Applying rapid-prototyping in the innovation process

Climate control design for a food storage warehouse

Master thesis Industrial Engineering and Management

University of Groningen

July 2006

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Preface

For my master thesis I was interested in an assignment with a great amount technical/engineering aspects. Since starting with the master program I have developed a great interest in modelling, simulation and control engineering. My supervisor Dr. H. Hasper was able to give me an assignment that matched with my interests. He was also able to keep a management aspect in it, the design process of a new system and the methodology to efficiently accomplish this. I was also given the opportunity to have some practical experience by working with a microprocessor. This was very nice because it gave me the opportunity to see things in a more realistic way.

Now that I am finishing my master program thanks goes in first place to Dr. H. Hasper. He was my first supervisor for this assignment but has been a teacher for different courses and a mentor since I first worked with him. I thank him for all his help and support in all these years.

I also want to thank Tamer Oral for his help with the HC12 microprocessor. Because of my less technical orientation he was of great help by showing me how to work with the microprocessor and taking care of the more technical aspects of this system. He was also responsible for the building of the electronic parts to show how rapid-prototyping works. I also want to thank Ing. H. Westera (VDH) and F. Schra (Omnivent) for their time and answers to my questions. Thanks goes also to mr. Groenwold for allowing me to visit his food storage warehouse. This gave me a better understanding of the structure of a storage warehouse which was important for building the model.

Danny Dirksz

Groningen, July 2006

Abstract

This thesis describes a design methodology in which rapid-prototyping plays a very important role. At the start of a design project there will be a lot of unclear or vague issues. Rapid-prototyping brings the steps of setting or changing specifications and analyzing their impact and feasibility closer to each other on a shorter time period. This is achieved with the use of advanced simulation software. When designing controllers these software are also able to deliver the programs, in C-code, which can be downloaded into a microprocessor and tested in a relatively short period of time. The reasons why design time can be reduced are:

- Changes can be made in the model and simulated very fast. In a short period of time designers can understand the system and find the best design parameters.
- Wrong and unfeasible specifications can efficiently be found at an early stage in the design process.
- The software can deliver the programming code (for a controller) within seconds; there is less need for programming by designers. The downloading of this code into a processor makes it possible to test the design in no time.

To show this in practice a climate control system was designed for a food storage warehouse. A model was build to simulate the temperature changes of products, in this case potatoes. The idea of using the weather forecast was modelled to investigate whether this was a more energy efficient solution. A storage period of seven months was simulated and compared against the traditional climate control approach. Analysis of the results showed that no significant differences existed between the climate control methods. However the simulation process showed how using only a model and simulations different scenarios could be tested in a short period of time. It showed how with a few resources information could be gathered of different scenarios and showed the possibility to give back information to clients or to designers in a shorter time.
The thesis finalizes with guidelines of how a system can be described on a high level of abstraction. Abstraction can help avoid being distracted by details and can open the way for innovative ideas when searching for design solutions. An overview is given of different functions and elements to accomplish this.

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1. Introduction

In general the design of a new product or process is very time consuming. At early stages of the design process solutions have to be found to realise a new design and specifications have to be set. Most of the times there will be specifications that are not feasible or that do not cause the desired effects on performance. These faults are often discovered later in the design process and designers have to start again with thinking of new or better set of specifications. Not identifying these faults at an early stage increases the duration of the design process. This project presents a slightly different design approach in which modelling plays a key role. Models make simulations possible in a relatively short period of time. In these models specifications can be changed and simulated almost immediately. These specifications are also known as design parameters. The result is that the specifications process can be performed parallel or partially parallel to the simulations. It gives the possibility to observe the effects of those changes almost immediately. The simulations can so help determine whether design parameters are feasible and if they will have a positive effect on performance. In this thesis this is seen as part of the rapid-prototyping process. Rapid-prototyping[1] is here defined as the process of reducing the time to design, test and realise a new first design. Simulation programs nowadays are also able to generate C-code for a design (model). C-code is a high level programming language widely used for software programming. For this reason rapid-prototyping is limited to control systems in this thesis. Microprocessors are then used in which the code can be programmed. The advantage now is that the code for this software is automatically generated and can be downloaded into the microprocessor in a very short time.

In this thesis it is also the intention to give an overview of how design problems can be described more abstractly. Describing a system on a very high abstraction level can give designers more insight into the problem. It helps designers avoid being distracted by details, making it easier to focus on the whole issue. Abstraction can also open the way for innovation because it encourages filling the details in a more creative way. The popular functional decomposition technique can then be used for a more detailed description. The link with rapid-prototyping is that this can also help in

[1] Rapid-prototyping is better known as fast fabrication of a physical model of a product concept. In this thesis rapid-prototyping is taken as a process going farther than only the automatic fabrication of physical objects.

the specification process. New ideas or solutions always have to be translated in specifications. The specifications or design parameters can be more innovative in this case and may require more testing.

Rapid-prototyping in practice

This research aims at reducing the time for determining and testing design parameters for a real design problem, to show how simulations can help in the design process. The problem is to develop energy saving techniques for a potato storage warehouse. A potato storage is here used as example but a broad range of similar processes can be treated in the same way. In this problem it is of major importance to keep the appropriate climate conditions inside the warehouse because the climate conditions determine the quality of the stored products. The biological heat of the stored products, in this case potatoes, will cause them to warm up. For optimal storage the temperature and relative humidity have to be kept inside a certain range. A control system has to follow the changes of the climate conditions inside the warehouse and take action when necessary. These actions are then turning on ventilators and/or opening ventilation windows.

An energy saving idea is the use of the weather forecast to determine the best way to control the climate inside the warehouse. The focus in this research will therefore be to design a climate control system that uses the weather forecast for saving energy. A control strategy takes the expected weather conditions into consideration and determines the best moment (day) to ventilate. Data and specifications for this problem will be given by the companies VDH Products Roden and Omnivent Zeewolde, specialized in measurement systems, agricultural storage and climate control. It is also expected that the presented way of working will let designers understand the specifications and let them pass this phase faster and with more success.

Thesis outline

In the next chapter the problem statement is formulated for this research. The methodology for dealing with the sub questions, resulting from the problem statement, is also described.

Chapter 3 gives a short description of the design approach (or methodology) for the storage problem. This approach can of course be applied on different systems. Chapter 4 and 5 describe how a simulation model is build and used for the designing of a control system that can use weather forecasts. Chapter 5 also describes how rapid-prototyping is applied for this design. The chapter also shows first steps towards implementation. Chapter 6 continues with an analysis of the performance of the control system when compared to a more traditional climate control approach.

In chapter 7 theories for describing systems on an abstract level are applied on the storage problem. The chapter shows how this is done and an attempt is made to find alternative solutions. The thesis finishes with a conclusion, chapter 8, and a reflection on this master assignment. The reflection evaluates some important aspects of this project and recommendations are given for further research.

2. Problem statement and research methodology

This chapter presents the problem statement for this master assignment. The problem statement consists of a business goal, a main research question and sub questions. Together the answers of the sub questions give answer to the main research question. How these questions will be approached, the methodology, will also be explained in this chapter. In the problem statement research constraints and conditions are also given.

2.1 Problem statement

Business goal

To show how model building and simulations can help set and understand design specifications, first step implementation and reduce the time to design and test a climate control system for a food storage warehouse in which weather forecasts are used.

Main research question

How can the rapid-prototyping process be shown for the food storage process that uses weather forecasts for climate control?

The answer to this questions shows the steps of modelling the process, designing a climate control system and analyzing this new design. At the end the possibility of downloading models into a microprocessor is described.

Research constraints and conditions

- The duration of the research is limited to five months
- The findings deal in general with technical systems
- Rapid-prototyping here deals only with the design of control systems. The designed controller(s) or control strategies are downloaded to a microprocessor.
- The simulations of the climate control system should run parallel or partially parallel to the parameters design process
- A scale model will be built to, more realistically, show the working of the control system

- Simulation software will be MATLAB/SIMULINK
- The microprocessor will be the Motorola HC12 Evaluation Board, which is supported by SIMULINK.

2.2 Sub questions

- *How can the warehouse and its dynamics be modelled mathematically?*
  The result is a set of mathematical equations that describe the dynamics inside the warehouse. Dynamics refer to the change of important climate quantities (e.g. temperature, humidity) with time. With the equations the food storage process can be simulated.

- *How can a climate control system be designed that takes advantage of the weather forecast?*
  A control system is here designed that takes advantage of the weather forecast to control the climate inside the warehouse. With design is meant the implementation of strategies or formulas for determining the best approach for climate control.

- *Does the use of the weather forecast offer cost advantages?*
  The warehouse model is used to compare the performance of the control system when it uses the weather forecast against a conventional feedback control strategy. The performance is in this case measured in energy costs. A significance test is made to determine whether the alternative control system can offer significant cost differences.

- *How can the storage problem be described with the purpose of finding new energy saving solutions?*
  In the early stages of product design the product (or process) to be designed is usually described with black boxes using general functions to help the search for solutions. Different approaches for achieving this are here described, especially the ones that can make the description as abstract as possible.

- *What are alternative solutions?*

  The abstract description of the storage problem is intended to help find alternative solutions for saving energy. As was described in the introduction, an abstract description can encourage creativity. These alternatives will have to be weather independent.

2.3 Methodology

In this paragraph the methodology that will be used in this research is described. First the methodology for dealing with the climate control system design is explained. This is also the most important part of the research. After that the approach for abstractly describing design problems is described.

2.3.1 The storage problem

The best approach to this part of the research is to follow the four phases described in the Pr – Pm – Sm – Sw model [1], figure 2.1. The model describes a proposed method for dealing with industrial engineering research. The four phases are now described more in depth.

Pr

In this phase the problem, as described in reality, is examined. In general the problem is examined from different viewpoints because of the involvement of different stakeholders. In the storage problem the problem is rather well defined and is not a vague set of symptoms as is usually the case in less technical, industrial, research. The real "problem" here is that an innovative solution has to be designed and tested. In this project the purpose is to design a controller using innovative ideas and to show how rapid prototyping can speed up the design process and bring the design closer to reality during the testing phase.

Pm

The problem, as was described in the previous phase, is modelled. In this case mathematical equations are derived for the warehouse dynamics. The derived equations are then modelled in a simulation program. The model will also be validated in this phase.

Sm

In this phase the model is used to find solutions for the problem, as defined by the model. The model is used to simulate different control strategies and with these simulations the best parameters for the control system are found. In the storage problem the solution is a control system that minimizes energy costs and that can keep the storage temperature within the desired range (minimize quality loss).

Sr

The model solution is translated into a real solution to be implemented in the real problem situation. The programming of the climate control system into a microcontroller that is connected to different climate control mechanisms is an example. Normally the real solution is also validated and the degree in which it solves the real problem is evaluated. Letting simulation software generate the programming code and downloading this into a microprocessor is a first step in this phase.

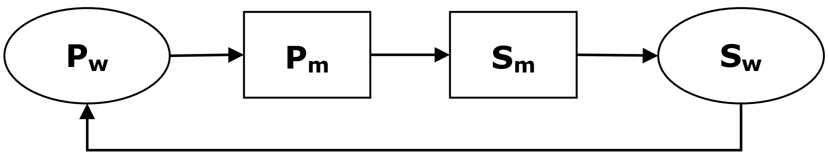


Figure 2.1 Pr – Pm – Sm – Sr model

2.3.2 Abstract problem description

As a tool to help in this part of the research a conceptual model is drawn. A conceptual model is used to show what the expected relations are between central concepts in the research problem and other concepts that may play an important role [2]. It is important to show what the role is of those concepts. An important issue in this research is the level of abstraction to describe a product or process, from now on called industrial systems. Abstraction level can also be called aggregation level and is defined as the *degree of detail* by de Leeuw [3]. Different degrees of detail can be used when describing industrial systems. In 't Veld [4] defines a system as *a by the researcher distinguished collection of elements inside the total reality that have relations with other elements inside that total reality.* So in order to describe a system on an abstract level the degree of detail of the description of the elements and relations should be reduced. According to Pahl and Beitz [5] a description is abstract when it is intangible and solution-neutral. With solution-neutral is meant that the description should not suggest any solution or solution form. Some further thinking brings the idea that a description gives information about something and information can be defined as the interpretation of a set of data. A lot of data gives more information, making the description less abstract. Figure 2.2 shows the conceptual model.

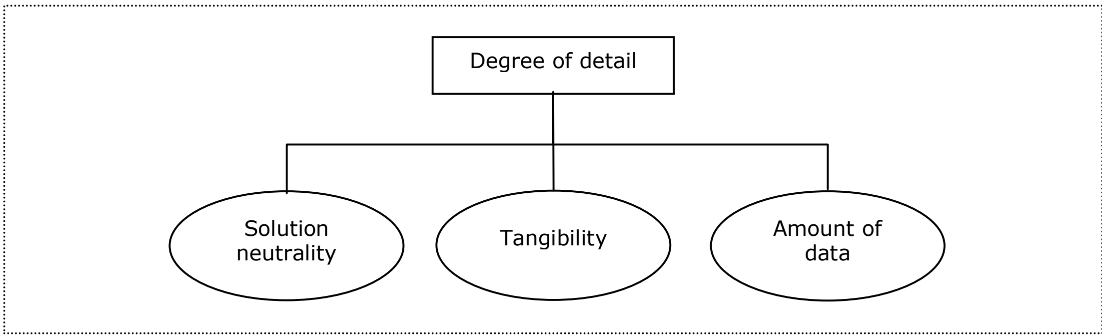


Figure 2.2 Conceptual model

The conceptual model shows the important characteristics of an abstract description. These are therefore important issues when searching for methods to describe the relations and elements of an industrial system.

3. Design methodology

3.1 The design process

The design of a climate control system for a storage warehouse in this thesis is the means to illustrate a systematic design approach. Rapid-prototyping is here the most important issue because of the ability to simulate a system and quickly change and test different parameters for this system (in simulations).
Advances in technology have made it possible for competitors to deliver products in which the physical aspects are of very high quality. These competitors can then only distinguish their products by the software that they deliver with these products. For that reason the focus lies on the design of control systems rather than the physical product itself. Simulation packages like MATLAB/SIMULINK also make it possible to rapidly program these software programs which can then be downloaded into a microprocessor or microcomputer. In this chapter the methodology (or the systematic approach) is described. The goal is to present a way of thinking and designing that can hopefully help designers:

- find creative and better solutions to design problems
- rapidly change and test designs, also in a more realistic way
- achieve a robust design

The traditional product design process is shown in figure 3.1. The traditional method has the disadvantage that it takes longer to verify design decisions. The design team sets the specifications, the design parameters, for the system and continue with the design of a concept for the system. After this design a prototype is build and tested. It is in the design/testing phase that faults in the design are discovered. The team has to go back in the design process and set new parameters, make a new design, build a new prototype and retest the prototype. Depending on the complexity of the system, the design process may have to be repeated many times. Specially when dealing with innovative projects in which few is known about the system. Many changes and tests will then have to be made before a good design is achieved. It can take very long before the right set of specifications can be discovered.

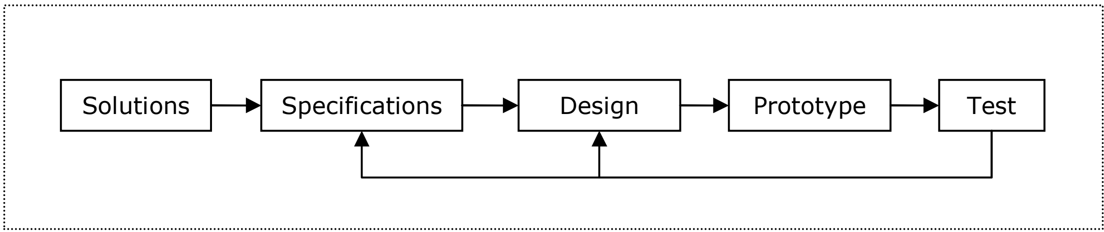


Figure 3.1 The traditional design process

The methodology to be presented has just the same steps as the traditional approach. The difference here is that in the design phase models and simulations are extensively used. A model has the advantage that design parameters can be changed quickly and makes it possible to see the effect of these changes in a very short time. In this way designers can continue with the physical design, prototyping and testing of the system when they have accomplished optimal results in their simulations. Look at it as a faster way for designers (or other persons involved) to understand the system and to receive feedback. Just as with the traditional approach designers will have to reset their specifications, make changes to the design and retest the design. The difference here is that as designers think of changing specifications these changes can be made and simulated almost immediately in the model. Instead of thinking of a new set of specifications and continue to the design phase the changes can be first tested with simulations. In figure 3.2 the extra thick line from the design/simulate block to the specifications block shows this important difference. Simulations with the model can then quickly show what the effect is of these changes. Less prototypes are also needed since designers continue to this phase only when they have achieved acceptable results within the model. Figure 3.2 the alternative design process.

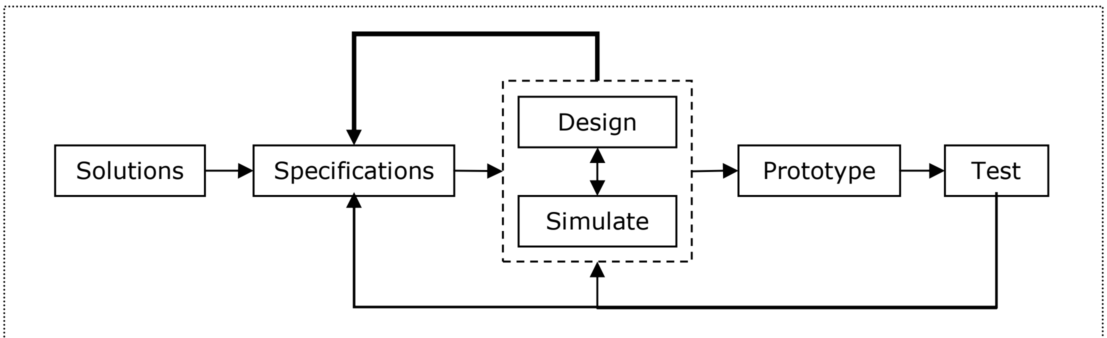


Figure 3.2 The alternative design process

This thesis also presents a slightly different approach for the first phase of the design process. When searching for ideas for the design of a new system functional decomposition [5] is the most popular approach. The system to be designed is seen as a black box. Some quantities enter the black box and leave the black box in the desired form. The black box is then described by a *main (or overall) function*. This function is decomposed in a number of sub functions and solutions are thought for these specific functions. This thesis will give some guidelines to describe the system on a more abstract level than functional decomposition.
A short description of the phases shown in figure 3.1 b will now be given.

