform.

The northwest region (PI) is characterized by a complex geological setting where volcanic rocks are more common than in other regions. The density of thermal manifestations is higher here than in other parts of the country. Out of 70 hot springs in Tunisia, 28 are located in this region. The hot springs are preferably associated with tectonic activity (faults and fissures) and the natural flow rate is usually small (less than 10 l/s). In South Tunisia the flowrate from the hot springs is usually higher (Stefánsson, 1986). Outside the northwest region, the geothermal aquifers have been found in well defined geological formations (sedimentary rocks) which in some cases are mapped over large areas (basins). These reservoir rocks often have very high permeability and many of the wells drilled in the south have artesian flow rates on the order of 100 l/s (Ben Mohamed, 1997).

A very coarse classification of the geothermal resources would, therefore, be to distinguish only between two regions, the northwest part and the remaining part of the country. The northwest region has many unique characteristics. In the southern part of the country the thermal gradient is in the range of 21-46°C/km. These values are in the same range as the world average values for thermal gradient. In general it is, therefore, expected that the geothermal resources in Tunisia are the result of normal conductive heat flow in the crust. This means that, in general, high-temperature (≥200°C) geothermal resources are not expected to be found in Tunisia, the only exception or question mark is the northern part of the country. At present it cannot be excluded that resources close to 200°C might be found in this area, but further investigations are needed in order to obtain better data (Stefánsson, 1986).

In the southern part of Tunisia, geothermal resources are obtained from aquifers crossing from Atlasic Tectonic to the desert plate (Sahara). Generally the temperature is between 20 and 75°C. There are three main aquifers, the Complexe Terminal (CT), the Djeffara and the Continental Intercalaire (CI). Other formations with temperature above 35°C exist inside Prenien, Triassic and Jurassic but have very high salinity (10-75 g/l). These formations are used for oil drilling.

The Complexe Terminal covers the regions of Nefzaoua, Gafsa and Djerid. It has been exploited at relatively low depths for more than thirty years and contains water with a low enthalpy which is characterized by a temperature ranging from 20 to 45°C and depth between 100 and 1,200 m. The salinity varies from 1 to 6.5 g/l. Geothermal resources are estimated at 1,125 l/s of which 1,000 l/s are used (about 89%). The Djeffara covers the regions of Gabes and Médenine. It is exploited at shallow depths (100-500 m) with varying temperatures of 21-29°C. Geothermal resources, which are estimated at 1,100 l/s, are all used. At present, the two reservoirs mentioned above are almost fully used (92%). The Continental Intercalaire covers the regions of Nefzaoua, Djerid, Gabes and the extreme south of Tunisia. It is deeper than the CT and extends to Algeria (part of the Sahara) and Libya. It is mainly exploited for agricultural purposes (irrigation of oases, irrigation and heating of greenhouses). It is characterized by a temperature ranging from 35 to 75°C , a depth varying from 1,200 to 2,800 m, high pressure and salinity between 2.2 and 4.2 g/l. Geothermal resources in this aquifer are evaluated at 3,200 l/s and exploited at 90%. At present, the potential of geothermal resources in South Tunisia is estimated at 5,500 l/s and is exploited to 92%.

2. PRELIMINARY STUDIES

2.1 Control project analysis using the SADT method

SADT or Structured Analysis and Design Method is an analysis tool specially used in the operational specification phase of systems including, or not, software parts. This technic is easy to use and understand due to the simple graphical and textual formalism. This method permits system behaviour analysis in a down flow hierarchical decomposition before technical study, and establishes a structured communication between the different persons dealing with the specific problems. According to the whole geothermal project analysis, presented in Figure 1, we can distinguish the different interconnected action control tasks. From the mother diagram A0-0, we go hierarchically down in a decomposition analysis. Diagram A0 shows the project control subsystem connections. The next level diagrams, A1, A2 and A3 respectively deal with the control connection details of the production well, the hot water installation and the greenhouse climate.

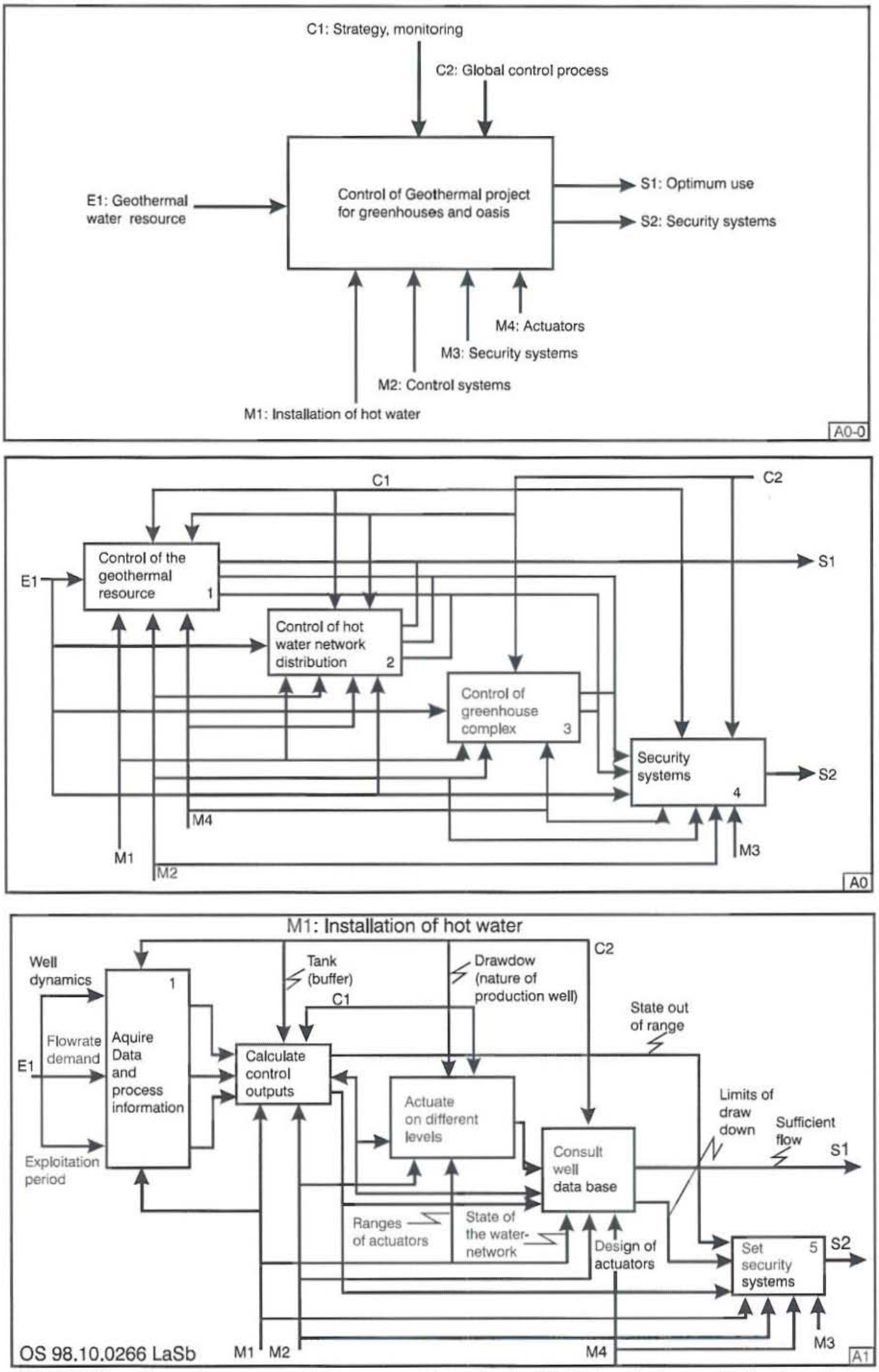

FIGURE 1: Control system task interconnections in the SADT analysis model for the whole project. A0-0: Mother diagram; A0: Project control subsystem decomposition; A1: Production well control; A2: Water installation control; A3: Greenhouse control

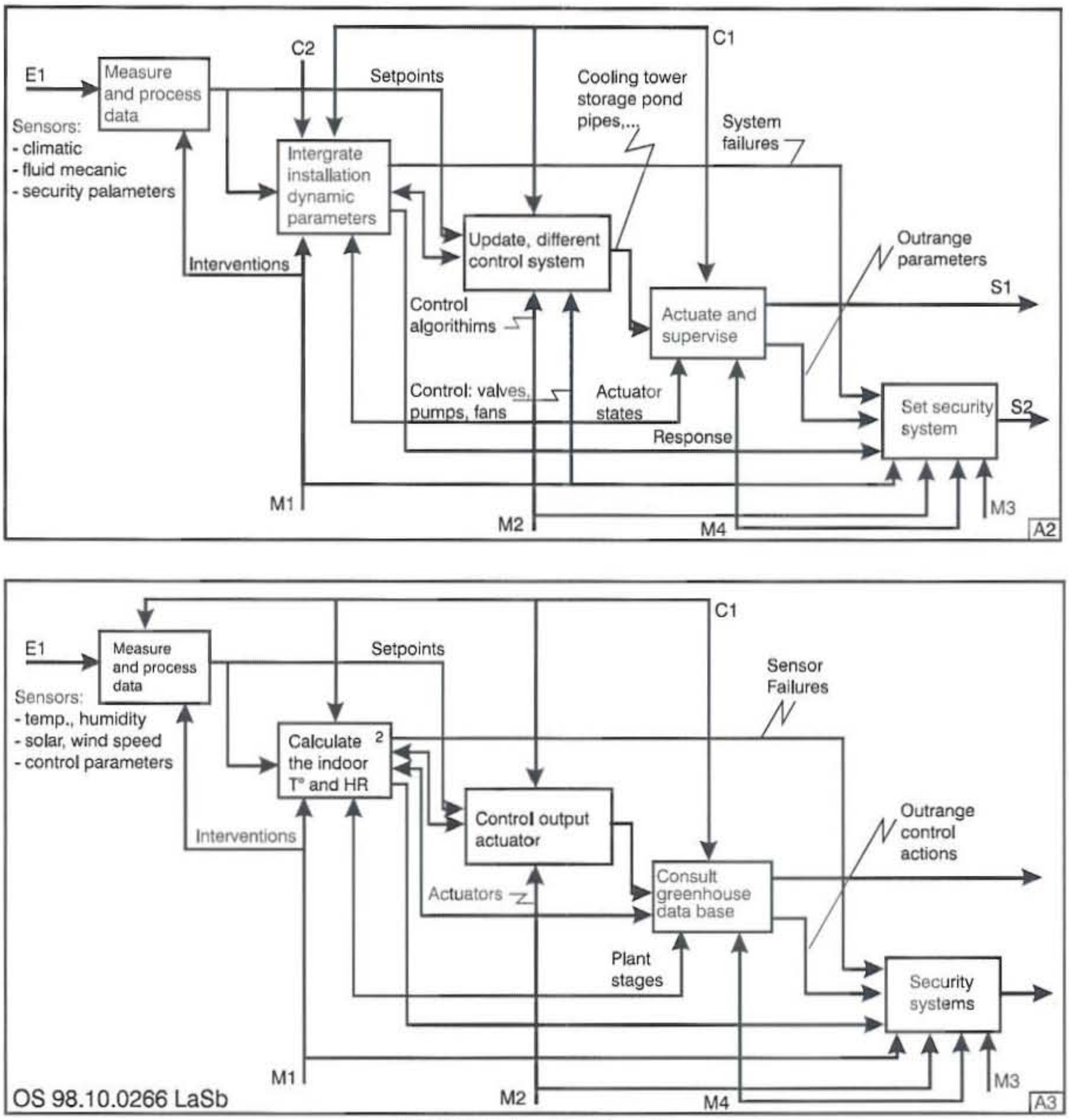

FIGURE 1: Continued

2.2 Project management

In the management of any business, the operator not only has to work with short-term problems, but he must plan over several periods of varying length (Hanan,1998). In this respect, management decisions of actual geothermal resource utilisation in agriculture in Tunisia can be studied at three different layers of the whole project and for each at three different management and decision levels as shown in Figure 2. These three layers are totally connected, but it is easier to treat them separately with regard to eventual interconnections. Briefly, each of them can be characterized as follows:

- The geothermal resources, distribution and global direct use;
- The oasis irrigation;
- The specific greenhouse farms using geothermal water.

According to the length of the time in the life of a project, three levels are actually well known in project management. One can easily see the large time scale which is the strategical level; the medium time scale is tactical; the most complicated level, i.e. the specific operational level, has a short time scale.

