Centro de Investigación y de Estudios Avanzados
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Modelado de la Temperatura y Humedad Relativa de un Invernadero por Medio de Redes de Petri Fluidificadas

Tesis que presenta:

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Continuous Timed Petri Nets Greenhouse Temperature and Relative Humidity Modeling

A thesis presented by:

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Thesis Advisors:

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Resumen

En esta tesis se propone una metodología de modelado del comportamiento de la temperatura y humedad relativa de un invernadero usando redes de Petri fluidificadas. Las redes de Petri son una representación de sistemas de eventos discretos que se integra por lugares, transiciones, arcos y marcas dentro de los lugares. Las redes de Petri modelan sistemas positivos y pueden describir sistemas concurrentes. Las marcas se pueden interpretar como recursos presentes en el sistema. La fluidificación es una técnica en la cual el modelo de la red de Petri se relaja para obtener un sistema de estados continuos que se comporta de una forma similar a la red de Petri de eventos discretos.

El invernadero es un sistema no lineal positivo de múltiples entradas y múltiples salidas que esta sujeto a perturbaciones del ambiente externas e internas. Al ser un sistema positivo, las redes de Petri fluidificadas pueden modelar el sistema si se pueden representar con las semánticas actuales de las redes de Petri fluidificadas. Algunas no linealidades del sistema y las perturbaciones se agregan a la red de Petri.

Se realizó una simulación de identificación paramétrica para el modelo en redes de Petri a partir de un modelo reportado en la literatura que resultó en una buena representación del invernadero. El modelo obtenido de la temperatura y humedad relativa del invernadero con redes de Petri fluidificadas aporta una representación visual de variables y la interacción de las mismas. También, la influencia de los actuadores (que tiene un límite en la práctica) está acotado por el marcado de los lugares que representan cada actuador.

Abstract

In this thesis a methodology for greenhouse temperature and relative humidity modeling using continuous timed Petri nets is proposed. A Petri net is a representation of a discrete event system (DES) which is integrated by places, transitions, arcs, and tokens positioned inside places. Petri nets model positive systems and can describe concurrent systems. Tokens are usually interpreted as resources presence. Fluidization is a technique in which the Petri net model is relaxed into a continuous state system thata behaves in similar way as a discrete event Petri net.

The greenhouse is a non linear positive system with multiple inputs and multiple outputs which is subject to inside and outside perturbations. Since it is a positive system, it can be modeled with continuous timed Petri nets if the system can be represented with the current defined semantics. Some non linearities and the perturbations are added to the Petri net.

A simulation of parametric identification is carried out for the continuous timed Petri net model from a model found in the literature which resulted in a good representation of the greenhouse. The obtained continuous timed Petri net greenhouse temperature and relative humidity model provides a pictorial representation of variables and interaction between them. Also, the actuators inputs (limited in practice) are bounded by the place marking representing each actuator.

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Glossary

Acronyms

PN	Petri net
CPN	Continuous Petri net
ContPN	Continuous timed Petri net
IS	Infinite server semantics
PS	Product semantics
DES	Discrete event systems
RS	Reachability set

Variables

T_g	Greenhouse temperature
T_s	Soil temperature
T_{ss}	Subsoil temperature
T_p	Pipes temperature
$T_{p,in}$	Inlet pipes temperature
T_o	Outside temperature
T_r	Cover temperature
T_c	Canopy temperature
I_o	Global radiation
C_{H_2O}	Inside water vapor concentration
$C_{H_2O,o}$	Outside water vapor concentration
RH	Relative humidity inside the greenhouse
RH,o	Relative humidity outside the greenhouse
C_{CO_2}	Inside CO_2 concentration
$C_{CO_2,o}$	Outside CO_2 concentration

v	Wind speed

Functions

λ_i	Firing rate of transition t_i
m_i	Marking of place p_i. Used instead of $m(p_i)$
I_{c_i}	Represents the i-th input of the Petri Net
$q_{o,g}^{rad}$	Solar radiation aborsed by the greenhouse
$q_{g,o}^{vent}$	Heat exchange with outside due to ventilation
$q_{g,o}^{cond}$	Heat exchange with outside due to conduction
$q_{g,s}$	Heat exchange with soil
$q_{p,g}$	Heat supplied via the pipe system
$q_{g,h}$	Heat withdrawn by humidifiers
$q_{g,\tau}^{cons}$	Heat released due to condensation of moisute on cover
$q_{g,c}^{trans}$	Heat withdrawn by canopy evapotranspiration
$q_{s,ss}$	Heat exchange between soil and subsoil
$q_{o,p}^{rad}$	Solar radiation aborsed by the pipe system
$q_{boil,p}^{vent}$	Heat supply to the pipes by the boiler
$\mathfrak{C}$	Binary variable. Is one if water can be evaporated
E_c	Evapotranspiration rate of the canopy
$\varphi_{H_2O,h,g}$	Water vapor incremet by humidifiers
$\varphi_{H_2O,g,o}^{vent}$	Water vapor concentration exchange between inside and outside
$\varphi_{H_2O,g,r}^{cons}$	Water condensation at the greenhouse cover
$p_{H_2O}^{sat}(T)$	Water saturation vapor pressure at temperature T
T^C	Temperature in degrees Celsius
$k_{g,r}$	Condensation mass transfer rate
$\eta_{CO_2/dw}P$	CO_2 loss by canopy photosynthesis
$\eta_{CO_2/dw}R$	CO_2 gain by canopy respiration
$\varphi_{CO_2,g,o}^{vent}$	Outside and inside CO_2 exchange by ventilation
u_v	Air flow inside the greenhouse
u_v^{Aplsd}	Leeward side window percentage opening
u_v^{Apwsd}	Windward side window percentage opening
u_v^{ap}	Window opening

u_{hum}	Water flow given by the humidifier
u_{vent}	Fan percentage power
u_{CO_2}	CO_2 supply
$u_{CO_2}^{vp}$	CO_2 supply valve opening percentage

Parameters

K_g	Virtual greenhouse heat capacity of greenhouse
K_s	Virtual greenhouse heat capacity of soil
K_p	Virtual greenhouse heat capacity of pipes
ρ_a	Air density
$c_{p,a}$	Heat capacity of air
V_g	Greenhouse volume
A_g	Area covered by the greenhouse
$A_{g,o}$	Total area of the cover
$A_{g,s}$	Effective contact area of the soil
$A_{p,g}$	Contact area of the pipes with the air
A_r	Total area of cover
η_g	Contribution of radiation to heat gain of air inside the greenhouse
η_p	Radiation absorbe by the heat pipes
η	Abosrbed heat relative to radiation energy received
τ_r	Transmitance of the roof
$U_{g,o}$	Heat transfer coefficient of the cover
$U_{g,s}$	Heat transfer coefficient toward the soil
$U_{p,g}$	Heat transfer coefficient from the pipes to the greenhouse air
$U_{s,ss}$	Heat transfer coefficient between soil and subsoil
κ	Leat evaporation heat of water
ρ_{H_2O}	Density of liquid water
c_{H_2O}	Heat capacity of liquid water
M_{H_2O}	Molar mass of water
R_g	Gas constant
p_{H_2O}	Water vapor pressure inside the air

c_{si}	Saturation pressure parameters ($i = 1, 2, 3$)
c_{mi}	Condensation parameters ($i = 1, 2$)
F_{hum}	Maximum water flow of humidifier
F_P	Maximum water flow inside the pipes
p_{pi}	Pipe parameters ($i = 1, 2$)
F_{vent}	Maximum air flow of fan
p_{vi}	Ventilation parameter ($i = 1, \cdots, 5$)
u_{vmax}	Maximum flow of air if all windows are fully opened
γ_1	Fraction of water not evaporated
γ_2	Fraction of water lost to the enviroment during condensation
α_c	Evapotranspiration parameter
β_c	Evapotranspiration parameter

Chapter 1

Introduction

A greenhouse is a metal structure covered with transparent material (usually plastic) which is commonly used for growing plants (it can also be used to breed and raise fishes). Greenhouses protect crops from external hazards and are also used to create an inside climate different yet dependent from the outside. This dependence of the greenhouse climate can be reduced using actuators to modify the greenhouse climate. The actuators used vary from the automation level of the greenhouse. For example, to increment water vapor concentration in a non automated greenhouse, the floor is irrigated so when it evaporates it increases the water vapor concentration.

Protected agriculture has increased its use in recent years due to its advantages. Growing plants in a greenhouse provides protection from external hazards, improves volume and quality of crops, and season dependent plants can be produced thoughout the year if the inside climate is controlled. Particularly in Mexico, greenhouses are mostly used to grow tomatoes, on a smaller scale, flowers; even be used for avocado production. Also, they may be used to grow cucumbers, strawberries, blueberries, lettuce, peppers, eggplant, basil, etc. According to a study carried out by Fideicomisos Instituidos en Relación con la Agricultura (FIRA)[1], the yield for tomato planted in the open is 40 metric tons by hectare while tomato planted in greehouses yielded 140 metric ton by hectare. In [25], the rentability of greenhouse tomato production is shown.

The use of control loops tuned as the agronomist and biologist researches propose, improves the use of water, energy and fertilizers. Simultaneously, the volume and quality of crops is increased. One of the main problems with greenhouse climate control is the computation of a fine mathematical model capturing the dynamic greenhouse behaviour. The models are most modeled by non linear differential equations including disturbances where the parameters are varying with time, i.e. even if the model is known, the parameters can change constantly causing an error between the real system and the model. The obtained models lead to very complex differential equations.

1.1 Greenhouse Systems Modeling State of Art

Researchers have used many modeling approaches for greenhouses, most of them mainly based in the heat and mass balance equations. In [7], a greenhouse model including natural ventilation and evaporative cooling is presented. Authors use heat and mass balance equations to derive the model. Since that approach includes a linearization stage, the model is only valid in the nearby of the operating point. Another approach deals with linear and non linear identification of the greenhouse behaviour using neuronal networks [6]. This method uses, however, a large amount of data samples due to their large number of degrees of freedom, and also requires a large computation time for training. In [14], a method for robust non linear identification of a climate system using evolutionary algorithms was proposed. Although the model is validated, the convergence of the algorithm could be too long. In [26], a fuzzy model of a greenhouse by taking heat and water measurements is proposed. However, the number of fuzzy rules needed to compute an actual greenhouse model is too large and it is not clear how to find out the rules.

1.2 Our Approach

A Petri net is a representation of a discrete event system (DES) which can describe the topology of a distributed, parallel, or concurrent system. It is integrated by places, transitions, arcs, and tokens positioned inside places. Arcs can only connect a place with a transition in any direction, they can not connect two places or two transitions. Transitions decreases tokens in an input place and increases the ones in the arrival place. A transition is enabled if all its input places have enough tokens. Tokens are usually interpreted as resources presence. Petri nets model positive systems which poses no problem with the greenhouse temperature and relative humidity. Also, since some actuators can be modeled as a source place, Petri nets provide a bound to some system components through tokens.

Continuous timed Petri nets allow to model highly populated DES. They are a nice approach since the state combinatorial explosion appearing in DES are translated to problems in differential equations.

When infinite server semantic (IS) is used in continuous timed Petri nets ($ContPN$) ([16], [19], [20], [3], [24]), the state combinatorial explosion is translated into the analysis of a number of linear differential equations dependent on the number of places and sincronizations. Although it seems to be a problem, several authors showed that interesting properties can be analysed despite the large number of linear systems.

When product semantics (PS) is used, the model is represented by one set of non linear differential equation. These nets have been widely used to model biological systems ([5]).

In both semantics, the non linearities are introduced by the synchronizations nets. In *IS*, the non linearities are represented by a set of linear systems while in *PS* just a non linear differential equation is required.

The modeling developed in this work uses $ContPN$ to capture the greenhouse dynamics. This model includes the external conditions (solar radiation, outside temperature, etc) as disturbances. The modeling methodology starts by representing every state variable by a Petri net place p_v. Afterwards, positive (as solar radiation) and negative variables are represented by a function place p_f which have input and output transitions to p_v respectively. Positive/negative variables are represented by both, input and output transitions. The output of this first step is a Petri net structure, the next step deals with the identification of the transition's firing rates. This task is performed by a least squares algorithm. Due to the fact that the obtained $ContPN$ includes only two synchronizations, the identification algorithm converges rapidly to the actual system parameters.

1.3 Work Objectives

There are various variables to control inside a greenhouse, some of them are: temperature, relative humidity, CO_2, luminosity, etc. Both temperature and relative humidity are a priority to control in order to create a good climate for the crop.

This work focuses in obtaining a model for the greenhouse temperature and relative humidity with continuous timed Petri nets in order to have a methodology to construct a modular model for a greenhouse to allow an easier adding or removal of equipment both physical and in the model. Since this work only includes a model, in future work the control of the temperature and relative humidity will be studied.

Some supositions for modeling are:

- The greenhouse temperature is considered uniform in the greenhouse.
- The radiation exchange between objects is not considered. Only solar radiation absortion is considered.
- No plants inside the greenhouse is considered.

1.4 Contributions

- A heat and mass balance modeling methodology for continuous timed Petri nets.
- A continuous timed Petri net model representation of greenhouse temperature and relative humidity.

- A parameter identification process for the model previously mentioned.

1.5 Contents General Description

Chapter 2 presents Petri nets preliminaries from the definition of a Petri net, a continuous Petri net, and continuous timed Petri net. For the latter, infinite server semantics and product semantics are explained since they will be used for modeling in Chapter 4. Also, the least squares method is shown. Chapter 3 explains some greenhouse subsytems like cooling, heating, CO_2 inyection, assimilation light, and other subsytems are explained. Also, a greenhouse temperature and relative humidity model from literature is explained for later use in the document. In Chapter 4, a Petri net model is obtained based on a methodology proposed in this thesis and a simulation of the greenhouse parametric identification is carried out. Appendix A shows the values of the parameters used in the simulations.

Chapter 2

Preliminaries

In this chapter, Petri nets concepts and the least squares identification method are described. The concepts cover Petri nets, continuous Petri nets, and continuous timed Petri nets. For the latter, the infinite server semantics and the product semantics are shown, and function places are presented.

2.1 Petri Nets Concepts

This section introduces basic concepts on **continuous timed Petri nets**. In order to have more detailed information, an interested reader may also consult [10], [12], [18], and [29].

Definition 2.1. The **Petri Net structure** is a bipartite digraph formed by the four-tuple $N = \langle P, T, \mathbf{Pre}, \mathbf{Post} \rangle$ where P is a finite set of nodes called places; T is a finite set of nodes called transitions; **Pre** and **Post** are $|P| \times |T|$ matrices representing the weighted arcs going from places to transitions and from transitions to places respectively.

Let $q \in P \cup T$ be a node of N. The input set of q, denoted by $\bullet q$, is defined as $\bullet q = \{q_i \in P \cup T |$ there exists an arc from q_i to $q\}$. Similarly, the output set of a node q, denoted by $q\bullet$, is defined as $q\bullet = \{q_i \in P \cup T |$ there exists an arc from q to $q_i\}$.

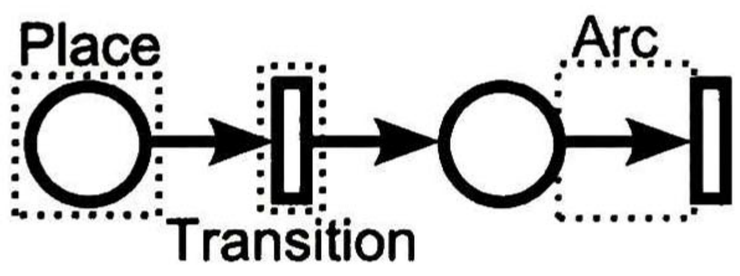


Figure 2.1: A Petri net

Definition 2.2. A Petri net system or simply a **Petri net** (PN) is the tuple $\langle N, \mathbf{m_0} \rangle$ where N is the Petri net structure and $\mathbf{m_0}$ is the initial token distribution or initial marking; a

marking $\mathbf{m} : P \to \mathbb{Z}_{\geq 0}^{|P|}$ is a vector representing the number of tokens residing inside each place. The notation $m(p_j)$ denotes the marking in the place p_j.

The evolution of the discrete PN marking is given by

$$\mathbf{m}_{k+1} = \mathbf{m}_0 + \mathbf{C}\vec{\sigma} \tag{2.1.1}$$

which is known as the fundamental PN equation, where $\mathbf{C} = \mathbf{Post} - \mathbf{Pre}$ is the incidence matrix, $\mathbf{m_0}$ is the current marking, $\vec{\sigma}$ is a $|T|$-dimensional vector with the i-th entry representing the number of ocurrences of t_i in σ, and $\mathbf{m_{k+1}}$ is the resulting marking after the fired transitions.

When a transition is fired, a number of tokens are substracted from the input place and another number of tokens are added to the output place. The number of tokens substracted or added are dependent on the weight of the arcs. A transistion is fired when a certain event happens, it can be dependent on a sensor reading or pushing a button. Equation (2.1.1) shows the change in marking since the transitions fired are represented in $\vec{\sigma}$ and are multiplied to the incidence matrix which have the information of which places and how many tokens to substract or add to the current marking $\mathbf{m_0}$.

Right and left annullers of $\mathbf{C}$ are called ***T-*** and ***P-flows*** respectively; i.e., $\mathbf{Cx} = 0$ ($\mathbf{yC} = 0$) is a *T-* (*P-*)*flow* for $\mathbf{x} \neq \mathbf{0}$ ($\mathbf{y} \neq \mathbf{0}$).

Example 2.3. The Petri net of Figure 2.2, has the next incidence matrix:

$$\mathbf{C} = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 \\ 1 & 0 & -1 & -1 & 0 \\ 0 & -1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

and its annullers are:

$$T\text{-}flow = \text{span}\left\{ \begin{bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \\ 1 \end{bmatrix} \right\}; \qquad P\text{-}flow = \text{span}\left\{ \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 1 \end{bmatrix} \right\}$$

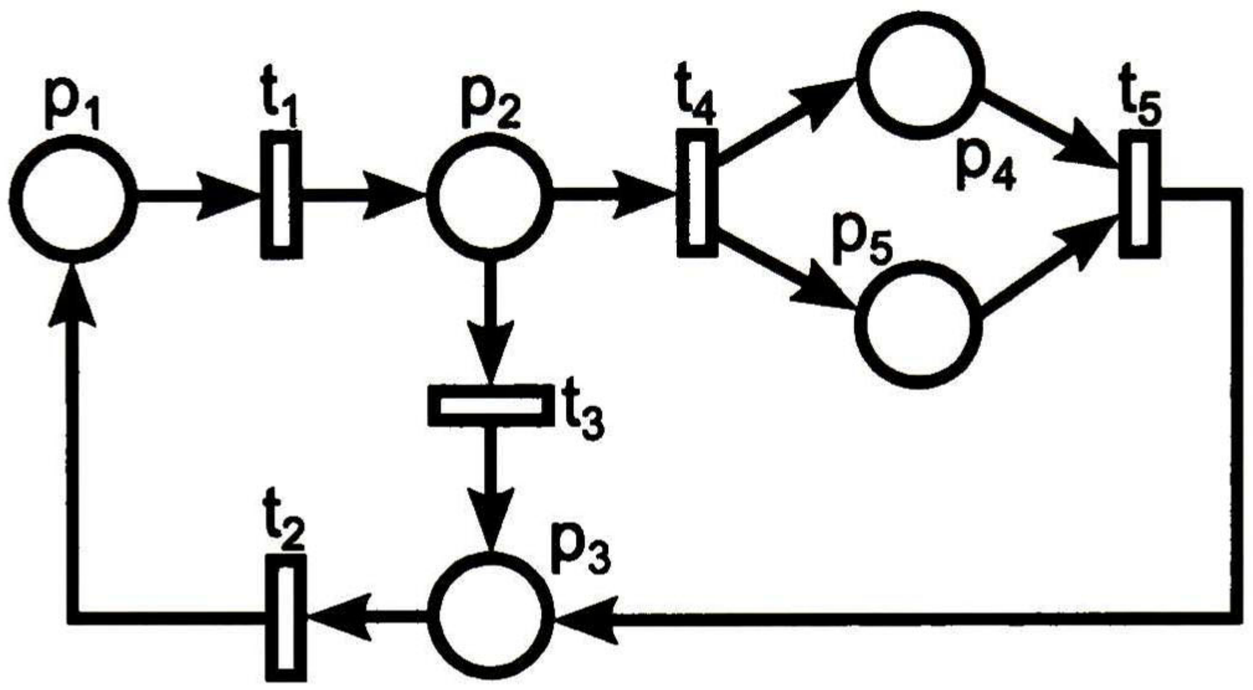


Figure 2.2: PN of example 2.3

A transition t_i is named a **join** (a place p_i is named an **attribution**) if $|\bullet t_i| > 1$ ($|\bullet p_i| > 1$). A Petri net structure is said to be **free choice** (FC) ([12]) if for every $p_1, p_2 \in P$, either $p_1\bullet \cap p_2\bullet = \emptyset$ or $p_1\bullet = p_2\bullet$.

(a) Join (b) Attribution

Figure 2.3: A join transition (a), and an attribution place (b)

A **continuous Petri net** (CPN), which can be seen at in [9] and [29], is a relaxation of the discrete PN model, where **parts** of tokens can be moved between places. As a consequence, the number of tokens in each place is a positive real number.