Solutions and specifications

As described in product design literature the first step is to formulate the design problem. The design problem is then described using specific functions or elements. The difference now is that this should be done on a relatively high level of abstraction. As was mentioned before doing this can help designers discover whole other solution possibilities. Another advantage is that thinking on an abstract level can help the modelling process in SIMULINK. Abstract functions can be described by one or more SIMULINK blocks. Chapter 7 describes in detail how a system can be described on a high level of abstraction. If still needed the problem can then be decomposed into more specific functions.
Specifications are needs of customers translated into a metric and a value [6]. No attention is given to how specifications are established since this is not part of the project. A good systematic approach for setting specifications is described in [6].

Design and Simulation

Abstractly describing the system can also help with the identification of important physical quantities. This is important for the next step in which a mathematical model is derived for the system that has to be designed. With the model simulations can be run to, theoretically, test the system and to understand how the system works. These models consist, most of the time, of differential equations, describing how the quantities change in time. With MATLAB/SIMULINK it is possible to build your model by using simple blocks. The nice thing about this program is that you can build a visually simple model. Adjustments to the design can quickly be made in the model after which simulations can be run to study the effects of these adjustments.

Simulations also offer the possibility to discover whether a design will actually work in reality. This discovery can be very important because the design project can then be stopped at an early stage. Money and resources that would have been spent in the next phases in the design process are then spared.
When designing a system it is also a goal to make this the least sensitive to noise. During operation of the system noise factors in the environment can cause it not to function as one would desire. Most of the times a system has to achieve a certain target value, noise can cause it to deviate from this target. Taguchi [6] saw any deviation from the target as quality loss. His method for designing, *robust design*, is described in appendix A1. The Taguchi approach is a method to efficiently find the best parameters for a design. These are the design parameters that make the system the least sensitive to noise. In robust design several simulations are run with every time a different combination of parameters.

Prototyping and testing

Remember that an optimal combination of design parameters are first determined using the Taguchi method. After designing a robust system and testing it with simulations a prototype can be built. A prototype is a more realistic representation of the system that has been designed, most of the times a full scale model, for testing purposes [7]. It is not possible to simulate all the factors that play a role during the operation of the system to be designed. A prototype gives some help since it can be tested in more realistic situations.
As was described before, it is possible to model a system in SIMULINK using mainly simple blocks. It is then a matter of inserting the right settings and the program can deliver the complete C-code, a high programming language, of the model. That means that instead of having to program everything something can do that for you, in almost no time. The code can than be downloaded to a microprocessor, which also takes only a few seconds, and then connect the microprocessor to a more realistic system.

3.2 The power of designing with SIMULINK

SIMULINK contains many blocks that can be used for model building and simulation. Blocks like these make it possible to build a model that is visually simple. Using these blocks makes the model building process also easier if compared with programming the model oneself. Two very important advantages of using a simulation program like SIMULINK in the design process are described.

1. Faster understanding of the system

With a model the dynamics of a system can be simulated relatively fast. Days or weeks can be simulated in minutes, sometimes even seconds. This depends in particular on the computation speed of the used computer and on the complexity of the model. Because simulation time is relatively short it is possible to simulate different situations or different design parameters (specifications). In SIMULINK it is possible to change parameters during simulations. With scopes or displays in the model it becomes possible to see how these changes affect system outputs, while the simulation is still running. Outputs can be stored in the MATLAB workspace making it possible to use MATLAB data analysis possibilities. The simulations also make it possible to discover specifications that are unfeasible or that do not cause the desired outputs earlier in the design process. No resources or money is then spent on prototypes that are useless. Figure 3.3 shows an example of a SIMULINK model of an anti-lock braking system (ABS).

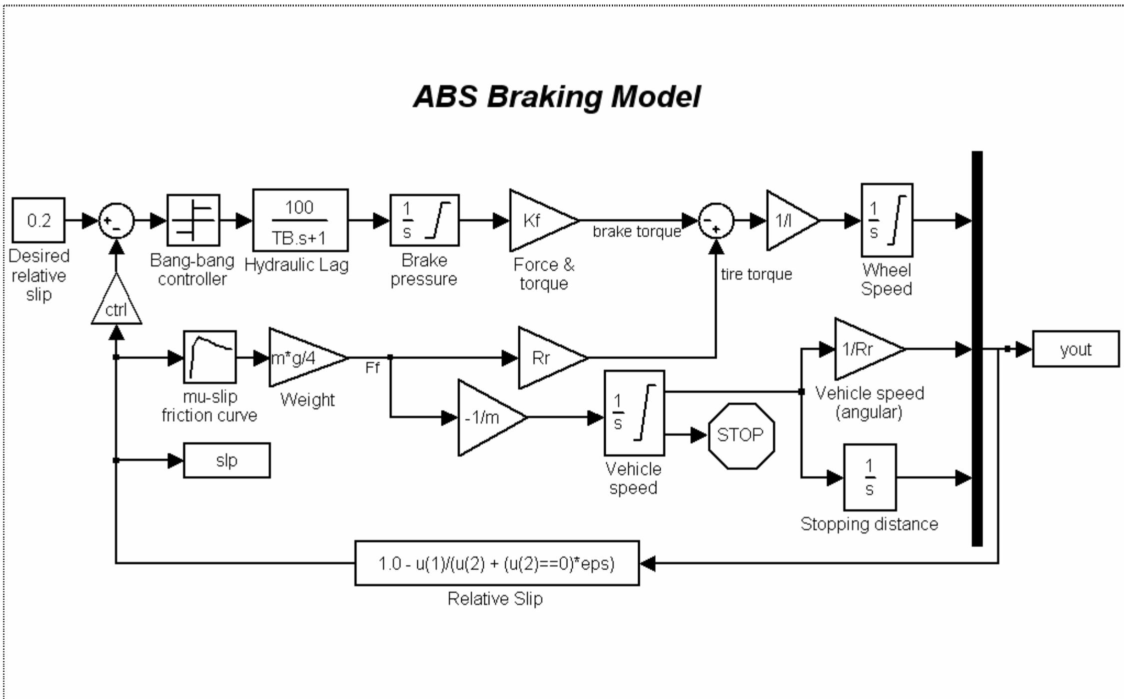


Figure 3.3 ABS SIMULINK model (SIMULINK demo)

It should be remarked that the time advantage is possible only if the necessary knowledge (mathematics, physics etc.) for modelling the system is present.

2. Code generation and prototyping

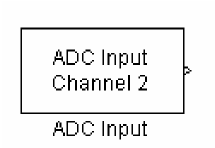
Being able to simulate systems is very helpful and nice but more interesting is the code generation ability of SIMULINK. The SIMULINK blocks offer the possibility to model a designed system relatively easy and a special feature of SIMULINK is able to generate efficient C-code for the modelled system. In combination with another software, Metrowerks Codewarrior [2], the code can be downloaded into a microprocessor. In general the process of code generation and downloading into a microprocessor takes no more than a few minutes. Besides being able to simulate systems relatively fast designers now also have the advantage that the code generation and downloading into a microprocessor is also relatively fast. Changes to a design can be made relatively easy and fast within the SIMULINK blocks. The code can then be generated and downloaded. The microprocessor can be connected to a real (test) system for realistic testing or implementation purposes.

The model in figure 3.3 is not yet ready for code generation and downloading since it is build with continuous blocks (e.g. integrators). SIMULINK also has discrete blocks making it possible to generate code for downloading by adjusting the model with discrete blocks.

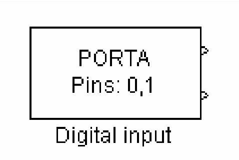
In this thesis a special SIMULINK toolbox was used to show a climate control system can be downloaded into a microprocessor. The toolbox, RTMC9S12, was build by the university of Adelaide in Australia. This toolbox has its own blocks which makes working with the microprocessor (Motorola HC12) easier. The blocks make it possible to model a system in which input can be send to the processor or output from the processor to another device. Drivers for these blocks have already been written by the creators which make it possible for SIMULINK to generate C-code for these special blocks. The toolbox also makes it possible to use serial communication allowing data from the microprocessor (or another slave) to be shown on scopes or displays in SIMULINK. The data can also be stored in the MATLAB workspace for further analysis (as was described before). The most important blocks are shown in figure 3.4. Another nice feature of the toolbox is the possibility to make changes online. While the microprocessor is connected to a real testing system and running changes can be made in the SIMULINK model. These changes are changed, online, in

[2] Compiler and debugging software

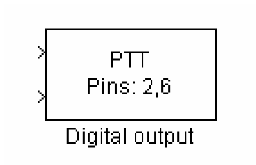
the microprocessor with no need to stop the system to make any changes in parameter values. How the output of the system changes can then be observed in the SIMULINK scopes or displays and/or stored in the MATLAB workspace for further analysis. Figure 3.5 shows a *slider gain*, which makes it possible to vary a value within a certain range during simulations or prototyping.



Analog to digital converter. An analog input voltage is send to the ADC of the microprocessor. This input is converted into discrete form. The channel corresponds to a certain ADC pin on the processor

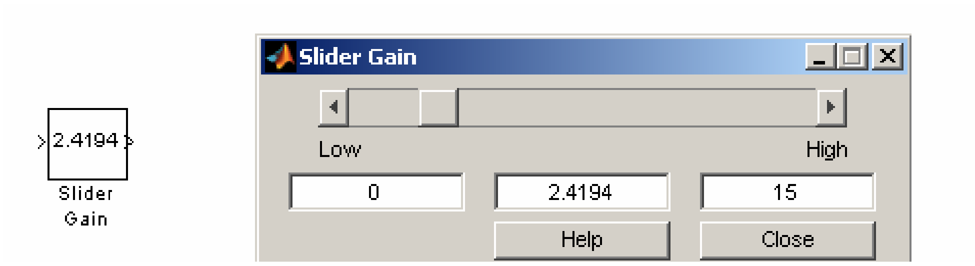


Digital input. With this block a signal can be send to the specified port (here port A) of a microprocessor. The signal should be high or low, in this case 5V or 0V.



Digital output. A signal, from SIMULINK, is send to this block. The output block will give a high signal (on, 5V) when its input is higher than a certain value, threshold 1, and a low signal (off 0V) when this value is lower than a certain value, threshold 2. The signal can be measured on the specified port (port T in this block).

Figure 3.4 ADC, input and output blocks of the RTMC9S12 SIMULINK toolbox



Double clicking on the block opens the Graphical User Interface

Figure 3.5 The SIMULINK slider gain block

Figure 3.6 shows a simple example made with some of the blocks in this toolbox. In the model two inputs from the ADC, channels zero and one, are shown in the scopes. These inputs can be voltages measured by a senor or from a different source connected to the ADC on the microprocessor. There is also a variable value (0-5) which can be send to an output block. The output block will give a high signal (on) when its input is higher than a certain value, threshold 1, and a low signal (off) when this value is lower than a certain value, threshold 2. The output can be measured on the assigned port (port A, pin 2) on the microprocessor. This block copes with the hysteresis, described in chapter 5.3. SIMULINK has also a special block that can cope with hysteresis (the discontinuity block *relay*).

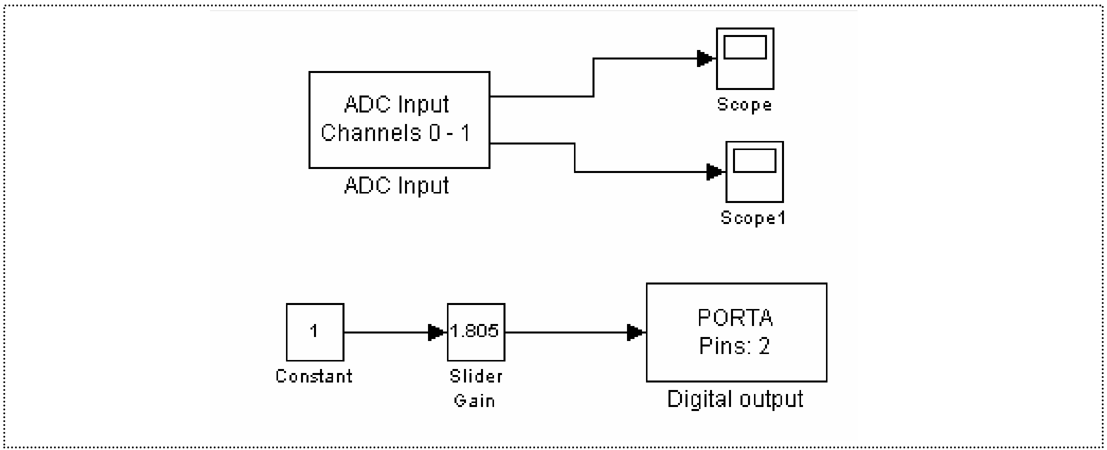


Figure 3.6 Simple SIMULINK model for prototyping

After downloading and running the code one can change the value of the slider gain online or double click on the scopes to see the signal that is going into the ADC of the microprocessor.

The RTMC9S12 toolbox was build for MATLAB version 6.5.1. Newer versions of MATLAB, with their HC12 toolbox, also support Stateflow[3] and embedded MATLAB function blocks. In the Stateflow block different states and the conditions for those states can be modelled very easily. It has shown to be a very useful feature of SIMULINK. The embedded MATLAB function block allows one to program with MATLAB code, which is a little easier. SIMULINK will then convert these blocks into C-code.

Comparing figures 3.1 and 3.2 does not give any indication of a reduction in design time. The shorter design time is the result of the advantages explained above. SIMULINK is the tool to bring the steps of setting or changing specifications, analyzing the effect and feasibility of these specifications and the prototyping of the system closer to each other in time. Simulations and changing specifications (parameters) comes very close to be a parallel process.

[3] Surf to www.mathworks.com for examples and more information.

4. Modelling the warehouse dynamics

This chapter will describe how a mathematical model is derived for the storage warehouse. The mathematical equations make it possible to build a model in SIMULINK, the simulation program to be used. Other possibilities also exist, like difference equations. SIMULINK does the same and only simple blocks are used, keeping the model visually simple.
The chapter will start with a short description of the warehouse and explains some simplifications that have been made in order to build a model. The mathematical equations will follow thereafter.

4.1 The storage warehouse

Figure 4.1 shows a sketch of the warehouse that will be modelled. The structure of this warehouse is standard for the storage of around 1000 tons of potatoes[4]. The potatoes lie on a perforated floor through which air can flow to the potatoes.
When the potatoes have to be cooled the ventilators are turned on and the side windows are opened. Air from outside the warehouse then flows through the window in the channel and through the perforated floor. The amount of outside air used for cooling depends on the window opening. The speed of the air flow, through the products, is constant and low, around 0.11 m/s.

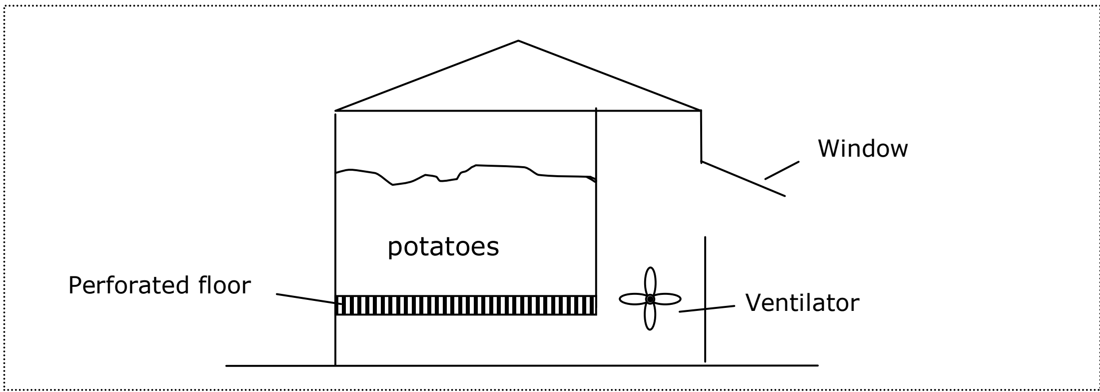


Figure 4.1 The potato storage warehouse

To simplify the modelling process the most important quantities and variables of the system have to be identified. As was mentioned before, the storage conditions are

[4] The storage dimensions are approximately (L x W x H): 25 x 17 x 4 m

determined by the temperature of the products and the relative humidity. In a real warehouse two different product temperatures are measured: temperature of the lower products (50-100 cm above the floor) and temperature of the higher products (50-100 cm under top potato surface). These two measurements determine what control action has to be taken. Two control actions are possible,

1. cooling: opening the windows and ventilating using outside air, mixed with inside air
2. recirculation of air: ventilating using only inside air, the windows are kept closed

This fact brings other quantities that are of interest: the air temperature inside the warehouse and the air temperature used for cooling. The most important quantities that have to modelled are then:

- The temperature of the air above the products, T_i
- The temperature of the lower products, T_{low}
- The temperature of the higher products, T_{high}
- The temperature of the air under the floor, T_f (a.k.a. channel temperature)
- The relative humidity, RH_i

The temperature of the air under the floor is important because it is assumed that when ventilators are turned on the air that will flow to the products, through the floor, will be the same as temperature of the air under the floor. The air in the channel (space above the ventilator) is neglected. Figure 4.2 illustrates the simplified version of the warehouse.

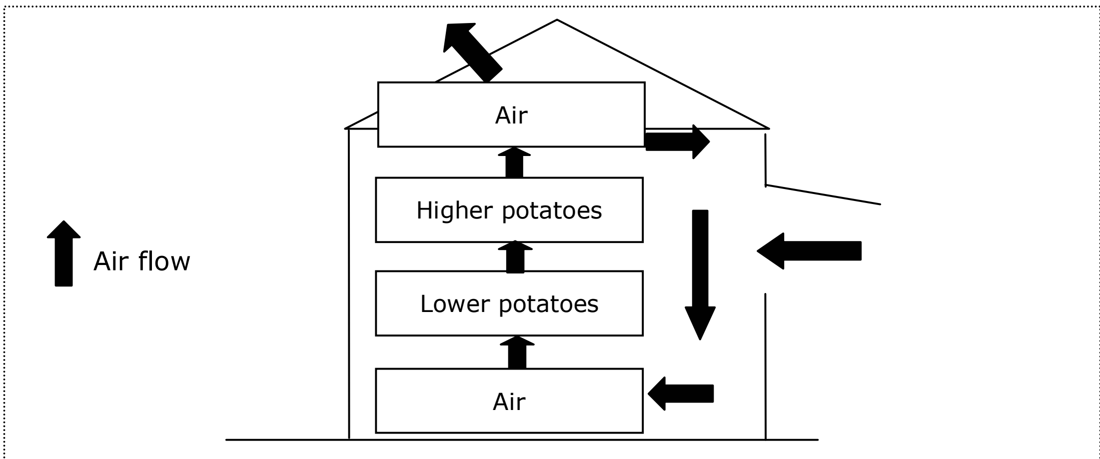


Figure 4.2 Simplified warehouse

4.2 The warehouse dynamics

4.2.1 Heat transfer: general theory

The derivation of equations for describing the temperature behaviour brings forward the area of heat transfer. In heat transfer energy is transferred from one body to another as the result of a difference in temperature. Theory about this subject distinguishes three categories of heat transfer "mechanisms" [8], also shown in figure 4.3.