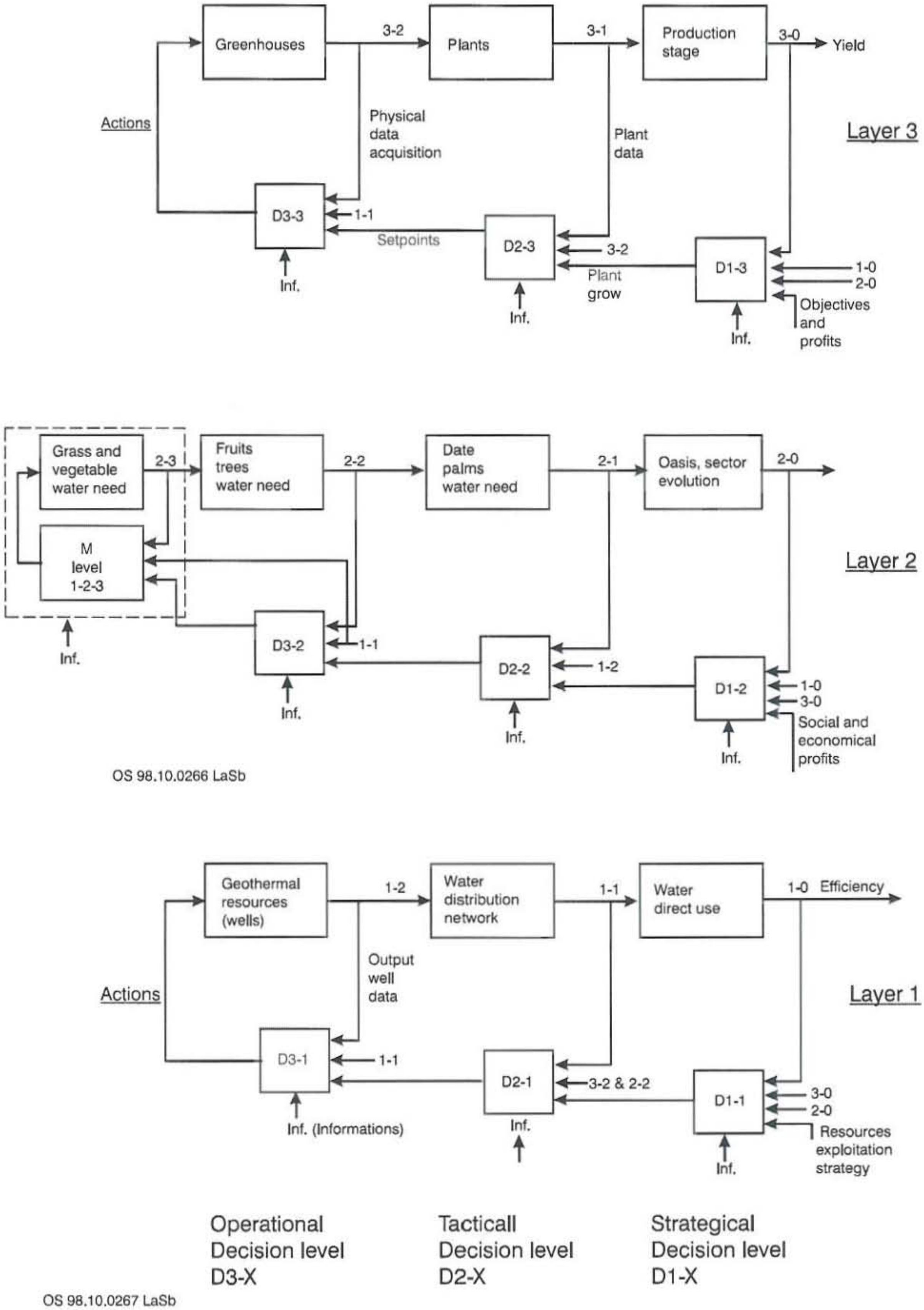

FIGURE 2: Time span decision levels and layer decompositions of the geothermal project

2.2.1 Geothermal resources

There is concern in the optimisation of the energy use in several real and potential applications. As illustrated in Figure 2-*layer1*, first level *D1-1* is related to the strategy of dynamic use of the geothermal water (direct use in Tunisia), meaning how to plan priorities with more efficiency of geothermal resource exploitation. Second level *D2-1* treats the interface between the well and the customer. This interface is the heavy investment in the network of hot water distribution. In the second level many direct interventions occur after each decision in level 1, and follow each event happening in the level below. This level is mainly connected with efficient functioning of the network. Third level *D3-1* is the geothermal energy resource, where a tied operational level makes rapid decisions to control well behaviour in order to prolong well life (pressure decline, mechanical damage, re-injection....).

2.2.2 Oasis irrigation

The oasis area has been considered socially and economically important in the use of the geothermal resources for many thousands of years. It is classified agriculturally as being used on three floors (Ben Mohamed, 1997). In layer 2, the decision level is based on water need for each floor and the water carried between the oasis farmers. The first decision level *D2-1* deals with the upper floor which is composed of date palms. The second level *D2-2* considers the water need for the middle floor which is composed of trees under date palms (apple, fugue, grape, apricot, grenade) and the third one *D2-3*, takes into account the substantial water need relative to the open field composed of grass and vegetable cultivation. These three oasis floors constitute the socio-economical system and are actually managed at the same time and irrigated by the same water. However more efficient water sharing is needed. This water is provided to the oasis by a storage pond after the cooling tower process. Small natural cooling ponds are added to the actual system to avoid irrigation of the third floor by hot water. Here, we can suggest control action in the cooling tower as a money saving and well adapted process for these purposes. The management of this sector is mainly a social and economically linked decision. The irrigation of date palms seems to be a primordial decision in some areas where supreme quality of "deglet nour", mainly for exportation, is used. In other date palm areas, these trees need a low frequency of irrigation. In fact the grass and vegetable need more than the two upper floors. In the middle floor, the fruit trees represent a less important axis in the irrigation strategy level, but let's say that generally the need for water lies between the upper and lower floors. The operational level is assumed by the farmers unions (UTAP), service cooperatives and water organisations. In this operational management level, with regard to greenhouse complex use, and oasis irrigation, the valve storage pond output has at least three control actions per day.

2.2.3 Greenhouse complex

Over several years, decisions on the strategic level in *layer3, D3-1* determine the technical decision possibilities of *D3-2* for climate control and long-term nursery policies on such factors as marketing, product quality, etc. At the tactical level, one formulates the crops, cultivars, timing, and so-forth in the expectation of average weather. Deviation in climate, market and crop behaviour can occur, requiring changes at operational level *D3-3* with a duration ranging from a few minutes to as long as a week. This operational stage includes climate control which has a time span of minutes, or nearly instantaneous. The complexity of this level suggests the need for a digital computer of sufficient capacity and speed.

In order to optimise greenhouse control (second and third level), information from other sources such as weather prediction and financial data are required. This means the use of an adequate recording system of actual greenhouse data, plus production and marketing. These data are used in price predictions and product requirements. Also, collected data from climate measurements are needed for calculating new set points based on actual investment situations, market dynamics, and weather forecasts. The official and advisory organisations must hold an information data base system. These organisations must use conventional and advanced communication potentials for obtaining useful information.

2.3 State of the art in greenhouse control systems

2.3.1 Conventional control systems

Throughout the 1940s and into the 1950s, control systems were primitive, consisting mostly of on/off temperature controls with heating and ventilation determined by separate thermostats. Examples of such devices are still in use in some greenhouse farms. Such control inevitably results in a temperature difference between the on and off points. Depending upon the particular situation, temperature variation can be much more than one to two degrees within the thermostat range. Improper heating system balance, unsuitable thermostat location and protection, or rapid changes in radiation or external temperature can result in unstable control with *on/off* temperature variation sufficient to reduce crop quality significantly. Suitably designed *on/off* systems, however, can be quite good and economically feasible. These conventional control devices are very limited in providing an optimum needed climate.

2.3.2 Simple control for a greenhouse

Powerful mathematical calculations are not necessary for successful climate control. The grower may use simple, direct-acting devices to control the environment quite successfully. A published example is Hanan's (1998) description for control of four (6 × 15 m) research greenhouses. Transfer functions, as found in control theory, were not employed. Temperature, averaged from three stations in each house, was ±1°C during both night and day. Local control system problems were small. These local automatic sets available in the market are not economically useful when control is dealing with a whole greenhouse complex.

2.3.3 Advanced centralised control for a greenhouse complex

For a whole greenhouse complex, simple controls are hardly sufficient. Computers are the answer. Computers are wonderfully versatile machines, allowing an individual to program and control many environments in any fashion he sees fit, and to include as much, or as little, control as may be feasible. A second advantage is that new programs and changes in existing software may be made quickly whenever necessary. Once the initial capital investment has been made, upgrades can be introduced at nominal cost. Advanced control systems using a centralised computer seems to be an optimal solution for the greenhouse complex. An advanced centralised computer control system can be utilized to modify the set points and to relieve the grower of the need to continuously monitor them. A computer system should also protect managers from inadvertent mistakes that conflict with the numerous interactions and disturbances that could crash operations or prevent the grower from maximising profitability. In the possibility of upper level control failure (a central computer failure), the system should be capable of minimal control with a reduced set of algorithms and set points that the grower could operate manually. Many companies are actually on this turn-key control system market, and they offer a integrated control of greenhouse complex utilities (climate, artificial light, CO_2 enrichment, weather station and ferti-irrigation).

3. DYNAMIC MODELLING OF THE GEOTHERMAL PROJECT

3.1 Selection of simulation parameters

The greenhouse climate is mainly characterised by indoor temperature and humidity. These two parameters are the reactors of plant comfort which means good health and good yield under phytosanitar conditions. High humidity is a generator of diseases while reduced humidity increases plant water absorption (more minerals in the dry matter) and implies a weak morphology. The environment of a greenhouse is very widely discussed by Hanan (1998). This environment is very complex and needs the intervention of multi-disciplinary group work to succeed in an acceptable growing environment. The most common parameters are very dependent on the location of the greenhouse project according to the specificity of the local climate. These parameters in the Tunisian case are defined as helping the process in a semi arid climate. In fact, sunny days are usually common and yield a hot, dry micro climate inside a greenhouse when aeration is not well manipulated. This natural aeration is insufficient to reduce some boundary limits in the climate-plant reaction process. The utilisation of an additive cooling process, the cooling evaporative method, is of primary importance to assure a long period of plantation. This semi arid climate also results in cold nights. For this reason, geothermal water has been used as a heating tool, essentially in the night time. In 1985, an experimental production unit of about 60 tunnel type (500 m^2) plastic greenhouses was started. In this paper, a simulation study based on a dynamic model of the greenhouse is provided. The simulation includes the effects of an essential climate conditioning process. The whole project is articulated around the geothermal resource (well). A typical geothermal project which interconnects the greenhouse direct hot water use and the oasis irrigation is proposed. A proposed control system for the different composites is presented to perform a pre-feasibility study to assure efficient use and management of this energy source. The proposed system is illustrated in Figure 3.

3.2 Greenhouse dynamic model theory

In this section a greenhouse climate dynamic model is proposed. This model incorporates the effects of natural ventilation, geothermal radiator heating and an evaporative cooling process as climate control parameters. With the climate conditions that prevail in this semi arid region, efficient climate control is the major challenge growers have to face. Most of the shelters are provided with hand operated systems of ventilation. The insufficient ventilation and/or its inadequate management leads to inappropriate extreme air temperatures and saturation deficits. The resulting microclimate is far from being satisfactory to the crop during a large part of the year. So, the performance and control of natural ventilation are crucial factors for crops during hot periods of the year and for improved yield and quality. The cooling evaporative process is an inevitable technique to add to natural ventilation in order to face the temperature problems. Hot geothermal water has been used with satisfactory results for 13 years in Tunisia, but more advanced control of the indoor greenhouse climate and optimal use of the geothermal resources are needed. In a previous study, the reduction of the complete thermodynamic model of a greenhouse to a reduced one, well adapted to control implementation schemes was presented (Souissi et al., 1996). Here, the reduced dynamic model takes into account a virtual thermal mass compartment (Draoui, 1994, Boulard, 1996) corresponding to the greenhouse structure plus the soil (incorporating substratum) and vegetation, and characterised by temperature T_m (°C) and calorific capacity C_m(J/°Km^2). The inside air is characterised by indoor temperature T_i (°C), actual water vapour pressure e_i (hPa), and water vapour calorific capacity C_i(J/°Km^2). In Figure 4 the different energy flux and compartments used in this dynamic model are described. In the following, the mass and heat balance equations describing this model are given.

Heat balance of the thermal mass:

$$C_m \times \frac{dT_m}{dt} = h \times (T_i - T_m) + Q_{Heat} + \beta \times R_g \tag{1}$$

where

R_g = Global solar radiation flux (W/m^2);
h = Convective exchange coefficient between indoor air and the thermal mass (W/Km^2)
β = Solar radiation absorption coefficient of the thermal mass.