Definition 2.4. A continuous Petri net (CPN) is the pair $\langle N, \mathbf{m_0}\rangle$ where $N = \langle P, T, \mathbf{Pre}, \mathbf{Post}\rangle$ is the PN structure and $\mathbf{m} : P \to \mathbb{R}^{|P|}_{\geq 0}$ assigns a real number of tokens inside each place. The initial token assignment is $\mathbf{m_0} \in \mathbb{R}^{|P|}_{\geq 0}$.

Let $m(p_i) = m_i$ be the marking of a place p_i. A transition $t \in T$ is enabled iff for every $p_i \in \bullet t, m(p_i) > 0$.

The enabling degree of a transition is given by

$$\text{enab}(t, \mathbf{m}) = \min_{p \in \bullet t} \left\{ \frac{m(p)}{\mathbf{Pre}[p, t]} \right\}.$$

As in discrete PN, the firing of a transition t_i leads to a new marking; in this case it is computed, by

$$\mathbf{m}' = \mathbf{m} + \mathbf{C}\vec{\sigma} \tag{2.1.2}$$

where the firing vector $0 \leq \vec{\sigma} \leq \text{enab}(t_i, \mathbf{m})$, $\vec{\sigma} \in \mathbb{R}^{|T|}_{\geq 0}$.

If $\mathbf{m}$ is reachable from $\mathbf{m_0}$ by firing the finite sequence σ of enabled transitions, then $\mathbf{m} = \mathbf{m_0} + \mathbf{C}\vec{\sigma}$ is named the CPN state equation where $\vec{\sigma} \in \mathbb{R}^{|T|}_{\geq 0}$ is the firing count vector; i.e., $\vec{\sigma}_j$ is the cumulative amount of firing of t_j in the sequence σ.

The set of all reachable markings from $\mathbf{m_0}$ is called the **reachability set** and it is denoted by $RS(N, \mathbf{m_0})$. In the case of a CPN system, $RS(N, \mathbf{m_0})$ is a convex set [30].

A CPN is bounded when every place is bounded; i.e., $\forall p \in P, \exists b_p \in \mathbb{R}$ s.t. $m(p) \leq b_p$ at every reachable marking $\mathbf{m}$, and it is live when every transition is live (it can ultimately be fired from every reachable marking). The concept of bounded and live can be defined for an infinite firing secuences as lim-bounded and lim-live [31].

In order to include the notion of time in the CPN models, a function $\lambda : T \to \mathbb{R}^{T}_{>0}$ is used. This function assigns to each transition a positive value representing the maximum number of tokens that can flow through the transition per time unit ([18]) and it is called the firing rate of the transition.

Definition 2.5. A **continuous timed Petri net** ($ContPN$) is a 3-tuple $\langle N, \lambda, \mathbf{m_0} \rangle$ where $(N, \mathbf{m_0})$ is a CPN and $\lambda : T \to \mathbb{R}^{T}_{>0}$ is a function associating a firing rate to each transition.

It is possible to differentiate (2.1.2) to obtain a state equation

$$\dot{\mathbf{m}} = \mathbf{C}\dot{\vec{\sigma}} = \mathbf{C}\mathbf{f}(\tau) \tag{2.1.3}$$

where τ is the time variable and $\mathbf{f}(\tau) = \dot{\sigma}(\tau)$ is the transition flow.

The different ways of defining the transitions flow $\mathbf{f}$ of (2.1.3). One of them is called Infinite Server Semantics which is defined next:

Definition 2.6. A $ContPN$ is called **infinite server semantic** $ContPN$ ($IS-ContPN$) if the flow of a transition t_i is

$$f_i = \lambda_i \cdot \text{enab}(t_i, \mathbf{m}) = \lambda_i \cdot \min_{p \in \bullet t_i} \left\{ \frac{m(p)}{\text{Pre}[p, t_i]} \right\} \tag{2.1.4}$$

where f_i is is the flow of transition t_i and the i-th row of the vector $\mathbf{f}$.

Notice that a $IS - ContPN$ can actually be considered as a piecewise linear system (a class of hybrid systems) which is a system composed of disjointed convex polyhedrals whose union form the space $\Re^n$ Each partition has a linear system and the linear system in use depends on the polyhedral where the current values of the state variables are at a given time doing the swithching between systems dependent on internal variables ([4]). An $IS - ContPN$ can be considered a piecewise linear system due to the *minimum* operator that appears in the enabling function in the flow definition since it makes the switching

among the embedded linear systems internally. Equation (2.1.3) can be expressed as a piecewise linear system given by

$$\dot{\mathbf{m}} = \mathbf{C}\boldsymbol{\Lambda}\boldsymbol{\Pi}(\mathbf{m}) \cdot \mathbf{m}. \tag{2.1.5}$$

The **firing rate matrix** is denoted by $\boldsymbol{\Lambda} = diag\left(\lambda_1, \ldots, \lambda_{|T|}\right)$. A configuration of a $ContPN$ at $\mathbf{m}$ is a set of (p,t) arcs describing the effective flow of all transitions:

$$\boldsymbol{\Pi}\left(\mathbf{m}\right)[i,j] = \begin{cases} \dfrac{1}{\mathrm{Pre}\left[p_i, t_j\right]} & \text{if } p_i \text{ is constraining } t_j \\ 0 & \text{otherwise.} \end{cases}$$

where a place p_j is constraining t_j if its marking m_i is the minimum of the marking of all places $p \in \bullet t_i$.

Definition 2.7. A $ContPN$ is called **product server semantic** $ContPN$ (PS–$ContPN$) if the flow of a transition t_i is

$$f_i = \lambda_i \prod_{p \in \bullet t_i} \left\{ \frac{m(p)}{\mathbf{Pre}[p, t_i]} \right\} \tag{2.1.6}$$

One way to define constant flow transitions (source transitions) is to model a transition t_i together with a place p_j such that $\bullet t_i = p_j \subset t_i \bullet$ and $\mathrm{Pre}[p_j, t_i] = \mathrm{Post}[p_j, t_i] = 1$ as shown in figure 2.4.

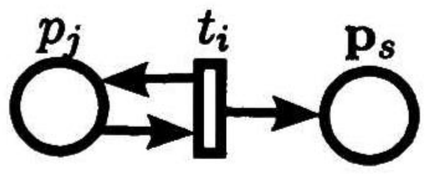


Figure 2.4: A well defined source transition

Definition 2.8. In a $ContPN$, a transition $t_i \in T$ is named **well defined** if $|\bullet t_i| \geq 1$; i.e., it has at least one input place. A $ContPN$ is named **well defined** if $\forall t_i \in T$, t_i is well defined.

As proposed in [13], join transitions are separated from single input transitions in order to work either with the linear part or the non linear part of the $ContPN$.

Definition 2.9. The set of single input transitions is the set

$$T_{si} = \{t_j \in T || \bullet t_j| = 1\}.$$

Definition 2.10. The set of join input transitions is the set

$$T_J = \{t_j \in T || \bullet t_j| > 1\}.$$

It can be seen that $T_{si} \cap T_J = \emptyset$ and $T_{si} \cup T_J = T$.

The transitions in a *ContPN* can be renamed to match the first transitions to single input transitions and the following ones to join transitions. Then, the incidence matrix is reformulated as $\mathbf{C} = [\mathbf{C}_{T_{si}}\ \mathbf{C}_{T_J}]$. Thus, (2.1.3) is expressed as

$$\dot{\mathbf{m}} = [\mathbf{C}_{T_{si}}\ \mathbf{C}_{T_J}] \begin{bmatrix} \mathbf{f}_{T_{si}} \\ \mathbf{f}_{T_J} \end{bmatrix} \tag{2.1.7}$$

or

$$\dot{\mathbf{m}} = \mathbf{C}_{T_{si}}\mathbf{f}_{T_{si}} + \mathbf{C}_{T_J}\mathbf{f}_{T_J}. \tag{2.1.8}$$

For both $IS - ContPN$ and $PS - ContPN$, for a transition $t_k \in T_{si}$,

$$\mathbf{f}_k = \frac{\lambda_k}{\mathrm{Pre}[p_a, t_k]} \cdot \mathbf{m}(p) = \alpha_{ak} \cdot \mathbf{m}(p) \tag{2.1.9}$$

where $p_a \in \bullet\, t_k$ and $\alpha_{ak} = \dfrac{\lambda_k}{\mathrm{Pre}[p_a, t_k]}$. It can be seen that $\mathbf{C}_{T_{si}}\mathbf{f}_{T_{si}}$ is linear. Thus, equation (2.1.8) can be represented by

$$\dot{\mathbf{m}} = [\mathbf{C}_{T_{si}}\ \mathbf{0}]\, \alpha_{T_{si}} \cdot \mathbf{m} + \mathbf{C}_{T_J}\mathbf{f}_{T_J} \tag{2.1.10}$$

where $\mathbf{C}_{T_J}\mathbf{f}_{T_J}$ is a non linear term, $[\mathbf{C}_{T_{si}}\ \mathbf{0}]$ has as many columns with all zero elements as transitions are in T_J, and $\alpha_{T_{si}}$ is a $|T| \times |P|$ matrix given by

$$\alpha_{T_{si}}[i,j] = \begin{cases} \alpha_{ak} & \text{if i=k and j=a} \\ 0 & \text{otherwise.} \end{cases}$$

In the case of **mixed semantics** (both infinite and product server semantics are used), the join transitions can be arranged such that infinite server semantics are separated of product server semantics as $\mathbf{C}_{T_J} = [\mathbf{C}_{T_{IS}}\ \mathbf{C}_{T_{PS}}]$.

Following a procedure as stated before, the state equation can be expressed as

$$\dot{\mathbf{m}} = [\mathbf{C}_{T_{si}}\ \mathbf{0}]\, \alpha_{T_{si}} \cdot \mathbf{m} + \mathbf{C}_{T_{IS}}\mathbf{\Lambda}_{T_{IS}}\mathbf{\Pi}_{T_{IS}}(\mathbf{m}) \cdot \mathbf{m} + \mathbf{C}_{T_{PS}}\mathbf{f}_{T_{PS}}. \tag{2.1.11}$$

The state equation may be separated in two parts if (2.1.5) representation is used for both $IS - ContPN$ and linear equations are added:

$$\dot{\mathbf{m}} = [\mathbf{C}_{T_{si}}\ \mathbf{C}_{T_{IS}}\ \mathbf{0}]\, \mathbf{\Lambda\Pi}(\mathbf{m}) \cdot \mathbf{m} + \mathbf{C}_{T_{PS}}\mathbf{f}_{T_{PS}}. \tag{2.1.12}$$

Example 2.11. Figure 2.5 shows the structure of two ContPNs, one with IS and the other with PS. The initial conditions are: $m_1(0) = 6$, $m_2(0) = 2$, and $m_3(0) = 3$; the rates are: $\lambda_1 = \lambda_2 = 1$.

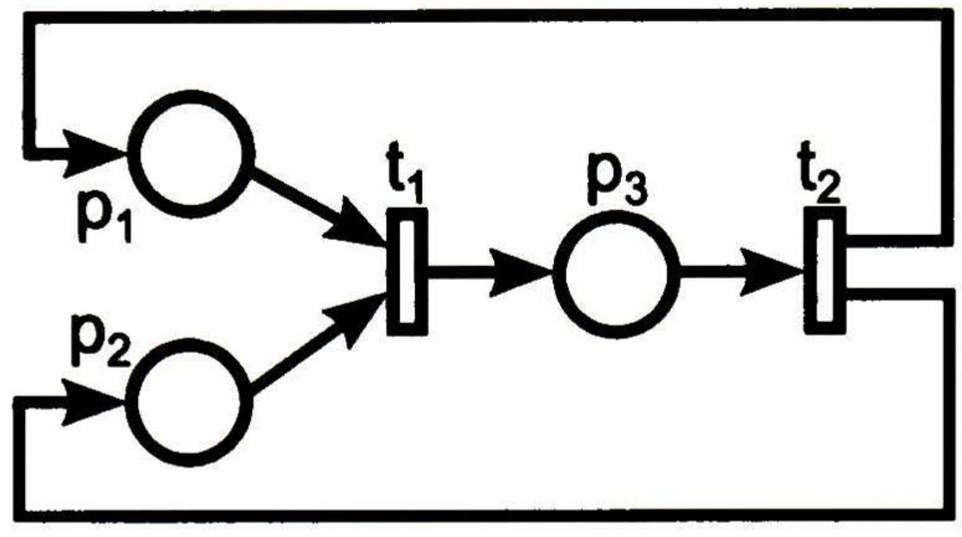


Figure 2.5: *ContPN* of Example 2.11

The infinite server semantics equations are given by:

$$\begin{aligned}\dot{m}_1 &= -\lambda_1 \min(m_1, m_2) + \lambda_2 m_3 \\ \dot{m}_2 &= -\lambda_1 \min(m_1, m_2) + \lambda_2 m_3 \\ \dot{m}_3 &= \lambda_1 \min(m_1, m_2) - \lambda_2 m_3.\end{aligned}$$

And the product server semantics equations are given by:

$$\begin{aligned}\dot{m}_1 &= -\lambda_1 m_1 m_2 + \lambda_2 m_3 \\ \dot{m}_2 &= -\lambda_1 m_1 m_2 + \lambda_2 m_3 \\ \dot{m}_3 &= \lambda_1 m_1 m_2 - \lambda_2 m_3.\end{aligned}$$

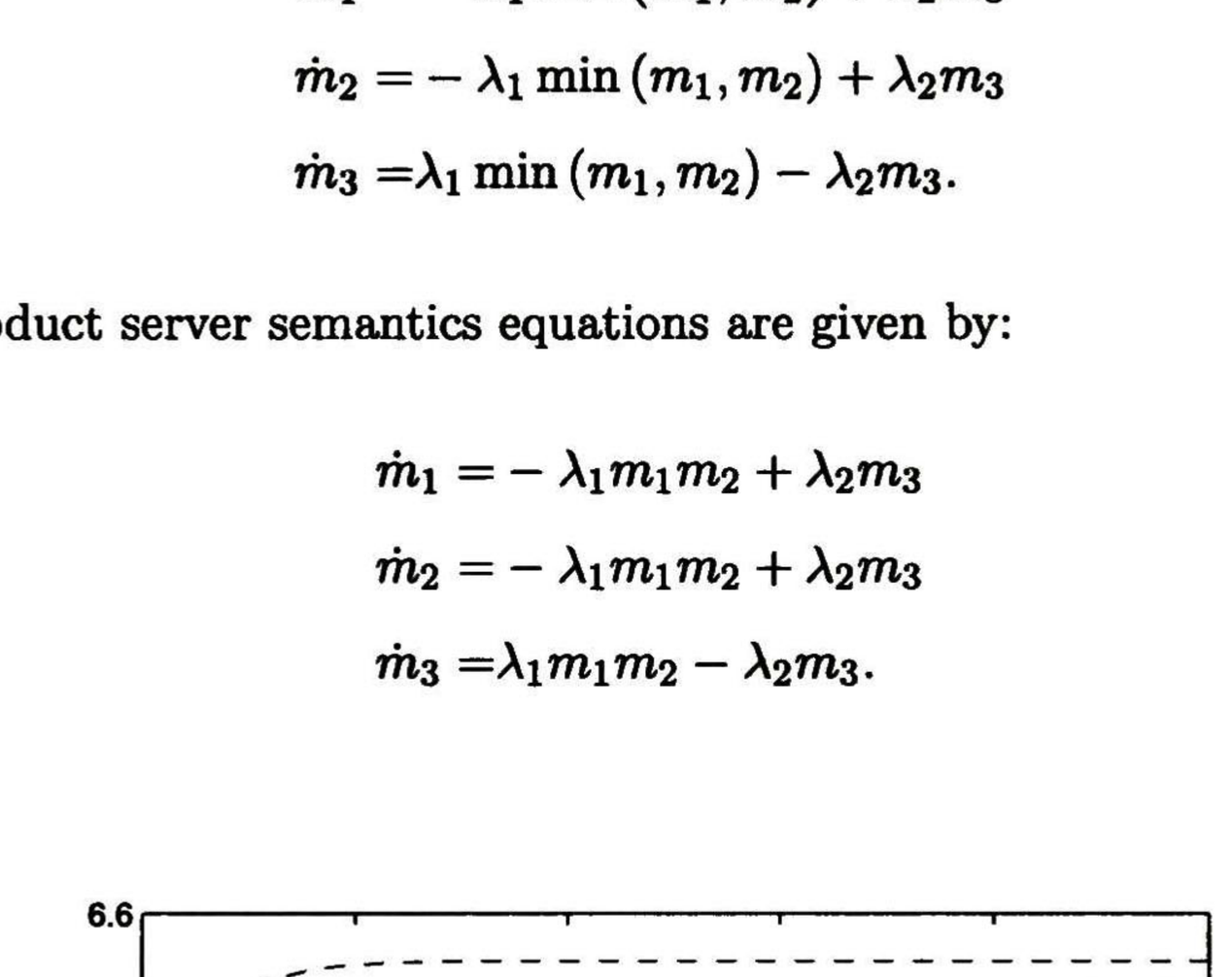


Figure 2.6: Evolution of tokens in p_1

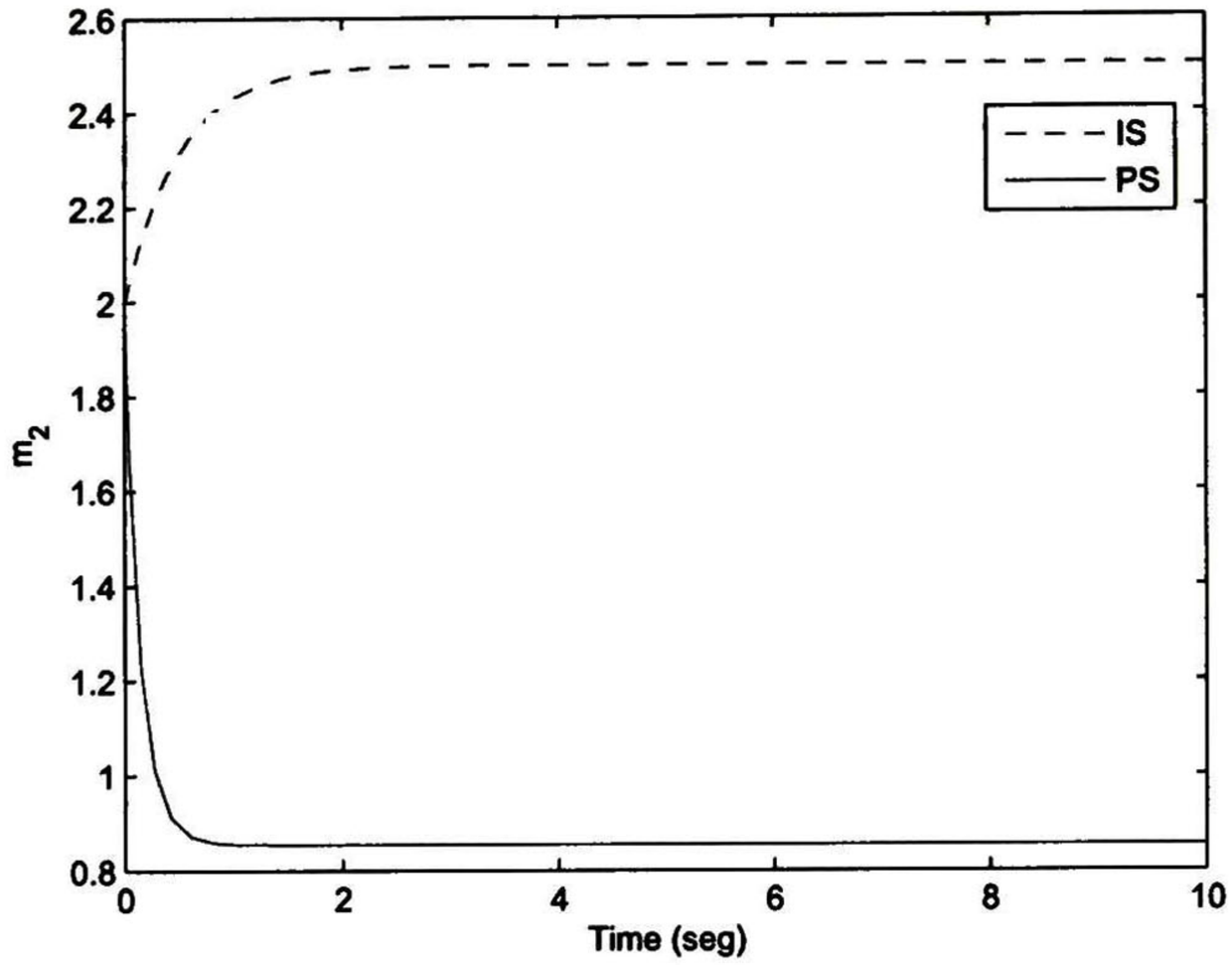


Figure 2.7: Evolution of tokens in p_2

In figures 2.6, 2.7, and 2.8, the evolution of tokens of p_1, p_2, and p_3 are shown. The equilibrium points for the $PS-ContPN$ is $m_1 m_2 = m_3$ and for the $IS-ContPN$ in this case is $m_2 = m_3$.