1. *Conduction*
   The heat transfer across a stationary medium (solid or fluid) when a temperature gradient exists in that medium.
2. *Convection*
   Heat transfer that will occur between a surface and a moving fluid when they are at different temperatures.
3. *Radiation*
   All materials emit energy in the form of electromagnetic waves. In the absence of an intervening medium, there is a net heat transfer between two surfaces at different temperatures.

In the figure the symbol q stands for heat flow [W] and q" stands for heat flux [W/m^2]. These symbols will be applied for the remaining of this research.

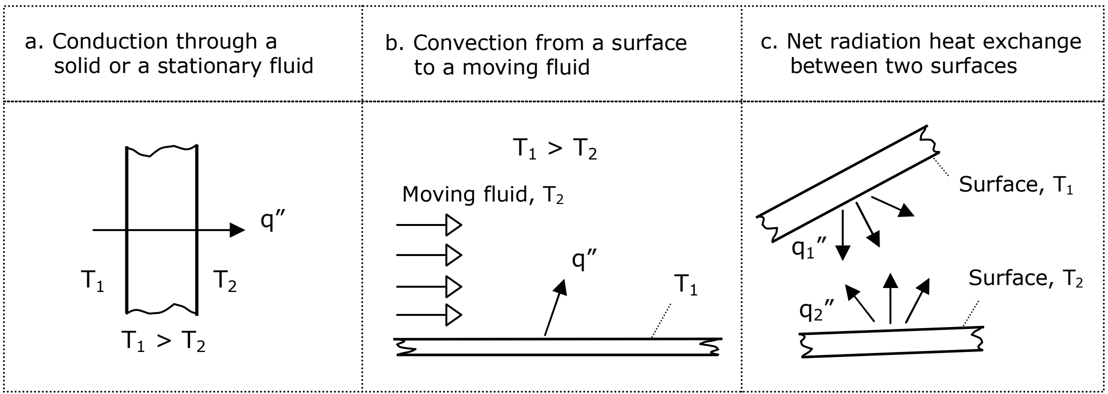


Figure 4.3 Heat transfer mechanisms [12].

The theory of heat transfer is applicable in the storage problem for the following reasons:

- Difference between inside and outside warehouse temperature
- Difference in temperature between the stored products and air inside the warehouse
- Difference in temperature between climate control mechanisms (air conditioning, heating etc.) and the air inside the warehouse
- Energy dissipated by the climate control mechanisms
- Solar radiation on the warehouse

In this research the effects of radiation will be neglected. It concerns here the radiation of heat by the stored products and the walls. It is assumed that this radiation will have little effect on the results. Only the effect of solar radiation on the roof will be modelled.

In the following paragraph the above described situations will be modelled. The equations determine the heat flow [W] in the different situations and at the end these heat flows will be summed to determine a total effect on temperature. Newton's law of cooling,

$$q = Ah(T_1 - T_2)$$

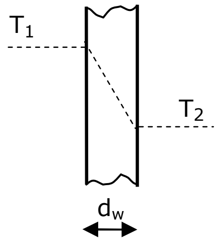
which gives the rate of heat loss of a body caused by temperature difference with its surroundings, will play an important role. In the equation h stands for the heat transfer coefficient [W/ m^2K] and A for surface [m^2].

4.2.2 Heat transfer: application

1. Conduction through the walls

A heat flow is the result of a difference between the temperatures, T_1 and T_2, as was shown in figure 4.3a. The media are the walls of the warehouse. This is again shown in figure 4.4. The heat flow is expressed as

$$q = A_w \frac{k_w}{d_w}(T_1 - T_2) \qquad h_w = \frac{k_w}{d_w}$$



k_w = thermal conductivity [W/mK] of wall
A_w = wall surface [m^2]
d_w = wall thickness [m]
x = distance [m]

Figure 4.4 Conduction through a plane wall

Conduction through the walls applies for three different situations:

- heat flow between outside air and inside air (air above the products)

  $q_1 = A_{w1} h_w (T_o - T_i)$
- heat flow between outside air and the products

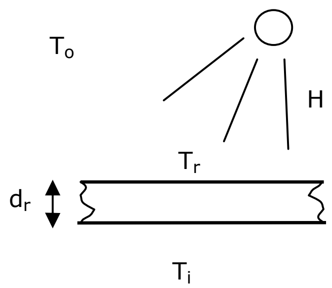
  $q_{2a} = A_{w2} h_w (T_o - T_{low})$

  $q_{2b} = A_{w2} h_w (T_o - T_{high})$
- heat flow between outside air and the air under the floor

  $q_3 = A_{w3} h_w (T_o - T_f)$

2. Conduction through the roof

Due to solar radiation the temperature of the (outside) roof surface will be, depending on the absorption factor, higher than the air temperature T_o. The roof will be approached as a black body in order to calculate the roof temperature T_r. The principles of heat conduction can then be used (as with the walls).



K_r = thermal conductivity [W/mK] of roof
A_r = roof surface [m^2]
d_r = roof thickness [m]
σ = Stefan-Boltzmann constant
α = absorption factor [0-1]
H = solar radiation [W/m^2]

Figure 4.5 The roof

$$q_4 = A_r h_r (T_r - T_i) \qquad h_d = \frac{k_r}{d_r}$$

With roof temperature

$$\sigma T_r^4 = \sigma T_o^4 + \alpha H$$

$$T_r = (T_o^4 + \frac{\alpha}{\sigma} H)^{\frac{1}{4}}$$

3. Heat flow between stored products and inside air

A difference in temperature between the higher products T_{high} and the air above those products T_i will also cause a heat flow. The conduction principles still apply in this case, where the heat transfer coefficient depends on the thermal conductivity of the products.

$$q_5 = A_p h_p (T_i - T_{high}) \qquad h_p = \frac{k_p}{d_p}$$

A_p = cross-sectional area of the warehouse
k_p = thermal conductivity products

The distance between the top surface of the products and the point at which T_{high} is measured is taken as d_p. This is the same distance between the floor and the point at which the lower temperature is measured.

4. Heat flow between the stored products and the air under the floor

The same theory applies as with the previous heat flow but this time it concerns the temperature of the lower products, T_{low}, and the temperature of the air under the floor, T_f.

$$q_6 = A_p h_p (T_f - T_{low}) \qquad h_p = \frac{k_p}{d_p}$$

5. Heat flow between the lower and higher products

The difference in temperature between the lower and higher products will cause a heat flow between these two.

$$q_7 = A_p h_p (T_{high} - T_{low}) \qquad h_p = \frac{k_p}{d_p}$$

5. Product heat emission

The stored products, in this case potatoes, emit carbon dioxide gases. These gases also have a certain amount of heat. The heat flow caused by these gases can be approached with

$$q_{8a,b} = m_p \cdot q_{bio}$$

where m_p is the mass of the products (half of the total stored mass) and q_{bio} is the heat flow per unit of mass.

6. Heat flow caused by ventilation

When the ventilators are turned on air will flow through the stored products. To calculate the heat flow caused by this air flow the same principles will be applied when dealing with a packed bed of solid particles [8, 9]. These principles also take into consideration the fact that the air flow starts with a temperature, in this case T_f, but will warm up when flowing through the products.

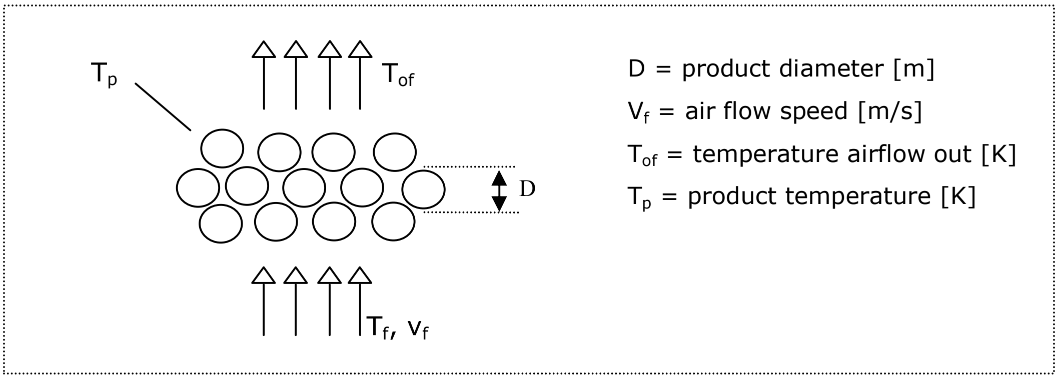


Figure 4.6 Flow through the products

The general principle is described by

$$q = h_f A_{p,t} \Delta T_{lm}$$

$$\varepsilon \cdot j_H = 2.06 \mathrm{Re}_D^{-0.575} \qquad 0.30 \le \varepsilon \le 0.50$$

$$\mathrm{Re}_D = \frac{v_f}{\nu}$$

$$St = \frac{h}{\rho v_f c_p} = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}}$$

ε represents de porosity of the packed bed and is most of the time assumed to be 0.4. j_H is the Colburn j factor.

$$Nu = \tfrac{1}{2} C_f \,\mathrm{Re}$$

$$\tfrac{1}{2} C_f = St \,\mathrm{Pr}^{2/3} = j_H$$

$$h_f = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}} \cdot \rho v_f c_p$$

To derive the air flow speed v_f all the air that is send by the ventilators, $\dot{V}_v$, has to go through the floor surface. In the equations $A_{p,t}$ is the total surface area of the potatoes and $A_{c,b}$ is the bed cross-sectional area.

$$\dot{V}_v = LB_f v_f$$

$$v_f = \frac{\dot{V}_v}{LB_f}$$

$$\Delta T_{lm} = \frac{(T_p - T_f) - (T_p - T_{of})}{\ln\left(\dfrac{T_p - T_f}{T_p - T_{of}}\right)}$$

$$\frac{T_p - T_{of}}{T_p - T_f} = \exp\left(-\frac{h_f A_{p,t}}{\rho \mathrm{v}_f A_{c,b} c_p}\right)$$

$$T_{of} = -(T_p - T_f)\exp\left(-\frac{h_f A_{p,t}}{\rho \mathrm{v}_f A_{c,b} c_p}\right) + T_p$$

Because in the model the products are divided in two groups, high and low, the equation also has to be changed for each group. For the lower products the temperature of the air, at the inlet, will be equal to the temperature of the air under the floor. The air that flows out of the lower products will then enter the higher products.

$$q_{9a} = h_f A_{p,t} \Delta T_{lm,low}$$

$$\Delta T_{lm,low} = \frac{(T_{low} - T_f) - (T_{low} - T_{of,low})}{\ln\left(\dfrac{T_{low} - T_f}{T_{low} - T_{of}}\right)}$$

$$T_{of,low} = -(T_{low} - T_f)\exp\left(-\frac{h_f A_{p,t}}{\rho \mathrm{v}_f A_{c,b} c_p}\right) + T_{low}$$

$$q_{9b} = h_f A_{p,t} \Delta T_{lm,high}$$

$$\Delta T_{lm,high} = \frac{(T_{high} - T_{of,low}) - (T_{high} - T_{of,high})}{\ln\left(\frac{T_{high} - T_{of,low}}{T_{high} - T_{of,high}}\right)}$$

$$T_{of,high} = -(T_{high} - T_{of,low}) \exp\left(-\frac{h_f A_{p,t}}{\rho v_f A_{c,b} c_p}\right) + T_{high}$$

7. Heat flow from the air flowing out of the products (T_{of}, T_i).

The air that leaves the products has a certain heat capacity which will cause a heat flow between that air flow and the air above the products.

$$q_{10} = \dot{m} c_{p,a} (T_{of,high} - T_i)$$

Where $\dot{m}$ is air mass flow and $c_{p,a}$ is the air specific heat.

8. Heat flow caused by product transpiration

Product transpiration also produces heat [10].

$$q = r k_v A_{sp} \left(100(-1.7011 + 7.7835 e^{T_p / 17.0798}) - \frac{X_i P}{0.622 + X_i} \right)$$

r = evaporation heat of water

k_v = evaporation constant

A_{sp} = specific area

X_i = water/air concentration

P = air pressure

This equation also has to be adjusted for the lower and higher products.

$$q_{11a} = r k_v A_{sp} \left(100(-1.7011 + 7.7835 e^{T_{low} / 17.0798}) - \frac{X_i P}{0.622 + X_i} \right)$$

$$q_{11b} = r k_v A_{sp} \left(100(-1.7011 + 7.7835 e^{T_{high} / 17.0798}) - \frac{X_i P}{0.622 + X_i} \right)$$

9. Heat flows under the floor

The heat flow through the wall has already been defined as q_3. This is the only heat flow when the ventilators are turned off. When the ventilators are turned on and the windows are opened outside air will mix with inside air. In this case mechanical heat produced by the ventilators is also taken into consideration. This heat flow, when ventilators are turned on, is described by

$$q_{12} = \dot{m}_L c_{p,a}(T_o - T_f) + \dot{m}_i c_{p,a}(T_i - T_f) + \beta P v$$

In the equation β is a fraction of the total ventilator power P_v that is lost as heat. The amount of inside air that is mixed with outside air depends on the effective window opening area A_L. It is known how much air is displaced by the ventilators, $\dot{V}_v$. The speed of air flowing through the window is also known, v_L. The air mass flows are then:

$$\dot{V}_v = \dot{m}_L + \dot{m}_i$$
$$\dot{m}_L = A_L v_L$$
$$\dot{m}_i = \dot{V}_v - \dot{m}_L = \dot{V}_v - A_L v_L$$

in which $\dot{m}_L$ is the air mass flow through the window and $\dot{m}_i$ the air mass flow from inside the warehouse.

10. Natural convection

It is possible to have convection within a fluid but without the velocity being forced by external means. This is known as natural (or free) convection and occurs when there are density gradients in a fluid. In the storage warehouse the biological heat of the products will cause them to warm up. The air around these products will thus also warm up and a difference in temperature with the air above the products will, most of the times, cause the warmer air (around the products) the flow up, figure 4.7.

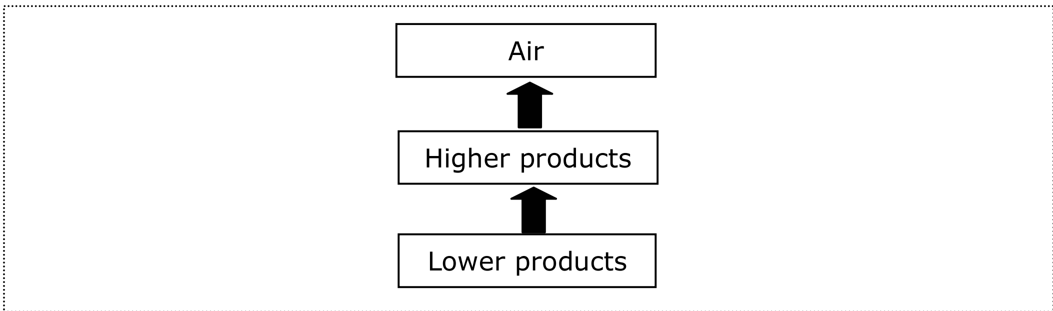


Figure 4.7 Heat flows due to natural convection

This fact is important since it means that the higher products will be slightly warmer than the lower products. This part will describe how this effect will be approximated. It will be very complex to exactly use the formulas describing natural convection because the temperatures are not only used to determine the heat flow but also other parameters. The temperatures are also used to calculate the Rayleigh number which is used to determine the heat transfer coefficient. Choosing to exactly describe this effect means that every time the average temperature should be calculated, look up the corresponding properties and calculate the Rayleigh number. Instead an average temperature is chosen and the same properties (or coefficients) will be used every time to calculate the Rayleigh number. As average temperature 277 K (4 °C) is chosen which is close to the optimal storage temperature (5 °C) but a little lower to account for the colder air in the warehouse.

First the Rayleigh number has to be determined

$$Ra = \frac{g\beta(T_1 - T_2)L^3}{\nu\alpha} \quad \text{with:}$$

g = gravitational acceleration [m/s^2]

β = volumetric thermal expansion [K^{-1}]

L = characteristic length [m]

ν = kinematic viscosity [m^2/s]

α = thermal diffusivity [m^2/s]

With the Rayleigh number the Nusselt number can be determined and so the heat transfer coefficient too. T_1 is the temperature of the products and T_2 the temperature of the air above them.

$$\mathrm{T}_1 > \mathrm{T}_2 : Nu = 0.15 Ra^{\frac{1}{3}}$$

$$\mathrm{T}_1 < \mathrm{T}_2 : Nu = 0.27 Ra^{\frac{1}{4}}$$

$$h_{fc} = \frac{Nu \cdot k}{L}$$

h_{fc} = heat transfer coefficient [W/m^{2}K]

k_a = thermal conductivity [W/mK]

The heat flows caused by natural convection are then

$$q_{13a} = A_p h_{fc}(T_{laag} - T_i)$$

$$q_{13b} = A_p h_{fc}(T_{hoog} - T_i)$$

4.2.3 Mass transfer

Relative humidity is the ratio of the amount of water vapour in the air at a specific temperature to the maximum amount that the air can hold at that temperature. This means that the model has to determine the mass flows of water vapour in the air. The equations used for determining the mass flows are very similar to the equations used for the heat flows. One important difference is that in this case the driving force is a difference in concentration (X) of a certain matter. The water mass flow in the warehouse will mostly be caused by the difference in concentration of water vapour in the warehouse air and the air outside. This means that the concentration will change the most when the windows are opened and outside air is send to the products.

$$n_1 = \rho_a A_L v_L (X_o - X_i)$$

with X_i being the water vapour concentration inside the warehouse and X_o the water vapour concentration outside the warehouse. ρ_a is the air density.