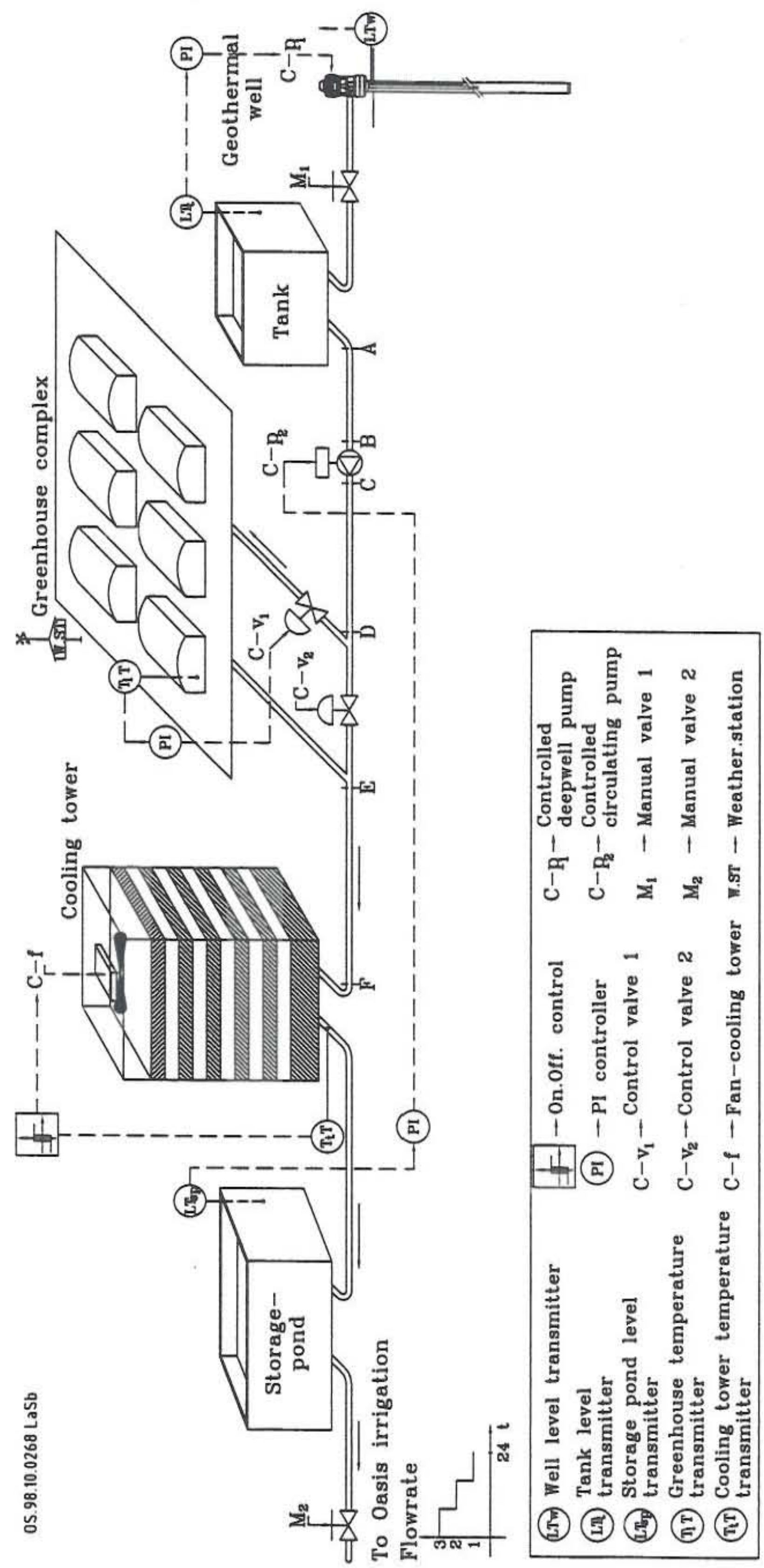

FIGURE 3: Schematic representation of the whole proposed geothermal project with control system

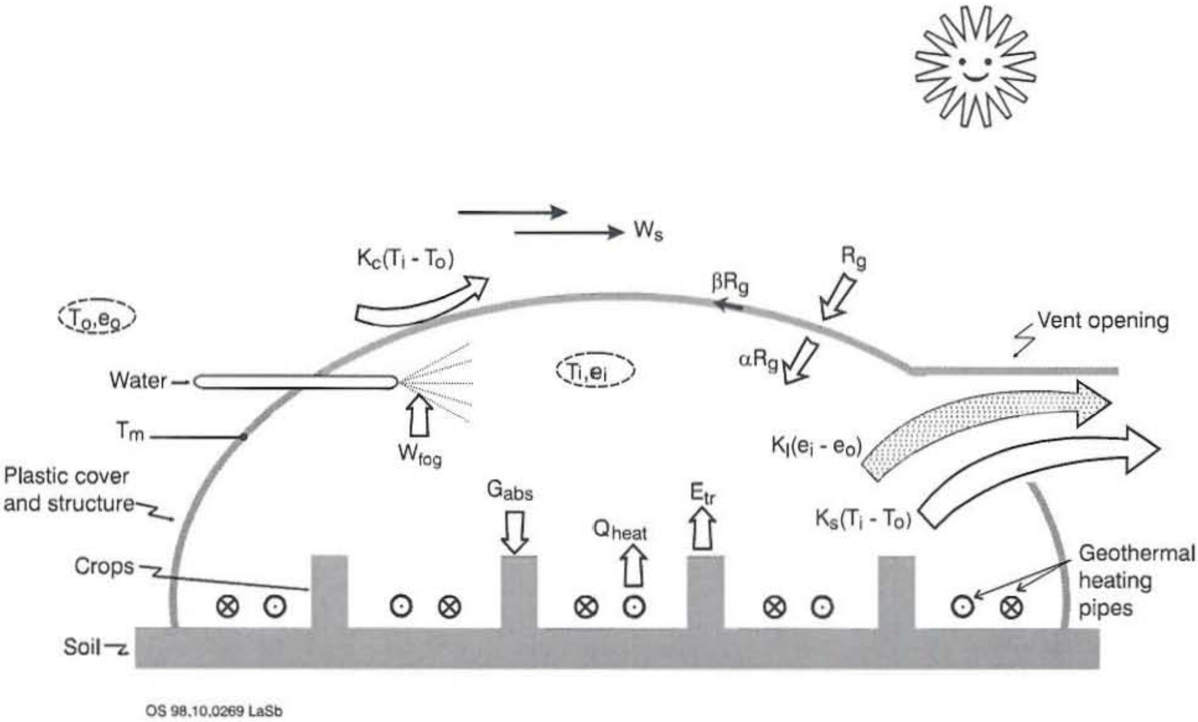

FIGURE 4: Schematic of different elements and heat flux considered in the greenhouse dynamic model

Heat balance of the greenhouse indoor air:

$$\frac{1}{C_{pair} \times \rho_{air} \times V_g} \times \frac{dT_i}{dt} = \alpha \times R_g + Q_{Heat} + h(T_o - T_i) + K_c(T_o - T_i) + K_s(T_o - T_i) + K_l(e_o - e_i) \tag{2}$$

where T_o = Outside temperature (°C)
e_o = Actual water vapour pressure (hPa);
Q_{heat} = Energy flux from the heating radiator (W/m^2);
V_g = Greenhouse volume (m^3);
S_g = Greenhouse soil area (m^2);
C_{pair} = Air heat capacity and density (kJ/kg°C)
ϱ_{air} = Air density (kg/m^3).

The overall heat loss coefficients K_c (W/°Km^2) through the cover, K_s (W/°Km^2) sensible and K_l (W/hPam^2) latent due to ventilation flux G (m^3/s), are, respectively

$$K_c = 8.87 + 0.73\,W_s\,, \quad K_s = \rho_{air} \times C_{pair} \times \frac{G}{S_g}\,, \quad K_l = \rho_{air} \times \frac{C_{pair}}{\gamma} \times \frac{G}{S_g} \tag{3}$$

Water vapour mass balance:

$$C_l \frac{de_i}{dt} = K_l(e_i - e_o) - E_{tr} - W_{fog} \tag{4}$$

where E_{tr} = Crop transpiration flux (W/m^2);
W_{fog} = Energy flux of cooling system sprayed water vaporisation (W/m^2).

3.2.1 Natural aeration physical modelling

Natural ventilation by operating vent openings (roof and side) is actually the main cooling practice in greenhouses in Tunisia. A theoretical and practical study was held in Tunisia to model and quantify the natural aeration mechanisms in a tunnel type case of geothermal greenhouses. This study was guided by PNM (Program National Mobilisateur-INRST: 1993-1996) under the auspices of the Tunisian state Secretariat of scientific Research and Technology (Sbita, 1997). In the physical modeling, wind effect is considered to be the most important driving force for ventilation in greenhouses. It has two components: a static one, linked to the wind pressure field over the greenhouse cover and a turbulent one, linked to the wind turbulence along the opening. The static effect gives rise to a vertical and horizontal distribution of pressures, respectively between the side and roof vents, and between the upwind and downwind part of the same vent. In addition we must consider the 'chimney' effect linked to the vertical distribution of static pressures between inside and outside the greenhouse giving rise to an inflow in the lower part of the opening (or through a lower vent) and an outflow from the upper part.

The ventilation air flow rate G (m^3/s) of the greenhouse described can be simulated with good accuracy by a simple model combining these wind and chimney effects (Boulard, 1996; Sbita, 1998)

$$G = A\frac{S_v}{2}\times\sqrt{[2g\varepsilon^2\times(\frac{DT}{T})\times(\frac{H}{2})+C_w W_s^2]}\ , \quad where\ \varepsilon = \frac{2\sqrt{2b}}{\sqrt{(1+b)\times(1+b)^2}} \quad with\ b = \frac{S_R}{S_S+s_0} \qquad (5)$$

where S_v = Vent opening area (the open cross-sectional area) (m^2);
DT = Difference between the inside and outside air temperatures (°C);
W_s = Wind speed (m/s);
g = Gravitational constant (m/s) and;
H = Distance separating roof and side vents (i.e. the height of the "chimney") (m).

The 'chimney' effect depends on the relative importance of the roof S_R and the side S_S vent surfaces (S_S can be assumed to be door and/or lateral openings), their sum $S_v = S_R + S_S + s_o$. The leakage area estimated value is represented by s_o giving the onset of ventilation (or leakage) when $S_R + S_S = 0$ or when $W_s = 0$.

3.2.2 Modelling the canopy cover transpiration

Using the well known Penmann-Monteith formula, we can easily express the crop transpiration flux as function of the measurable climatic parameters (Sbita, 1997). This energy flux E_{tr} can be shown to be composed of two different mechanisms. The first is the radiative component, proportional to the radiation absorbed by the crop G_{abs} (Figure 3), and the other is the advective term, proportional to the vapor pressure deficit (Sbita et al., 1996)

$$E_{tr} = A_{tr}\times G_{abs}+B_{tr}\times D_i \quad with \quad D_i = e_s(T_i)-e(T_i) \qquad (6)$$

where $e_s(T_i)$ and $e(T_i)$ are the saturated and the actual water vapour pressure, respectively at T_i.

3.2.3 The greenhouse heating system

The design and operation of heaters in geothermal schemes is of special importance because the outlet temperatures ultimately determine the efficiency of geothermal water utilisation. In some geothermal

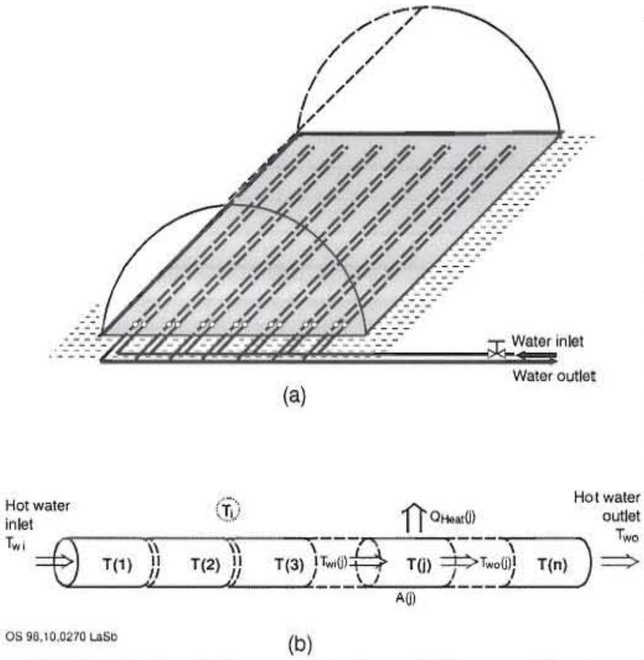

FIGURE 5: a) Representation of the greenhouse geothermal heating scheme used in Tunisia; b) Geothermal water heating pipe sectioning used in dynamic model of pipe heat loss

projects with combined oasis irrigation and greenhouse heating, it was demonstrated that irrigation may be the primary consumer. Thus, the energy efficiency of greenhouse heating is of secondary importance. The heaters have to be sized in a way which satisfies the demands of the users. The need for low return temperatures is an additional consideration. There are, therefore, two conditions which govern the heating system design:

- The heat output must be high enough to satisfy the demands of users.
- The temperature of the water at the outlet must be as low as possible (control of the flow rate).

Heater emission. The radiators transfer heat from the hot water to the indoor air (Figure 5). The actual heat transfer processes are complex, involving radiative and conductive mechanisms. However, they can be treated as passive water to air heat exchanges. The rate of heat transfer is given by the following expression:

$$Q_{heat} = A_{pipe} \times K_{pipe} \times \Delta T_{PA} \tag{7}$$

where Q_{heat} = Flux of heat transfer from radiator to greenhouse air (W/m^2);
K_{pipe} = Overall heat transfer coefficient of heater (W/°Km^2);
A_{pipe} = Surface area of heater (m^2);
ΔT_{PA} = Effective temperature difference between water in heater and indoor air, across the heater surface (°K).