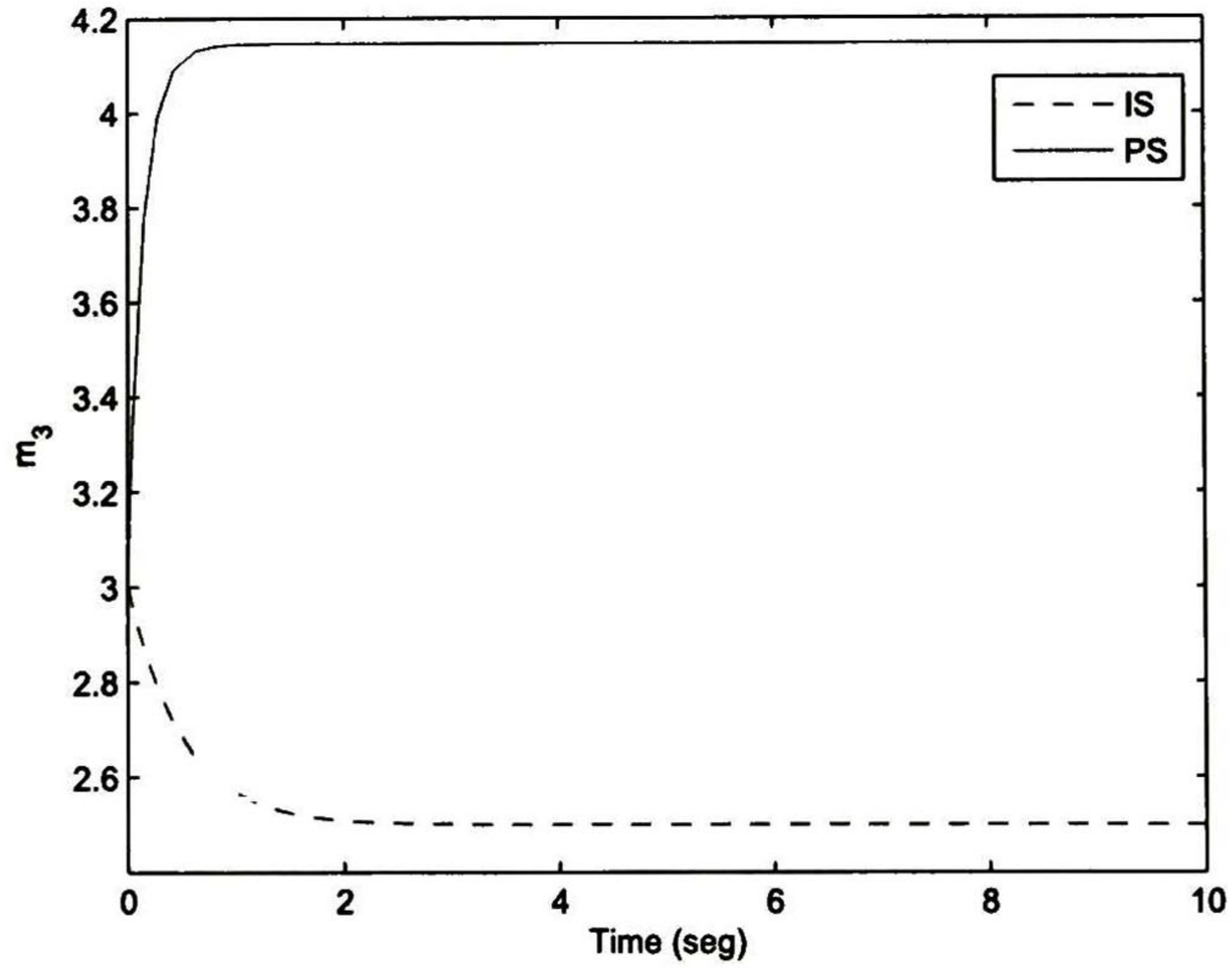


Figure 2.8: Evolution of tokens in p_3

In order to apply a control action in (2.1.3), a substracting term u, such that $\mathbf{0} \leq \mathbf{u}_i \leq \mathbf{f}_i$ is added to every transition t_i to indicate that its flow can be reduced. This control

represents a system with maximun capabilities that can only be reduced through control.

Then, the controlled flow of transition t_i becomes $\mathbf{w}_i = \mathbf{f}_i - \mathbf{u}_i$. Introducing $\mathbf{u}$ in (2.1.3), the forced state equation is

$$\dot{\mathbf{m}} = \mathbf{C}[\mathbf{f} - \mathbf{u}] = \mathbf{C}\mathbf{w}$$
$$\mathbf{0} \leq \mathbf{u}_i \leq \mathbf{f}_i$$

which in the case of $IS-ContPN$, $\mathbf{f} = \mathbf{\Lambda\Pi(m)} \cdot \mathbf{m}$; also, the state equation can be simplified, the input vector $\mathbf{u}$ is rewritten as $\mathbf{u} = \mathbf{I}_u \mathbf{\Lambda\Pi}(\mathbf{m}) \cdot \mathbf{m}$, where $\mathbf{I}_u = diag\left(I_{u_1}, \ldots, I_{u_{|T|}}\right)$ and $0 \leq I_{u_i} \leq 1$. Then the matrix $\mathbf{I}_c = \mathbf{I} - \mathbf{I}_u$ is constructed and the state equation can be rewritten as

$$\dot{\mathbf{m}} = \mathbf{C}\mathbf{I}_c\mathbf{f} = \mathbf{C}\mathbf{w}. \tag{2.1.13}$$

Thus, the control I_{u_i} is the fraction of eduction to the flow of transition t_i due to the control action.

A transition is called non controllable when its flow cannot be reduced. Every non controllable transition t_j has associated a constant input control $I_{c_j} = 1$.

In the case of mixed semantics, from equation (2.1.12), the infinite server semantics part is taken from the result reached at (2.1.13). For the product server semantics transitions, $\mathbf{f}_{TPS}$ is divided in controllable and non controllable transitions ($\mathbf{f}_{TPS} = \mathbf{f}_{TPSc} + \mathbf{f}_{TPSnc}$). While non controllable transitions have a flow transition as defined in (2.1.14), controllable ones are defined as

$$f_i = \lambda_i I_{c_i} \prod_{p \in \bullet t_i} \left\{ \frac{\mathbf{m}(p)}{\mathbf{Pre}[p, t_i]} \right\} \tag{2.1.14}$$

It has to be noted that transitions t_j and t_i may have a flow rate given by $I_{c_x}\lambda_j$ and $I_{c_x}\lambda_i$ respectively, meaning the control input affects two or more transitions.

2.1.1 *ContPN* Function Places

Regular *ContPN* models do not cover disturbances and nonlinearities, therefore it is required to add places that allow us to incorporate them. The next definition is proposed:

Definition 2.12. A place is called a **function place** if its marking at time τ is determined by a non linear function $h : \Re^+ \cup 0 \mapsto \Re^+ \cup 0$ of the actual marking of other places or external disturbances. Thus, the marking of a function place p_i is described by

$$m_i(\tau) = h(\mathbf{m}, \mathbf{D}) \tag{2.1.15}$$

where $m_i(\tau)$ is the marking of place p_i at time τ, $h(\bullet)$ is a known function and $\mathbf{D}$ is a measurable disturbance.

Notice that the marking of function places it is not directly determined by the differential equations. Also, since functions places are mainly seen as disturbances, their markings do not represent controllable variables.

2.2 *ContPN* Identification via Least Squares Method

The least squares method is a well known method for offline identification, it requires to process collected data from a system to calculate the system parameters. In order to calculate the parameters of the *ContPN* model, we construct the next array:

$$\begin{bmatrix} \dot{m}_i(1) \\ \vdots \\ \dot{m}_i(k) \end{bmatrix} = \begin{bmatrix} m_1(1) & m_2(1) & \cdots & m_n(1) \\ \vdots & \vdots & \vdots & \vdots \\ m_1(k) & m_2(k) & \cdots & m_n(k) \end{bmatrix} \begin{bmatrix} a_{i,1} \\ \vdots \\ a_{i,n} \end{bmatrix} \tag{2.2.1}$$

where $\dot{m}_i(b)$ is the b-th sampled element of $\dot{m}_i$, $m_i(b)$ is the b-th sampled element of m_i, and $a_{i,j}$ contains the parameters associated to m_j (for example, it may happen $a_{i,j} = \lambda_a + \lambda_b$) for place p_i. This equation can be abbreviated as

$$\boldsymbol{\Upsilon} = \boldsymbol{\Psi}\boldsymbol{\Theta} \tag{2.2.2}$$

where $\boldsymbol{\Upsilon}$ is a vector containing samples of the differential of the marking of place p_i; $\boldsymbol{\Psi}$ is a matrix with samples of the marking of places p_i with $i = 1, \ldots, n$; and $\boldsymbol{\Theta}$ is a vector with the parameters related to m_j for $j = 1, \ldots, n$ in the dynamics of place p_i. The solution of $\boldsymbol{\Theta}$ is obtained from

$$\boldsymbol{\Theta} = (\boldsymbol{\Psi}^T\boldsymbol{\Psi})^{-1}\boldsymbol{\Psi}^T\boldsymbol{\Upsilon}. \tag{2.2.3}$$

In order to identify the parameters of an $IS-ContPN$, after having reformulated the incidence matrix as in (2.1.7), $\boldsymbol{\Psi}$ is reformulated in order to include the minimum operator:

$$\begin{bmatrix} m_1(1) & \cdots & m_r(1) & \min\limits_{p_x \in \bullet t_{k+1}} \left\{ \dfrac{m_x(1)}{\mathrm{Pre}[p_x, t_{r+1}]} \right\} & \cdots & \min\limits_{p_x \in \bullet t_n} \left\{ \dfrac{m_x(1)}{\mathrm{Pre}[p_x, t_n]} \right\} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_1(k) & \cdots & m_r(k) & \min\limits_{p_x \in \bullet t_{k+1}} \left\{ \dfrac{m_x(k)}{\mathrm{Pre}[p_x, t_{r+1}]} \right\} & \cdots & \min\limits_{p_x \in \bullet t_n} \left\{ \dfrac{m_x(k)}{\mathrm{Pre}[p_x, t_n]} \right\} \end{bmatrix} \tag{2.2.4}$$

where $t_1, \ldots, t_r \in T_{si}$ and $t_{r+1}, \ldots, t_n \in T_J$. Note that $\mathrm{Pre}[p_x, t_i]$ must be known when $t_i \in T_J$ and $p_x \in \bullet t_n$.

In order to identify the parameters of a $PS-ContPN$, after having reformulated the incidence matrix as in (2.1.7), $\boldsymbol{\Psi}$ is reformulated in order to include the minimum operator:

$$\begin{bmatrix} m_1(1) & \cdots & m_r(1) & \prod\limits_{p_x \in \bullet t_{r+1}} m_x(1) & \cdots & \prod\limits_{p_x \in \bullet t_n} m_x(1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_1(k) & \cdots & m_r(k) & \prod\limits_{p_x \in \bullet t_{r+1}} m_x(k) & \cdots & \prod\limits_{p_x \in \bullet t_n} m_x(k) \end{bmatrix} \tag{2.2.5}$$

where $t_1, \ldots, t_r \in T_{si}$ and $t_{r+1}, \ldots, t_n \in T_J$. For $PS-ContPN$ it is not necessary to know $\mathrm{Pre}[p_x, t_i]$ when $t_i \in T_J$ and $p_x \in \bullet t_n$ since it will be identified in the parameters $a_{i,j}$.

Example 2.13. The $IS-ContPN$ of Example 2.11 will be used assuming that all places are measured. It has to be noted that $\mathrm{Pre}[p_2, t_1]$ must be known in order to switch the system just as the original one; in the other side, $\mathrm{Post}[p_2, t_2]$ is not necessary since it is present in the equations of the $IS-ContPN$. The array for all places is given by

$$\begin{bmatrix} \dot{m}_i(1) \\ \vdots \\ \dot{m}_i(k) \end{bmatrix} = \begin{bmatrix} m_3(1) & \min(m_1(1), m_2(1)) \\ \vdots & \vdots \\ m_3(k) & \min(m_1(k), m_2(k)) \end{bmatrix} \begin{bmatrix} a_{i,1} \\ a_{i,2} \end{bmatrix}$$

If a identification of the $PS-ContPN$ from the same example is desired, the function $\min(m_1(1), m_2)$ is changed to $m_1 m_2$:

$$\begin{bmatrix} \dot{m}_i(1) \\ \vdots \\ \dot{m}_i(k) \end{bmatrix} = \begin{bmatrix} m_3(1) & m_1(1)m_2(1) \\ \vdots & \vdots \\ m_3(k) & m_1(k)m_2(k) \end{bmatrix} \begin{bmatrix} a_{i,1} \\ a_{i,2} \end{bmatrix}$$

The difference is that the $PS-ContPN$ can identify $\mathrm{Pre}[p_2, t_1]$ since it is not an element of the $PS-ContPN$ non linearities.

Figures 2.9, 2.10, and 2.11 show the error between the original and the identified system (for the $IS-ContPN$) for m_1, m_2, and m_3.

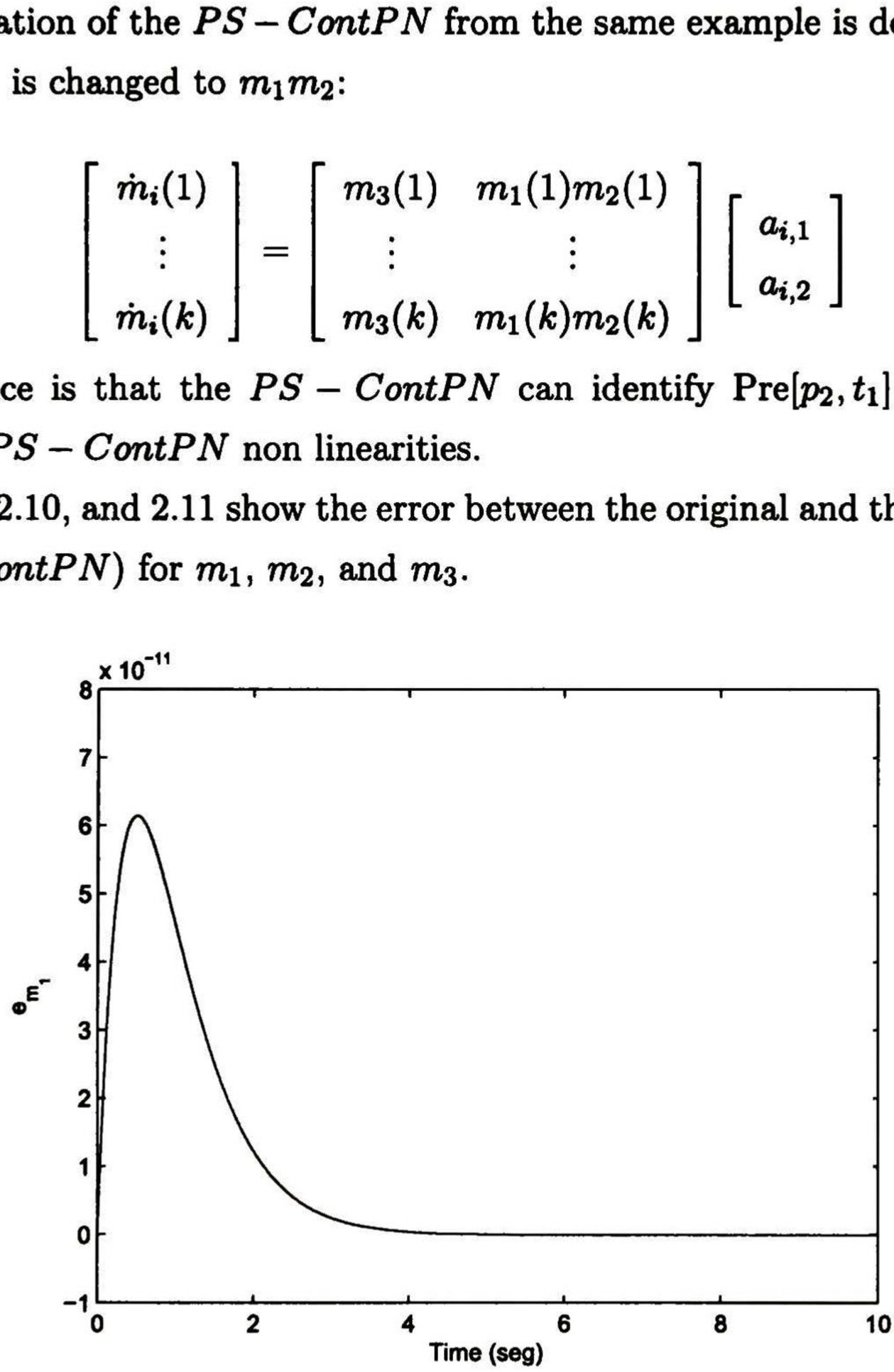


Figure 2.9: Error between the original and the identified system for m_1

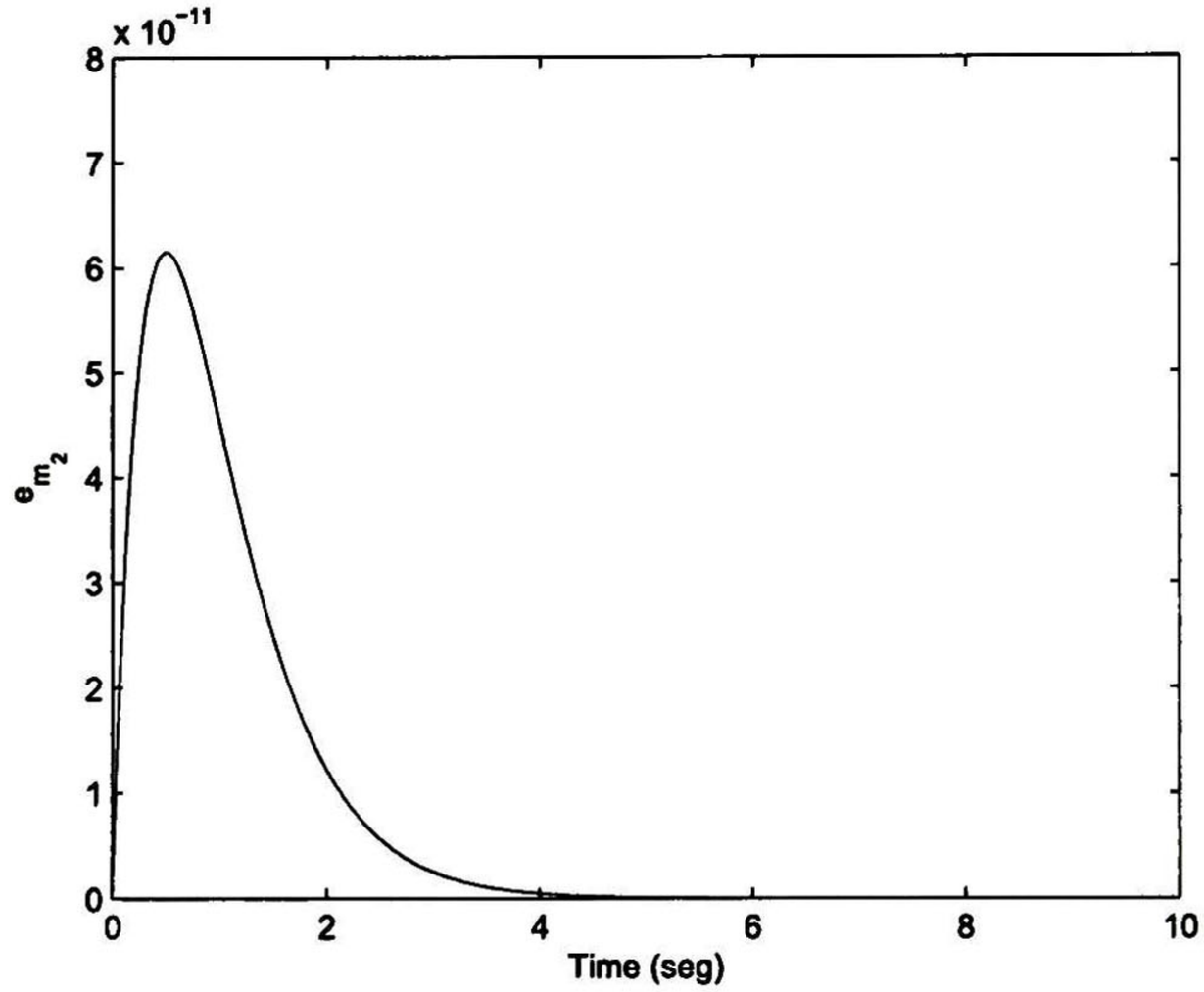


Figure 2.10: Error between the original and the identified system for m_2

Figure 2.11: Error between the original and the identified system for m_3

Chapter 3

Greenhouse System

There are different types of greenhouses named according to its shape: gable, flat arch, raised dome, sawtooth, tunnel, etc. In some cases, the greenhouse type is subject to what crop will be inside it. In order to automate a greenhouse, there may be needed cooling sytems, heating, CO_2 inyection, motors for windows, artificial light, etc.