Transpiration of the products will also cause a water mass flow and is given by the equation [10]

$$n \ = k_v A_{sp}\left(100(-1.7011 + 7.7835 e^{T_p/17.0798}) - \frac{X_i P}{0.622 + X_i}\right)$$

which has to be applied for the lower and higher products

$$n_{2a} = k_v A_{sp}\left(100(-1.7011 + 7.7835 e^{T_{low}/17.0798}) - \frac{X_i P}{0.622 + X_i}\right)$$

$$n_{2b} = k_v A_{sp}\left(100(-1.7011 + 7.7835 e^{T_{high}/17.0798}) - \frac{X_i P}{0.622 + X_i}\right)$$

4.2.4 Model output

The most important quantities where described at the beginning of this chapter, T_i, T_{high}, T_{low}, T_f and X_i. With the heat flows it is possible to determine these temperatures (with a certain starting value given). The general theory gives the following expression:

$$mc_p \frac{dT}{dt} = q$$

This means that integrating the expression can give the value for the temperature T.

$$\frac{dT}{dt} = \frac{q}{mc_p}$$

$$\int dT = \int \frac{q}{mc_p} dt$$

The temperatures of interest, and also the water vapour concentration, are expressed in the same way.

$$\frac{dT_i}{dt} = \frac{q_1 + q_4 - q_5 + q_{10} + q_{13b}}{\rho_a V_i c_{p,a}}$$

$$\frac{dT_{low}}{dt} = \frac{q_{2a} + q_6 + q_7 + q_{8a} - q_{9a} - q_{11a} - q_{13a}}{m_p c_{p,p}}$$

$$\frac{dT_{high}}{dt} = \frac{q_{2b} + q_5 - q_7 + q_{8b} - q_{9b} - q_{11b} + q_{13a} - q_{13b}}{m_p c_{p,p}}$$

$$\frac{dT_f}{dt} = \frac{q_3 - q_6 + q_{12}}{\rho_a V_f c_{p,a}}$$

Theory on packed beds [9] suggest the following formula for deriving the heat capacity $m_p c_{p,p}$:

$$m_p c_{p,p} = (1-\varepsilon)\rho_p c_{p,p} + \varepsilon \rho_a c_{p,a}$$

The same principle applies for determining the water concentration in the warehouse.

$$\frac{dX_i}{dt} = \frac{n_1 + n_{2a} + n_{2b}}{\rho_a V_i}$$

The water concentration gives little information about the humidity in the warehouse. For this reason some additional calculations are made to convert this quantity in a value that can give more information, relative humidity. This can be done with the following formula [10]

$$RH = \frac{X_i P}{-1.059 - 1.7011 X_a + 4.848 e^{T_{high}/17.0798} + 7.7835 e^{T_{high}/17.0798}}$$

in which P is the air pressure. The formula uses the product temperature for calculating the relative humidity. In this case the temperature of the higher products is used since this is the temperature closer to the air above the products.

4.3 Model validation

Validation is the process of ensuring that the model is sufficiently accurate for the purpose at hand [11]. It is not common practice by farmers and companies to keep records of the temperature and humidity measurements in storage warehouses. This makes it a little difficult to validate the model. The validation is an important part of the research and some way has to be found to still make the validation possible. To validate the model of the warehouse dynamics the following approach will be taken:

- Study the results given by the model and use common sense to analyze these results. Questions should be asked whether it is understandable and logical what is happening in the model. The effect on the results when model parameters are changed is here also evaluated. Again logic is used to determine if the results were expected.
- Scientific studies. There are some scientific studies that relate, some more than others, to this project. The results given in these studies can be compared to the results given in by the warehouse model.

4.3.1 Common sense and model behaviour

The model behaviour is studied using a number of situations for the storage warehouse. The first simulation represents a situation in which no control activities are taken. This means that only natural processes (biological heat, weather conditions) will affect the quantities of interest. In the second situation ventilators are turned on for a certain period of time.

Situation 1. Ventilators off

Figure 4.8 shows the temperature of the products for a period of two days. Notice that after a certain period of time the temperature of the lower products increases slightly slower than the temperature of the higher products. This was expected since the products will warm up, caused by their biological heat. The air around the products will also warm up and the density of air decreases as the temperature increases. That means that the warm air will rise (natural convection) making the higher products a little warmer than the lower products. The figure also suggests that the temperature will increase 2 K in two days (1 K per day). The increase in temperature can be explained by the biological heat of the products. In this simulation a biological heat was used of 40 W/ton (given by Omnivent). The following calculation gives confirmation.

$$m_p c_p \frac{dT}{dt} = m_p \cdot q_{bio}$$

$$\frac{dT}{dt} = \frac{q_{bio}}{c_p} = \frac{0.04}{3500} Ks^{-1}$$

$$48 \cdot 3600 \cdot \frac{0.04}{3500} = 1.98K$$

m_p = product mass
q_{bio} = product biological heat, 40 W/ton
c_p = specific heat products

The calculation shows that in two days the temperature will increase with 1.98 K (≈ 2 K). Of course there are other factors influencing the change in temperature, specially the temperature on the outside. Calculating the heat flow through the walls (made of isolating material) shows that the heat flow is relatively low compared to the biological heat and has for that reason almost an insignificant influence on product temperature. The following calculation shows this in which a temperature difference between inside and outside of 5 K is assumed.

$$q = A \frac{k_w}{d_w} \Delta T$$

$$q = 365.4 \cdot \frac{0.02}{0.16} \cdot 5$$

$$q = 228.4W$$

A = total wall area
k_w = thermal conductivity wall (0.02 W/mK)
d_w = wall thickness (0.16 m)

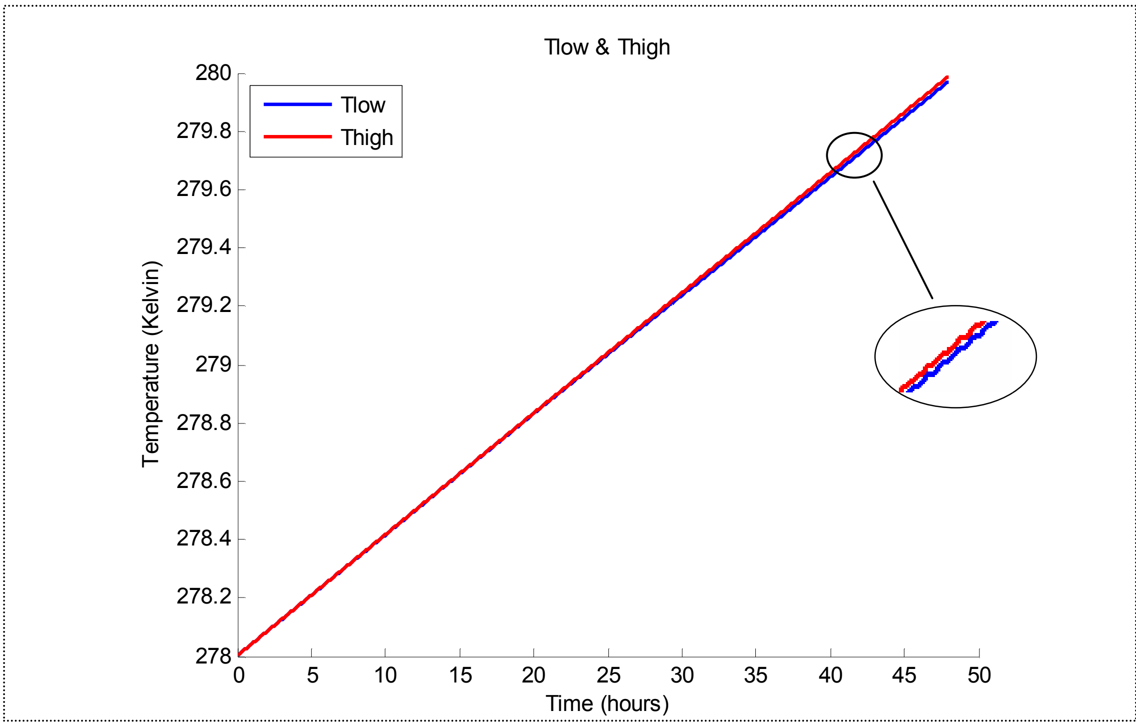


Figure 4.8 Product temperatures for two days. Bio-heat 40 W/ton.

The figure is also intended to show the effect of natural convection, where the higher products will have a temperature a little higher than the lower products.

The total biological heat for a 1100 ton storage is 44000 W compared to a heat flow of 228.4 W caused by difference in temperature between inside and outside.
Since a biological heat of 40 W/ton can cause the temperature of the products to increase with 1 K per day one can assume that 20 W/ton will cause an increase of 0.5 K per day. The behaviour of T_{low} and T_{high} should remain similar to figure 4.8. Figure 4.9 gives confirmation. This figure also shows the small difference between the temperature at the two levels.

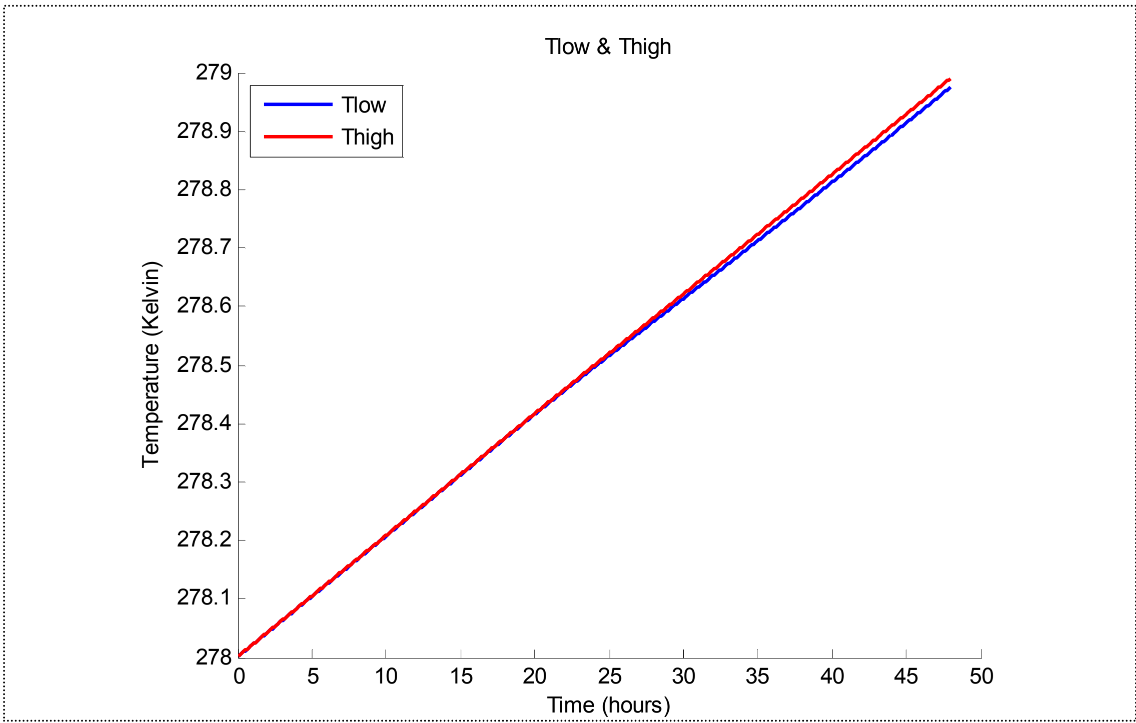


Figure 4.9 Product temperatures for two days. Bio-heat 20 W/ton

When the model does not account for biological heat it can be expected that the outside temperature will have some influence on the temperature of the products. Figure 4.10 shows how the temperatures change when there is no biological heat.

Figure 4.11 shows how the inside air temperature (T_i) changes when the biological heat is 40 W/ton. The temperature increases as the temperature of the products increases but is still affected by the outside air temperature. The inside temperature of course will also differ due to the low thermal conductivity of the isolating materials used for the walls. In the model the outside temperature is given, the inside temperature is determined with the model.

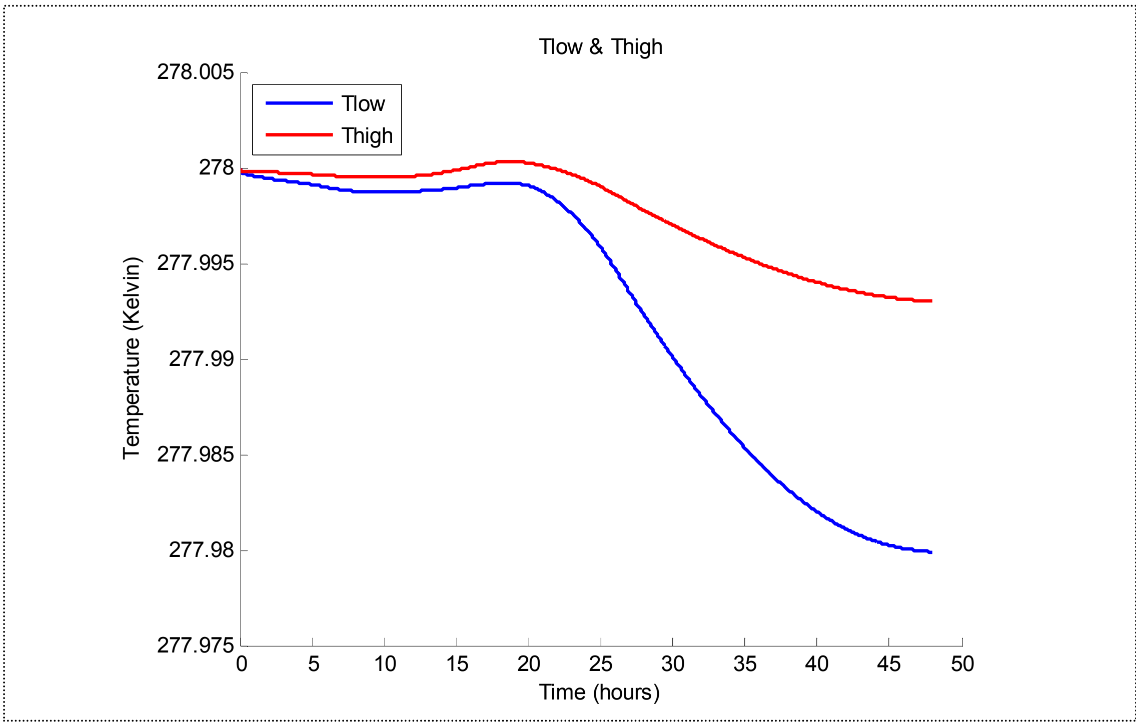


Figure 4.10 Product temperatures for two days. No bio-heat

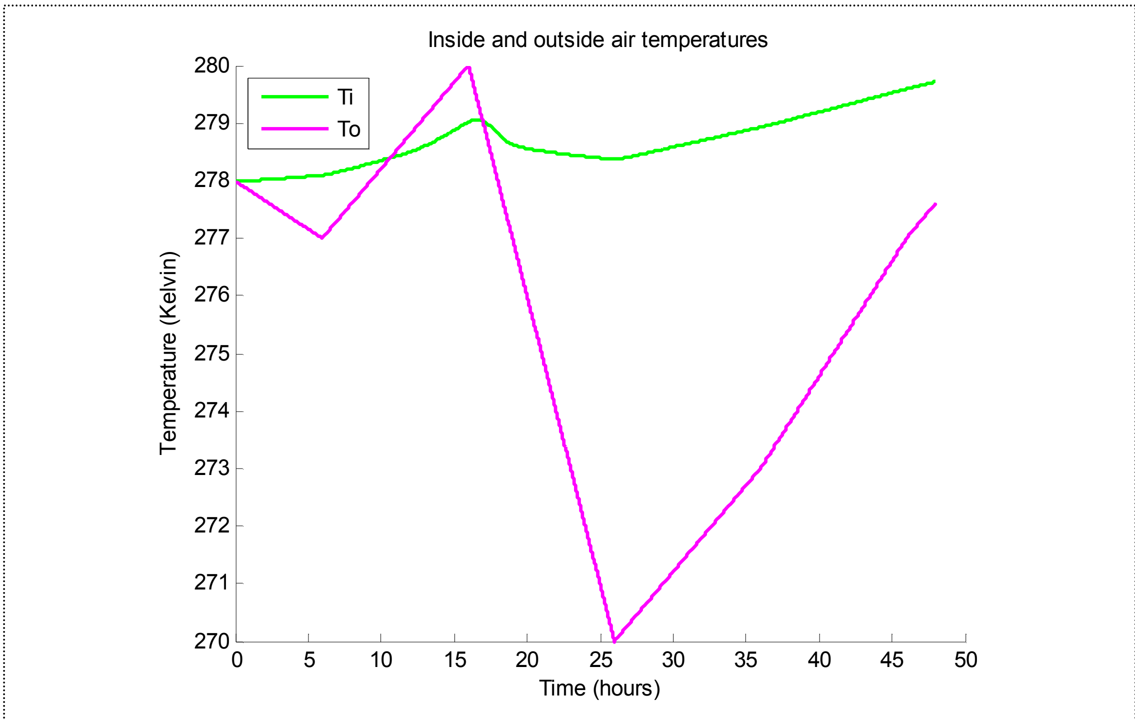


Figure 4.11 Inside and outside temperatures for two days.

The last aspect to check is the relative humidity. Figure 4.12 shows the relative humidity of the air around the products. The figure shows a very slow decrease in relative humidity. The products are getting warmer and warmer air can hold more water. This increase in water holding capacity, due to increase in temperature, causes the relative humidity to decrease.

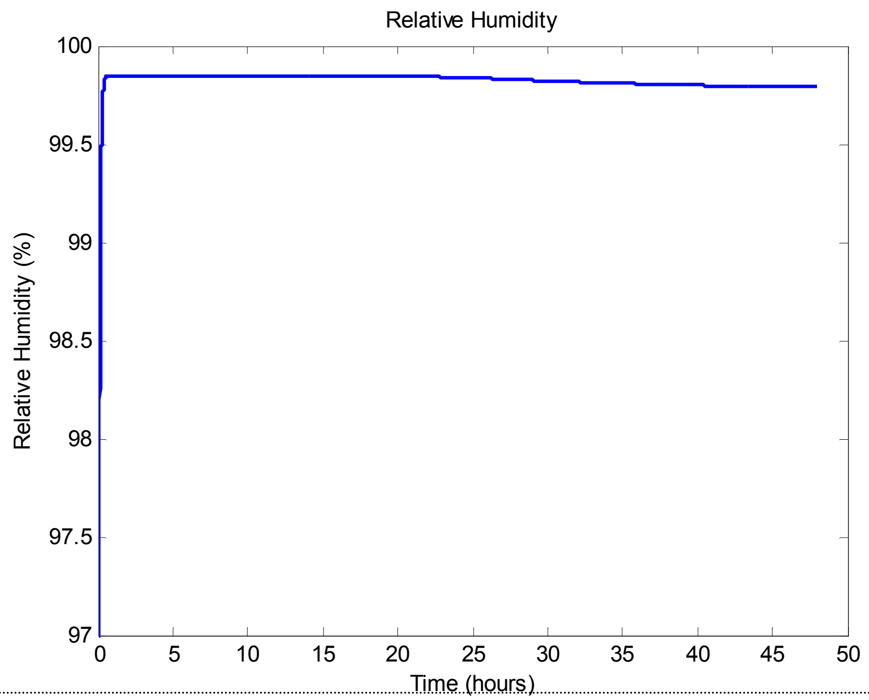


Figure 4.12 Relative humidity for two days.