The radiators inside the greenhouse consist of many loops of polyethylene corrugated pipes. Inside the greenhouse, these pipes constitute a ground surface located heating system. The system of pipes can also be located on the ground surface, between the plant rows. The pipes are made of polypropylene or polyethylene and most common are corrugated pipes of Ø 25 mm and Ø 32 mm (see Figure 5a). These types of pipes don´t allow heating fluid temperatures higher than 60°C. They fit the low-temperature geothermal water use in Tunisia and have relatively economical prices. The heating fluid should be clean, without hard particles and without tendency to deposition. For corrugated pipes, the last limitation is sometimes not valid; temperature elongation destroys the deposition structure and the inside pipe surface is always clean. This system presents a good and fast response to temperature changes of the fluid. For this heating system, automatic regulation is convenient. In order to calculate the total heat transfer across the radiator, we consider here that this is equal to the sum of the heat across each elementary loop. This loop is a long tube carrying hot water and it can be shared into n elementary sections. Each of these parts is considered to have a constant temperature of hot water and exchange heat according to the temperature difference relative to the surrounding air T_i as shown in Figure 5b. The global radiator heat transfer is given by Equation 8. For the part number j, the heat transfer is

$$Q_{Heat}(j) = A_{pipe}(j) \times K_{pipe}(T(j) - T(i)) \tag{8}$$

The temperature of the water for the next *j+1* section is deduced as

$$T(j+1) = T(j) - \frac{Q_{Heat}(j)}{q_w \times C_{pw}} \tag{9}$$

Using this iterative method we can obtain the hot water outlet tube temperature by measuring the inlet temperature.

3.2.4 Evaporative cooling process

The process of cooling and humidifying the greenhouse climate in the hot period of the day or year round was presented by Boulard in 1996 and Hanan in 1998. In this study, the fog intensity injected into the greenhouse can be represented by a linear variation (Equation 10) or a saturation state (Equation 11) as follows:

$$W_{fog} = h_{evap} \times I_{water} \tag{10}$$

where h_{evap} = Enthalpy of water vapour (kJ/kg);
W_{fog} = Effective evaporative cooling;
I_{water} = Fog injection intensity (kg/m^{2}s).

As explained in Equations 2, 3 and 4, the latent heat loss depends on the ventilation rate. Then fog injection and aeration are coupled in the cooling mechanism. Section 6.1 presents the control of the indoor climate using simultaneously aeration and fog injection.

3.3 Cooling tower modelling

The purpose of the cooling tower is to cool down the hot geothermal water, to make it suitable for irrigation. The idea of a cooling tower started with the spray pond, where warm water is sprayed into the air and cooled by the air as it falls into the pond. Some spray ponds are still in use for cooling geothermal water used directly for oases irrigation in Tunisia. But they require 25 to 50 times the area of a cooling tower (for the same efficiency). In spray ponds, water loss due to air drift is high, and they are unprotected against dust and dirt. In Tunisia, the ventilated atmospheric cooling tower is the type selected for cooling hot water from the well for irrigation purposes. This cooling tower is a semi enclosed wet cooling tower as described by Figure 6a. The air in the cooling tower is hot and has a high water vapour content and, thus, is lighter than the outside air. Consequently, the light air in the tower rises, and the heavier

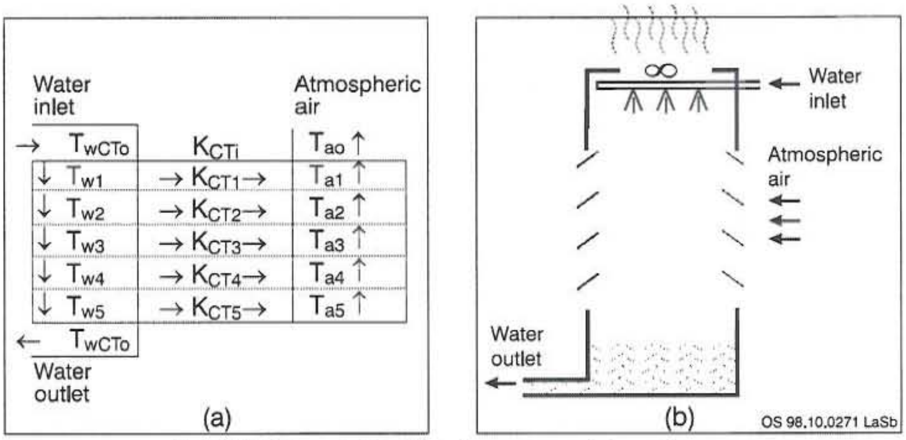

FIGURE 6: a) Cooling tower -model sections;
b) Representation of the cooling tower

outside air fills the vacant space, creating an air flow from the bottom of the tower to the top. The purpose of spraying is to expose a large surface of water to the air. As the water droplets fall under the influence of gravity, a fraction of the water evaporates (usually a few percent) and cools the remaining water. The temperature and the moisture of the air increase during this process as shown in Figure 6b. The cooled water collected at the bottom of the tower and its circulation to the oases storage pond is facilitated by gravity. To control the temperature of the cooling tower water output, we shall use a fan to accelerate air circulation; the cooling tower then behaves like a forced-draft one. In the simulation model, the cooling tower was divided into five sections (see Figure 6a).

The energy stored in the water vapour is

$$Q_{vapor} = h_{evap} \times m_{evap} \tag{11}$$

where Q_{vapor} = Energy from evaporation (J);
h_{evap} = Enthalpy of water vapour (kJ/ kg);
m_{evap} = Mass of evaporated water (kg).

$$h_{vapour} = 2501.3 + 1.82T \tag{12}$$

If the humidity of the air is increased, the energy needed is thus

$$Q_{vapour} = h_{evap}\, m_{evap} = h_{evap} V(m_v(T1) \times RH1 - m_v(T2) \times RH2) \tag{13}$$

where $m_v(T)$ = Water density in air at 100% humidity at temperature T (kg/m^3);
V = Volume of air (m^3);
$RH1$, $RH2$ = Relative humidity (%).

In Table 1, saturated vapour pressure, P_g (kPa), in air at 100 kPa atmospheric pressure, is defined as a function of temperature; the table also shows the vapour density, m_g in the air, the dry air density, ma and the total density of the saturated air.

TABLE 1: Air characteristics according to the temperature

T (°C)	P_g (kPa)	m_g (kg vapour/kg dry air)	m_a (kg/m^3)	Wet bulb enthalpy (kJ/kg dry air)
0	0.[611	0.0038	1.265	9.56
5	0.871	0.0055	1.26	18.74
10	1.227	0.0077	1.254	29.52
15	1.704	0.0108	1.246	42.34
20	2.337	0.0149	1.235	57.87
25	3.166	0.0203	1.221	76.91
30	4.241	0.0275	1.203	100.55
35	5.622	0.0371	1.18	130.2
40	7.375	0.0495	1.15	167.67
45	9.582	0.0659	1.114	215.48
50	12.335	0.0875	1.07	277.1
55	15.741	0.1162	1.016	357.52
60	19.921	0.1547	0.952	464.18

In Table 1 the mass of water and dry air per m^3 at 100 kPa pressure is calculated according to

$$R_a = 0.287 \; kPam^3/(kgK), \quad R_v = 0.4615 \; kPam^3/(kgK)$$

$$m_a = \frac{(100 - P_v)}{(Ra \times (T + 273.15))}, \quad m_v = \frac{P_v}{(R_v \times (T + 273.15)} \tag{14}$$

The relative humidity is defined as

$$\phi = \frac{m_v}{m_g} = \frac{P_v}{P_g} \quad with \quad RH = \phi \times 100 \; (\%) \tag{15}$$

where m_v = Actual water density in air (kg/m^3);
P_v = Actual vapour pressure;
P_g = Saturated vapour pressure;
m_g = Saturated water density.

The cooling tower heat transfer is simulated as an equivalent heat exchanger with a given K_{CT} value (heat transfer coefficient). The tower is divided into partial cooling tower cells (5, in our case), the K_{CT} value for each section is therefore assumed: $K_{CTi} = K_{CT}/5$ (W/°K). The temperature of the air, T_a, is the wet bulb temperature, calculated from the enthalpy of the air and a table of wet bulb as a function of air temperature.

The heat transfer at section 1 is therefore

$$dh1 = \frac{T_{w1} - T_{a1}}{K_{C1}} \tag{16}$$

The temperature drop is

$$dT_w = \frac{dh1}{q_{wCT} \times C_{pw}} \tag{17}$$

where q_{wCT} = Water flow (kg/s);
C_{pw} = 4.179 kJ/(kg°C).

An iterative calculation method is then used to get the down stage cooling tower water temperature which is the cooling tower outlet temperature. The outlet temperature is used to control fan action.

3.4 Production well level; analytical model study of well behaviour due to increased production

3.4.1 Dynamic model

The ability to provide a continuous and adequate flow of geothermal water from one or more production wells is a basic requirement for any geothermal heating scheme. In practical terms, the main reasons for installing a pump in a well is to provide an adequate rate of water flow. In addition to pump power and setting depth, the other pumping parameters, which consist of the number of wells and their separation, are influenced by the characteristics of the geothermal reservoir. Because a geothermal reservoir can be quite complex, a considerable amount of information may be needed to describe the response of the reservoir to both static and dynamic conditions. It is sometimes possible in a global reservoir analysis to provide a general means of classifying reservoirs based on the type and degree of permeability that they exhibit. Such considerations need more investigation and further studies, because such considerations can have a strong influence on many aspects of geothermal scheme design and operation. The flow pattern affects how the rate of flow is related to pressure exerted by the geothermal fluid. Since the pressure of the fluid flowing through the well affects, directly or indirectly, the well pumping parameters, the relationship between flow rate and fluid pressure is very important (Harrison et al., 1990). Let us have a look at some basics about the well as a system. In this section, we deal especially with some practical well behaviour characteristics. In reservoir engineering, points of equal pressure are usually indicated by an imaginary surface called the piezometric surface. The head of fluid, in or above the well, which can be supported by the formation pressure under non-flowing conditions is a part of the piezometric surface. However, as shown in Figure 7, the static head h_0 is not equal to the fluid level that will be established after flowing, or dynamic conditions, called dynamic head h_p. This level is governed by the dynamic piezometric surface. When fluid is extracted at any given rate of flow from a production well, the fluid level in or above the wells falls by a distance known as drawdown h_d. Drawdown results from changes in pressure as the fluid flows from the reservoir and the well. The various causes which contribute to such pressure changes are often known as well losses and these include resistance to fluid flow through the reservoir, influence of neighbouring wells, prevention of fluid flow due to reservoir boundaries, additional fluid flow due to water entering, fluid losses due to dewatering of the reservoir, turbulent flow in the immediate zone around the well, etc. In the reservoir engineering practice, a well drawdown model has been developed at Orkustofnun - National Energy Authority of Iceland (Björnsson et al., 1997). Using this model the water level drawdown in a production well can be described by the following:

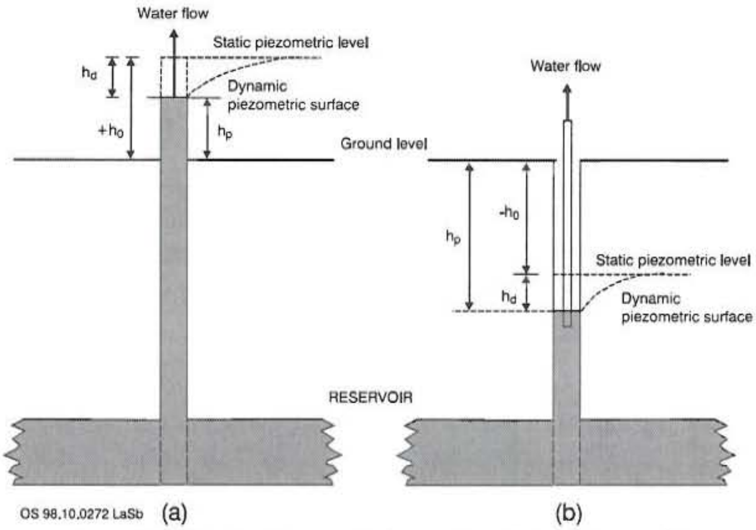

Figure 7: Production well dynamics a) Artesian well; b) Non artesian well

$$h_d = h_0 + b(t) \times q_{well}(t) + c \times q_{well}(t)^2 \text{ , } with\ b(t) = a_1(1 - \exp(-\lambda_1 t)) + a_2(1 - \exp(-\lambda_2 t)) + a_3 \quad (18)$$

where h_0 = Static well head (m);
$b(t)$ = Laminar drawdown coefficient as a drawdown time dependent parameter (m s/l);
c = Turbulent draw down coefficient (m s^2/l);
$q_{well}(t)$ = Well discharge (flow rate) (l/s).

3.4.2 Automatic control

The well behaviour, mainly the water level drawdown, can be controlled using the deep well variable speed pump to control extracted fluid flow. A level transmitter as shown in Figure 3 detects the drawdown and automatically interacts with the pump through a PI controller and a variable speed drive. When the level is under a minimal limit, the pump is slowed down and an alarm is set to prevent damage to both the well casing and the pump due to cavitation problems. Figure 8 shows the simulated drawdown curves for both an artesian (h_0 = - 10 m) and non artesian well (h_0 = 5 m). These curves correspond to different flow rates (10-60 l/s) as functions of the pumping duration all year round.