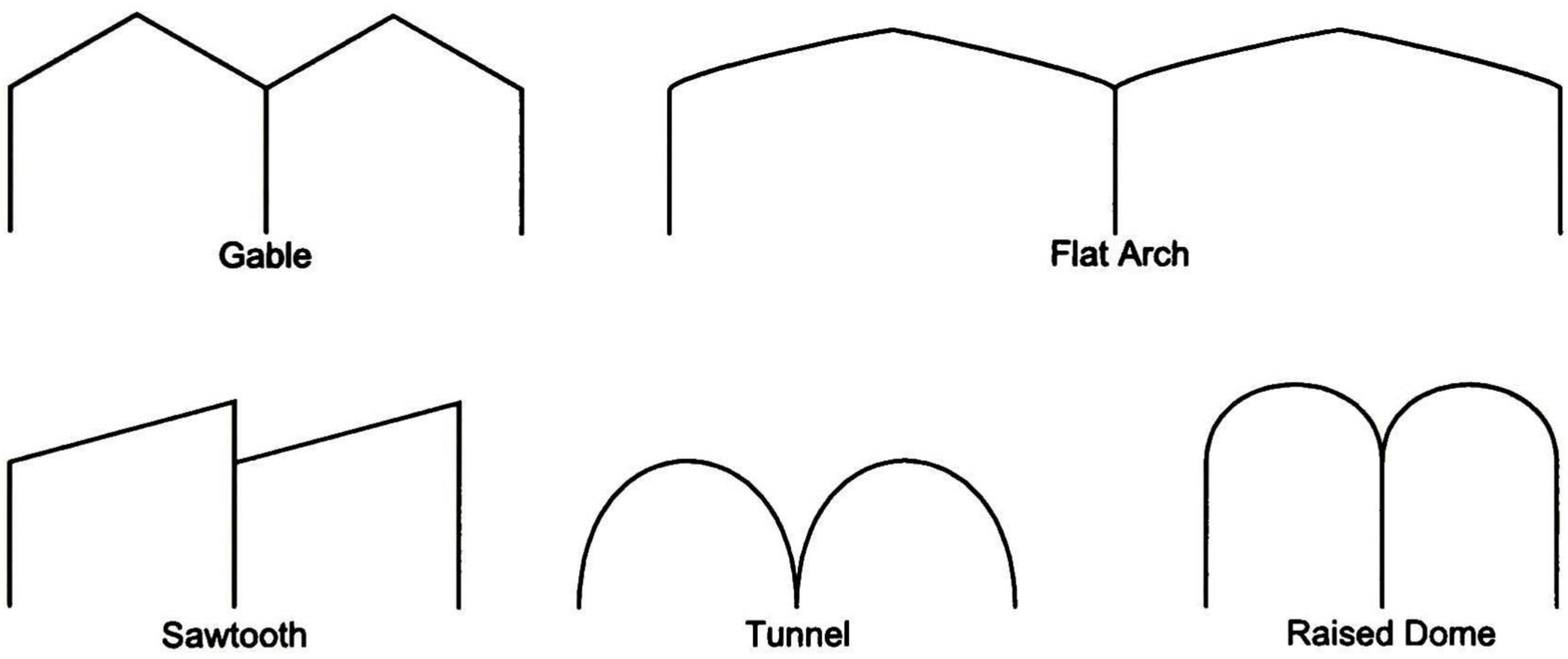


Figure 3.1: Some greenhouses types

Inside a greenhouse, two systems are dealed: climate and crop. The climate includes: air temperature, soil temperature, water vapor concentration, CO_2 concentration, assimulation light, etc. The crop can also be modeled, some of the variables are: roots mass generation, leaf mass generation, fruit mass generation (dependent on the crop), assimilates production, photosynthesis, respiration, etc. In this work, biological (crop) equations are not considered, but if interested, [34], [36], and [22] can be seen. The reason not to work with crop variables at the moment is simplicity; it may be tackled in future work.

This chapter presents some common greenhouse components such as CO_2 inyection,

heating, cooling, assimilation light, etc.; and explains the mathematical model of greenhouse temperature and relative humidity. The mathematical model starts with heat and mass balance equations; later on, they are detailed according to which variable is modeled and what external variables it is dependent on. In this work, the variables modeled are: greenhouse temperature, soil temperature, heating pipes temperature, water vapor concentration, and CO_2 concentration.

3.1 Greenhouse Subsystems

In this section some greenhouse components are described. In [23] and [35] additional equipment and further component selection procedures are presented.

3.1.1 CO_2 Distribution

In the photosynthetic process, CO_2 is used as a substrate to form the primary building blocks such as sugars, aminoacids, and organic acids. Those blocks are transported along the growing parts of the plants where they are transformed into structural dry mass. Sugars are also a source of energy in the conversion process and are used in maintenance respiration.

Aside from the CO_2 in the air, to improve the plant production, additional CO_2 may be added to the system. The supply system must be arranged in a way such that the CO_2 reaches the plants by an uniform diffusion and flow. The best way to benefit from the additional CO_2 is to install the conduction tubes beneath the plants between beds.

The CO_2 can be provided from a tank connected to the ducts that distribute it to the plants or it can be produced by a heat storage system and a gas purifier; for example, assuming a density of $150kg/m^3$ for natural gas and $700kg/m^3$ for CO_2, natural gas is burned freeing 0.53 m^3 of CO_2 by 1 m^3 of natural gas ([32]) and the heat produced by burning the natural gas can be stored to be used later; a downside is that the CO_2 must be purified before use because ozone, NO_X, CO, and SO_2, which are present at the combustion, are toxic to the plants.

3.1.2 Heating System

The heating system must be able to keep a minimum temperature inside the greenhouse during extreme circustances. To heat, usually a cylindric flame combustion tube of triple extraction is used. Other sources of heat are heating pipes, assimilation light, stored heat, and heat/energy generation.

The most used heating pipe system is the Tichelmann system (Figure 3.2). In this

system, the water in the returning pipe flows in the same direction as in the distribution pipe so the water distribution is virtually ideal and the heat exchange is the same in all parts if the hydraulics connections are the same and the distance of the boiler is similar to all heat exchangers. Usually, 8 heat pipes by each 6.4 m of greenhouse are installed. The pipes are usually laid in the floor to guarantee a proper heat distribution in the cultivation; other pipes heating systems are located aerial to heat the greenhouse air, a combination of both tipes of pipes can be used for better control. Occasionally, aerial heating is completely obviated, though is risky due to the possibility of the plants getting wet at low temperature of air and get infected with Botrytis.

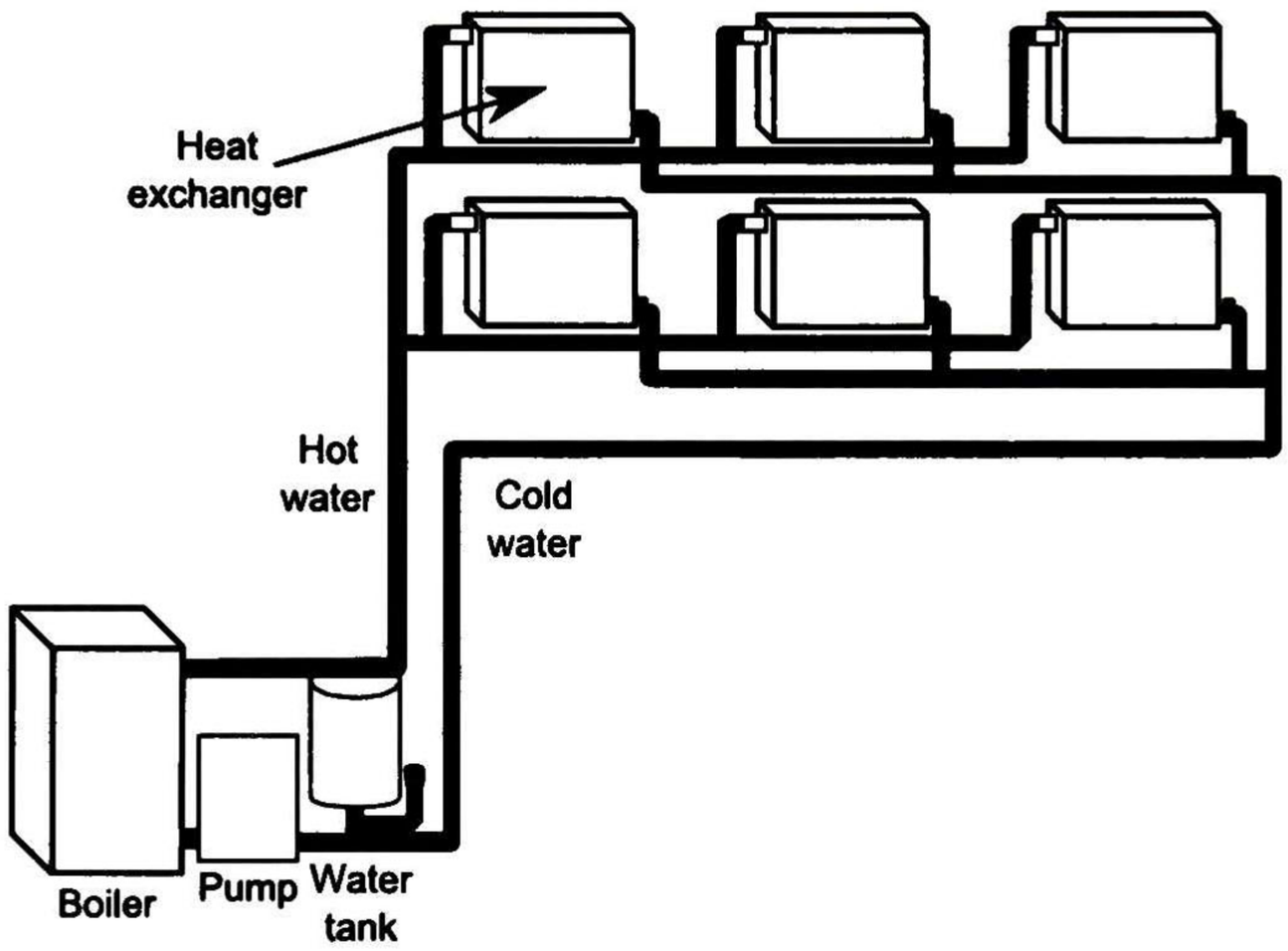


Figure 3.2: Draft of the Tichelmann system

An interested reader can look at [28] for other heating technologies.

3.1.3 Cooling System

To lower the greenhouse temperature, usually natural ventilation is used. The only problem is that it depends on external temperature and wind speed to work. There also exists forced ventilation to supersede the wind speed, but it still depends on outside temperature.

Another method, evaporative cooling, is used when ventilation is not possible or desirable. The process is to obtain small drops of water to absorb the energy in the air to evaporate and lower the temperatue at the same time. This can be done by using fan and pad, or foggers. A hybrid between mechanical and evaporative cooling named indirect evaporative cooling can be used in order not to increase the humidity of the greenhouse while cooling.

An interested reader can look at [27] and [17] for other cooling technologies.

3.1.4 Assimilation Light

Artificial light is used commonly to stimulate photosynthesis and increase quality. The lamps used to light the greenhouse can also provide some heat to the climate. The lighting system must be thought carefully to avoid loses, specially voltage related, and to reduce the shadow they give to the plants while maximizing the radiation provided.

3.1.5 Additional Systems

Sulfur vaporizers prevent some diseases and plagues, sulfur is vaporized and disperse through the greenhouse. An special mesh is used to reduce the light provided by the sun but at the same time, it can concentrate the heat inside the greenhouse. Insect screens are used to keep insects out the greenhouse. Desalinisaton systems may be used to purify the water before irrigation

3.2 Mathematical Model

The greenhouses have an inside microclimate that is usually modeled by heat and mass balance equations. The model can be as accurate as desired but its complexity increases. A basic greenhouse model will be presented. The model vary due to the greenhouse structure features or by using aditional equipment.

3.2.1 Heat Balances

The heat balance equation complies the law of conservation of energy. A general energy balance equation can be defined as

$$\frac{\mathrm{d}Q_x}{\mathrm{d}t} = q_{in,x} - q_{out,x} + p_x \tag{3.2.1}$$

where Q_x (in J) is the system energy (being a sustance or object), $q_{in,x}$ (in Js^{-1}) the ammount of energy enters a system x per unit of time, $q_{out,x}$ (in Js^{-1}) is the energy output, and p_x (in Js^{-1}) the generated energy. The system has a boundary that is the real or imaginary surface that separates the system of its surroundings.

The energy Q_x is related to the temperature T_x (in Kelvin) of the system through its thermal capacity c_x (in JK^{-1})

$$Q_x = c_x\, T_x. \tag{3.2.2}$$

Replacing (3.2.2) into (3.2.1) we obtain

$$c_x \frac{\mathrm{d}T_x}{\mathrm{d}t} = q_{in,x} - q_{out,x} + p_x. \tag{3.2.3}$$

The temperature is related to the average cinetic energy present in a sustance or object. If the temperature is not uniform in al parts of an object or sustance, there is heat exchange between those parts of the hole system (sustance or object).

Air Temperature

The temperature of the air in the greenhouse is affected by convection mainly from the greenhouse hull, the plants, the soil, crop transpiration, and exchange with the ventilation or leakages. The heating pipes system exchanges heat by convection, but heated air can be introduced into the system. The cooling system is heat loss by convection. The temperature of the greenhouse hull is affected by solar radiation, outside air convection, inside air convection, radiation exchange with the sky, radiation exchange with the interior of the greenhouse, and latent heat released by condensation of water vapour. The model to be used does not consider all previous relationships and is given by

$$K_g \frac{\mathrm{d}T_g}{\mathrm{d}t} = q_{o,g}^{rad} - q_{g,o}^{vent} - q_{g,o}^{cond} - q_{g,s} + q_{p,g} - q_{g,h} + q_{g,r}^{cons} - q_{g,c}^{trans} \tag{3.2.4}$$

where T_g is the average greenhouse temperature and the other terms are explained further in the section. The temperature T_g is just an average, this means there may be places in the greenhouse where the air is hotter or colder than T_g.

An interested reader may look at [2] for a more accurate model.

The latter equation is expressed in watts per square meter (Wm^{-2}). The virtual heat capacity of the greenhouse compartment (expressed in $Jm^{-2}K^{-1}$) is computed from

$$K_g = \rho_a c_{p,a} \frac{V_g}{A_g} \tag{3.2.5}$$

where ρ_a is the density of the air inside the greenhouse (kgm^{-3}), $c_{p,a}$ the heat capacity of that air ($JK^{-1}kg^{-1}$), V_g the volume of the greenhouse (m^3), and A_g the area covered by the greenhouse (m^2).

Equation (3.2.5) is a lower bound for greenhouse heat capacity since the crop and other components increases it. Also, the relation between heat capacity and temperature is non linear because its value is accurate only in a range of temperatures.

This model does not consider the exchange by convection of the radiation received by materials inside the greenhouse, it considers only the solar radiation absorbed by the overall system:

$$q_{o,g}^{rad} = \eta_g I_o \tag{3.2.6}$$

where I_o is the global solar radiation and η_g is the contribution of radiation to heat gain of air and solids inside the greenhouse.

The radiation absorbed by heating pipes is considered apart as

$$\eta_p = \frac{A_p}{A_g}\eta \tag{3.2.7}$$

where A_p is the pipe surface area and η is the absorbed heat relative to radiation energy received ($\eta \in [0, 1]$). So η_g can be written as

$$\eta_g = \eta - \eta_p = \left(1 - \frac{A_p}{A_g}\right)\eta. \tag{3.2.8}$$

A higher bound aproximation of η is the transmitance of the roof (τ_r):

$$\eta = \tau_r \tag{3.2.9}$$

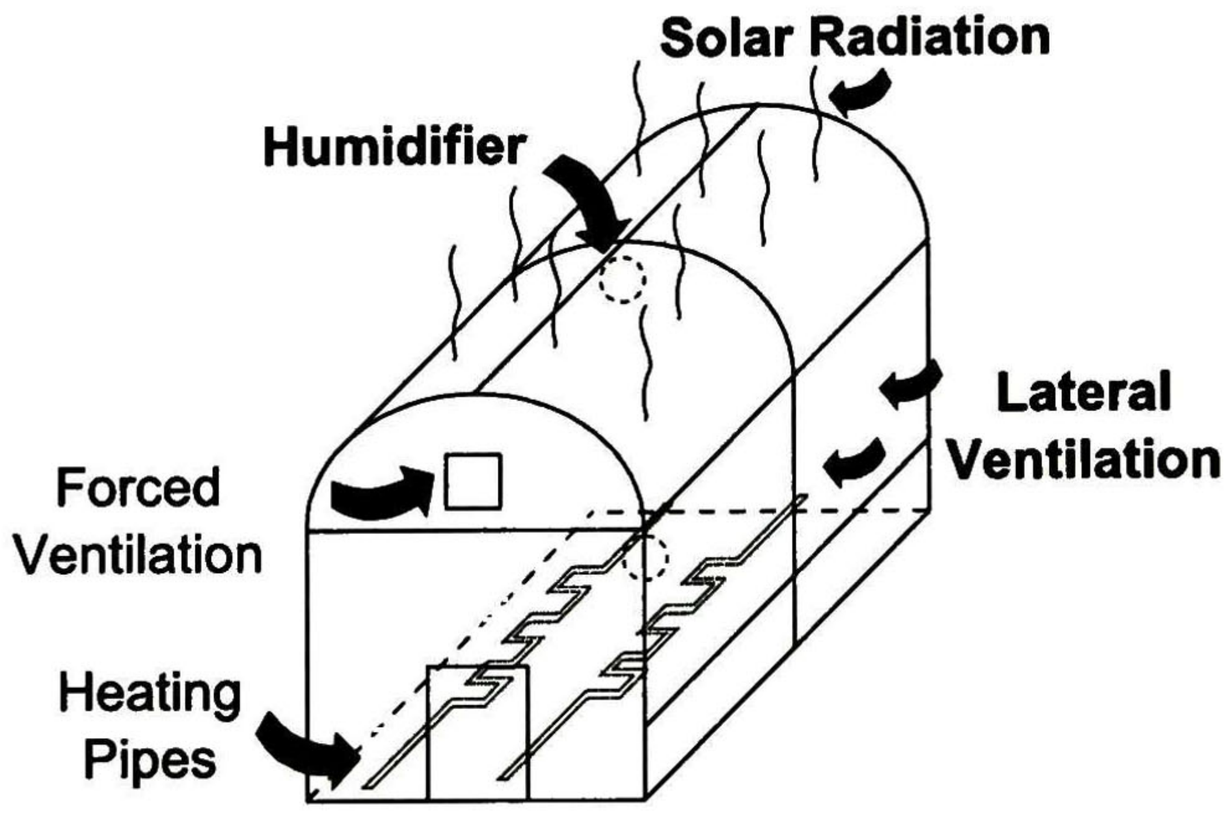


Figure 3.3: Greenhouse with forced and lateral ventilation

Inside temperature is affected by the exchange with the outside temperature T_o due to ventilation, as described by

$$q_{g,o}^{vent} = u_v \rho_a c_{p,a}(T_g - T_o) \tag{3.2.10}$$

where u_v is the natural air flow dependent on wind speed, and window opening percentage in both windward u_v^{Apwsd} and leeward side u_v^{Aplsd} according to [11], [33]:

$$u_v = \left(\frac{p_{v1}u_v^{Aplsd}}{1 + p_{v2}u_v^{Aplsd}} + p_{v3} + p_{v4}u_v^{Apwsd}\right)v + p_{v5} \tag{3.2.11}$$

where p_{vj} is $j = 1, \ldots, 5$ are ventilation parameters and v is wind speed. Normally, windows are opened first on the leeward side and then on the windward side.

If forced ventilation is desired, u_v can be reformulated to consider the fan air flow capacity in a square meter of projected greenhouse.

There is heat loss or gain by conduction through the plastic cover, as described by

$$q_{g,o}^{cond} = U_{g,o}\frac{A_{g,o}}{A_g}(T_g - T_o) \tag{3.2.12}$$

where $U_{g,o}$ $(Wm^{-2}K^{-1})$ is the heat transfer coefficient of the cover (roofs and walls) and $A_{g,o}$ is the total area of the cover.

There is heat loss or gain by exchange with the soil (soil temperature is denoted as T_s), as described by

$$q_{g,s} = U_{g,s}\frac{A_{g,s}}{A_g}(T_g - T_s) \tag{3.2.13}$$

where $U_{g,s}$ $(Wm^{-2}K^{-1})$ is the heat transfer coefficient toward the soil and $A_{g,s}$ is the effective contact area of the soil. The ratio $\frac{A_{g,s}}{A_g}$ is close to one.

There is heat supplied via the pipe system, as described by

$$q_{p,g} = U_{p,g}\frac{A_{p,g}}{A_g}(T_p - T_g) \tag{3.2.14}$$

where $U_{p,g}$ $(Wm^{-2}K^{-1})$ is the heat transfer coefficient from the water in the pipe to the greenhouse air, $A_{p,g}$ is the contact area of the pipes with the air in the greenhouse, and T_p is the temperature of the pipes.

There is heat withdrawn by water evaporation by the humidifier, as described by

$$q_{g,h} = \frac{1}{A_g}(1-\gamma_1)\mathfrak{C}\kappa\rho_{H_2O}u_{hum} \tag{3.2.15}$$

where κ $(J\,kg^{-1})$ is the latent evaporation heat of water, γ_1 represents the fraction of water not evaporated, and u_{hum} (m^3s^{-1}) is the flow of water through the humidifier. Since this cooling method depends on ambient relative humidity (RH), $\mathfrak{C}$ is used as a binary variable:

$$\mathfrak{C} = \begin{cases} 1 & \text{if } RH < 100 \\ 0 & \text{if } RH = 100. \end{cases} \tag{3.2.16}$$

Some heat is released due to condensation of moisture on walls and roof:

$$q_{g,r}^{cons} = \kappa(1-\gamma_2)\varphi_{H_2O,g,r}^{cons} \tag{3.2.17}$$

where γ_2 represents the fraction lost to the environment (outside the greenhouse) and $\varphi_{H_2O,g,r}^{cons}$ $(kg[H_2O]m^{-2}s^{-1})$ is defined in (3.2.37).