Situation 2. Ventilators on

Figure 4.13 shows what happens when the ventilators are turned on and the ventilating windows are fully open. The ventilation is simulated for a duration of eight hours (the period between two and ten hours). The biological heat is again taken as 40 W/ton. As expected the temperature of the products decreases in the ventilated period. After ten hours, due to the biological heat, the temperatures will start increasing again. The slow decrease of T_{high} was not expected but will be explained later (paragraph 4.3.2). An extremer way to evaluate the ventilation process is to ventilate for a very long period, 24 hours. Since outside air is used it can be expected that the temperature of the products will follow the outside temperature. Figure 4.14 shows the temperatures when the ventilation period is 24 hours.

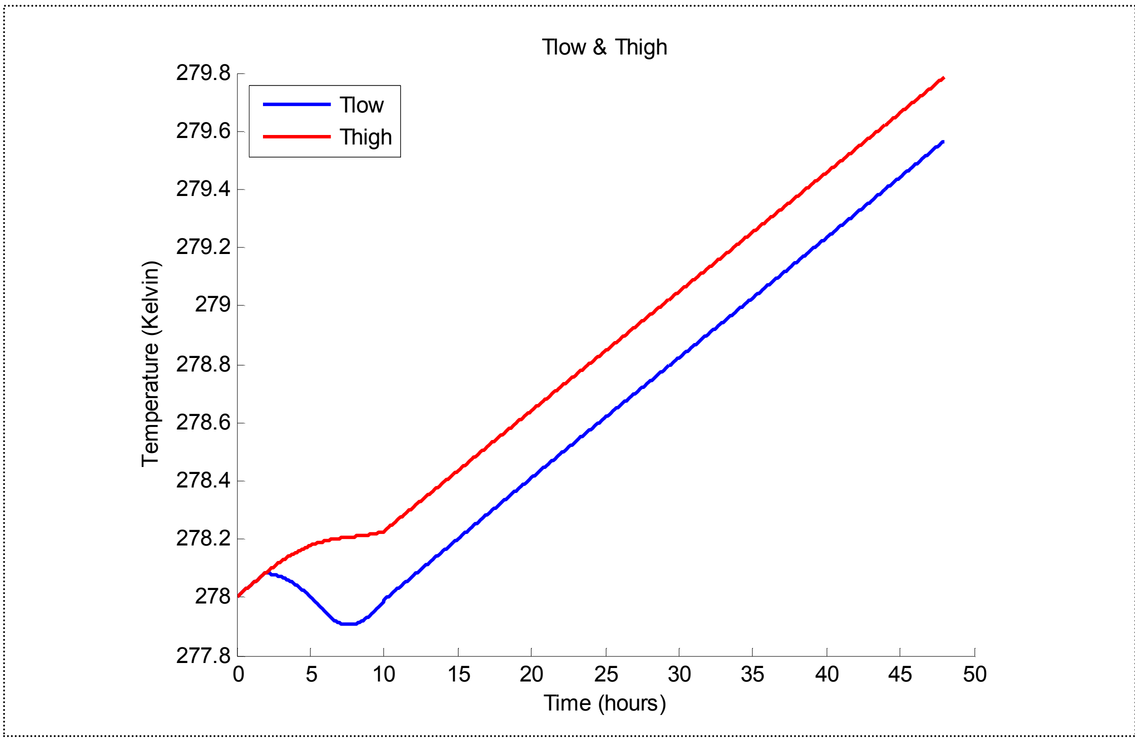


Figure 4.13 Product temperatures for two days, ventilation 2-10 hours

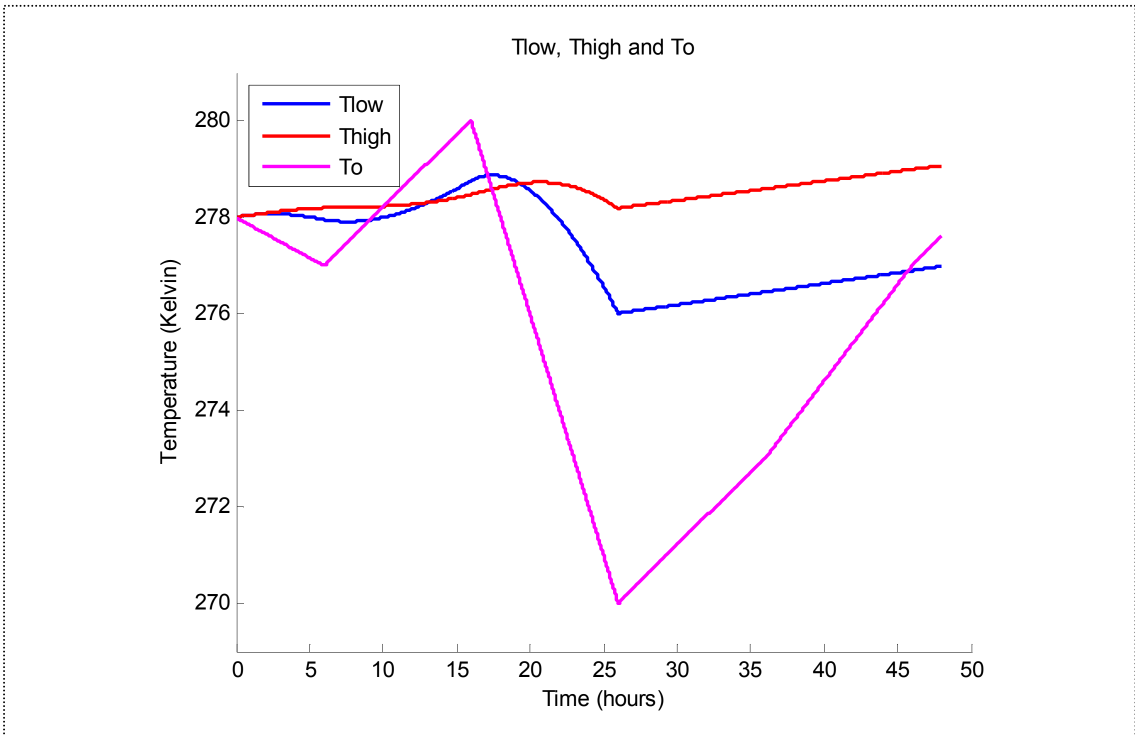


Figure 4.14 Product and outside temperatures for two days, ventilation 2-26 hours

Figure 4.15 shows how the relative humidity changes with different outside temperatures when ventilating. In these tests the relative humidity outside is set to 100%. It is known [12] that when air at 0 °C and 100% relative humidity is warmed up to 5 °C the relative humidity will decrease to approximate 70%. Notice how the relative humidity of the air around the potatoes decreases but does not approximate the value of 70%. The explanation: the temperatures of the products will also decrease when ventilating and colder air has a lower water holding capacity. This means that the concentration is decreasing, but so does the temperature which determines the water holding capacity. When warmer air (5 °C) is used for ventilation the relative humidity remains relatively high. That is because the air has a temperature very close to the temperature of the products. The relative humidity does not stay at 100% because of the warming up of the air caused by the biological heat of the products. The warmer air will then have a higher water holding capacity (which causes a decrease in the ratio).

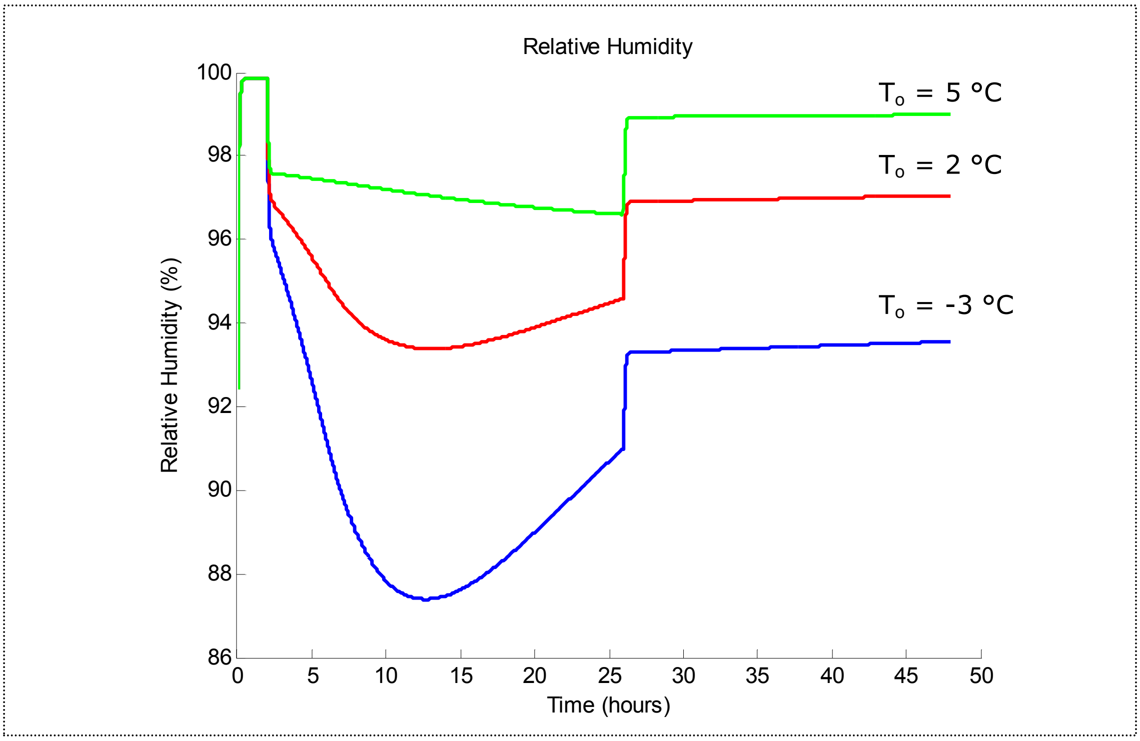


Figure 4.15 Relative humidity for two days, ventilation 2-26 hours.

4.3.2 Scientific studies

This part refers to two scientific articles, [13] and [14]. In article [13] a model was also derived for a storage warehouse. With this model the effect of ventilation is studied when varying the air temperature and the relative humidity. The article shows that products lying close to the perforated floor (the air inlet) will approximate the air temperature in a short period of time. On the other hand products lying high in the pile will cool down very slowly, decreasing only a few degrees after long hours of ventilation.

In [14] the authors have derived a two-dimensional model for a packed bed of spheres. No potato will have a spherical form, however the model can be very useful. Experiments were also used by these authors to derive the model. As expected their results also show how products lying close to the air inlet cool down faster than products close to the air outlet. The model proposed by these authors was expanded to take account for the biological heat, the transpiration and natural convection. The results were very similar.

The reason for the (much) slower cooling of the products is the fact that as the air enters the pile heat is exchanged between the products and the air. The colder air warms up and the warm products cool down. That means that as the air flows through the products it warms up and approaches the temperature of the products when it leaves the pile [14].

As last article [10] is mentioned, this was the source for most of the equations used to describe the relative humidity of the stored potatoes.

5. Climate control system design

Now that a model has been developed that can simulate the thermal behaviour in the warehouse a climate control system will be designed. This chapter will begin with summarizing some first insights from the simulations for the validation of the model. Hereafter the control strategies and implementation forms are described. In this part Taguchi techniques [6] are used to identify the best combination of controller parameters. The chapter finishes with showing how rapid prototyping is used when designing this control system.

5.1 First insights

In chapter 4 a model was developed and validated for the storage problem. The first thing that the results showed was that the product temperature depends almost entirely on the biological heat, when no control actions are taken. This means that this biological heat alone can provide good estimations of how the products will warm up during a certain period of time.
Another important observation is the fast cooling down of the lower products compared to the higher products. After the lower products have reached a desirable temperature the ventilation process will still have to continue to lower the temperature of the higher products. It tells that the recirculation of air in the warehouse is very important because this process can bring the temperatures closer to each other. In the case of recirculation only inside air is send to the products by the ventilators. In the first simulation the ventilation windows were kept fully open during the ventilation process. This means that the temperature T_f was not being controlled.

5.2 Controller design

5.2.1 Climate control strategy

The purpose of the new climate control system, as was described in the introduction, is to use the weather forecast to determine the best days to ventilate. The controller will have to determine when to ventilate and how much. This problem can be compared to planning or scheduling problems in the area of management. In a (small) manufacturing company plans are made to tell people when to produce

products and how much. In the warehouse something similar has to be done. The control system has to plan when it wants to turn ventilators on and by which angle it wants the windows to be open. It also has to determine the duration of the ventilation process.
The control system has to identify the best moments to ventilate in order to keep energy costs low and to prevent the storage conditions to deviate from desired values. Notice that feedback control takes action only after a deviation has been measured. In the new design predictions are used to avoid (or delay) these deviations (feed forward, predictive control). By using the weather forecast to determine the dynamics in the warehouse it is possible to predict, for a certain period (and with a certain uncertainty):

1. when the temperature of the products will deviate from desired values
2. the best moment to ventilate

This knowledge makes it possible to pick the most advantageous moment to ventilate with the purpose of keeping the storage conditions optimal and, if possible, to ventilate when energy costs are low. Energy prices are lower in the hours between 23:00 and 7:00. It will be smarter to try to keep ventilation to this period. According to the KNMI[5] the lowest temperature on a day will be reached around the hours of 5:00 in the morning. These two facts suggest that ventilating within these hours will be more efficient since the air temperature will be the lowest and the energy costs low. First it has to be studied if only ventilating in this period is enough to keep product temperature within acceptable values for at least a day. If this is the case one can also implement an algorithm that makes the system wait for the coldest day to ventilate. Of course the temperature can not deviate from desired values while waiting. It may even be possible to take advantage of weekends and holidays since lower energy prices also apply on these days (the whole day).
The model is used, along with the weather forecast, to predict the thermal behaviour of the products. The necessary actions will be taken by the controller if there is any indication that a deviation will happen. The deviation from desired conditions is then prevented (or delayed). However the model has shown that it is not possible to wait for a colder day because the products increase 1 °C in temperature each day. This means ventilation is needed every day. This applies if 40 W/ton is taken as the

[5] Koninklijk Nederlands Metereologisch Instituut; the Dutch national weather forecasting service.

biological heat. Other sources suggest different biological heat values. When doing this research many different values were found for the biological heat of potatoes, ranging between 9 – 40 W/ton, see appendix A2 for a complete overview. The biological heat is a very important factor because at 40 W/ton the products warm up 1 °C a day making the use of the weather forecast for climate control almost impossible. On the other hand a biological heat of 9 W/ton means that the products will warm up at a rate of around 0.22 °C a day. In this case it is sure possible to use the weather forecast and wait for the more appropriate moment to ventilate. Because high biological heats do not make the use of forecasts possible only the biological heat of 9 W/ton will be studied more extensively.

5.2.2 Predictive control

In predictive control (feed forward) a model is used to predict the output of a system for a certain period of time. The prediction is then used to take control actions to keep the output close to a certain target before it deviates from that value. The same idea will be applied when controlling the climate inside the storage warehouse. The idea is to:

- Predict the temperature of the products for a period of T_n days.
- Determine when these values will lie outside the desired range
- Determine with the weather forecast the best moment to ventilate and delay the deviation form the desired storage conditions

The best moment to ventilate is obviously when the outside temperature is low, lower than the storage temperature, and also between the hours of 23:00 and 7:00. The cost of electricity is lower between these hours.
The validation of the model in chapter 4 showed that the biological heat has by far the greatest effect on the change in temperature. This makes it easy to give simple equations to estimate the change in temperature of the products as function of time. These equations are only used for estimation. The real model is still used to simulate the storage process more precisely. 40 W/ton causes a change in temperature of 1 °C a day. The following equations are then used for temperature predictions.

$$T_{hoog}(t) = \frac{q_{bio}}{40} \cdot \frac{1}{24} t + T_{hoog}(0)$$

$$T_{laag}(t) = \frac{q_{bio}}{40} \cdot \frac{1}{24} t + T_{laag}(0)$$

Here q_{bio} is the biological heat in W/ton and t the time duration in hours. The relative humidity depends for a great deal on the temperature of the products. For this reason it is chosen not to predict the humidity behaviour.

The KNMI gives a five-day weather forecast each day. Part of this forecast gives the minimum and maximum expected temperatures for these five days. In this case the minimum temperatures are of greater interest. According to the KNMI the minimum temperature of a day can be measured around 5:00 in the morning. If the ventilators are turned on around this time the air can be expected to be at its lowest temperature. Of course one has to keep in mind that how farther away the day the more uncertain the prediction. The flowchart in figure 5.1 shows the climate control steps when the biological heat is 9 W/ton. This decision process is called each day at time t_v, to be determined later. If ventilation is needed this can also be done during the hours with lower energy prices. The figure shows that the controller determines for a prediction horizon T_n the temperatures T_{high} and T_{low}. The moment at which a deviation from the desired range is expected determines the control horizon T_c, the time period in which can be ventilated. The temperature forecasts for period T_c determine whether the ventilation moment can be postponed to another day (a colder day).

Figure 5.2 shows the flowchart when the ventilators are turned on. The idea is to adjust the temperature of the air that flows to the products (T_f) according to T_{low}. The lower products will cool down very fast meaning that the ventilators will be turned off very soon when the temperature of the air flow is kept lower than the allowed minimum temperature. If this air temperature is increased as soon as the lower products reach their lower bound the ventilators will remain on for a longer time. This will make it possible for the higher products to cool down a little more. Changing T_f is done by increasing or decreasing the opening angle of the ventilation windows. The temperature T_1 (ΔT for cooling) will be determined later.

In the case of much higher biological heats it is not possible to wait a couple of days to ventilate the products. Ventilation will be needed every day. Another issue with higher biological heats is that the process of cooling down is slower, especially for the higher products. The idea this time is to let the controller ventilate every day, between the hours that the energy prices are lower. The ventilation will have to start around 23:00 because of the slow cooling down of the higher products. The flowchart in figure 5.2 still applies.