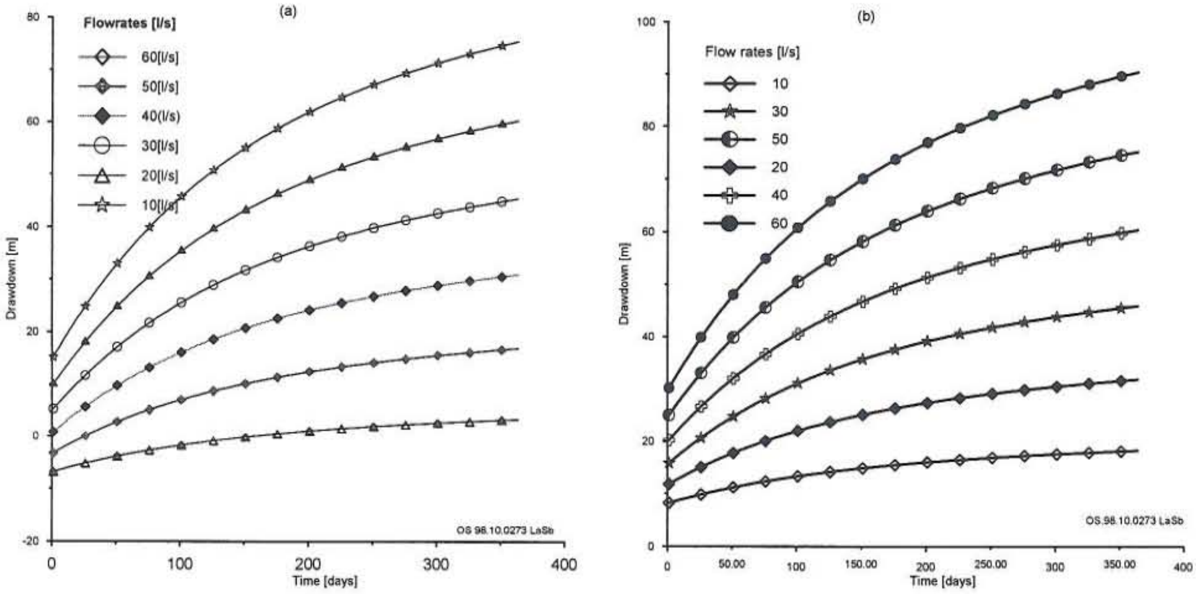

FIGURE 8: a) Artesian well (h_0=10 m) drawdown simulation;
b) Non artesian well (h_0=5 m) drawdown simulation

3.5 Heat and pressure loss in the pipe

Geothermal water transportation and distribution for heating systems in greenhouses are made by means of pipes of different sizes and materials. To enable water flow in the pipes, it is necessary to create a pressure lift at one end of the pipe, consisting of two components: static "p_s"and dynamic "P_d". The total fluid pressure can be expressed as a summary of these two components. An indirect method can be used to calculate the pressure loss in the pipe. In fact, the flow rate is related to the pressure drop and the height of the pipe as

$$q_{pipe} = Kv_{pipe}\sqrt{\frac{P_i - P_o - H_{pipe}}{G_w}} \tag{19}$$

where P_i / P_o = Inlet / outlet pipe pressures, respectively;
H_{pipe} = Height difference between the pipe ends;
G_w = Density of water.

The pipe transporting water from the tank to the greenhouse tap off, is fed by a variable speed pump that controls the flow rate according to water demand. This pipe is standard steel and 500 m long. For the design and pressure loss estimation, we use a diagram adopted in the heating system in Reykjavík (Gunnarsson, 1997). Assuming a maximum flow rate of 30 l/s gives pipe of 6 inches diameter a pressure drop of 150 Pa per metre. The total pressure loss is then, 0.75 bar between the pump and the greenhouse complex. From the greenhouse tap off to the cooling tower we have the same kind of pipe, 200 m long, which gives 0.3 bar pressure loss. For heat loss in the pipe the same model is used as in Section 3.2.3.

3.6 The tank and the storage pond

The storage pond for the oasis irrigation is a big one. The design parameter is the storage capacity that must be equal to the return storage water from the greenhouse heating system for three nights (Said, 1997). With permission of the government this type of storage pond was installed. The oasis level is lower than the main geothermal installation. The geothermal tank is designed as a buffer one; it has to be designed for emergencies to cover at least the longest heating durations in case of well pump failure, and also to supply peak heating loads, allowing for up to double the greenhouse area, currently limited by peak flow. The longest heating duration corresponding to the critical cold period is 16 hours.

4. DESIGN OF THE PROJECT CONTROL SYSTEMS

In this section we study the **geothermal supply control system devices** i.e. the way in which the control valve and variable speed pump control the rate of flow passing through it. The design of each of them determines their sizing coefficient. This sizing parameter is also called valve or pump flow rate coefficient, K_v for valve and K_p for pump respectively.

4.1 Heat flow control

For the **control valve** the flow rate is directly proportional to the pressure drop over it and the flow rate coefficient; thus:

$$q = K_v \sqrt{\left(\frac{dP_v}{G_w}\right)} \tag{20}$$

where q = Liquid flow rate (l/s);
dP_v = $P1$ - $P2$, actual pressure drop across the valve is equal to the inlet pressure minus the outlet one (bar), $P1$: Upstream (inlet) pressure , $P2$: Downstream (outlet) pressure.

As shown in Figure 3, the control valve v_1 is in a control loop where the feedback comes from an inside greenhouse temperature transmitter. We create a closed loop flow control system with the control valve as its centrepiece, while the greenhouse heating temperature set point is given by an operator or in an advanced scheme by the main processing computer. The PI output control signal sets the flow rate over the control valve v_1 to achieve the ultimate controlled temperature. To keep an approximately constant supply pressure across the greenhouse complex, another control valve v_2 is implemented. This second control valve has a complementary control input of the control signal applied to valve v_1. The total fluid is then only slightly disturbed by the heating control loop. The valve characteristic is defined by the relationship between flow coefficient K_v and the valve opening. For our simulation study, we use the typical values of 9.8% increase in K_v for every 10% increase in opening (Hans, 1991). In such a case the characteristic can be assumed to be linear with good accuracy.

4.2 Production and demand flow control systems

4.2.1 Controlled pump

Energy costs associated with the operation of production well pumps constitute a large expense for many geothermal schemes (Culver and Rafferty, 1998) in direct use systems, particularly those serving variable flow requirements. As a result, an efficient means of controlling flow should be an integral part of these systems. There are three methods available for controlling flow; throttling pump output with a valve, varying the pump speed and intermittent pump operation with a storage tank. Throttling the output of the water handling device is simply dissipating energy through the addition of friction. This is an inherently inefficient approach to flow control. Intermittent pump operation can impose serious shock loads in the pumping system. When the means of the electronic speed control of an electrical motor became available in the mid-70's, a thought occurred: "Why not vary the speed or number of revolutions of pumps in order to control the flow rate of liquids in process control systems?". Since then, many applications of this technique have taken place in geothermal utilities. The use of the variable speed drives leads to satisfactory results. It can significantly increase pump life and save energy. The well pump referred to in our project is designed as a controlled variable speed one. This has, in our control system design, a double effects: on one hand, the control of the tank level and saving pump energy consumption and on the other hand, the slowing down of the pumping rate is a security measure for the pump and the well when drawdown occurs. The well pump Floway 8JKH was chosen, having a 30 l/s flow rate at maximum efficiency (Figure 9). A variable speed centrifugal pump "P2" has been selected for transporting geothermal water along pipe 1. This pump is the centerpiece of the control loop dealing with increasing or decreasing water flow according to oasis and greenhouse demands. The designed maximal flow rate of pump P2 is defined by the system load and is 30 l/s. For the line shaft turbine well pump, the dynamic speed expression is:

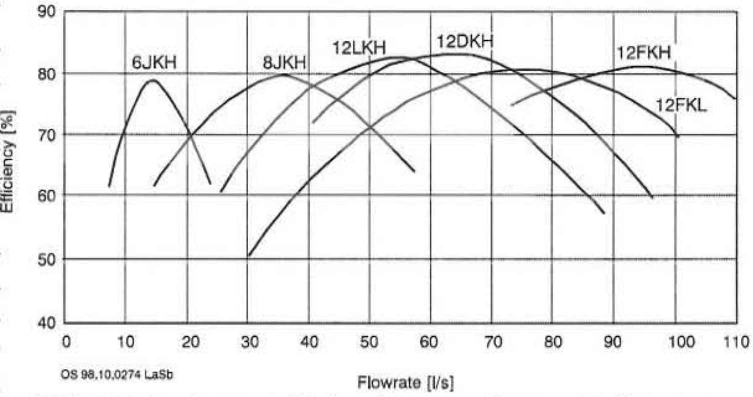

FIGURE 9: Pumps efficiencies according to the flow rate

$$\frac{dn}{dt} = \frac{(Trm - Trl)}{Imp} \tag{21}$$

where n = Actual production pump speed;
Trm, Trl = Motor and the pump torques, respectively (Nm);
Imp = Combined inertia of motor and pump.

As can be seen above, the flow rate "q" is dependent on the actual pressure drop, P_{drop}, across the pump

$$q = K_p \sqrt{\frac{P_{drop}}{G_w}} \tag{22}$$

P_{drop} can be simply defined as

$$P_{drop} = dP_{noflow} - dP \tag{23}$$

where dP = Actual pressure over the pump.

At zero flow, the pressure rise over the pump is:

$$dP_{noflow} = P_{rated}\left(\frac{n}{n_{rated}}\right)^2 \tag{24}$$

where P_{rated} = Pressure across pump at rated speed and zero flow (Pa);
n_{rated} = Rated pump speed.

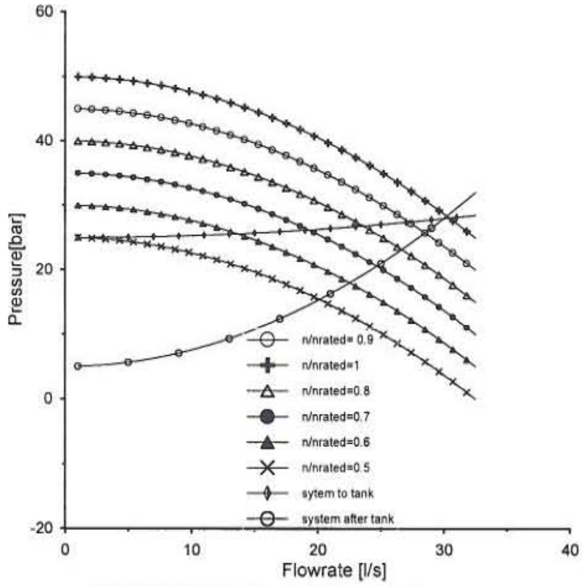

FIGURE 10: Variable speed pump and system characteristics

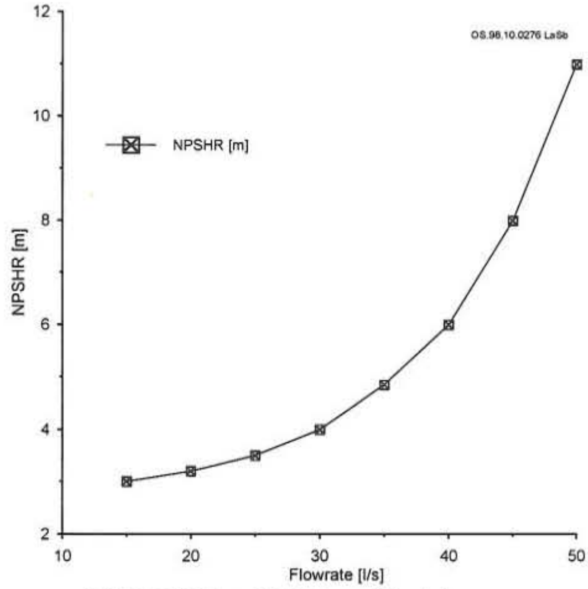

FIGURE 11: $NPSH_R = f$(minimum submergence heigh)

In Figure 10, the effect of variation of pump speed n for a constant rated speed on the pump characteristics is illustrated as well as the two system characteristics relative to the tank and the distribution installation.

4.2.2 Minimum submergence (h_{min})

The minimum pump submergence height model is given in Equation 25 (Gunnarsson, 1998). The geothermal water used in the case referred to, is from a low-temperature area (20-90°C). The conditions satisfying the temperature range application of the equation $T \leq 100°C$

$$h_{\min} = \frac{P_{boil} - P_a}{\rho_T g} \times 10^5 + (NPSH_R + h_w) G_w \tag{25}$$

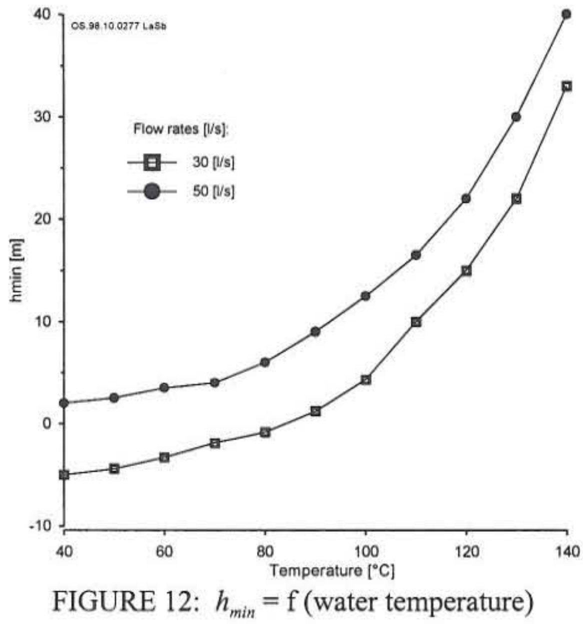

FIGURE 12: h_{min} = f (water temperature)

where P_{boil} = Boiling pressure of pumped water (bar);
P_a = Atmospheric pressure (bar);
ρ_T = Density of water at temperature T (kg/m^3);
$NPSH_R$ = Net positive suction head required (m/s);
h_w = Pressure losses in bowl suction case (m/s) (usually h_w can be neglected);
T = Temperature of pumped water.