The heat withdrawn by the canopy evapotranspiration is given by

$$q_{g,c}^{trans} = \kappa E_c \tag{3.2.18}$$

where E_c $(kg[H_2O]m^{-2}s^{-1})$ is the evapotranspiration rate of the canopy, explained later on.

Soil Temperature

A first order approximation of heat exchange between the air and the ground in the greenhouse is considered, assuming that it does not receive direct heat by radiation:

$$K_s \frac{\mathrm{d}T_s}{\mathrm{d}t} = q_{g,s} - q_{s,ss} \tag{3.2.19}$$

where K_s is the virtual heat capacity of the soil and T_s is the temperature of the soil.

There is heat loss from soil to deeper soil given by

$$q_{s,ss} = U_{s,ss}(T_s - T_{ss}) \tag{3.2.20}$$

where $U_{s,ss}$ $(Wm^{-2}K^{-1})$ is the heat transfer coefficient toward the deeper soil and T_{ss} is the subsoil temperature assumed to be constant.

Heating Pipe System

The heating pipe equation is given by

$$K_p \frac{\mathrm{d}T_p}{\mathrm{d}t} = q_{boil,p} - q_{p,g} + q_{o,p}^{rad} \tag{3.2.21}$$

with K_p $(J\,K^{-1}m^{-2})$ as the pipe heat capacity given by

$$K_p = \rho_{H_2O} c_{H_2O} \frac{V_p}{A_g} \tag{3.2.22}$$

where c_{H_2O} is the heat capacity of liquid water $(JK^{-1}kg^{-1})$.

The received radiation is described by

$$q_{o,p}^{rad} = \eta_p I_o \tag{3.2.23}$$

where η_p is given by (3.2.7). Note that

$$q^{rad} = q_{o,g}^{rad} + q_{o,p}^{rad}. \tag{3.2.24}$$

The heat supply to the pipe system by the boiler is given by

$$\begin{aligned} q_{boil,p} =& q_{in,p} - q_{out,p} \\ =& \frac{1}{A_g} \rho_{H_2O} c_{H_2O} F_P (T_{p,in} - T_{p,out}) \end{aligned} \tag{3.2.25}$$

where $T_{p,in}$ is the temperature of the water when it enters the heating system, $T_{p,out}$ the temperature of water when it exits the pipes returning to the water tank, and F_P the flux of water inside the pipes $(m^3 s^{-1})$.

To simplify the previous equation, a mean temperature is used:

$$T_p = \frac{T_{p,in} + T_{p,out}}{2} \tag{3.2.26}$$

clearing $T_{p,out}$ and replacing in (3.2.27) (assuming $T_{p,in}$ is constant and near to the temperature of the boiler)

$$q_{boil,p} = \frac{2}{A_g}\rho_{H_2O}c_{H_2O}F_P(T_{p,in} - T_p). \tag{3.2.27}$$

3.2.2 Mass Balances

The same considerations as the heat balance are used in the mass balance over a volume:

$$\frac{\mathrm{d}Q_m}{\mathrm{d}t} = q_{in,m} - q_{out,m} + p_m \tag{3.2.28}$$

where Q_m (in kg) is the mass of an element in the system, $q_{in,m}$ and $q_{out,m}$ (in $kg\ s^{-1}$) are the input and output mass flows respectively, and p_m is the mass produced per unit of time ($kg\ s^{-1}$). The last one is a misuse of language because we only use part of a mass balance relating that produced mass; for example, a plant gets minerals and water from the floor, during photosynthesis that water taken by the roots is transpired into the greenhouse adding some mass, but it is not like it was generated, just transported from one place to another.

The mass Q_m is related to the concentration C_m ($kg\ m^{-3}$) and the volume V (in m^3):

$$Q_m = VC_m. \tag{3.2.29}$$

Replacing (3.2.29) into (3.2.28) we obtain

$$V\frac{\mathrm{d}C_m}{\mathrm{d}t} = q_{in,m} - q_{out,m} + p_m. \tag{3.2.30}$$

Water Vapor

As all terms are normalized to the projected area of the greenhouse beacuse some terms have the dependence of the projected area naturally, the water vapor concentration C_{H_2O} is given by

$$\frac{V_g}{A_g}\frac{\mathrm{d}C_{H_2O}}{\mathrm{d}t} = E_c + \varphi_{H_2O,h,g} - \varphi^{vent}_{H_2O,g,o} - \varphi^{cons}_{H_2O,g,r}. \tag{3.2.31}$$

The evapotranspiration is modeled with a general Penman-Monteith form [15]:

$$E_c = \alpha_c\eta_g I_o + \beta_c\Delta p_{H_2O}\{\cdot\} \tag{3.2.32}$$

where $\Delta p_{H_2O}\{\cdot\}$ is the vapor pressure deficit; α_c and β_c are parameters that depend slightly on temperature, radiation intensity, and CO_2 concentration. In this model that dependency is ignored, a more complete model can be found in [34]

The vapor pressure deficit is the difference between the saturation vapor pressure at the canopy temperature T_c and the actual vapor pressure inside the air p_{H_2O}:

$$\Delta p_{H_2O}\{\cdot\} = p^{sat}_{H_2O}(T_c) - p_{H_2O} \tag{3.2.33}$$

where $p^{sat}_{H_2O}$ is the saturation pressure at temperature T (in K) given by

$$p^{sat}_{H_2O}(T) = c_{s1} \exp\left(\frac{c_{s2}T^C}{c_{s3}+T^C}\right) \tag{3.2.34}$$

where T^C is temperature T in degrees Celsius. For simplicity, canopy temperature is considered the same as greenhouse temperature ($T_c = T_g$). Evapotranspiration model can be adjusted by a factor $f_m\{\cdot\}$ depending on crop growth.

At the same time the humidifier lowers temperature, it also increases water vapor concentration in greenhouse:

$$\varphi_{H_2O,h,g} = \frac{1}{A_g}(1-\gamma_1)\rho_{H_2O}u_{hum}. \tag{3.2.35}$$

The vapor exchange between water vapor concentration inside (C_{H_2O}) and outside ($C_{H_2O,o}$) the greenhouse due ventilation is given by

$$\varphi^{vent}_{H_2O,g,o} = u_v\left(C_{H_2O} - C_{H_2O,o}\right). \tag{3.2.36}$$

Since condensation only occurs when moisture concentration in the air is higher than the saturation concentration dependent on roof temperature. So condensation is given by

$$\varphi^{cons}_{H_2O,g,r} = k_{g,r}\frac{A_r}{A_g}\frac{p_{H_2O} - p^{sat}_{H_2O}(T_r) - |p_{H_2O} - p^{sat}_{H_2O}(T_r)|}{2} \tag{3.2.37}$$

where A_r is the total surface cover (roofs and walls). The mass transfer rate $k_{g,r}$ is given by

$$k_{g,r} = c_{m1}\left|\frac{T_g - T_r}{c_{T_{g,r}}}\right|^{c_{m2}} \tag{3.2.38}$$

where c_{m1} and c_{m2} are parameters [21]. The denominator $c_{T_{g,r}} = 1\,K$ with the only purpose of making the equation dimensionally correct.

The cover temperature is a weighted average between outside and inside air temperature:

$$T_r = (1-\gamma_2)T_g + \gamma_2 T_o. \tag{3.2.39}$$

Since measurements are taken as relative humidity (RH) which is defined as

$$RH_x = \begin{cases} 100\dfrac{p_{H_2O,x}}{p^{sat}_{H_2O}(T)} & \text{if } p_{H_2O,x} > 0 \text{ and } p^{sat}_{H_2O}(T) > 0 \\ 0 & \text{if } p_{H_2O,x} \leq 0 \text{ or } p^{sat}_{H_2O}(T) \leq 0 \end{cases} \tag{3.2.40}$$

where the subindex x represents if the measurement is inside the greenhouse (p_{H_2O}, RH, C_{H_2O}) or outside the greenhouse ($p_{H_2O,o}$, RH_o, $C_{H_2O,o}$).

To compute the concentration given the RH_x, the ideal gas equation is used; after computing $p_{H_2O,x}$ from last equation, the water vapor concentration is obtained:

$$C_{H_2O,x} = \frac{p_{H_2O,x}M_{H_2O}}{R_g T_g} \tag{3.2.41}$$

where M_{H_2O} is the molar mass of water (in $kg\ mol^{-1}$) and R_g is the gas constat ($J\ mol^{-1}\ K^{-1}$).

Carbon Dioxide

The CO_2 concentration model is given by

$$\frac{V_g}{A_g}\frac{\mathrm{d}C_{CO_2}}{\mathrm{d}t} = -\eta_{CO_2/dw}P + \eta_{CO_2/dw}R - \varphi^{vent}_{CO_2,g,o} + u_{CO_2} \tag{3.2.42}$$

where $\eta_{CO_2/dw}P$ and $\eta_{CO_2/dw}R$ are CO_2 losses or gain due to canopy photosynthesis and respiration respectively, might be considered as perturbations since biological equations asides evapotranspiration are not considered.

The CO_2 exchange between the concentration inside (C_{CO_2}) and outside ($C_{CO_2,o}$) the greenhouse due ventilation is given by

$$\varphi^{vent}_{CO_2,g,o} = u_v\left(C_{CO_2} - C_{CO_2,o}\right). \tag{3.2.43}$$

The CO_2 supply can be expressed as a valve opening ($u^{vp}_{CO_2} \in [0,\ 1]$):

$$u_{CO_2} = u^{vp}_{CO_2}\varphi^{max}_{CO_2,in,g} \tag{3.2.44}$$

where $\varphi^{max}_{CO_2,in,g}$ is the maximum flux of CO_2 given by the CO_2 tank.

Chapter 4

Continuous Timed Petri Net Based Greenhouse Modeling

In this chapter a modeling methodology of inside temperature and water vapor concentration of a greenhouse with *ContPN* is proposed.

The proposed modeling methodology consists on:

1. Elementary modules are defined according to each basic equation involved in the energy and mass balance equation.

2. The system variables are associated with places and disturbances with function places.

3. Modules are constructed representing the physical effect between variables using the elementary modules defined in the first step.

4. Once constructed, the modules are merged in order to model a complete (greenhouse) system.

5. Least square method is applied in order to identify the model parameters.

Sections 4.2, 4.3, 4.4, and 4.5 explains points 2 to 5 using the greenhouse as an example. The model of Section 3.2 will be used as a reference, except for some components and some considerations presented next:

- The heating pipes are not considered so (3.2.21) is not used, thus $q_{p,g}$ is not present in (3.2.4).

- The greenhouse is considered without crop, so the evapotranspiration terms $q_{g,c}^{trans}$ and E_c are not considered in (3.2.31) and (3.2.21) respectively.

- Also, since no crop is considered, $-\eta_{CO_2}P + \eta_{CO_2}R$ are zero in (3.2.42).
- No CO_2 injection system is considered, so u_{CO_2} is zero in (3.2.42).

With the previous considerations, the particular greenhouse mathematical model obtained is:

$$\begin{aligned}
K_g \frac{\mathrm{d}T_g}{\mathrm{d}t} &= q_{o,g}^{rad} - q_{g,o}^{vent} - q_{g,o}^{cond} - q_{g,s} - q_{g,h} + q_{g,r}^{cons} \\
K_s \frac{\mathrm{d}T_s}{\mathrm{d}t} &= q_{g,s} - q_{s,ss} \\
\frac{V_g}{A_g} \frac{\mathrm{d}C_{H_2O}}{\mathrm{d}t} &= \varphi_{H_2O,h,g} - \varphi_{H_2O,g,o}^{vent} - \varphi_{H_2O,g,r}^{cons} \\
\frac{V_g}{A_g} \frac{\mathrm{d}C_{CO_2}}{\mathrm{d}t} &= -\varphi_{CO_2,g,o}^{vent}.
\end{aligned} \tag{4.0.1}$$

A concept that will be used during the chapter is heat capacity. The heat capacity is involved in how much the temperature of a susbstance or object changes.

Heat capacity (or thermal capacity) is the amount of heat required to change a substance's temperature by a given amount. The specific heat capacity is the heat capacity per unit mass of a material.

The energy gained or lost (Q in W) during an increment or decrement of temperature (ΔT in K) in an object is related by the heat capacity (K in $W\ K^{-1}$). The heat capacity can be expressed as the proportional relationship between the specific heat (c in $W\ kg^{-1}\ K^{-1}$) and the mass of the object (m in kg).

If one of the components during a heat exchange has a bigger heat capacity, the resultant temperature will tend to its initial temperature. This can be seen normaly if a cofee cup is left in a room, even if the cofee is hot, the temperature of the room is practically unchanged.

4.1 Elementary Modules

The elements of heat and mass balance equations can be separated into: variables to be controlled (inside temperature, water vapor concentration, etc.), devices for control (fans, humidifiers, heaters, etc.), external variables (ouside temperature, solar radiation, etc.), and non controlled consumption or generation systems (like the crop not considered in external variables).

The heat exchange could be given by conduction, convection, or radiation (the concepts of heat exchange can be studied at [8]). Further, a module will be constructed in order to represent each one of the heat exchange type.

Elementary modules are proposed in order to represent the interactions between heat (mass) variables. As first proposal, the next model (Figure 4.1) for marking exchanges.

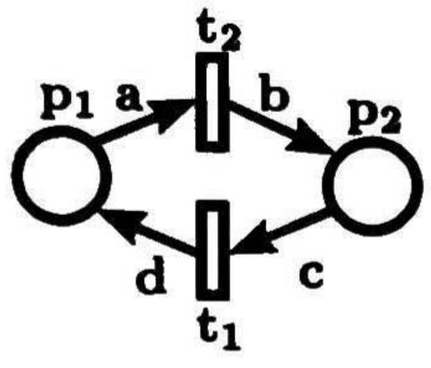
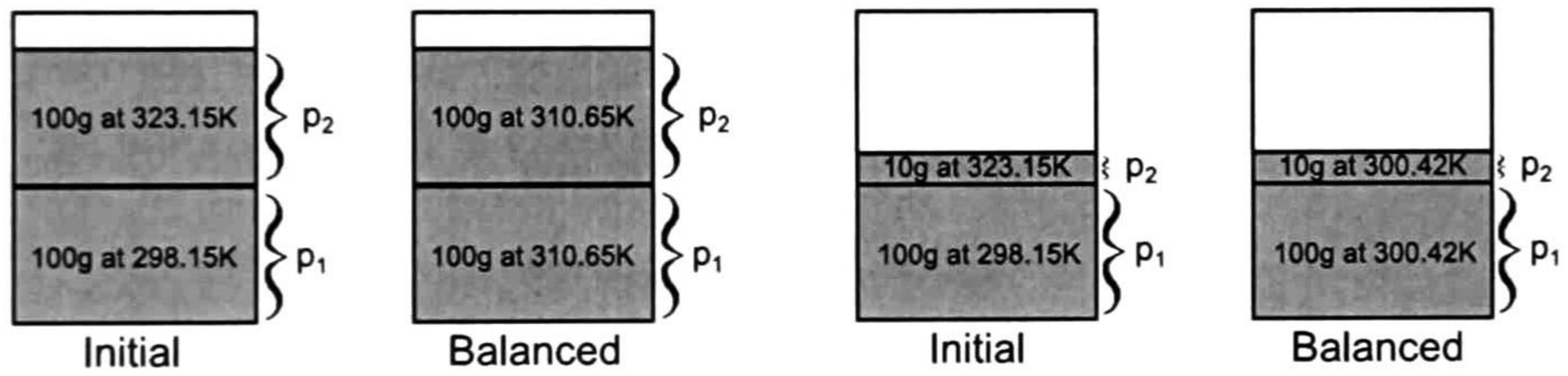


Figure 4.1: *ContPN* representation of tokens exchange

For example, if p_1 represents temperature of 100 g of water and p_2 the temperature of another 100 g of water, and the temperatures m_1 and m_2 are 298.15 K and 323.15 K respectively. The flow f_1 and f_2 represents the heat differential between temperatures. If p_1 and p_2 are mixed supposing no heat loss to the enviroment, results in both p_1 and p_2 reaching a temperature of 310.65 K (obtained from $100c_{H_2O}(m_1(t_{ss}) - m_1(0)) = 100c_{H_2O}(m_2(0) - m_2(t_{ss})))$ since $m_1(t_{ss}) = m_2(t_{ss})$). But if instead, p_2 represents 10 g of water at 323.15 K, the mixture is 110 g of water at 300.42 K (obtained from $100c_{H_2O}(m_1(t_{ss}) - m_1(0)) = 10c_{H_2O}(m_2(0) - m_2(t_{ss})))$.



(a) Example 1 (b) Example 2

Figure 4.2: Water heat balance example

The *ContPN* of Figure 4.1 has the following matrices:

$$\mathbf{C} = \begin{bmatrix} -a & d \\ c & -c \end{bmatrix}$$

$$\mathbf{\Pi} = \begin{bmatrix} \frac{1}{a} & 0 \\ 0 & \frac{1}{c} \end{bmatrix}$$

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}.$$

Thus, the marking equations are given by:

$$\dot{m}_1 = -\lambda_1 m_1 + \frac{d}{c}\lambda_2 m_2$$
$$\dot{m}_2 = \frac{b}{a}\lambda_1 m_1 - \lambda_2 m_2.$$

The balance of the marking is given when the steady state marking of m_1 and m_2 are equal. So, the equilibrium points of latter equations must be $m_1 = m_2$. Thus, the relationships required are:

$$\frac{b}{a} = \frac{c}{d} = \frac{\lambda_2}{\lambda_1}. \tag{4.1.1}$$

Replacing the latter relationships, the equations of the marking are:

$$\begin{aligned} \dot{m}_1 &= -\lambda_1 m_1 + \lambda_1 m_2 \\ \dot{m}_2 &= \lambda_2 m_1 - \lambda_2 m_2. \end{aligned} \tag{4.1.2}$$

For example, given a temperature in p_1 and a different temperature in p_2, the difference between λ_1 and λ_2 is because of the heat capacity of each system's temperature.

To prove that the equilbrium points are stable, the Lyapunov function $V(m) = \frac{1}{2\lambda_1}m_1^2 + \frac{1}{2\lambda_2}m_2^2$ is used:

$$\begin{aligned} \dot{V}(m) &= \frac{1}{\lambda_1}m_1\dot{m}_1 + \frac{1}{\lambda_2}m_2\dot{m}_2 \\ &= -m_1^2 + 2m_2m_1 - m_2^2 \\ &= -(m_1 - m_2)^2 \end{aligned}$$

which is always negative, so the equilibrium points are stable.

Notice that if the transformation $m_1' = m_1 + a$ and $m_2' = m_2 + a$, where $a = m_1(t_{ss}) = m_2(t_{ss})$ and it is constant, is used, the same system as (4.1.2) is obtained. Thus, the proof works for all equilibrium points.

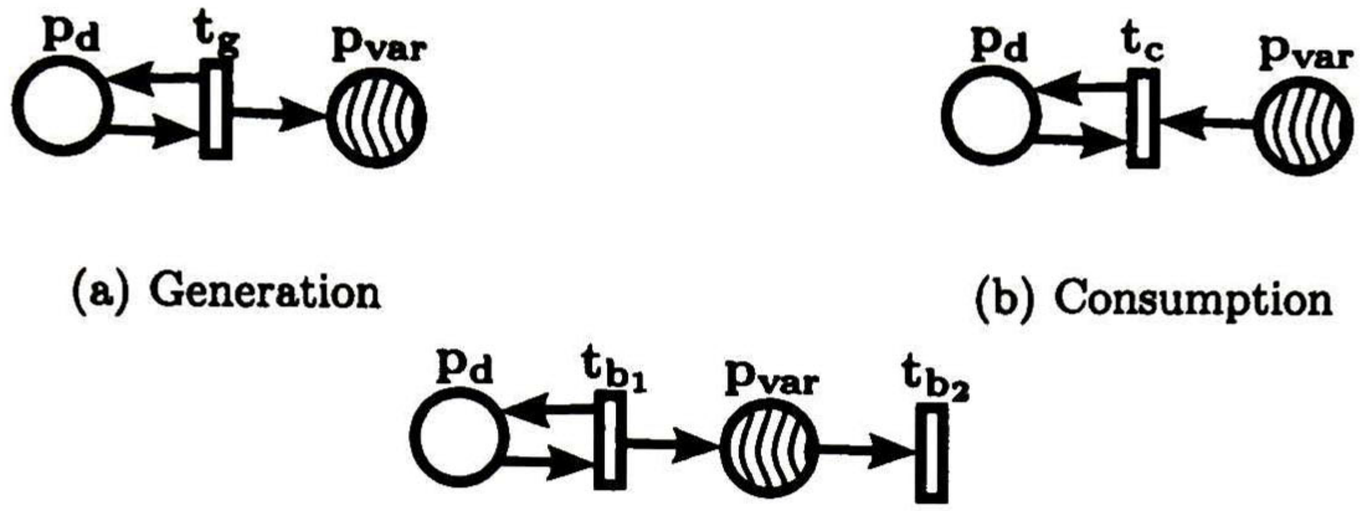
The number of tokens in the steady state are dependent on the initial values $m_1(0)$ and $m_2(0)$. The marking at the equilibrium point can be separated in three cases: $\lambda_1 < \lambda_2$, $\lambda_1 > \lambda_2$, and $\lambda_1 = \lambda_2$.