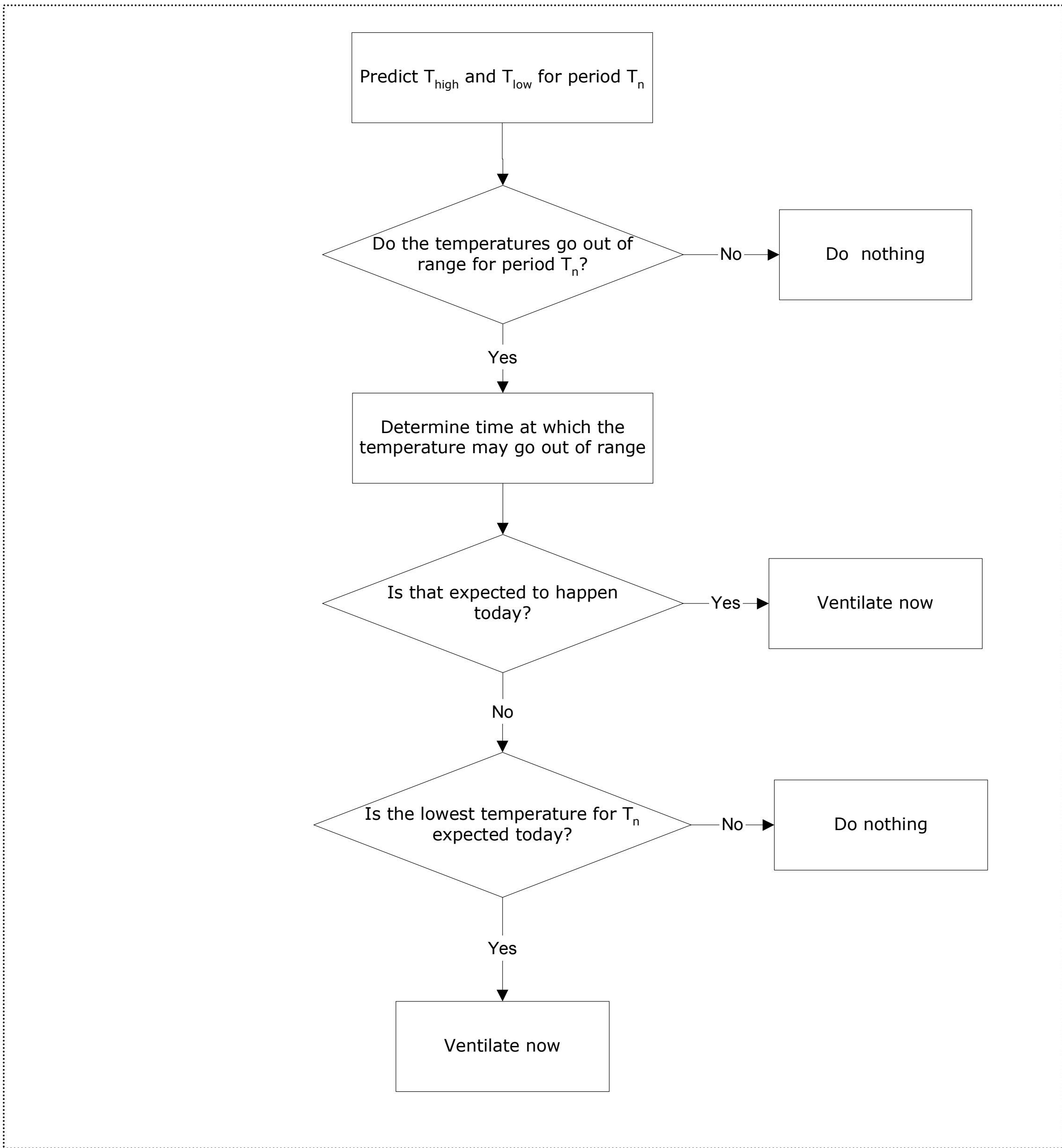


Figure 5.1 Flowchart: predictive control

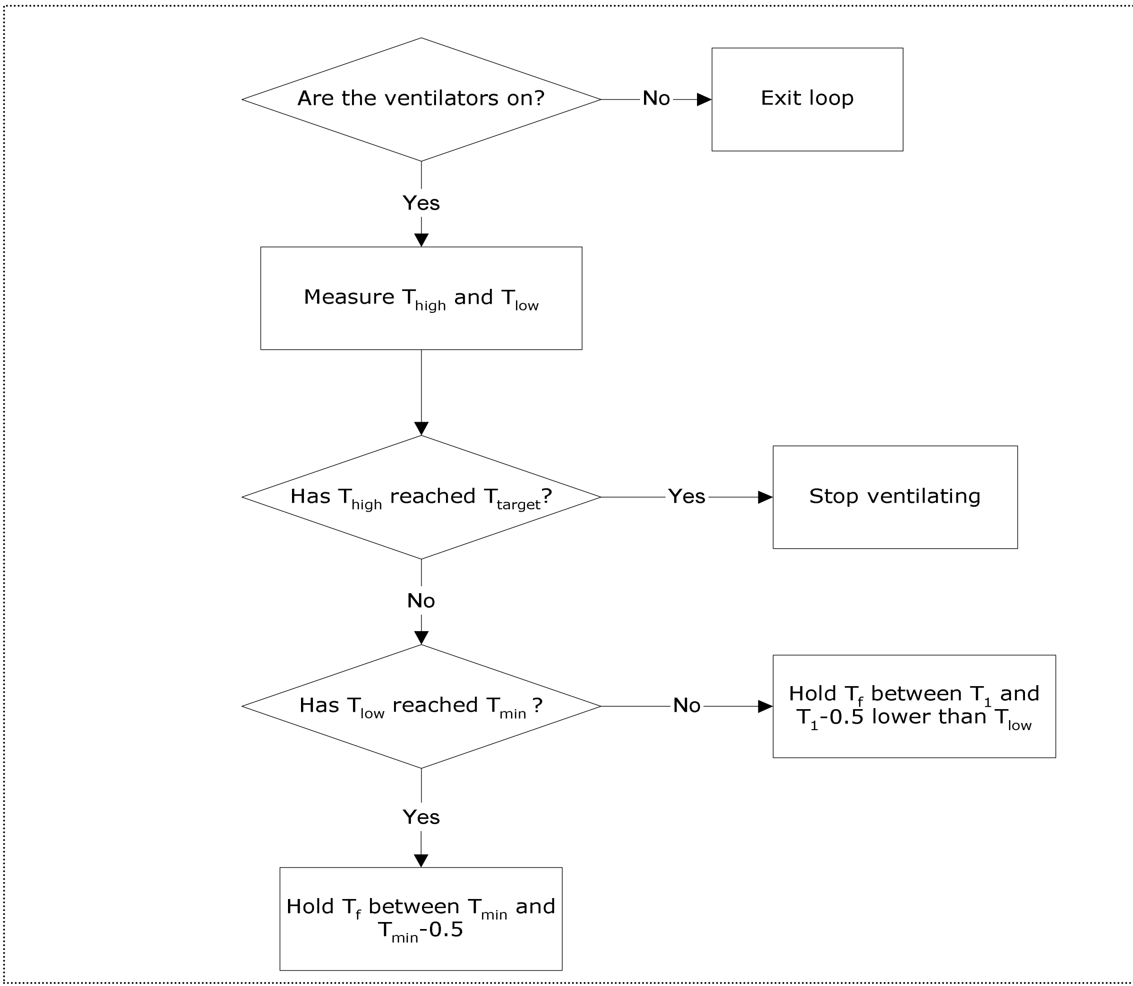


Figure 5.2 Flowchart: adjusting the air flow temperature (T_f)

5.2.3 Robust design

There are several parameters that may have an important effect on the performance of the control system. Think for example of the temperature of the air that has to be used for the cooling of products. This temperature can have any value between in the range of 2-3 °C colder than the temperature of the products. Another issue is the prediction horizon T_n. Should this be one, two or five days? The optimal choice for these parameters can efficiently be found with Taguchi's design of experiments (appendix A1). The parameters to be studied are:

- T_{set}, the temperature (ΔT) of the air used for cooling
  Specialists advice an air temperature of around 2-3 °C colder than the product temperature [12]. Two possibilities are studied, 2 °C and 3 °C colder
- T_n, the prediction horizon
  The KNMI provides temperature forecasts for the coming five days which means 5 days is the maximum value for T_n. To keep the experiments as two-factorial two and three days for the prediction horizon will be tested
- T_{max} and T_{min}, the maximum and minimum allowed product temperatures
  The storage temperature is ideal at 5 °C. However two temperature ranges have been found, 4-6 °C and 4.5-5.5 °C. T_{max} will thus vary between 5.5 and 6 °C and T_{min} between 4 and 4.5 °C.
- t_v, the time at which the predictions are made
  The two possibilities for the prediction time will be late at night (23:00) or early in the morning (3:00)

It should be remarked that some of these parameters only apply when the biological heat is relatively low, making the use of predictions possible. Another point is the ideal storage temperature. The ideal storage temperature is not always 5 °C. The first two weeks of storage in September the temperature is hold at around 14 °C. After these two weeks the temperature decreases gradually to a holding temperature of 5 °C at the start of December. Table 5.1 shows the orthogonal array for the experiments.

For the simulations temperature and humidity measurements for a whole year are available. By this the weather conditions in the simulations are kept close to reality.

Table 5.1 Orthogonal array

	A	B	C	D	E	Costs	SN_{low}	SN_{high}
1	0	0	0	0	0	C_1	SN_{l1}	SN_{h1}
2	0	0	0	1	1	C_2	SN_{l2}	SN_{h2}
3	0	1	1	0	0	C_3	SN_{l3}	SN_{h3}
4	0	1	1	1	1	C_4	SN_{l4}	SN_{h4}
5	1	0	1	0	1	C_5	SN_{l5}	SN_{h5}
6	1	0	1	1	0	C_6	SN_{l6}	SN_{h6}
7	1	1	0	0	1	C_7	SN_{l7}	SN_{h7}
8	1	1	0	1	0	C_8	SN_{l8}	SN_{h8}

Table 5.2 shows the factors and their possible values.

Table 5.2 Factors and their values

	Factor	Minimum value	Maximum value
A	T_{set}	2 °C	3 °C
B	T_n	2 days	3 days
C	T_{max}	5.5 °C	6 °C
D	T_{min}	4 °C	4.5 °C
E	t_v	3:00	23:00

The performance measures that will be used are: the total energy costs, the signal-to-noise ratio (SN) for T_{high} and the SN ratio for T_{low}. The energy costs reflect the economical performance of the system and the SN ratio of the temperature is a measure of the quality of the products. Remember that temperature is the single most important factor in keeping the quality of the stored products, in this case potatoes [15]. For the SN ratio the formula when a target value is desired will be used (appendix A1).

5.2.4 Results and analysis

The results are analyzed as described in appendix A1. Table 5.3 shows the energy costs and the SN ratios for the different experiments. Appendix A3 gives some additional information like average temperatures and standard deviations. Energy costs are estimated with the following prices (derived from a household bill):

€ 0.1739/kWh in the hours between 7:00 – 23:00[6]
€ 0.128/kWh in the hours between 23:00 – 7:00[7]

[6] 0.0659 + 0.0380 Network costs + 0.07 Energy taxes => € 0.1739/kWh
[7] 0.0379 + 0.0201 Network costs + 0.07 Energy taxes => € 0.128/kWh

Table 5.3 Experiment results

Exp.	Energy costs (€)	SN_{low} (dB)	SN_{high} (dB)
1	182.60	-59.16	-64.08
2	210.90	-62.44	-66.68
3	155.70	-57.93	-61.15
4	180.90	-58.96	-61.08
5	180.00	-58.11	-59.81
6	161.70	-59.52	-61.21
7	168.00	-59.63	-64.00
8	210.30	-61.28	-64.93

Table 5.4 shows the mean effect (E) of energy costs for the factors. In the table the mean is determined for the energy costs for the different factors. For minimizing costs table 5.4 suggests the combination of parameters: A_0, B_1, C_1, D_0, E_0.

Table 5.4 Mean effect of factors

Factor	E_0	E_1
A	182.53	180,00
B	183.80	178.73
C	192.95	169.58
D	171.58	190.95
E	177.58	184.95

Tables 5.5 and 5.6 show the Pareto analysis (appendix A1) for the lower and higher product temperatures. Notice how factors C and D are the most important factors.

Table 5.5 Pareto analysis T_{low}

Factor	A	B	C	D	E	Total
Sum at factor level 0 1	 -238.49 -238.54	 -239.23 -237.80	 -242.51 -234.52	 -234.83 -242.20	 -237.89 -239.14	
Square of difference	0.003	2.04	63.84	54.32	1.56	121.77
Contribution ratio (%)	0.002	1.68	52.43	44.61	1.28	*

Table 5.6 Pareto analysis T_{high}

Factor	A	B	C	D	E	Total
Sum at factor level 0 1	 -252.99 -249.95	 -251.78 -251.16	 -259.69 -243.25	 -249.04 -253.90	 -251.37 -251.57	
Square of difference	9.24	0.38	270.27	23.62	0.04	303.56
Contribution ratio (%)	3.04	0.13	89.03	7.78	0.01	*

* rounding can cause totals to differ from 100%

According to the Pareto analysis the focus should lie on factors C and D. Just as with the analysis of means factor C_1 and D_0 should be chosen. The choice of the other factors differs between the different results. The Pareto analysis has shown that these factors are not significant factors which means that this difference is not important. The choice goes to the factors that minimize costs and the best values for factors A, B and E follow from the analysis of means: A_1, B_1, C_1, D_0, E_0.

5.2.5 Evaluation

The significance of factors C and D is understandable because these are the lower and higher temperature bounds for the products. The higher bound T_{max} determines when the temperature is too high. The choice goes to a value of 6 °C, which gives the temperature more "deviation space" than 5.5 °C and so periods without ventilation can be longer. The choice of 4 °C for T_{min} means that the lower products can be cooled off a little more, which makes it possible for more cold air to reach the higher products.

5.3 Prototyping and implementation

Chapter 3 described that SIMULINK can be used for modelling a system using simple blocks. SIMULINK has also the capability of generating C-code of the model. The model is rather complex because different temperatures and also concentrations have to be determined and send to the controller. Appendix A4 shows a model that will be used for prototyping. Building a model that can also be used with weather forecasting is too complex for this thesis since a real time clock has to be programmed. This model is simpler compared to the simulation model because there is no need to simulate temperature changes anymore. The model is also kept relatively simple to show the process of code generation and downloading into a

microprocessor. The temperatures, and relative humidity, are input to the microprocessor. Adjustable voltages will represent thermal sensor readings and will be supplied to the microprocessor. A change in the supplied voltage represents a change in temperature (or relative humidity). Building the SIMULINK model will result in the C-code for the climate control system ready to be downloaded into the microprocessor within seconds. The voltages send to the microprocessor can be varied here as one wishes. In this model a simple control strategy was modelled in which ventilators are turned on as soon as the temperatures become to high. More information about this model is also found in the appendix.
The output of the microprocessor indicates whether ventilators should be turned on/off and if the windows should open or close a little more.

The first step in deciding how to implement the control system is to determine the functions that have to be executed by the control system. These functions will then have to be divided into two groups: functions to be executed by the microprocessor and functions to be executed by other means, a host (e.g. PC). The purpose when making this division is to give the microprocessor a small amount of functions and so keep its "load" small.

There are also three important issues that need to be considered when thinking about the implementation of the climate control system.

Analog to digital converter (ADC)
The inputs of the microcontroller are mostly measurements of different sensors. These sensors measure a certain quantity, in this case temperature and relative humidity, and convert the measurements into a corresponding voltage. Discretization of the signal is necessary because the voltage supplied by the sensors is a continuous signal. The ADC converts the signal to a discrete form usable for the microprocessor. The HC12 microprocessor used in this project has an 8-bit ADC which means that the input signals can be represented by 8 bits. The signal can then be converted to an (unsigned) integer value between 0 – 255.

Hysteresis
Noise effects will most of the time cause the measurements of the sensors to fluctuate around a certain value. Imagine that a value higher than Y should turn

something on and a value under Y turns it off. The noise fluctuations can cause the device to rapidly be turned on and off, when the signal is close to Y.

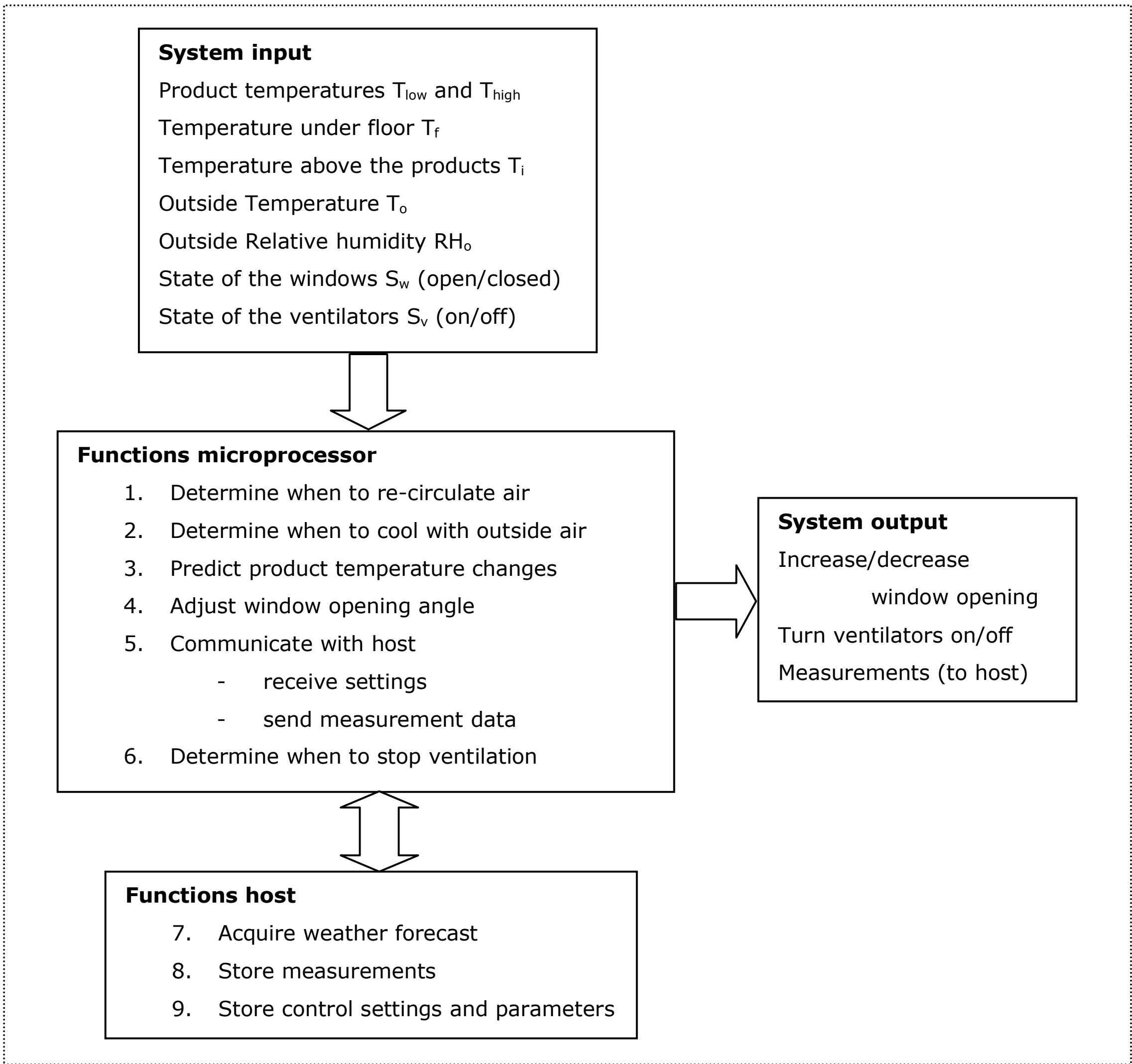


Figure 5.3 Controller functions

A SIMULINK block can be used to solve the hysteresis problem. The solution uses two threshold values, high and low. When a signal is higher than the higher threshold the state or response of a system is changed. The state or response changes again only when the signal becomes lower than the lower threshold. The response of the system not only depends on the present value of the signal but also on the previous values. Figure 5.4 shows this principle.