To demonstrate the influence of water temperature on h_{min}, for the selected Floway pump 8JKH, first it is necessary to determine the $NPSH_R$ as a function of flow from its performance curves, as seen in Figure 11. Next, h_{min} was calculated as a function of temperature, by using Equation 26 (h_w is assumed zero), for two flow rates (see Figure 12).

From Figure 12 it can be calculated that when water temperature is equal to 60°C, then the water level in the well can be 4 m below the suction case of the pump (suction pipe used) if the flow is ≤ 30 l/s, but 3 m above suction case when the flow is 50 l/s. If water temperature is 130°C and flow 50 l/s, then the submergence must be at a minimum of 30 m. In fact, we measure the water level in the well "*transmitter Ltw*" (Figure 3) and if a drawdown occurs, a control loop actuates the speed of the well pump to slow it down. When the well level is below h_{min} it causes the pump to cavitate then the pump must be stopped. In this case an alarm is generated and the response of the well must be studied. The reserve water in the storage tank and the pond must be used efficiently.

5. SIMULATION OF THE CONTROL SYSTEMS

5.1 Short description of the ACSL simulation language

With the development of digital computers in the late 1960's and the growth in capacity of the mainframe, digitalization became the primordial technique for simulating continuous systems. In 1980's, digital simulation spread to mini and microcomputers, enabling us to use the same simulation language that once was only available on mainframes. The simulation languages are generally classified into two groups: those for continuous systems and those for discrete systems. For example, on one hand DYNAMO is one of the simulation languages for continuous systems and on the other hand we can find GPSS and SIMAN which are mainly for discrete systems. However, most of the recent simulation language versions tend to handle both discrete and continuous systems. For our simulation work, the advanced continuous simulation language ACSL was chosen which can easily handle the continuous and discrete systems together. In this paper, we are dealing with the simulation of the control of a continuous process using discrete control systems by means of ACSL language. In order to make the algorithmic parts in this work understandable, the structure of the ACSL simulation program is shown in Figure 13.

5.2 Model of the control algorithms

5.2.1 The PI controller

When the different process environmental set points have been entered, the controllers (PI) start manipulating the signal outputs to the actuators to achieve the desired set points. Unfortunately, as the number of inputs of the control system grow, analog devices become cumbersome and complicated. Thus, computer control systems are more flexible in this regard. However, most of the signals from the sensors and to the actuators are continuous and must be converted from and to digital computer data

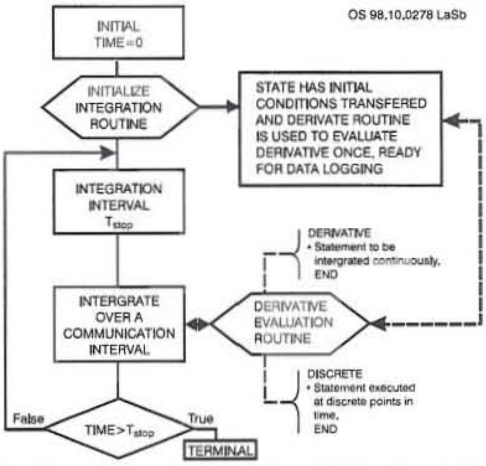

FIGURE 13: Simplified representation of the ACSL simulation language structure with time dependance

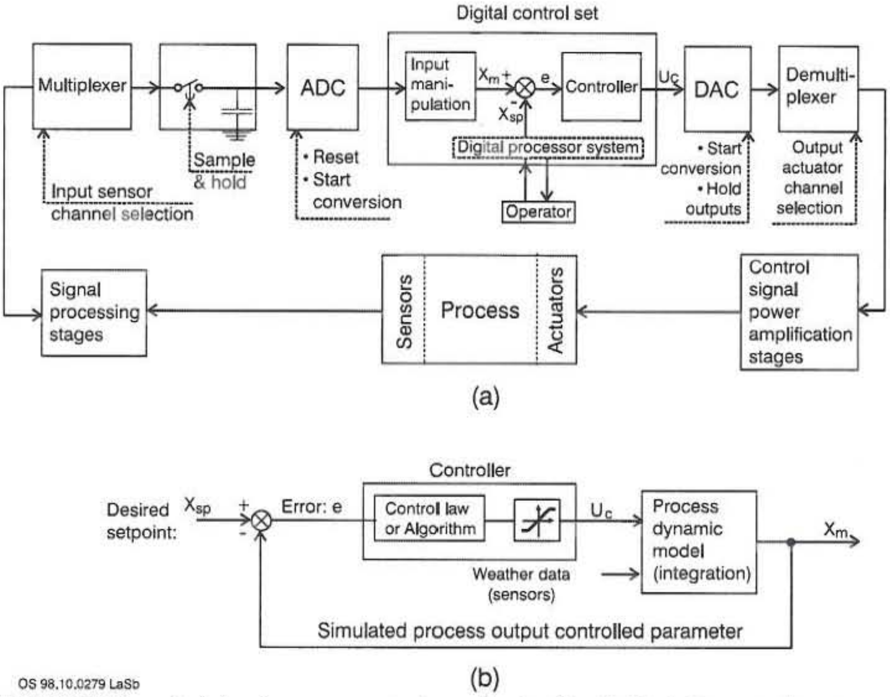

FIGURE 14: a) A basic representation of a feedback digital control system; b) Example of dynamic simulation of a closed-loop process control system

form. Since a numerical processor system is employed to do the integration of the plant models and control the parameters, the input and output data are processed at a sampling rate. In simulation of control systems, the data from the sensors and those to the actuators are assumed to be converted respectively by an analog to a digital converter (ADC) and a digital to an analog one (DAC). When the sampled signal has been stored and manipulated in the control scheme, then it must be output in a fashion to operate, for example a hot water control valve, a speed variable pump or a motorised greenhouse air conditioning device. This will require more than the analog/numerical converters. A power amplifier stage is needed to get the necessary voltage or current level to drive the control actuator. With the speeds and capacities of present numerical machines, the actions are, to the human observer, instantaneous. One can diagram this system as in Figure 14a, showing sensor, ADC, computer with operator input, DAC, power amplifier stage, and actuator. The control operational level of Figure 14b has been extended to show a typical closed-loop control system with one unit as the processor or plant. In this, the digital control system compares the sensor input to set points in memory [introduced by the operator). An error is then calculated as the difference between the values of the set point and the measured one. This error is applied to the PI discrete controller. The controller produces an output control signal to the actuator in a way that brings the environment back to the desired values (signal error is kept near zero).

As shown above, the PI controller used in a digital system must be discretized in order to be implemented in a computer. Here the continuous controller will be discretized into a digital form that suits computer implementation. In continuous controller design, the PI model is

$$u_c(t) = u_0 + K_{cont} e(t) + \frac{1}{T_i} \times \int e(t)\,dt \tag{26}$$

where K_{cont} = Controller gain;
T_i = Integral time;
$e(t)$ = Difference between set poin X_{sp} and measured value X_m.
u_0 = Bias value that will give the controller its proper average signal amplitude.

Therefore, the discrete model form of the PI controller is:

$$e(kh) = X_{sp} - X_m(kh) \tag{27}$$

$$U_c(kh) = U_0 + U_p(kh) + U_I(kh) \tag{28}$$

h is the sampling period, assumed to be constant. Signal variations during the sampling interval are neglected. The proportional part of the controller is:

$$U_p(kh) = K_{cont} \times e(kh) \tag{29}$$

The integral part is approximated by finite difference and given by:

$$U_I(kh) = U_I(Kh-h) + \frac{K_{cont}h}{T_i} e(kh) \tag{30}$$

The integral part forms a recursive expression, i.e. it is updated at every sampling interval. Note that the last term may be small if h is small and T_i large. Therefore, the word length has to be sufficiently large, so that the term $(K_{cont}h/T_i)$ can be expressed with sufficient precision. In addition the output signal is held within given limits.

5.2.2 ON/OFF control

The On/Off or two position control is the most common and least expensive system to install. In this kind of control, the actuating element has only two fixed positions which are, in many cases, simply on and off. Here it is used for the control of the cooling tower fans and in the evaporative cooling system in the greenhouse. In this case, the individual units are staged over a parameter range that is sufficiently wide to prevent continuous on/off operation - otherwise the wear and tear on the equipment is severe. There are many situations requiring on/off besides temperature control. Ventilator positioning, screen positioning, CO_2 injection, etc. are among the candidates. Note that the set points between heating and cooling are almost invariably partially separated. This is to avoid simultaneous heating, CO_2 injection and ventilation except in the interest of reducing humidity. The temperature lift that may be allowed between heating and cooling varies with the system and plant species. In warmth-requiring crops, temperature might be allowed to rise more than 5°C before cooling begins. A warm environment with high humidity may cause difficulty in labour efficiency.

Let the output signal from the controller be $U_{on/off}$ and the actuating error signal be $e_{on/off}(t)$. Then, $U_{on/off}$ remains a maximum (M1) or minimum (M2) value, depending on whether the actuating error signal is negative or positive, so that: $U_{on/off}(t)$ =M1 for $e_{on/off}(t)>0$, and $U_{on/off}(t)$ =M2 for $e_{on/off}(t)<0$. This control operation must be attentively manipulated according to the error acting range. The range through which the actuating error signal must move before the on or off switching occurs is called the differential gap. Such a differential gap is a specially needed to avoid too frequent operation of the on/off mechanism around the zero error signal.

5.3 The project control systems simulation algorithm

5.3.1 The project simulation method

The dynamics of the geothermal system from the control point of view, is mainly due to the response of different parts of the system to changes in the hot water flow rate and due to external conditions such as weather. This flow rate is very significant for the geothermal well characteristics and for the use of the transported energy by means of heat transfer and for the pressure dynamics over the system components. Unfortunately, the cooling tower causes a fatal waste of energy and pure water (evaporation estimated between 7 and 10%). The cascading of the greenhouse project with the cooling tower, therefore, makes good use of energy otherwise wasted. The simulation method we used here deducts the water flow from integration of the system characteristic in a dynamic way. This means, that each component of the whole installation and especially the actuators, cause change in the system dynamics in each calculation step. The flow rate in each part of the system is then indirectly deducted using the installation previous step state points. Let's have a look at the different calculation procedures of the dynamics of the whole system. The hot water system can, from a control point of view, be separated into two subsystems. On one hand, the well and the tank, and on the other hand, the water from the tank into the oasis and greenhouses. As is illustrated in Figure 13, for the control algorithm the iterative simulation method has been used. The calculation of different flow coefficients is presented below

Section B-C: Here we have the recirculating pump "P1" characterised by a flow coefficient K_{pl}.

$$K_{pl} = \frac{q_t}{\sqrt{\dfrac{dP_{noflow} - dP}{G_W}}} \tag{31}$$

For rated speed and corresponding flow rate we have all the data to calculate the K_{pl} coefficient.

Section C-D and E-F: The two pipes are designed for the maximum flow rate as can be seen in Section 3.5. For pipe 1 and pipe 2 we have $Kv_{pipe1} = 34.6$ $Kv_{pipe2} = 54.7$, respectively.

Section D-E: This section is composed of a greenhouse heating system and two control valves. Control valve v_2, is parallel with control valve v_1 which is in series with the Tichelman heating system. Let's say that the heating system has a flow coefficient Kv_{Heat}. For this series connection (heating system +control valve v_1) the flow coefficient Kv_{SYS} is defined as:

$$\frac{1}{Kv_{SYS}} = \frac{1}{Kv_{Heat}} + \frac{1}{Kv1} \tag{32}$$

The parallel section D-E has a combined flow coefficient Kv_{DE} as:

$$Kv_{DE} = Kv2 + Kv_{sys} \tag{33}$$

The pressure drop across the greenhouse Tichelman heating system for a greenhouse complex of 94 plastic (504 m^2 ground area) tunnel type greenhouses (Said, 1997) is estimated $dP_{Heat} = 0.08$ bar and $dPv_1 = 0.02$ bar for control valve1 for a flow rate of 25 l/s. We get $Kv_{Heat} = 88.39$, $Kv1 = 176.78$ and $Kv2 = 15.82$ for 25 l/s through v_1 when the pump P1 flow rate is 30 l/s. The control valves v_1 and v_2 are identical and at 70% opening they are handling 25 l/s. We can then deduce the maximum control valve flow rate coefficient; $Kv_{max} = 251.43$. As each control valve is supposed (as seen in Section 4.1) to have a linear characteristic, then the flow rate across each of them is:

$$Kv1(2) = Vv \times Kv_{max} \tag{34}$$

where Vv is the control parameter of the flow through the valve, and varies between 0-1.

System characteristic: The total flow rate in the system from point A to F is

$$q = Kv_{Total}\sqrt{dP_{Total}} \tag{35}$$

where

$$\frac{1}{Kv_{total}} = \frac{1}{Kv_{pl}} + \frac{1}{Kv_{CD}} + \frac{1}{Kv_{DE}} + \frac{1}{Kv_{EF}} \tag{36}$$

and

$$dp_{total} = P_{noflow,n} + H_t - H_{CT} - (dP_{Heat} + dP_{vl}), \quad with\ P_{noflow,n} = P_{rated}\frac{n}{n_{rated}} \tag{37}$$

where H_t and H_{CT} = Heights of the tank and of the cooling tower, respectively;
dP_{Heat} = 0.08 bar;
dP_{vl} = 0.02 bar as the control valve v_2 maintains approximately the pressure drop over the greenhouse tap/off constant at P_{v2} = 0.1 bar.