If $\lambda_1 < \lambda_2$, m_1 gains (or losses) tokens slower than m_2 losses (or gains), so the steady state marking value is closer to $m_1(0)$. If $\lambda_1 > \lambda_2$, m_1 gains (or losses) tokens faster than $m_2(0)$, so the steady state marking value is closer to m_2 losses (or gains). In the case $\lambda_1 = \lambda_2$, the steady state marking is given by $\frac{m_1(0) + m_2(0)}{2}$.

A variable may be affected by unknown variables or non modeled variables. For simplicity, the marking of those variables is measured (a variable that can be modeled but it is not necessary for control, it can be measured in order not to use its model). For example,

the temperature outside the system is affected by the system itself and by other elements of the climate not considered; thus, it will be measured. The *ContPN* of Figure 4.1 would model the relationship between the outside temperature (p_1) and another temperature (p_2), but it is desired to only measure m_1 while not modeling it.

So, instead of using the the *ContPN* of Figure 4.1, it is better to model it with the *ContPN* of Figure 4.3c.



(a) Generation

(b) Consumption

(c) Balance

Figure 4.3: Generation (a), consumption (b), and balance (c) modules

The only way the *ContPN* of Figure 4.3c represents the balance needed is if $\lambda_{b_1} = \lambda_{b_2}$ because the marking of p_{var} is given by

$$\dot{m}_{var} = \lambda_{b_1} m_d - \lambda_{b_1} m_{var}. \tag{4.1.3}$$

Definition 4.1. An elementary *ContPN* is called **balance module** (Figure 4.3c) if it has the following: a place p_{var} is assigned with marking m_{var} representing a variable x; a place p_d with marking m_d is assigned to represent a function $d(\tau)$; and transitions t_{b_1} and t_{b_2} are created with a maximum flux $\lambda_{b_1} = \lambda_{b_2} = k$ representing a gain factor. The next arcs are created: an input arc (t_{b_1}, p_{var}), a pair of arcs (t_{b_1}, p_d) and (p_d, t_{b_1}), and an output arc (p_{var}, t_{b_2}).

Notice that in a balance module, when $m_{var} < m_d$, marking m_{var} increases; and when $m_{var} > m_d$, marking m_{var} decreases. In other words, m_{var} always tends to equalize the value of m_d since the firing rates of both transitions are equal ($\lambda_{b_1} = \lambda_{b_2}$).

It is possible to have a balance module between two system variables, even if m_d is not reduced. In order to have a real balance between the two variables, two balance modules have to be used (if the *ContPN* of Figure 4.1 is not used): one with x_i as p_{var} and x_j as p_d, and the other with x_j as p_{var} and x_i as p_d.

Definition 4.2. An elementary *ContPN* is called **generation module** (Figure 4.3a) if it has the following: a place p_{var} is assigned with marking m_{var} representing a variable x; a

function place p_d with marking m_d is assigned to represent a function $d(\tau)$; and a transition t_g is created with a maximum flux $\lambda_g = k$ representing a gain factor. Arcs are created: an input arc (t_g, p_{var}), and a pair of arcs (t_g, p_d) and (p_d, t_g). Since $kd(\tau)$ is positive, it is increasing x.

It is called generation module because the disturbance p_d only adds energy (mass) to the variable represented by p_{var}. The marking m_d is not reduced since p_d is a function place and m_d depends on a function; in order to represent this in the $ContPN$ there are input and output arcs that preserve m_d.

Definition 4.3. An elementary $ContPN$ is called **consumption module** (Figure 4.3b) if it has the following: a place p_{var} is assigned with marking m_{var} representing a variable x; a function place p_d with marking m_d is assigned to represent a function $d(\tau)$; and a transition t_c is created with a maximum flux $\lambda_c = k$ representing a gain factor. The arcs created are: an input arc (p_{var}, t_c), and a pair of arcs (t_c, p_d) and (p_d, t_c). It differs from the adding module in the fact that tokens are used from m_{var}.

It is called a consumption module because the disturbance p_d only removes energy (mass) to the variable represented by p_{var}. The marking m_d is unaffected during the consumption.

Definition 4.4. An elementary $PS - ContPN$ is called **fluid balance module** (Figure 4.4) if it is a representation of a balance element with a proportional fluid flow relation. It is based on a balance module with: an extra place p_{conv} with a marking m_{conv} representing the fluid flow; the arcs (t_{fb_1}, p_{conv}), (p_{conv}, t_{fb_1}), (t_{fb_2}, p_{conv}), and (p_{conv}, t_{fb_2}). Since the relationship is proportional, transitions t_{fb_1} and t_{fb_2} have a flow as in (2.1.14).

This module is similar to the balance module except the heat (mass) transfer is affected by a fluid flow.

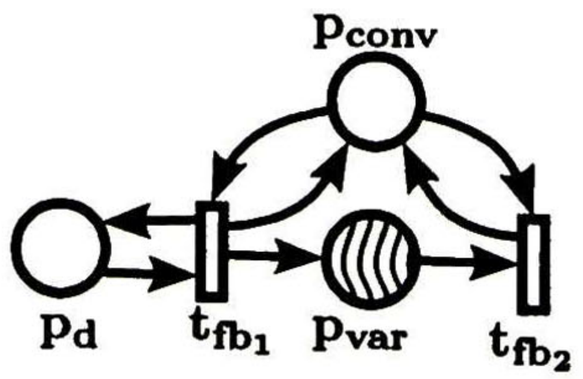
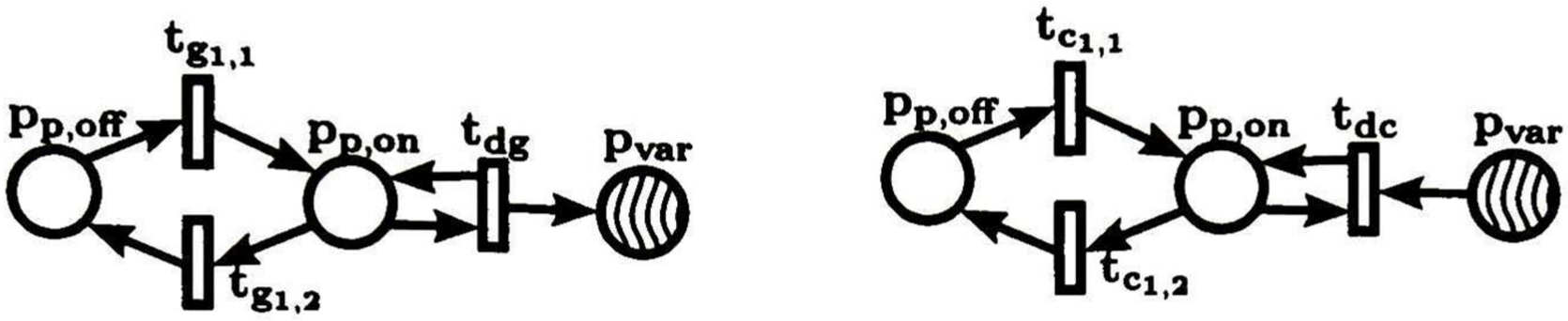


Figure 4.4: Fluid balance module

Definition 4.5. An elementary $ContPN$ is called **device generation module** (Figure 4.5a) if it has the following: a place p_{var} is assigned with marking m_{var} representing a variable x; a place $p_{p,on}$ with marking $m_{p,on}$ is assigned to represent a percentage used

of the maximum capacities of the device (temperature, water flow, etc.); a place $p_{p,off}$ with marking $m_{p,off}$ which represents a percentage not used of the maximum capacities of a device; transitions $t_{g_{1,1}}$ and $t_{g_{1,2}}$ to represent the dynamics of the actuator and are controllable; and a transition t_{dg} with a maximum flux $\lambda_{dg} = k$ representing a gain factor. The next arcs are created: $(t_{g_{1,1}}, p_{p,on})$, $(p_{p,off}, t_{g_{1,1}})$, $(t_{g_{1,2}}, p_{p,off})$, and $(p_{p,on}, t_{g_{1,2}})$; an input arc (p_{var}, t_{dg}); and a pair of arcs $(t_g, p_{p,on})$ and $(p_{p,on}, t_g)$.



(a) Generation

(b) Consumption

Figure 4.5: Device generation (a) and consumption (b) modules

This is a generation module that is controllable by a device; the device has its own dynamics to consider during the control law design. The place $p_{p,on}$ has the amount of tokens that are injected into the system variable p_{var}; for example, if a fan is not powered to have the maximum flow, the flow at the given time is represented in $p_{p,on}$ and the missing flow (the maximum flow minus the flow used) is represented in $p_{p,off}$.

This module considers that the device has an infinite supply of tokens so there are arcs that remain unaffected $p_{p,on}$ while affecting p_{var}. Some of these supplies may be air flow, water flow, electricity, etc.

If the dynamics of the actuator is faster than the dynamics of the system variable m_{var}, it may not be necessary to use the dynamics of the device in the model. Thus, a the device PN can be reduced to a normal generation model (Figure 4.3a) with the exception of $\lambda_g = I_{c_i} k$ denoting it is a controllable transition.

Definition 4.6. An elementary $ContPN$ is called **device consumption module** (Figure 4.5b) if it has the following: a place p_{var} is assigned with marking m_{var} representing a variable x; a place $p_{p,on}$ with marking $m_{p,on}$ is assigned to represent a percentage used of the maximum capacities of the device; a place $p_{p,off}$ with marking $m_{p,off}$ which represents a percentage not used of the maximum capacities of a device; transitions $t_{c_{1,1}}$ and $t_{c_{1,2}}$ to represent the dynamics of the actuator and are controllable; and a trantision t_{dc} with a maximum flux $\lambda_{dg} = k$ representing a gain factor. The next arcs are created: $(t_{c_{1,1}}, p_{p,on})$, $(p_{p,off}, t_{c_{1,1}})$, $(t_{c_{1,2}}, p_{p,off})$, and $(p_{p,on}, t_{c_{1,2}})$; an input arc (p_{var}, t_{dc}); and a pair of arcs $(t_c, p_{p,on})$ and $(p_{p,on}, t_c)$.

This is a consumption module that is controllable by a device. As with the device generation module, it can be reduced to a consumption module with $\lambda_c = I_{c_i} k$ denoting it is a controllable transition.

Definition 4.7. An elementary $PS-ContPN$ is called **device fluid dependent balance module** (Figure 4.6) if it is a representation of a controlled balanced element with a proportional fluid flow relation. It is based on a fluid balance module with: a place $p_{p,on}$ with marking $m_{p,on}$ is assigned to represent a percentage used of the maximum capacities of the device; a place $p_{p,off}$ with marking $m_{p,off}$ which represents a percentage not used of the maximum capacities of a device; and transitions $t_{f_{1,1}}$ and $t_{f_{1,2}}$ to represent the dynamics of the actuator. The next arcs are created: $(t_{f_{1,1}}, p_{p,on})$, $(p_{p,off}, t_{f_{1,1}})$, $(t_{f_{1,2}}, p_{p,off})$, and $(p_{p,on}, t_{f_{1,2}})$; and arcs $(t_{fdb_1}, p_{p,on})$, $(p_{p,on}, t_{fdb_1})$, $(t_{fdb_2}, p_{p,on})$, and $(p_{p,on}, t_{fdb_2})$. Since the relationship is proportional, transitions t_{fdb_1} and t_{fdb_2} have a flow as in (2.1.14).

This is a fluid balance module that is controlled by a device. As with the device generation module, it can be reduced to a fluid balance module with $\lambda_{fd_1} = \lambda_{fd_2} = I_{c_i} k$ denoting it is a controllable transition.

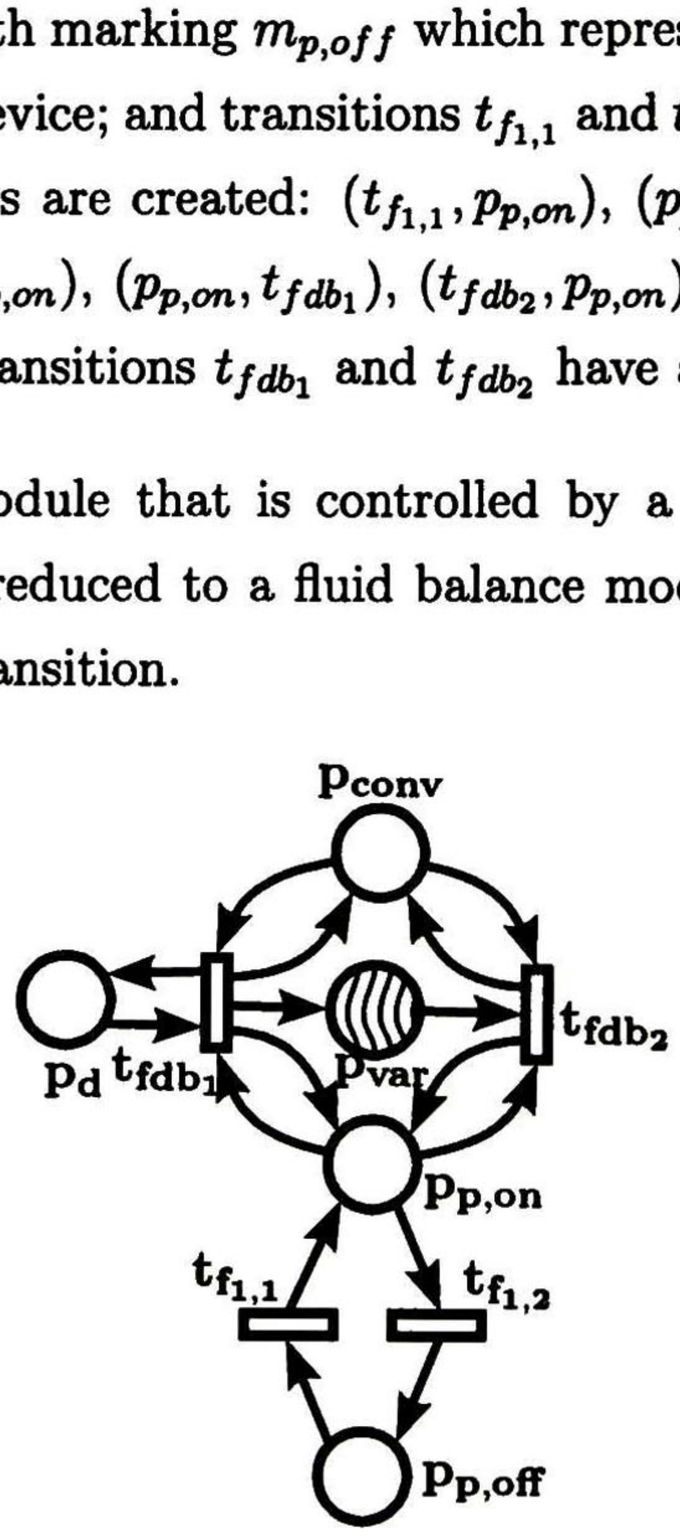


Figure 4.6: Fluid device dependent balance module

4.2 Place Association

The next step is to separate greenhouse variables from external ones which are considered perturbations. Greenhouse variables are represented by a place p_{var} while function places p_d are created to represent disturbances.

In order to model the greenhouse with $ContPN$, we need to identify variables and disturbances. Based on (4.0.1), T_g, T_s, C_{H_2O}, and C_{CO_2} are defined as variables. Also, external weather components like I_o, T_o, $C_{H_2O,o}$, $C_{CO_2,o}$, T_{ss}, v, F_{hum}, and $\varphi^{cons}_{H_2O,g,r}$ are

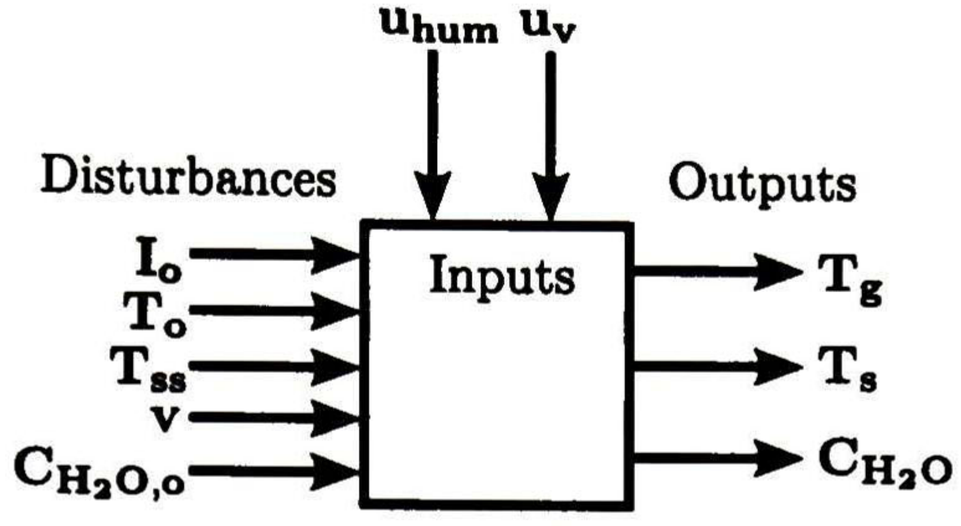


Figure 4.7: Greenhouse inputs (top), outputs (right) and disturbances (left)

considered as disturbances. The maximum water flow F_{hum} is a source place because it represents a constant flow transition which may be regulated by the control but does not change the place marking.

The Table 4.1 shows the places in the model we are proposing. Places p_1 to p_4 are assigned to variables, and function places p_5 to p_{12} are assigned to disturbances.

Variable	Place assigned		Variable	Place assigned
T_g	p_1		T_{ss}	p_7
T_s	p_2		$C_{H_2O,o}$	p_8
C_{H_2O}	p_3		$C_{CO_2,o}$	p_9
C_{CO_2}	p_4		v	p_{10}
I_o	p_5		F_{hum}	p_{11}
T_o	p_6		$\varphi^{cons}_{H_2O,g,r}$	p_{12}

Table 4.1: Correspondence of assigned places to variables and disturbances

4.3 Module Creation

With the places and functions places assigned representing variables and disturbances respectively, a module is created based on the elementary modules to match the physical effect between places with places (or places with function places).

For example, solar radiation will be analized. According to the previous section, a function place is created for solar radiation and a place is created for temperature of the system. Since solar radiation only increases heat in the greenhouse, an adding module is used to link their corresponding places.

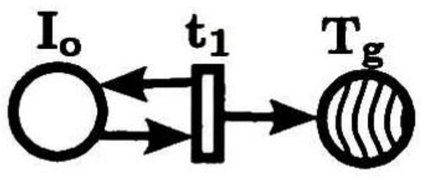


Figure 4.8: Solar radiation module

Table 4.2 shows the modules created to represent the relatioships of variables and perturbations of a greenhouse. All device modules are reduced since it is considered that all actuators have a faster dynamics than the greenhouse variables.

p_d		p_{var}		**Transitions**	**Elementary module associated**	**Relationship**
m_5	I_o	m_1	T_g	t_1	Generation module	Radiation absorption
m_6	T_o	m_1	T_g	t_2 and t_5	Fluid device balance module with m_{10} as m_{conv}	Controlled convection
m_6	T_o	m_1	T_g	t_3 and t_6	Fluid balance module with m_{10} as m_{conv}	Convection at leaks
m_6	T_o	m_1	T_g	t_4 and t_7	Balance module	Conduction through plastic
m_2	T_s	m_1	T_g	t_8 and t_9	Balance module	Exchange with soil
m_{11}	F_{hum}	m_1	T_g	t_{10}	Device consumption module	Heat loss by evaporation
m_{12}	$\varphi^{cons}_{H_2O,g,r}$	m_1	T_g	t_{11}	Generation module	Heat loss by condensation
m_1	T_g	m_2	T_s	t_{12} and t_{13}	Balance module	Exchange with air
m_7	T_{ss}	m_2	T_s	t_{14} and t_{15}	Balance module	Conduction with subsoil
m_{11}	F_{hum}	m_3	C_{H_2O}	t_{16}	Device generation module	Gain by evaporation
m_8	$C_{H_2O,o}$	m_3	C_{H_2O}	t_{17} and t_{20}	Fluid device balance module with m_{10} as m_{conv}	Controlled exchange with outside

m_8	$C_{H_2O,o}$	m_3	C_{H_2O}	t_{18} and t_{21}	Fluid balance module with m_{10} as m_{conv}	Exchange with outside at leaks by wind
m_8	$C_{H_2O,o}$	m_3	C_{H_2O}	t_{19} and t_{22}	Balance module	Exchange with outside at leaks
m_{12}	$\varphi^{cons}_{H_2O,g,r}$	m_3	C_{H_2O}	t_{23}	Consumption module	Water vapor loss by condensation
m_9	$C_{CO_2,o}$	m_4	C_{CO_2}	t_{24} and t_{27}	Fluid device balance module with m_{10} as m_{conv}	Controlled exchange with outside
m_9	$C_{CO_2,o}$	m_4	C_{CO_2}	t_{25} and t_{28}	Fluid balance module with m_{10} as m_{conv}	Exchange with outside at leaks by wind
m_9	$C_{CO_2,o}$	m_4	C_{CO_2}	t_{26} and t_{29}	Balance module	Exchange with outside at leaks

Table 4.2: Modules created

4.4 Merging of Modules

The modules created are merged according to the places in common. For example, there are three modules with a relationship between m_6 and m_1 and they are merged into two places with six transitions (Figure 4.9) with the maximum flow speed of transitions being: $\lambda_2 = \lambda_5 = I_{c_1} k_{2,5}$, $\lambda_3 = \lambda_6 = k_{3,6}$, and $\lambda_4 = \lambda_7 = k_{4,7}$.