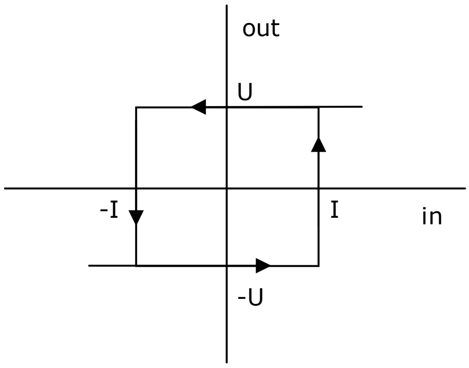


Figure 5.4 Hysteresis loop [7]

Watchdog

It is possible that some unknown cause makes the control system to shut down or to stop working properly. A *watchdog timer* is a computer hardware timing device that triggers a system reset if the main program, due to some fault condition, such as a hang, neglects to regularly service the watchdog (writing a 'service pulse' to it) [7]. The purpose is to bring the system back from the hung state into normal operation.

Turning on ventilators

The storage warehouse described in this thesis has six ventilators. It is not ideal to turn on these six ventilators at the same time since the turning on process would consume a lot of power at that short period of time. The microprocessor has to turn them on in a sequential order, with a certain time delay between ventilators (e.g. one second).

6. Control system performance

In this chapter the performance of the climate control system is compared with the actual control system. The actual control system ventilates as soon as the temperature of the products become to high and the weather conditions allow it. The control system uses no active cooling system and depends completely on the outside temperature. It works as some sort of feedback controller. The controller also re-circulates inside air when the temperature difference between higher and lower products exceeds 1 °C. This control strategy was also simulated in SIMULINK. To make comparison possible all model parameters are kept constant.

6.1 Sensitivity analysis

Taguchi methods were used to determine the combinations of parameters that can make the system the least sensitive to noise. A sensitivity analysis is now done on the performance of the system under changing conditions. These changing conditions are:

- Greater uncertainty in the temperature forecasts
  Weather forecasts are not always reliable so there will always be an uncertainty in the predicted temperatures. This uncertainty will be varied to test the sensitivity of the system. A prediction uncertainty of ±50% from the real temperatures will be tested. This means that the predicted temperatures will be 50% higher or lower than the real temperatures.
- Performance during whole storage period
  In chapter 5 the system parameters were determined simulating 30 days of the month January. To confirm the performance of the climate control system the performance in other months will also be simulated. In this case the whole storage period is simulated, September – March. Remember that the ideal storage temperature differs in the first three months

Table 6.1 shows the results for the climate control system under varying uncertainty. The table shows that the costs (and average temperatures) do not change when the temperature predictions are 50% higher or lower than the actual temperature.

Table 6.1 Performance under prediction uncertainty

Uncertainty	Costs	Avg. T_{high}	Avg. T_{low}
0%	151.80	278.46	277.93
+50%	151.80	278.46	277.93
-50%	151.80	278.46	277.93

It should be remarked however that this sensitivity was calculated for only the month of January. It is assumed that the sensitivity in the other months, specially the cold months, will also be very low.

Figure 6.1 shows the temperature for the total storage period when forecasts are used.

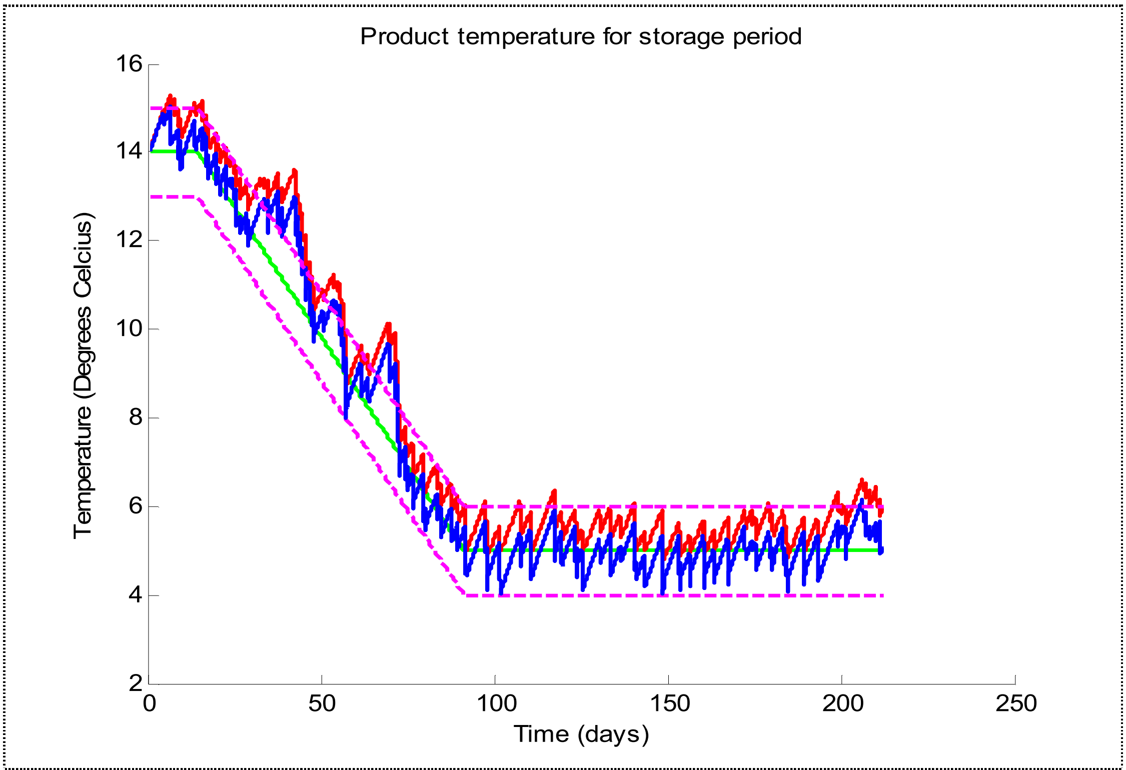


Figure 6.1 Product temperature during storage (1)

The green line shows the ideal temperature and the magenta lines the ideal storage temperature range. Blue and red represent the temperature of the lower and higher products respectively (T_{low}, T_{high}). Figure 6.2 shows the same when a feedback system is used. In figures 6.1 and 6.2 the temperature of the higher products is cooled down to the ideal temperature of 5 °C.

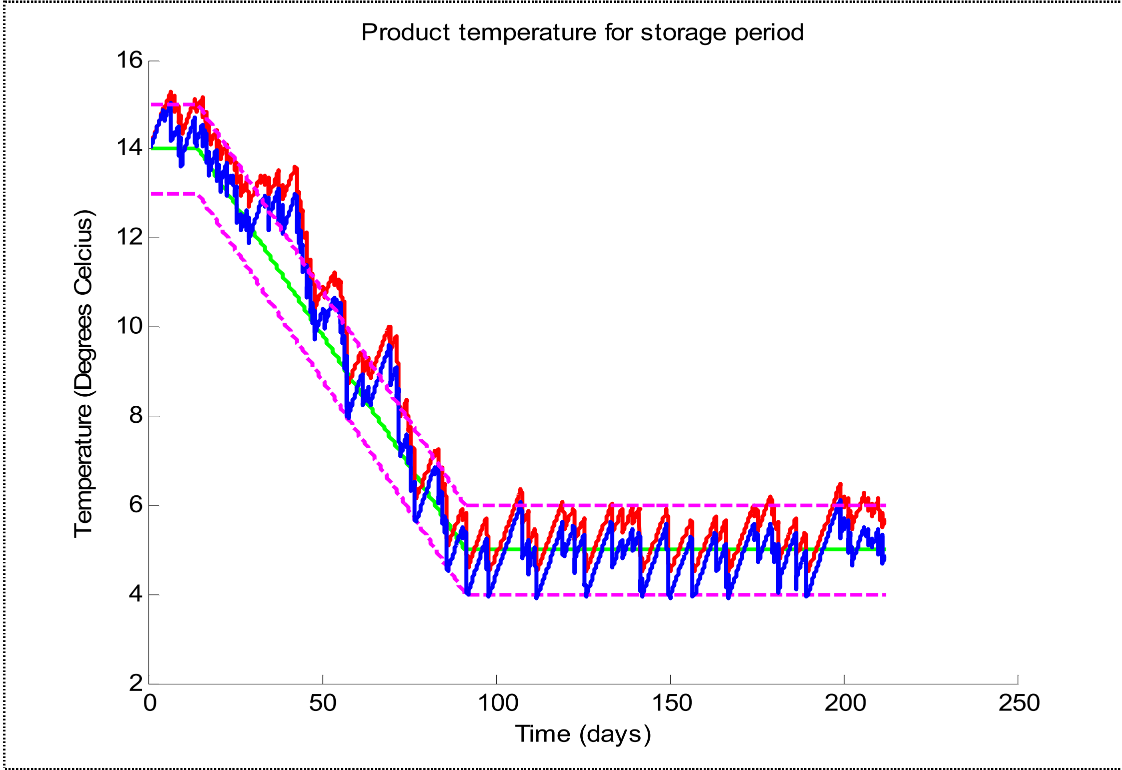


Figure 6.2 Product temperature during storage (2)

After looking at the figures it seemed interesting to study the effect of cooling down a little more under this ideal storing temperature. By cooling in this way some sort of “buffer” can be created. Figure 6.3 shows the results. Weather forecasts are also used in this case.

Figure 6.4 shows the monthly costs for the three control strategies. Bar 1 gives the costs when the higher products are cooled down to the ideal storage temperature and bar 3 until they reach a temperature of 0.5 °C under the ideal temperature. In both cases the weather forecast is being used. Bar 2 shows the costs for cooling when the product temperature becomes too high (feedback).

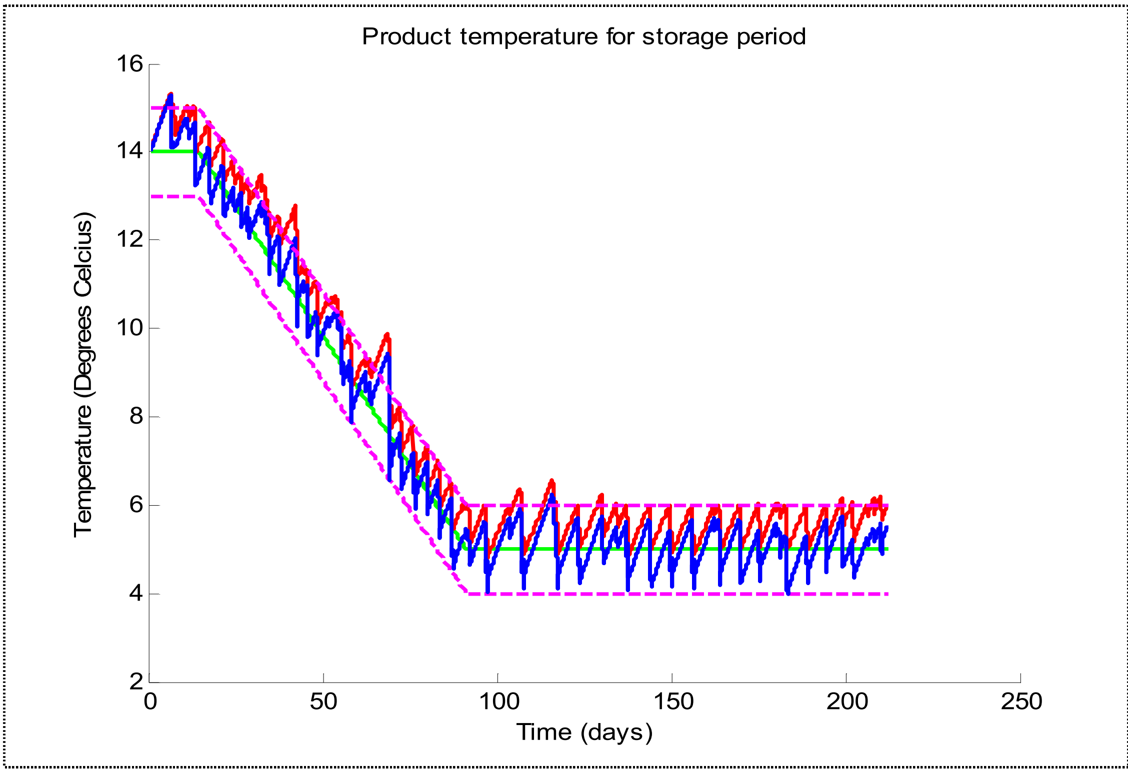


Figure 6.3 Product temperature during storage (3)

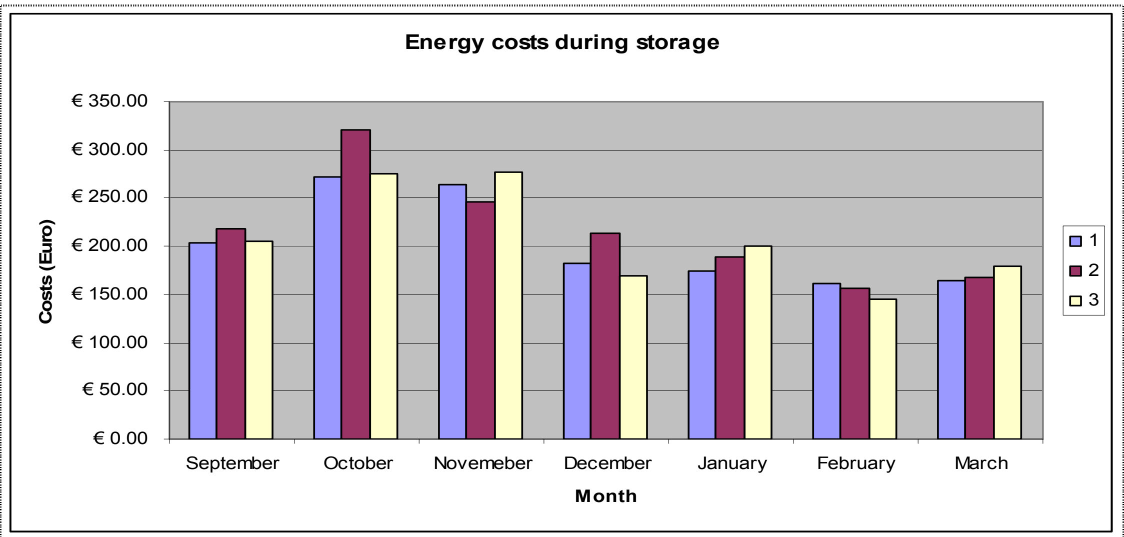


Figure 6.4 Monthly energy costs

6.2 Comparing the climate control methods

For comparing the performance of different systems it is not enough to say that a difference has been observed. An analysis should also be made that can tell if the difference is also significant. A confidence interval for the difference between the results can be calculated using the paired-t approach [11]. This confidence interval, appendix A5, shows that no significant difference exists for the costs of the different climate control methods.

The figures 6.1, 6.2 and 6.3 are used to compare the storage temperatures. Notice that when predictions are used, in the months after December, that the temperature of the higher products stays closer the ideal temperature. It is also strange that the temperature falls out of range when predictions are used for the period that the ideal storage temperature gradually decreases.

6.3 Economical analysis

The deviation from the target temperature is also important because of the huge impact that temperature has on the quality of the products. This can of course be translated to monetary costs since this is determined by the product quality. This is why great attention is given to the process of keeping the temperature within an acceptable range.

There are also the costs of designing/prototyping of the new control system. The most significant additional costs when applying the presented design approach are:

- software costs
- employee training

In reality no big changes are made in the way products are designed. The difference is now that modelling and simulation are extensively used. This calls for investments in the required software (MATLAB/SIMULINK, Metrowerks/CodeWarrior) and in teaching employees how to use these software packages. There are actually no major costs that can be identified. Programming is now done by software so there will be less need for programming. These costs are very low if one understands that the design time can now be shortened and the specifications process is more under control.

7. Abstract problem description

7.1 System abstraction: level 1

Functional decomposition is in literature the most popular approach for describing and solving design problems on a high level of abstraction. In this approach a system is treated as a black box. The black box has to realize a certain overall function and the overall function can be divided in sub-functions. The hierarchy of overall function with sub functions is called the *function structure* [5]. After a function structure has been completed and the designers have made a list of system requirements they can start with the search for solutions that satisfy the defined functions.
The use of a higher abstraction level when dealing with these situations can sometimes be convenient because the use of some functions can imply or suggest certain solutions. In the following an alternative approach for starting to describe systems on a high abstraction level will be proposed. The approach can give designers another way to look at the problem because the black box is now given by mathematic equations or symbols. General functions can then be used to describe what happens in the black box.