At point D, the total flow rate q is the sum of the partial flow rate q_1 through control valve v_1 and q_2 through control valve v_2

$$q = q_1 + q_2 \quad with \quad q_1 = \frac{Kv_{sys}}{Kv2}q_2 \tag{38}$$

For the production well and tank side, the system is composed of the well variable speed pump and a 1 km pipe line with a 5 m height difference. The same procedure as described above is then used, with one closed loop control for the well flow rate, by controlling the pump production speed.

6 SIMULATION RESULTS AND DISCUSSIONS

A complete simulation program was performed to predict the evolution of the control systems used for the geothermal project. The simulation algorithm scheme of the whole geothermal exploitation project is illustrated in Appendix I. Many results are available and could be extracted as exploitation of the simulation runs is oriented towards a specific problem. In this section, we limit ourselves to the main specific parameters we studied to envisage the control system time variation behaviour.

6.1 Study of the effects of different climatic control mechanisms in a greenhouse

In this section, the control of the greenhouse climate in Figure 15 is discussed. Figure 15a shows the outside climate conditions for a typical measured data. These conditions correspond to typical weather between the cold period and the hot one.

In the present report the dynamic climate behaviour of the greenhouse was studied as a production unit which is characterized by a thermal and biological environment leading to a heat and mass exchange through the structure of the greenhouse. The mass and heat transfer are related to processes such as crop

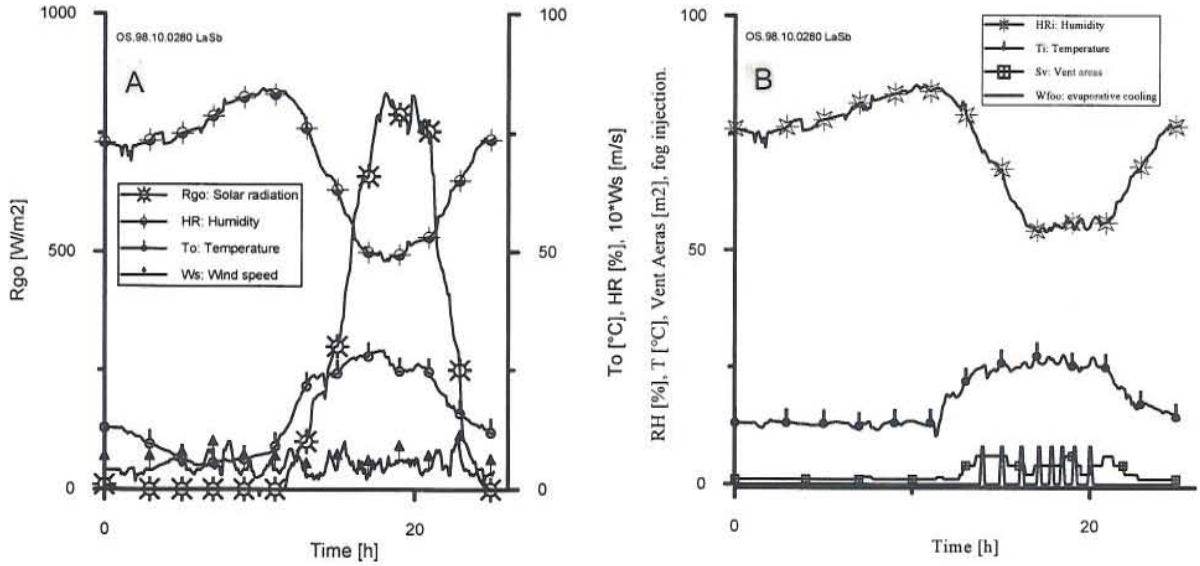

FIGURE 15: a) Outdoor climate; b) Indoor control climate

transpiration, natural ventilation, geothermal water heating, and evaporative cooling under the effect of external conditions. The "simulation run" means the time variation of the modelled parameters. The inside climate which was modelled is characterized by the humidity and temperature of the air inside the structure. The variation of these parameters is supervised by the control system. The greenhouse control system design is a technical and economical constraint, therefore, it has to be simple and realistic. In this respect, a *PI* controller is used to control the nocturnal temperature in the cold period as is presented in Figure 3. This temperature control is designed for a complex of greenhouses as a lumped model. The hot water is supplied to the radiators through the control valve. The data for the external factors (wind speed, relative humidity, outside temperature, etc.) is registered by a weather station located not far from the greenhouse complex area. Figure 15a illustrates the outside weather data measured in the southern part of Tunisia characterized by an oasis microclimate. This figure represents the outside humidity, temperature, wind speed and solar radiation variations. These parameters can be considered as model perturbations. For cooling the greenhouse and controlling the inside humidity, ventilation and evaporative cooling were used as control parameters. The control simulation algorithm is presented in Appendix II. An On/Off controller was used to control the aeration and evaporative cooling process. For the same input weather data, the controlled climate of the indoor temperature and humidity were simulated. The variation of these two parameters is also illustrated in Figure 15 with the reaction of the controller on the ventilation opening and evaporative cooling injection. The simulation was performed for 24 hours starting at 6 o'clock p.m (corresponding to 0.0 in the time scale of the simulation plot). As shown in Figure 15b the indoor temperature variation for a cool night (around 5°C) was controlled for a desired set point (13°C) by the PI controller of the system. The wind speed variation has a significant influence on heat loss through the cover generating a small variation due to the delay in the heating system response (geothermal water). Ventilation is simulated with an offset due to leakage through the greenhouse plastic cover. This causes latent and sensible heat loss according to ventilation flux, even though the openings are closed. According to the simulation results it can be seen that the greenhouse works as a solar collector. The indoor climate is an amplification of the outdoor weather condition. The variation of the humidity and the temperature inside and outside follows almost the same shape. The inside controlled parameters are limited by the outside conditions in the ventilation cooling system. In this way, the evaporative cooling is an additive process having a favourable effect in conditioning both humidity and temperature variation. The air inside the greenhouse in the semi-arid zone and in the hot period is characterized by a high water vapour deficit which effects the transpiration process of the crop. The evaporative cooling process is demonstrated as being the only solution for decreasing water vapour deficit. During the day, under the solar radiation effect this evaporative cooling must be used with natural ventilation in the control process to avoid an increase in temperature inside the greenhouse above the set point value. Figure 15b represents these two control parameters of the ventilation openings and the evaporative cooling injection.

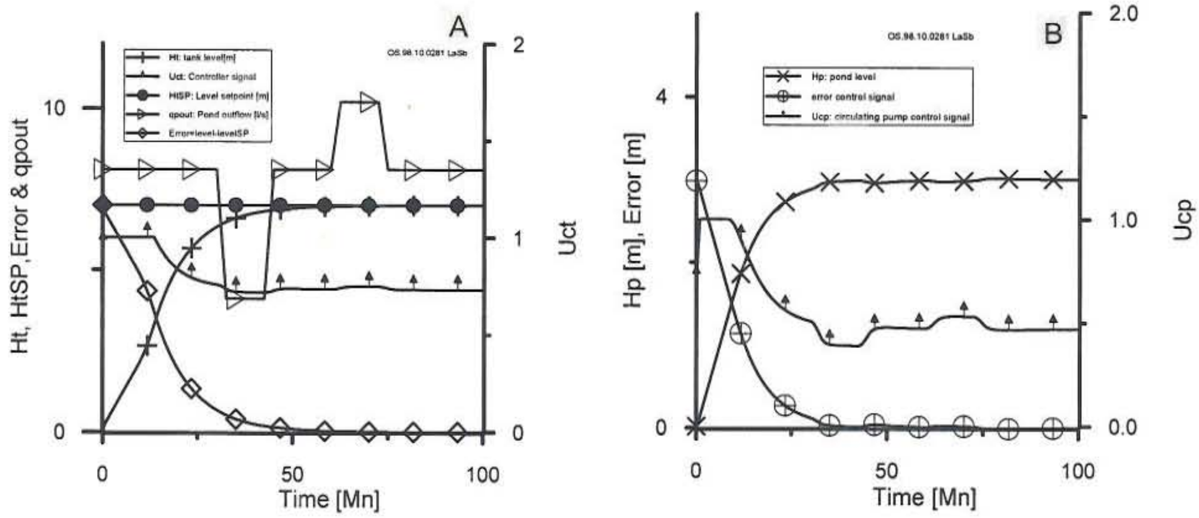

FIGURE 16: a) Water production control; b) Water demand control

6.2 Water flow rate control

The simulation of the control systems for the whole geothermal project is considered here. The main control actions can be illustrated as the control of: the geothermal water production flow rate, the water demand flow rate, the heating control of the greenhouse and the cooling tower outlet temperature. Thus, the following paragraphs focus on the aspects of the regulation of the whole process.

6.2.1 Interconnection of production and demand control

From the control point of view the design of the production and the water demand installation can be divided into two subsystems. As is shown in Figure 3, the buffer tank acts as a divider between the production system and the water distribution system. In Figure 16 the water flow control in these two subsystems is represented. In Figure 16a, a water demand fluctuation is applied as a system perturbation. The production system *PI* controller reacts by a control response of the well variable speed pump. The same figure illustrates the signal of the control error of the tank level due to the water demand. Figure 16b represents the response of the water demand control system. According to the same water demand fluctuation the signal from the controller is applied to the variable speed circulating pump (Figure 3). The storage pond level response is more sensitive in this regard than the well-buffer tank. The same figure illustrates the variations of the controller response error showing the more significant fluctuations that affect system response around the set point.

6.2.2 Installation water flow demand control

Here, are presented the simulation results of greenhouse heating and oasis irrigation water demand. Figure 17a and b present the time variation of the system state variables cooling tower outlet temperature, the storage pond level, the greenhouse indoor temperature and the different water flow rates. In the same figure are illustrated the control parameter variations and effects on these variables. In order to show clearly the evolution of the different parameters according to each other from one state point to another, the figure presents the evolution from start up to a final state of the system. This system state is defined by an oasis water demand of 10 l/s, a set point of the greenhouse indoor temperature of 15.2°C, storage pond level at 3 m, and cooling tower outlet temperature of 27.3°C. Holding up the indoor temperature under the influence of an external temperature of about 6°C, results in peak load water demand of 23 l/s for the greenhouse complex heating. The cooling tower control process starts one fan to increase the heat exchange coefficient until the outlet temperature goes below about 30°C. Then the fan stops and natural air circulation of the cooling tower decreases this temperature further with a smooth slope.

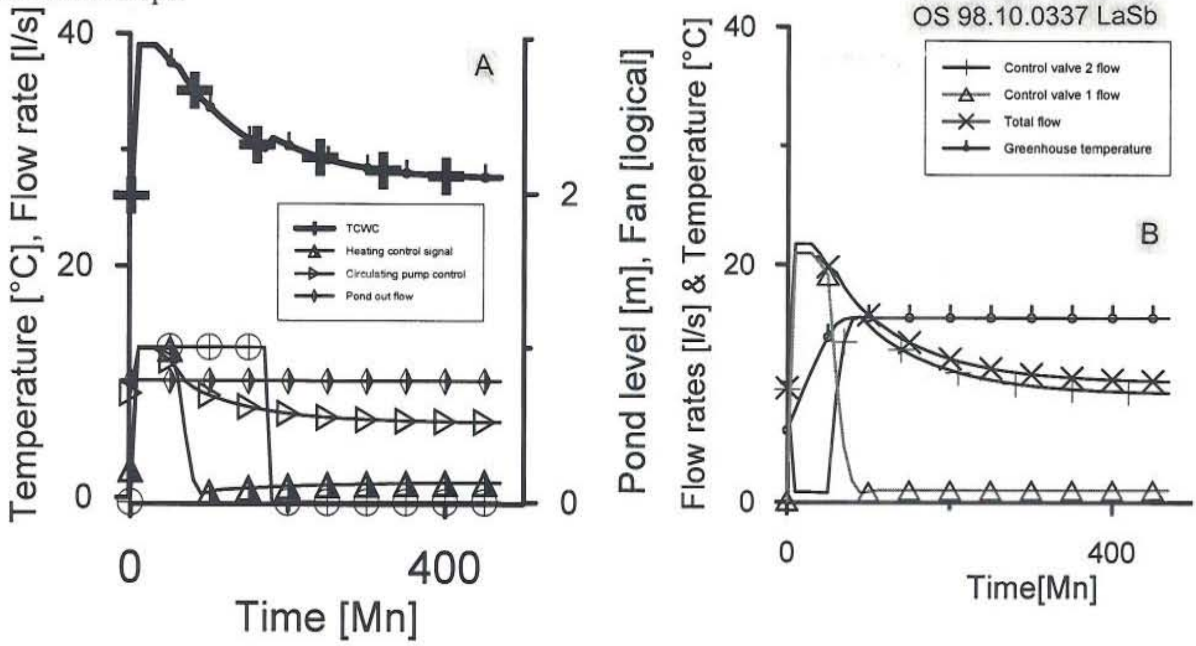

FIGURE 17: a) Control output and cooling tower water outlet response;
b) Flow rate control and greenhouse indoor temperature response

7. CONCLUSIONS

In this report, it has been shown that process controls can play an important role in a greenhouse and oasis irrigation project using geothermal resources. They are rather complex technological systems whose behaviour can hardly be studied fully without the aid of dynamic simulation models. It is also clear that process control of such a complex geothermal installation greatly benefits from the use of modern control systems, solid control knowledge and engineering developments. This is because the process is an interconnected large scale one with distributed elements, nonlinear elements and a complex network. One of the key findings of the simulation work described in this paper, is that the greenhouse area could potentially be doubled through the addition of a buffer tank and suitable control equipment.