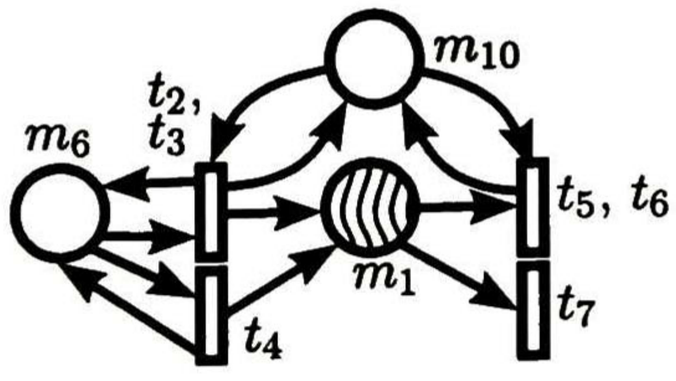


Figure 4.9: Example of module merging

If the device modules are not reduced; i.e., the ones in Figures 4.5a, 4.5b, and 4.6

are used; the places representing the devices would be merged and only one controllable transition appears in the *ContPN* for each device. Since the devices modules are reduced to the ones in Figures 4.3a, 4.3b, 4.3c, and 4.4, there are transitions that share the same control input I_{c_i}.

The places and transitions defined previously are represented in Figure 4.10 in a merged *ContPN*.

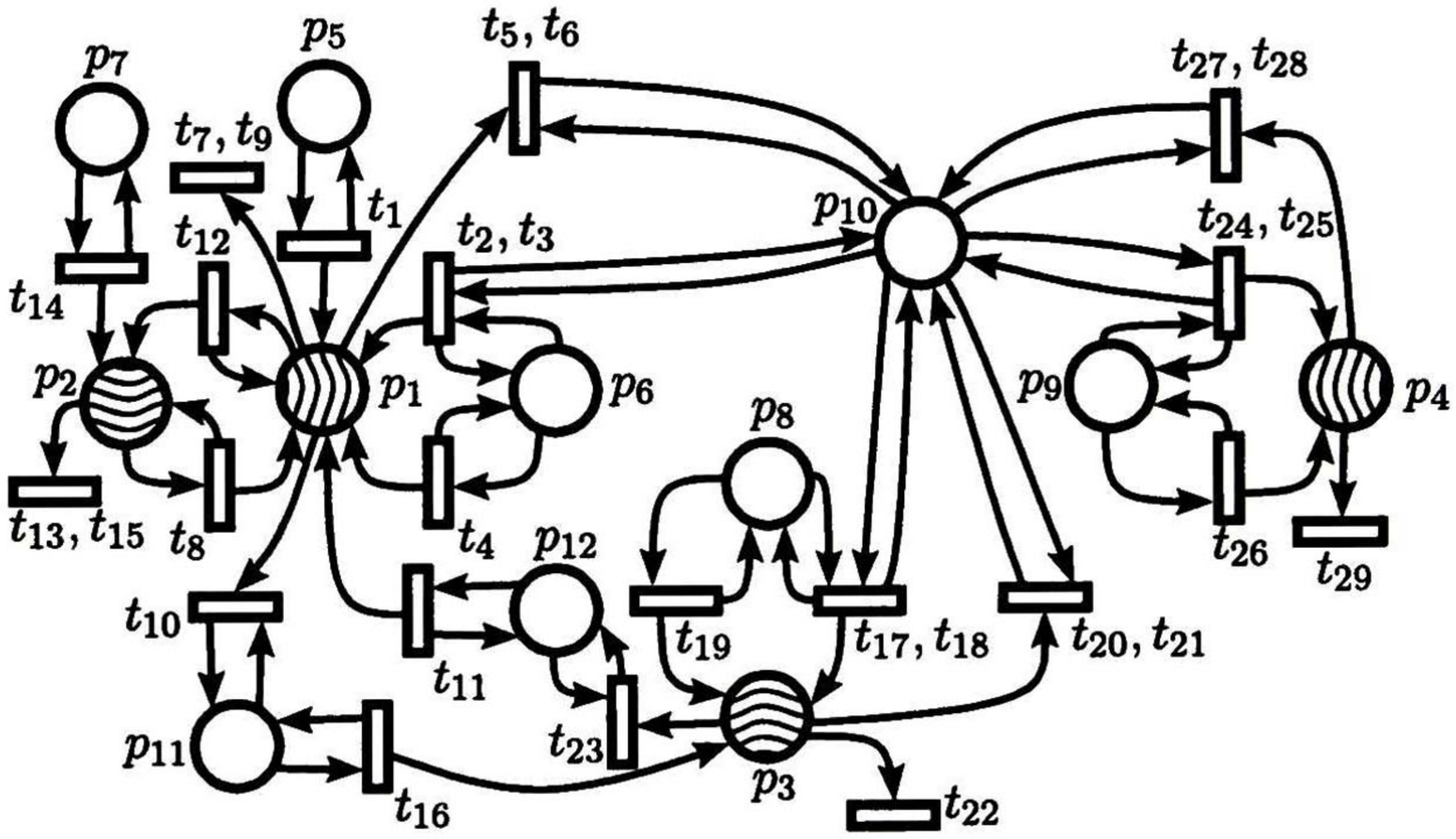


Figure 4.10: *ContPN* climate model of a greenhouse

The *ContPN* state equations of the greenhouse climate model are:

$$\begin{aligned}
\dot{m}_1 =& -(I_{c_1}\lambda_5 + \lambda_6)m_1m_{10} + (\lambda_7 + \lambda_9)m_1 + \lambda_8 m_2 + \lambda_1 m_5 \\
&+ (I_{c_1}\lambda_2 + \lambda_3)m_6m_{10} + \lambda_4 m_6 - I_{c_2}\lambda_{10}m_{11} + \lambda_{11}m_{12} \\
\dot{m}_2 =& \lambda_{12}m_1 - (\lambda_{13} + \lambda_{15})m_2 - \lambda_{14}m_7 \\
\dot{m}_3 =& -(I_{c_1}\lambda_{20} + \lambda_{21})m_3m_{10} - \lambda_{22}m_3 + (I_{c_1}\lambda_{17} + \lambda_{18})m_8m_{10} \\
&+ \lambda_{19}m_8 + I_{c_2}\lambda_{16}m_{11} - \lambda_{23}m_{12} \qquad (4.4.1) \\
\dot{m}_4 =& -(I_{c_1}\lambda_{27} + \lambda_{28})m_4m_{10} - \lambda_{29}m_4 + (I_{c_1}\lambda_{24} + \lambda_{25})m_9m_{10} + \lambda_{26}m_9 \\
m_5 =& I_o(\tau), m_6 = T_o(\tau), m_7 = T_{ss}(\tau) \\
m_8 =& C_{H_2O,o}(\tau), m_9 = C_{CO_2,o}(\tau), m_{10} = v \\
m_{11} =& F_{hum}(\tau), m_{12} = g(m_1, m_3, m_5)
\end{aligned}$$

where markings m_5 to m_{10} are determined by weather conditions; m_{11} by the operating conditions of the humidifier; and m_{12} by a relationship between T_g, C_{H_2O}, and T_o. In this model, transitions t_2, t_5, t_{17}, t_{20}, t_{24}, and t_{27} are controlled by the input I_{c_1}; transitions t_{10} and t_{16} are controlled by the input I_{c_2}. The rest of the transitions are non controllable.

4.5 Greenhouse *ContPN* Identification

The identification is used to compute the parameters of the *ContPN*. It has to be noted that identification may not solve globally the parametric identification since some parameters vary with time. Thus, the model has to be identified constantly to improve the controller performance.

Some firing rates λ_i are grouped at the identification process because the transitions are not reduced when merging; for example, from model (4.4.1), λ_{13} and λ_{15} are dependant on m_2 only which is reflected in one parameter for both firing rates after the identification.

From the greenhouse *ContPN* model (4.4.1), the incidence matrix $\mathbf{C}$ and the flow rates are known. Besides, every variable and disturbance in our model is measurable, then we can collect enough data in order to compute its parameters.

It has to be noted that for (4.4.1), the matrix Ψ has to to contain the transitions of the *PS* part of the *ContPN* in order to compute the firing rates of the non linear elements of the model. For example, for water vapor concentration with $I_{c_i} = 0$ for $i = 1, 2$:

$$\begin{bmatrix} \dot{m}_3(1) \\ \dot{m}_3(2) \\ \vdots \\ \dot{m}_3(k) \end{bmatrix} = \begin{bmatrix} m_3(1) & m_8(1) & m_{12}(1) & m_3(1)m_{10}(1) & m_8(1)m_{10}(1) \\ m_3(2) & m_8(2) & m_{12}(2) & m_3(2)m_{10}(2) & m_8(2)m_{10}(2) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ m_3(k) & m_8(k) & m_{12}(k) & m_3(k)m_{10}(k) & m_8(k)m_{10}(k) \end{bmatrix} \begin{bmatrix} a_{3,m_3} \\ a_{3,m_8} \\ \vdots \\ a_{3,m_8m_{10}} \end{bmatrix}$$

4.6 Simulation

This section shows the simulation of identification of (4.4.1) for T_g, T_s, and C_{H_2O}. The identification process is:

1. Identify parameters with $I_{c_i} = 0$ for $i = 1, 2$ (actuators off) and store the results. This requires to gather measurements and apply the least squares method.

2. Identify parameters of actuators. With the parameters obtained in the previous identification, the new parameters are computed after measuring.

The form of the matrix Ψ_{na,m_3} (identification with no actuator for m_3) is given in the previous section. It has to be noted that m_2 has no controllable transitions, then its parameters are identified in the first step. The form of the matrices with no actuators for

m_1 and m_2 are:

$$\Psi_{na,m_1} = \begin{bmatrix} m_1(1) & m_2(1) & m_5(1) & m_6(1) & m_{12}(1) & m_1(1)m_{10}(1) & m_6(1)m_{10}(1) \\ m_1(2) & m_2(2) & m_5(2) & m_6(2) & m_{12}(2) & m_1(2)m_{10}(2) & m_6(2)m_{10}(2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_1(k) & m_2(k) & m_5(3) & m_6(3) & m_{12}(k) & m_1(k)m_{10}(k) & m_6(k)m_{10}(k) \end{bmatrix}$$

$$\Psi_{m_2} = \begin{bmatrix} m_1(1) & m_2(1) & m_7(1) \\ m_1(2) & m_2(2) & m_7(2) \\ \vdots & \vdots & \vdots \\ m_1(k) & m_2(k) & m_7(k) \end{bmatrix}$$

The form of the matrices for the second step of the identification process for m_1 and m_3 are:

$$\Psi_{a,m_1} = \begin{bmatrix} m_1(1)m_{10}(1)I_{c_1} & m_6(1)m_{10}(1)I_{c_1} & m_{11}(1)I_{c_2} \\ m_1(2)m_{10}(2)I_{c_1} & m_6(1)m_{10}(1)I_{c_1} & m_{11}(2)I_{c_2} \\ \vdots & \vdots & \vdots \\ m_1(k)m_{10}(k)I_{c_1} & m_6(1)m_{10}(1)I_{c_1} & m_{11}(k)I_{c_2} \end{bmatrix}$$

$$\Psi_{a,m_3} = \begin{bmatrix} m_3(1)m_{10}(1)I_{c_1} & m_8(1)m_{10}(1)I_{c_1} & m_{11}(1)I_{c_2} \\ m_3(2)m_{10}(2)I_{c_1} & m_8(2)m_{10}(2)I_{c_1} & m_{11}(2)I_{c_2} \\ \vdots & \vdots & \vdots \\ m_3(k)m_{10}(k)I_{c_1} & m_8(k)m_{10}(k)I_{c_1} & m_{11}(k)I_{c_2} \end{bmatrix}$$

For the identification simulation, the model to be used as the original is the one in (4.0.1) with the parameters values of Appendix A.

The simulation values for external variables used are: $I_o = 400\sin 1.1 \times 10^{-4}t$, $T_o = 7\sin(1.1\times10^{-4}t)+298$, $T_{ss} = 3\sin(1.1\times10^{-4}t)+293.15$, $C_{H_2O,o} = 0.002\sin(2t)+0.0060692$, $v = 10\sin(0.001t)+1$ with an upper saturation of 10 and a lower one of 1, and $\varphi^{cons}_{H_2O,g,r} = 2\times10^{-10}\sin(t)+3\times10^{-10}$.

The inputs used for the identification simulation are: $I_{c_1} = 0.5\sin(0.01t)+0.5$ and $I_{c_2} = 0.13333\sin 1.1\times10^{-4}t$.

Figures 4.11, 4.12, and 4.13 show the errors obtained for variables T_g, T_s, and C_{H_2O} between the original and the identified model. It can be seen that the error between the original and the identified system is small, so a similar procedure may be used in the real system. Table 4.3 shows a comparison between the identified values and the original ones if the direct model match would be carried out.

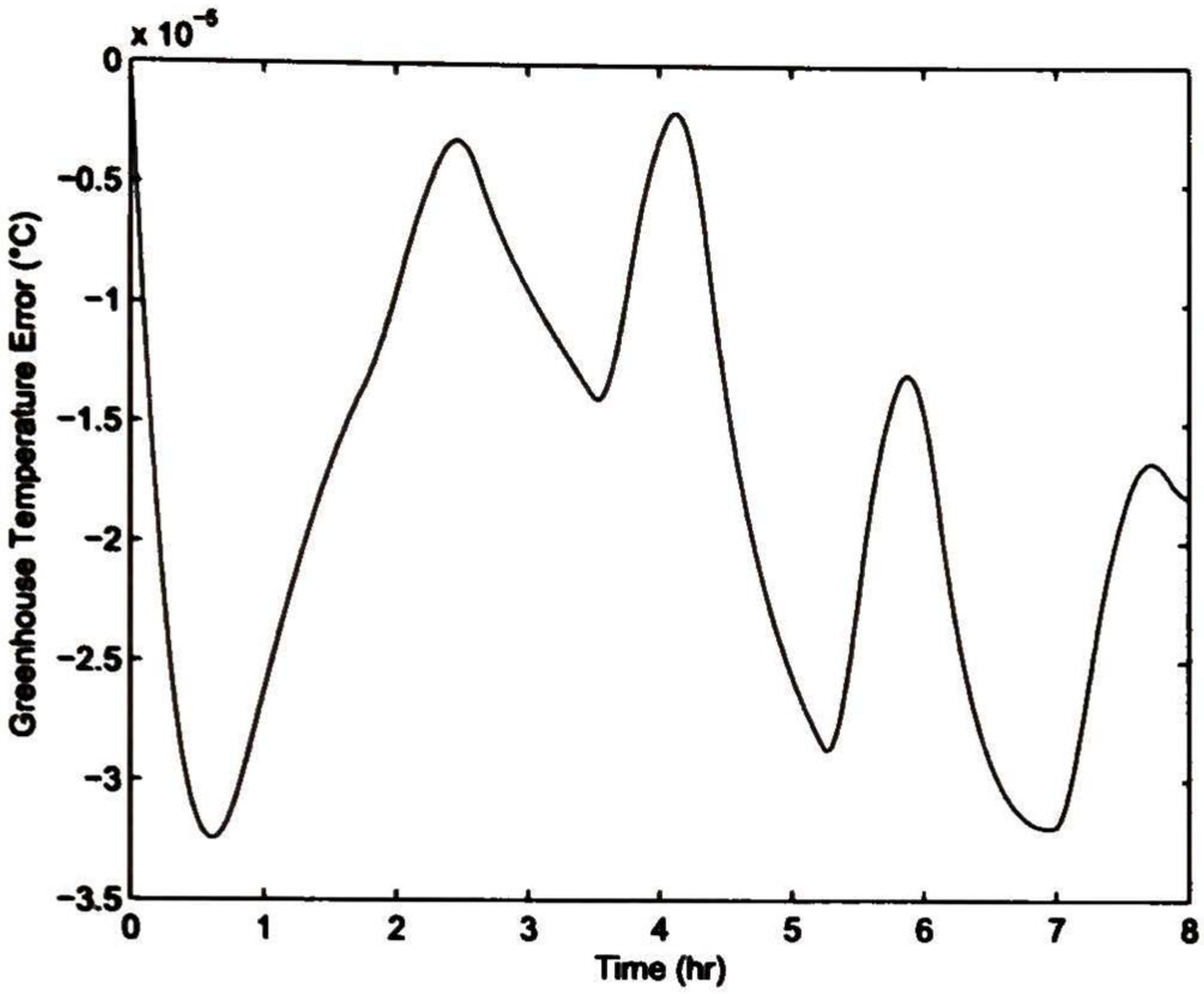


Figure 4.11: Greenhouse temperature error between original and identification

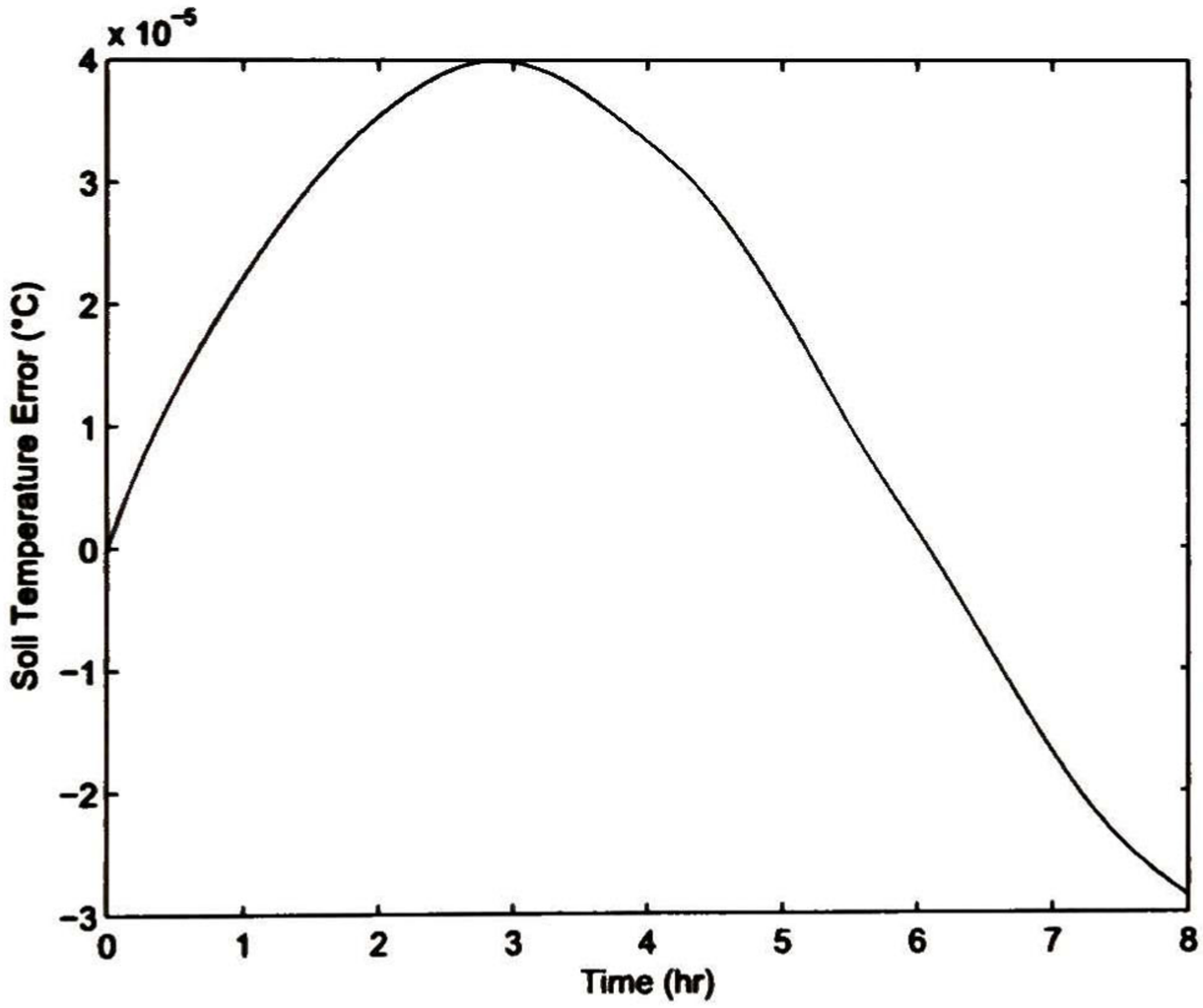


Figure 4.12: Soil temperature error between original and identification

Figures 4.14, 4.15, and 4.16 show the comparison between the original and the identified model.

Since identification of (4.4.1) can be carried out with variable wind speed, this identification process may be a good option to identify the values of a real greenhouse.

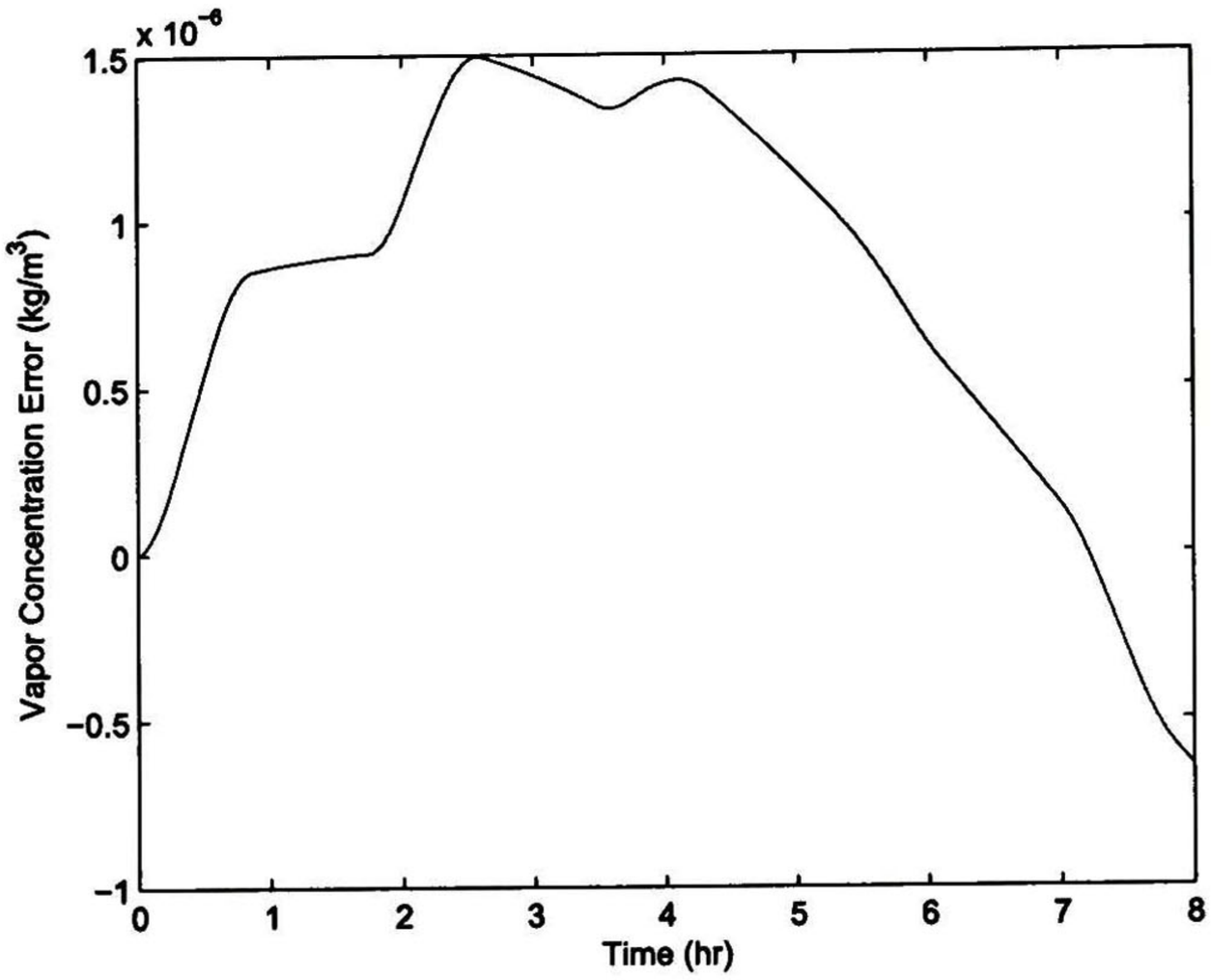


Figure 4.13: Water vapor concentration error between original and identification

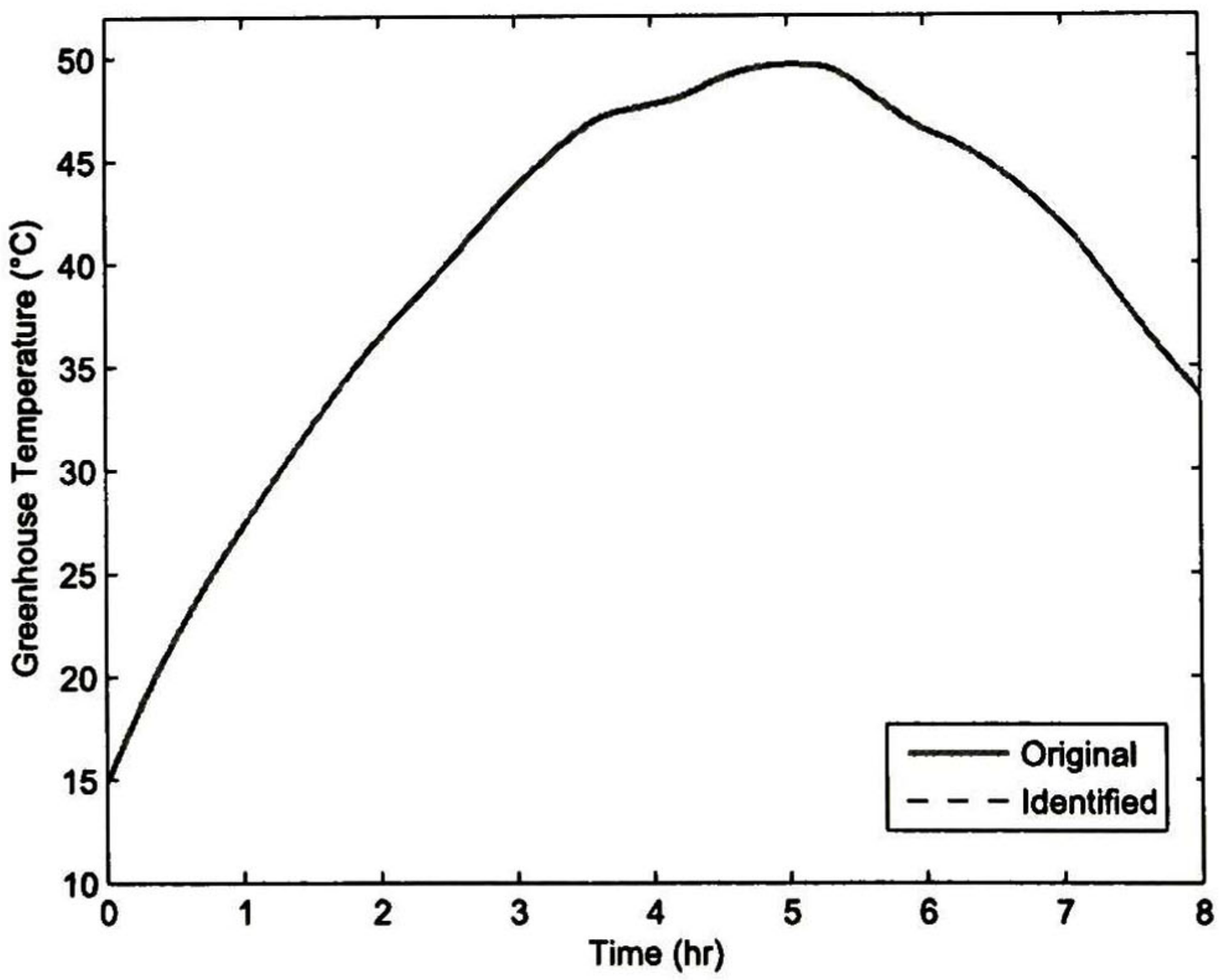


Figure 4.14: Greenhouse temperature comparison between original and identification

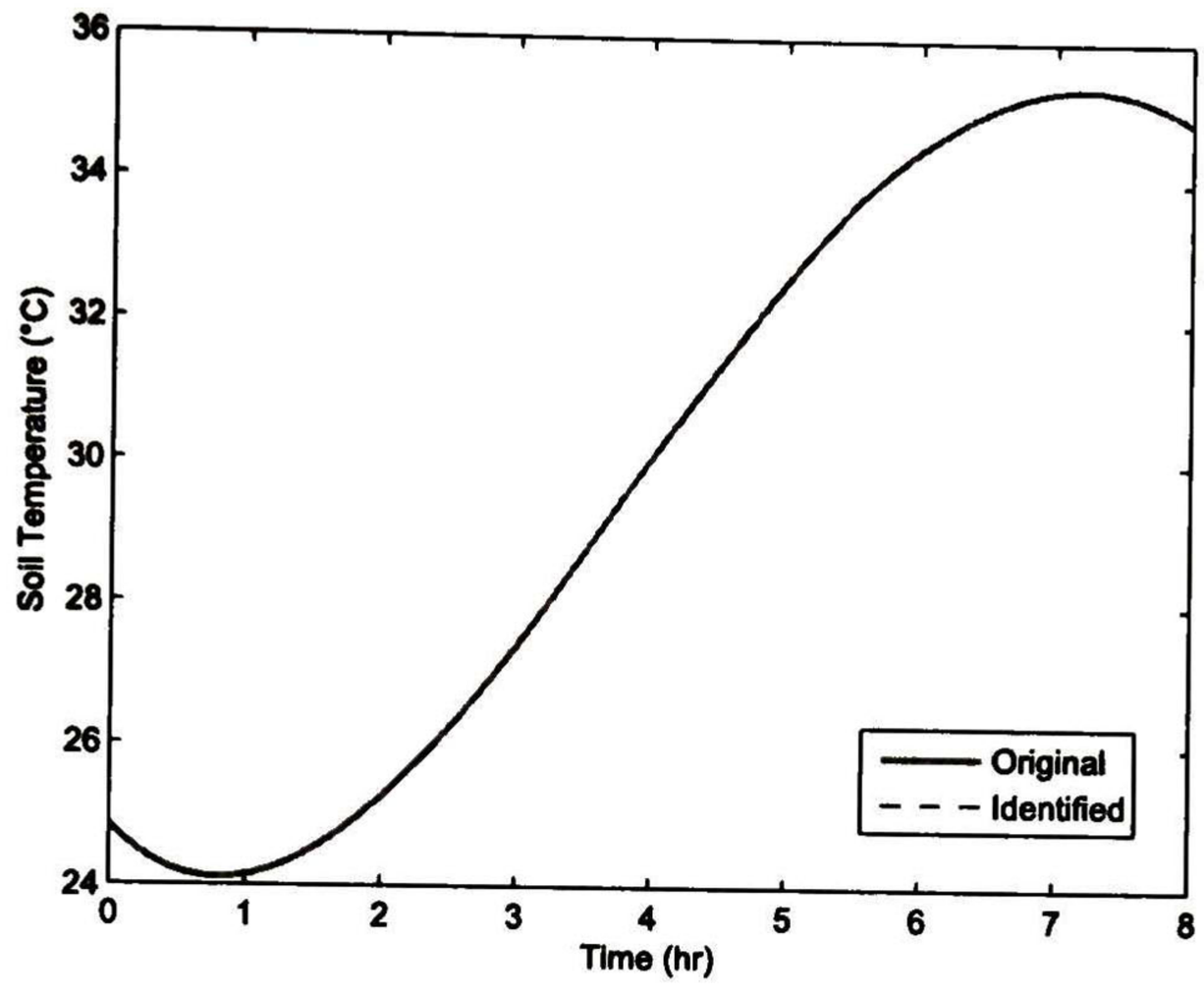


Figure 4.15: Soil temperature comparison between original and identification

Figure 4.16: Water vapor concentration comparison between original and identification

Parameters	Used	Identified
$\frac{1}{K_g}\left((\rho_a c_{p,a} p_{v5}) + U_{g,o}\frac{A_{g,o}}{A_g} + U_{g,s}\frac{A_{g,s}}{A_g}\right)$	4.2957×10^{-4}	4.2958×10^{-4}
$U_{g,s}\frac{A_{g,s}}{K_g A_g}$	1.79687×10^{-4}	1.79695×10^{-4}
$\frac{\eta_g}{K_g}$	2.18750×10^{-5}	2.18753×10^{-5}
$\frac{1}{K_g}\left((\rho_a c_{p,a} p_{v5}) + U_{g,o}\frac{A_{g,o}}{A_g}\right)$	2.49888×10^{-4}	2.49886×10^{-4}
$(1-\gamma_2)\frac{\kappa}{K_g}$	17.65625	17.64837
$U_{g,s}\frac{A_{g,s}}{K_s A_g}$	4.79167×10^{-5}	4.79169×10^{-5}
$\frac{1}{K_s}\left(U_{s,ss} + U_{g,s}\frac{A_{g,s}}{A_g}\right)$	6.45833×10^{-5}	6.45826×10^{-5}
$U_{s,ss}\frac{1}{K_s}$	1.66667×10^{-5}	1.66657×10^{-5}
$\frac{A_g}{V_g}p_{v5}$	3.01296×10^{-6}	4.05915×10^{-6}
$\frac{A_g}{V_g}p_{v5}$	3.01296×10^{-6}	0.03658
$\frac{A_g}{V_g}$	0.04071	0.0207
$\frac{A_g}{V_g}(1-\gamma_1)\rho_{H_2O}\kappa F_{hum}$	1.677513×10^{-3}	1.677499×10^{-3}
$\frac{A_g}{V_g}(1-\gamma_1)\rho_{H_2O}F_{hum}$	9.67094×10^{-7}	9.6729×10^{-7}
$\frac{1}{K_g}\rho_a c_{p,a} u_{vmax}$	5.447696×10^{-6}	5.447801×10^{-6}
$\frac{1}{K_g}\rho_a c_{p,a} u_{vmax}$	5.447696×10^{-6}	5.447801×10^{-6}
$\frac{A_g}{V_g}u_{vmax}$	5.447696×10^{-6}	5.43850×10^{-6}
$\frac{A_g}{V_g}u_{vmax}$	5.447696×10^{-6}	5.43287×10^{-6}
$\frac{1}{K_g}\rho_a c_{p,a} p_{v3}$	1.10339×10^{-6}	1.10343×10^{-6}
$\frac{1}{K_g}\rho_a c_{p,a} p_{v3}$	1.10339×10^{-6}	1.10343×10^{-6}
$\frac{A_g}{V_g}p_{v3}$	1.10339×10^{-6}	1.08977×10^{-6}
$\frac{A_g}{V_g}p_{v3}$	1.10339×10^{-6}	1.09673×10^{-6}

Table 4.3: Comparison between used and identified parameters

Chapter 5

Conclusions

The process to model a greenhouse with *ContPN* is presented. The advantages of *ContPN* modeling upon classic modeling are:

- The pictorial representation of variables which allows an easier understanding of the interaction between places (variables). This is an important point since it allows to model other systems.

- The lack of negative values in *PN* do not affect the system modeling because the greenhouse climate (temperature, water vapor concentration, and CO_2 concentration) is a positive system. Let us note that temperature is measured in Kelvin.

- The bounds in actuators are represented naturally by the marking of a place as with the humidifier. In the case of the humidifier, although the tokens flow from its place can be reduced with the control, the representing place is a source place because the tokens are constant and they represent the maximum capacity of water flow.

- The methodology allows to construct the model modularly. So, elements can be added or removed as necessary.

For example, if it is desired to remove the humidifier from the fisical greenhouse, the *ConPN* of (4.4.1) would require to eliminate the place p_{11} and the transitions t_{10} and t_{16} leaving a representation as in Figure 5.1.

Instead, if adding a device is desired, a places (or function places) have to be created along with its transitions according to elementary modules in order to represent the relation between the variables and the new device. For example, an air heater's first approach would require a place for the temperature of the heated air and a fluid device balance module in which the fluid speed is generated by the device so it may be reduced to a simple balance module with controllable transitions.

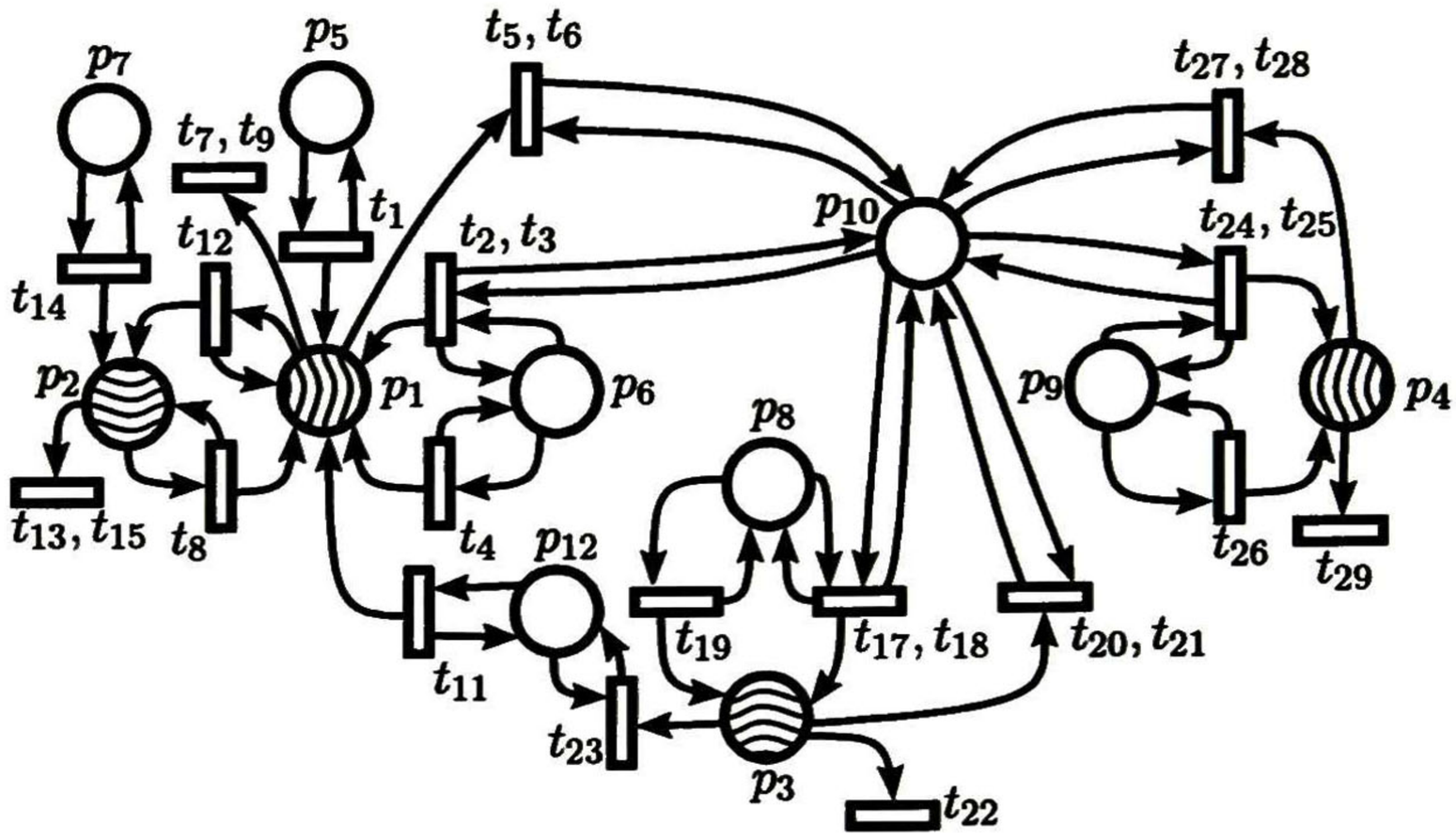


Figure 5.1: *ContPN* climate model of a greenhouse without humidifier

5.1 Future Work

- Validation of the model with a real greenhouse.
- Introduce crop dependent terms into the model equations.
- The control of the greenhouse temperature and relative humidity is to be studied either with Petri Nets or with a normal modeling.

Appendix A

Simulations Values

The next values are taken from [34][1] excepting F_{vent} and F_{hum}. The values presented in table A.1 are the ones simulations herein used[2].

Variable	Value		Variable	Value
η_g	0.7		ρ_a	1.29
$c_{p,a}$	1010		K_g	32000
$\frac{A_r}{A_g}$	1.3		A_g	40
p_{v1}	7.17×10^{-5}		p_{v2}	0.0156
p_{v3}	2.71×10^{-5}		p_{v4}	6.32×10^{-5}
p_{v5}	7.4×10^{-5}		K_s	120000
$U_{g,o}\frac{A_{g,o}}{A_g}$	7.9		$U_{g,s}$	5.75
$p_{p1}\frac{A_{p,g}}{A_g}$	1.524		p_{p2}	3
κ	2260000		ρ_{H_2O}	998
γ_1	0.3		γ_2	0.75
U_{sss}	2		c_{s1}	610.78
c_{s2}	17.08085		c_{s3}	234.175
α_c	2.6×10^{-7}		β_c	2.3×10^{-8}
c_{m1}	6.25×10^{-12}		c_m2	0.33
M_{H_2O}	18×10^{-3}		R_g	8.314
F_{hum}	1.36×10^{-6}		F_{vent}	1.9583

Table A.1: Values used in simulations

[1] Chapter 7

[2] Excepting control simulation, $\eta_g = 0.62$

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Modelado de la Temperatura y Humedad Relativa de un Invernadero por Medio de Redes de Petri Fluidificadas / Continuous Timed Petri Nets Greenhouse Temperature and Relative Humidity Modeling

del (la) C.

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