Solving technical problems in large geothermal installations requires considerable research and developmental effort. Advanced control principles should be applied if one is to ensure the most efficient utilisation of the geothermal energy resources. Moreover, certain processing controls (greenhouse climate, resource distribution) are not solvable without the use of sophisticated methodologies. As far as technical implementation is concerned, efficient measurement, signal and information processing, computing and actuator technologies ought to be used. A whole range of modelling, simulation and identification, as well as experimental studies have to be carried out. It is believed the most adequate approach for the development of processing controls in a geothermal project would be a top-down implementation with extensive use of computer aided techniques. In a large geothermal utility installation of this kind, including cascaded uses of geothermal energy, a distributed computerized control system with an integrated information base and multilevel organisation of control functions should be envisaged.

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APPENDIX I: The control algorithm scheme of the whole geothermal exploitation project

PROGRAMME Control systems simulation of :
The geothermal production well - Buffer tank - Water distribution installation - variable speed water flow control pumps, control valves -greenhouse climate control - cooling tower- oases storage pond
Simulation Programme initialisation:
set: integration and output (print, plot) step values
set: integration interval
set: integration numerical method algorithm (Rung-Kutta order 4)
Input control set points: Level tank (Htsp), level pond (Hspsp), indoor greenhouse climate (temperatures: $T_{ispnight}$ T_{ispday} ,$HR_{ispnight,}HR_{ispday}$), cooling tower outlet water temperature (T_{CTwo2} and T_{CTwo1})
initial of integration conditions: Buffer tank level (HtIC), storage pond level (HspIC)
initial controller parameters: e(h=0) , U_c(h=0)
input data: Water temperatures, weather data
water vapor characteristics

Variable speed deep well pump P1:
A variable speed pump used to control the production well flow to the Buffer tank
Pump characteristics: Power, efficiency, rated speed and pressure
Controller output (U_{ct}): PI buffer tank level regulation
Limitation of U_{ct} : $(n/n_{rated})_{no\ flow}$ - 1
Set control signal to the pump: $n/n_{rated} = U_{ct}$
calculation of; the flow rate coefficient: K_{vp1} and the pressure drop $P_{drop,P1}$
calculation of the outflow pump P_1: q_{p1}

Define the buffer tank level plant
tank characteristics; Area (At), maximum level (Htmax), minimum water level (Htmin)
Well tank system characteristic (definition of $(n/n_{rated})_{no\ flowP1}$)
Net tank inflow: Intank $=q_{p1}$
Net tank outflow: outtank $=q_{p2}$
Net storage pond water flow (Netflow)
Netflow = Intank - outtank
Actual water height of the tank (Ht)
Ht = INTEGER(Netflow,HtIC)/At
Tank level control loop
Actual tank level error: e_t =Htsp - Ht
call tank PI algorithm; update the controller output value (Uct) to the pump P1

Variable speed circulating pump P2:
It is a variable speed pump controlling the water demand flow (greenhouses and oasis)

Pump characteristics: Power, efficiency, rated speed and pressure
Control output (U_{cSP}) of the PI storage pond level regulation
Limitation of U_{cSP} between $(n/n_{rated})_{no\ flowP2}$ and 1
Set control signal to the pump: $n/n_{rated} = U_{cSP}$
calculation of; flow rate coefficient (K_{vp2})
q_{p2}: outflow pump P_2

Greenhouse "Tap-Off": Control valves v_1 and v_2
Control output (U_{cHeat}) of the PI greenhouse geothermal water heating system regulation
Limitation of U_{cHeat} between 0 and Vv_{max}
Set control signal to the Control valve v_1
$K_{v1} = U_{cHeat}$
Set control signal to the Control valve v_2
$K_{v1} = 1 - U_{cHeat}$

Calculation of the system characteristics
calculation of control valve flow rate coefficients
  valves' pressure drop; dP_{v1} and dP_{v2} at operational flow rate
  Calculation of valve characteristics ; Kv1max, Kv2max
  Calculation of control valves actual flow rate coefficients;
  $Kv1 = Vv_1$*Kv1max, $K_{v2} = Vv_2$*Kv2max
calculation of transport pipes flow rate coefficients
  Characteristics of the pipes; Length, diameter, material, height, path.
  Calculation of pipe flow rate coefficients;
  Pipe1; Kv_{pipe1} and Pipe2; Kv_{pipe2}
calculation of greenhouse complex heating system flow rate coefficients
  Heating system pressure drop; dP_{SYS}
  Calculation of actual greenhouse heating flow rate coefficient: Kv_{SYS}
Hot water installation system characteristic
  The total flow rate coefficient; Kv_{total}
  Total flow rate calculation q_t
  Hot water installation system characteristic (definition of $(n/n_{rated})_{no\ flowP2}$)
Control valve flow rates
  partial flow rate coefficient; Kv_{12}
  Calculation of q_1 (v_1) And q_2 (v_2)

Defining the storage pond level plant
Storage pond characteristics; Area (A_{SP}), maximum level (H_{SP} max), minimum water level (H_{SP} min)
Net storage pond inflow: Inpond = qt
flow rate oasis coefficient Kvoasis
maximum oasis flow rate: qaosis
Net storage pond outflow: Outpond = Kvoasis*qoasis
Net storage pond water flow (Netflow)
Netflow = Inpond - Outpond
Actual water height in the storage pond (H_{SP})
H_{SP} = INTEGER(Netflow,HspIC)/A_{SP}
storage pond level control loop
  Actual level pond error: esp =H_{SP} sp - H_{SP}
  call storage pond PI algorithm; update the controller output value (UcSP) to pump2

Define the geothermal water greenhouse heating dynamic plant
pipes heating radiator characteristics: pipes area per metre (Apipe), heat exchange global coefficient Kpipe, number of loops(NL) and total length per greenhouse (Lpt)
Calculation of the water radiator greenhouse heat gain Q_{Heat}
Control heat parameter q1(Kv1 = U_{cHeat})

Hot water inlet $T_{Heat,in}$
greenhouse heat gain calculation: Qheatand Heating pipes outlet temperature $_{Theat,out}$

Define the greenhouse dynamic climate plant
Greenhouse dynamic model:
model outputs: e_i and T_i and calculation of HR_i
The nocturnal temperature is regulated by PI (see control valve v1)
The aeration and evaporative cooling controlled by a on/off action (algorithm same as Cooling tower):
end *of the greenhouse dynamic climate plant*

Define the cooling tower water dynamic plant
Inlet cooling tower water temperature, T_{CTwi}:
Vv_1>0.5 then $T_{CTwi}=T_{Heat,out}$ else $T_{CTwi}=T_{Heat,in}$ (pipes heat loss)
Calculation of the wet bulb temperature of the surrounding atmospheric air $T_{o,wet}$
Cooling tower Ventilation coefficients according to the fan controls:
one fan activated: $k_{fx}=k_{f1}$, two fans activated $k_{fx}=k_{f2}$
calculation of the global water/air heat exchange coefficient $K_{CTi} = k_{fx}*K_{CT0}$, (K_{CT0}: without fan)
Integration of the cooling tower outlet water T_{CTwo}
Cooling tower outlet water temperature control loop
actual one fan acting error: $e_{CT1} = T_{CTwosp1} - T_{CTwo}$
actual one fan acting error: $e_{CT2} = T_{CTwosp2} - T_{CTwo}$
Error acting air gap: ΔT_{CTw}
Cooling tower On/Off controller: update the cooling tower heat exchange global coefficient.
(We suppose the two fans are swished using a simple logic gate to only put one fan in the same time)
IF $e_{CT2} > 0$ THEN set fan2 with air gap ΔT_{CT} : $K_{fx} = K_{f1}$ ELSE fan2 off
IF $e_{CT1} > 0$ THEN set flags fan1=1 with air gap ΔT_{CT} :$K_{fx} = K_{f2}$ ELSE fan1 off :$K_{fx} = 1$.

END

APPENDIX II: The PI controller performances and algorithm

1. The controller performances

a. Control systems sampling rate: It is not trivial to choose a suitable sampling rate for control; in fact, finding the right sampling frequency still remains more of an art than science. A too long sampling period can reduce the effectiveness of a control loop. In an extreme case, if the sampling period is longer than the process response time, then a disturbance can affect the process and will disappear before the controller can take corrective action. Thus, it is important to consider both the process dynamics and the disturbance characteristics in selecting the sampling period. There is an economic penalty associated with sampling too frequently, since the load to the computer will increase. Consequently in selecting the sampling period one has to consider both the process dynamics and the computer capacity at disposal. Commercial digital controllers which handle a limited number of control loops typically employ a fixed sampling period of a fraction of a second. Thus the performance of these controllers closely approximates continuos (analog) controllers. In control applications the signals are usually not periodic and the computational time for reconstruction is limited. Therefore the sampling time has more constraints. Many additional rules for the choice of the sampling rate can be found in the control literature. Obviously, the more rapid the sampling clock signal, the closer the digital representation comes to actual analog input. Fortunately, with the slow responses of the studied geothermal plant parameters, a sample interval of several seconds can be sufficient to adequately represent the continuous data. Generally, the rate of sampling should be at least twice the signal's highest frequency. This is a minimal rate, not necessary e.g. the optimum.

b. Control signal limitations: The controller output value has to be limited, for at least two reasons. The desired amplitude shall not exceed the DAC range, and can not become larger than the actuator range. A valve cannot be more than 100% open, or a motor current for the motorised actuators has to be limited. Thus, the control algorithm needs to include some limit function. In several control loops it is important to introduce some dead band. If an recursive controller is used, each increment may be so small, that it is not significantly larger than other disturbances. It is of interest not to wear out the actuators. Consequently the control variable increments are accumulated until the control signal reaches a certain value. Naturally the dead band has to be larger than the resolution of the used DAC.

c. Integral control windup: Windup occurs when a PI controller encounters a sustained error, for example, a large load disturbance that is beyond the capacity of the control equipment. A physical limitation of the controller output can make it difficult for the controller to reduce the error to zero. If the control error has the same sign for a long time, the integral part of the PI controller will be large. This may happen if the control signal is limited. Since the integral part can become zero only some time after the error has changed sign, integral windup may cause large overshoots. Note that windup is a result of a non-linear element (the limiter) in the control circuit and can never occur in a truly linear system. The integral part of the PI controller is proportional to the area between the step response and the reference value. The areas provide either positive or negative contributions to the integral term depending on weather the measurement is below or above the set point. As long as the error is positive the integral term increases. Similarly, as long as there is no control signal there is no windup. When the control signal is limited, then the response is slower and the integrator will increase until the error changes sign. Even if the control error changes sign, the control signal is still large and positive which leads to the large overshoot of the system response.

One way to limit the integral action is by conditional integration. The basic rule is that the integral part is not needed when the error is sufficiently large. Then the proportional part is adequate, while the integral part is not needed until the error is small. In that instance it is used to remove the steady-state errors. In conditional integration the integral part is only executed if the error is smaller than a prescribed value. For large errors the PI controller acts like a proportional controller. It is not trivial, however, to find in advance the proper error. In digital PID controllers there is a way to avoid windup. The integral part is adjusted at each sampling interval so that the controller output will not exceed its limits.

d. Controller bumpless transfer: In the control operational level, the controller has the option to be shifted from manual to automatic mode. When it is shifted the controller output may jump to another value even if the controller error is zero. The reason is that the integral part of the controller is not zero. The controller is a dynamic system and the integral part represents one state that has to be known at all regulator mode changes. The sudden jump of the controller output can be avoided and the transfer is then called bumpless. The main feature in all bumpless transfer schemes is to update the integral part of the controller to such a value that the control signal is the same immediately *before* Uc(t+) and *after* Uc(t-) switching.

e. Controller rate-of-change limiting circuit: In many systems it is necessary to include circuits to limit the amplitude or the rate of change with the output control signal. For example a change of the set point can be supplied with a limiting protection. This is common practice, for example, in pump electric drive motors, a rate limiting function is obtained by a simple feedback system.

2. The controller algorithm

An illustration of the *PI* controller algorithm is here presented in the ACSL code. The control algorithm is executed at each sampling interval. An anti-windup, rate of range limiting and control output signal limitations features are added to the integral term. The core of the *PI* algorithm is as follows:

```
!----XSP and X variable set point and simulated values
!--- the instant kh
e(kh) = XSP - X
discrete PI
INTERVAL h
!----Con troller parameters
CONSTANT K_cont , T_i
!----Initial calculation
cl = K_cont*h/T_i
!----Controller
!----Proportional part Up
Up = K_cont*e(kh)
!----Anti-windup correction
Ve = K_cont* e(kh-h) ; Vuc = Uc(kh - h)
V = Ve + Vuc
!----Control output incremental
!----INCmax and Ncmin are the limit of INCUc
CONSTANT INCmax , INCmin
INC = Up + INCI - Ve
!----Control output rate of range limitting
INCUc = BOUND(INCmax,INCmin ,INC )
!----Uc: control output and signal limitations
!----BB1 and TB1 are the limits of Uc
CONSTANT BB1 , TB1
U = V + INCUc + K_cont* e(kh-h)
Uc(kh) = BOUND(BB1,TB ,U )
!---------current error becomes previous error
e(kh-h)  = e(kh)
!----make control value available to continuous
!----Uc(kh-h) = Uc(kh)
END ! of discrete section
```