Defining the black box:

- Formulate the problem in solution-neutral terms and use this to find an overall function
- Find (if possible) an abstracter meaning for the overall function
- Identify the most important quantities inside and outside the system
- Find how the quantities are used to realise the overall function
- Identify the inputs and outputs of the system
- Draw a black box. Give inside the black box what should happen to the quantities in order to deliver the desired output. Use equations or symbols.

This is one of the most abstract forms to describe a system since only one block is used, using mostly symbols and/or equations. Another alternative at this “highest” level is to identify the (physical) flows in the system and the efforts needed for those flows. The laws of physics can define what the effort should be for a specific flow. Table 7.1 shows some effort-flow variables [16,17].

Table 7.1 Effort-flow variables

System	Flow *f*	Effort *e*
Mechanical-translational	speed $\dot{x}$, [$\frac{m}{s}$]	force F, [N]
Mechanical-rotational	angular speed $\dot{\theta}$, [$\frac{rad}{s}$]	torque T, [Nm]
Electrical	current I, [A]	voltage V, [V]
Thermal	heat flow $\dot{q}$, [W]	Temperature T, [K]
Hydraulic	volume flow $\dot{V}$, [$\frac{m^3}{s}$]	pressure P, [Pa]
Chemical	mass flow $\dot{m}$, [$\frac{kg}{s}$]	concentration C, [$\frac{mol}{kg}$]

It is important to remark that it is not always helpful to define an effort-flow system, according to table 7.2, at an early stage of the abstraction process. If, for example, a system has to displace something, and one chooses to describe it as a system with a force F causing a flow $\dot{x}$, the possibility of using a mechanical-rotational system will be ignored.

In the next part other approaches will de described that serve the same goal. The difference will be that these approaches use more than one function or subsystem. They are useful to describe what happens inside the black box (zoom in) while keeping the high level of abstraction.

7.2 System abstraction: zooming in

7.2.1 System elements and functions

It is possible to describe the process inside the black box when zooming in and still maintain an acceptable level of abstraction. Pahl and Beitz [5] give an overview of some authors that have defined general functions for describing systems. General valid functions where defined by Rodenacker in terms of binary logic. Roth defined functions in terms of general applicability and Koller in terms of required physical effects. The functions of Krumhauer where defined by giving special attention to the relationship between input and outputs after changes in type, magnitude, number, place and time. Not discussed in Pahl and Beitz [5] are the elements of technical processes given by Isermann [16]. All the authors start with the black box given in figure 7.1. In available literature authors always define three input forms: energy, matter and signal (or information).

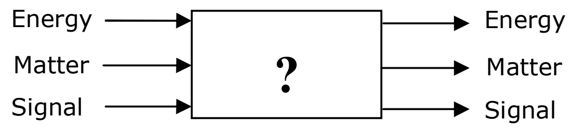


Figure 7.1 Black box

The goal is to define general functions that can transform the three input forms into the desired outputs (again in the three defined forms). An overview of the functions defined by the different authors is given in figure 7.2. Tables A6.1-A6.5 in appendix A6 give an explanation of the functions and elements. Figures A6.1-A6.3 in appendix A6 show the symbols used by some of these authors. The overview (figure 7.2) was originally given by Pahl and Beitz [5] but is here expanded with the approaches of Isermann [16] and Miller [18]. The addition of Miller's critical subsystems needs some explanation because its origin does not lie in the "technical world".

Miller defined 20 subsystems which a living system must contain (Living Systems Theory). These subsystems are shown in table A6.6, appendix A6. His intention was to formalize the concept of "life". Industrial systems are not alive but they sure have a lot of characteristics similar to living systems. This is a good reason why these subsystems could be used to describe industrial systems in an abstract manner. Because this approach is not a technical (or engineering) one it may give designers a complete different way to look at a design problem. The three input and output forms defined in technical literature are also used in this approach.

All the subsystems with the exception of the first one can be used when describing industrial systems. Industrial systems are not capable of making a copy of themselves. Note that the energy-matter processing subsystems show some similarities with the elements given by Isermann [16]. The information processing subsystems can be used to describe systems that use or need to use some kind of controller (most industrial systems nowadays need a controller). The arrangement with its three classes can be seen as an expansion of the Isermann [16] approach

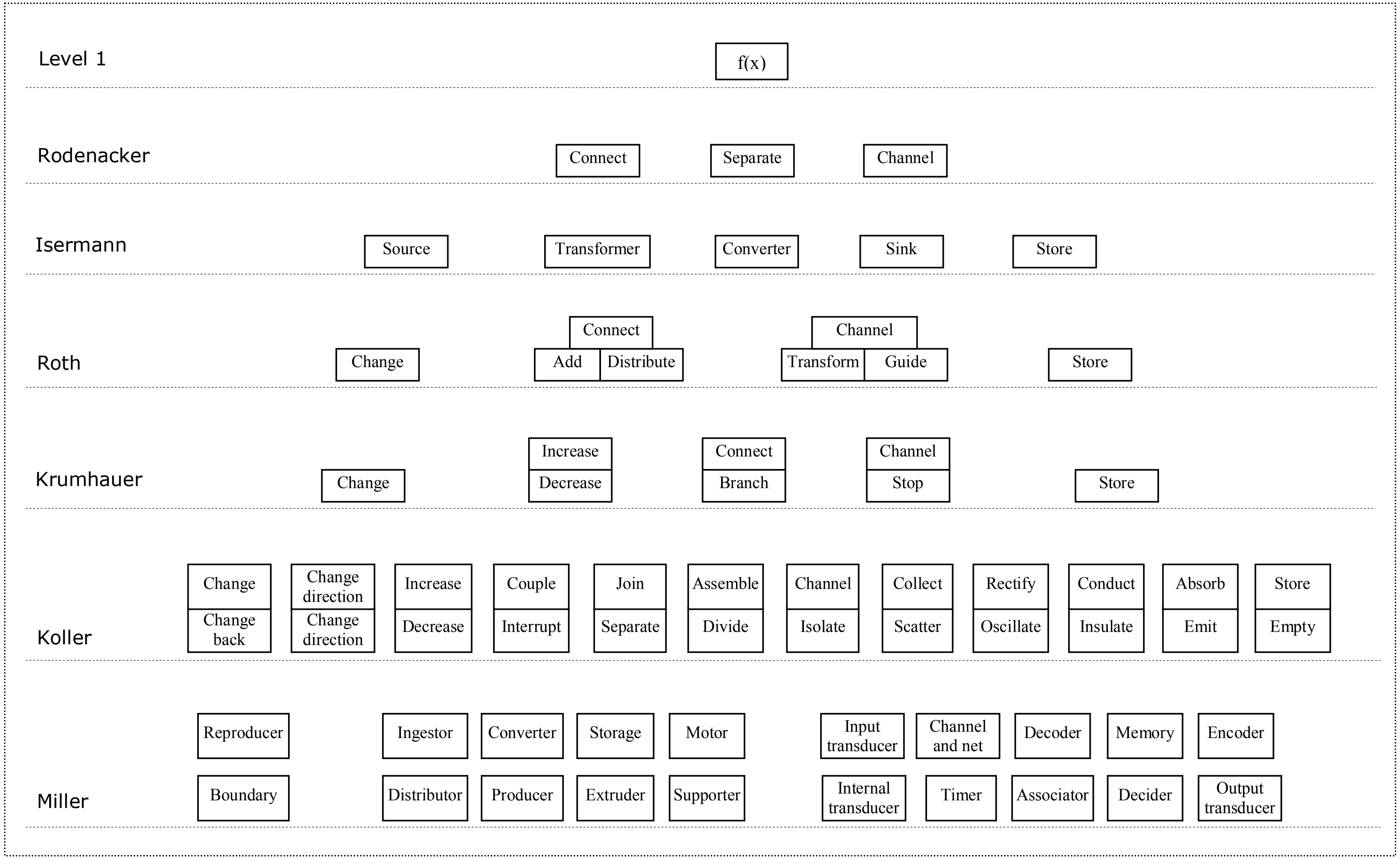


Figure 7.2 General functions and elements by author

since it makes possible to use specific subsystems to describe the controller and different subsystems to describe the system itself (the plant).

A last alternative to be presented is the use of simple mathematical operations. Compare this with a computer that, as a matter of fact, can only add and subtract binary numbers. The most basic mathematical operations are *adding, subtracting, dividing and multiplying.* Figure 7.3 shows these blocks and also shows that one block may be associated to several basic functions that were defined by the authors in figure 7.2.

+	-	:	X
Add Assemble Join Increase	Subtract Remove Separate Decrease	Divide Separate (Branch)	Multiply Increase (gain)

Figure 7.3 Basic mathematical operations

7.2.2 System relations

In paragraph 2.3.2 was noted that a system consists of elements and relations. That means that the next step is to define relations between the elements (or functions). In most occasions the output of a subsystem is the input of another subsystem. In the simplest way connections are drawn between these subsystems using lines or arrows. Logical links as described in Pahl and Beitz [5] (and in electronics) can be used to give more information about the kind of relation that exists between subsystems, especially when a subsystem has multiple inputs from different subsystems. The logical links show which inputs are necessary for a subsystem to deliver the desired outputs. Figure 7.4 shows the logical links as described in Pahl and Beitz [5].

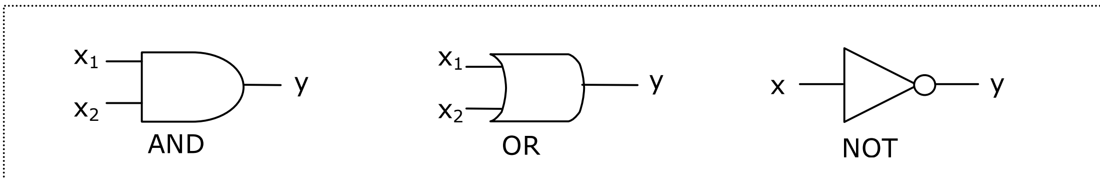


Figure 7.4 Logical links

7.2.3 Energy inputs and outputs

To reduce the great amount of possible solutions for an abstract problem the energy inputs and outputs can be defined in a more appropriate way. Hubner [19] gives a classification of six energy domains:

- Electrical energy
- Mechanical energy
- Magnetic energy
- Thermal energy
- Electromagnetic energy
- Chemical energy

By defining in which energy domains the solutions for a problem must lie a limit to the possibilities can be set without reducing abstraction.

7.3 Abstracting the storage problem

The described abstraction approach (chapter 3) is now applied to the storage warehouse. The first step is to formulate the problem in solution neutral terms. A problem formulation is actually very simple: keep the temperature of the stored products and the relative humidity in the warehouse inside a specified range. Notice how the words cooling down and warming up are not used. The formulation does not imply any solution, it just tells that the products have to be kept at a certain temperature and the relative humidity at a certain percentage. To *store* (agricultural) products is the overall function.

Figure 7.5 shows the first abstract description of the system, using only one black box. The figure shows almost no details about the system. With this black box in mind one can proceed to zoom in into the system using the general functions and elements given in figure 7.2. The subject of attention is not the storage warehouse itself but how the optimal storage conditions are maintained in it, the climate control system. Keep in mind that in this part one has to "look" to the problem from a very abstract point of view.

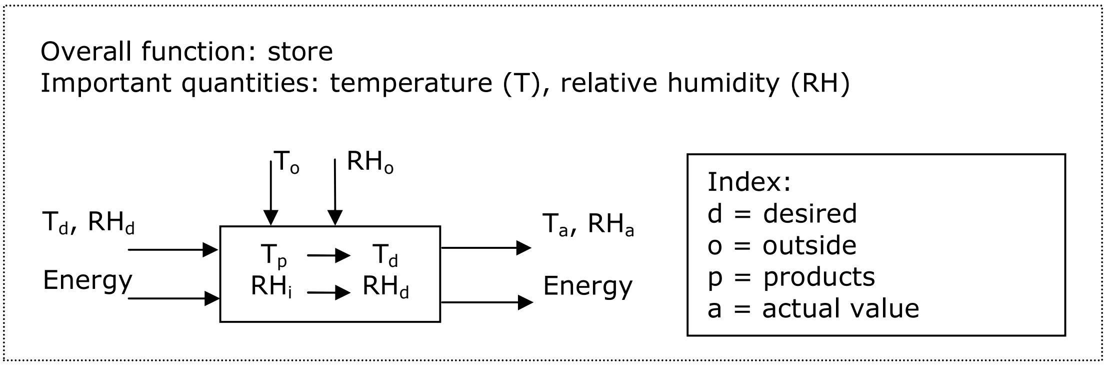


Figure 7.5 Abstract description climate control problem (1)

In technical or physical systems there is often something moving, a flow, and there is something causing this flow, an effort [16, 17]. A good way to continue the abstraction process is to define what are or should be the flows and how these are caused. To change the temperature of a body *heat* has to be added or removed. This heat is caused by a difference in temperature (ΔT) between the body and another element. The same idea applies for controlling the humidity. Water, that means a *mass,* has to be added or removed from the warehouse. This mass flow is caused by a *concentration* difference (ΔC) in a mixture (mix of air and water). Combining this way of thinking with the general functions can result in a system like the one shown in figure 7.6

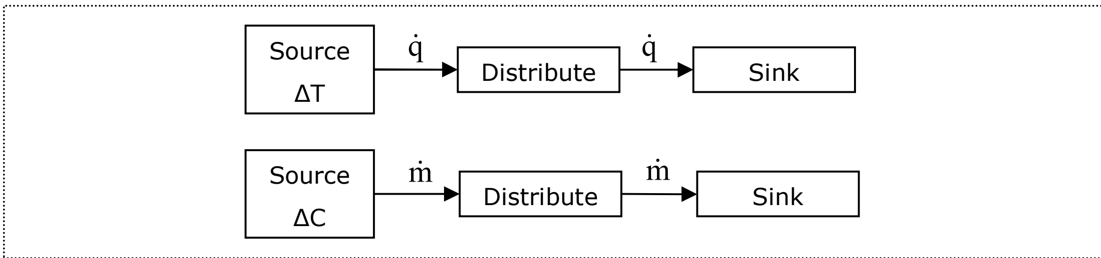


Figure 7.6 Abstract description climate control problem (2)

In its most simple form, a source delivers the effort (a difference in temperature or concentration) which causes the flows of heat and mass. The heat flow has to be distributed or spread over all the stored product, the same for the mass flow. After distribution the flows are “consumed” by the products and other elements in the warehouse. The figure does not make anyone think that cold air has to be ventilated to the products or that some device has to add water to the air. It only tells that the optimal conditions are obtained by a change in temperature and a change in concentration. It is up to the designers to think how this can be achieved. This description now implies that there should always be a difference in temperature and concentration (source). This is not true since the temperature of the products and the relative humidity are allowed to fluctuate around a certain target value. Changing the temperature or the humidity is necessary only when the deviation from this target value becomes too large. For this reason an element should be added to the system that can tell when the system needs to change the temperature or concentration.

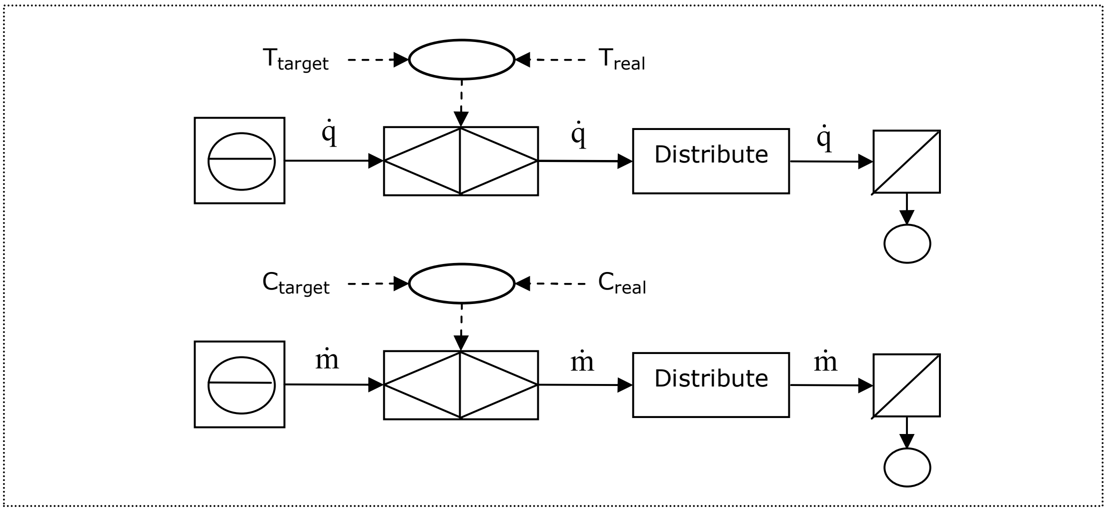


Figure 7.7 Abstract description climate control problem (3)

The effort will also need to vary depending on how much the temperature or humidity deviates from the target values. That means that the system not only has to decide when an effort has to be delivered but also how much effort. For this reason a decider element is added to the system. Describing the system as done in figure 7.7 not only gives an abstract view of the system but it also helps to identify the quantities for a mathematical model. In figure 7.7 the system is described with the symbols that are used for the general functions.
The major issues according to figure 7.7 are:

- how to create a difference in temperature and/or concentration
- how to determine when this difference is needed
- how to change this difference

- how to distribute the flows

The system can also be described as a process that has to remove heat. Remember that the biological heat causes an increase in temperature. Concerning the relative humidity it may be needed to either increase or decrease the concentration of water in air. Figure 7.8 shows the alternative description where a more mathematical approach is used.

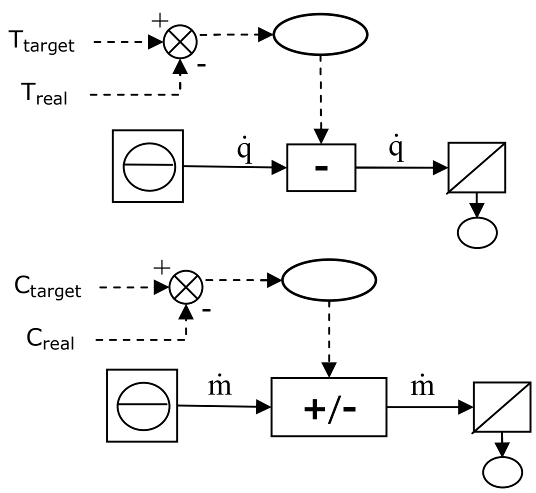


Figure 7.8 Abstract description climate control problem (4)

In the figure the source represents the products with their biological heat and also the air around these products where the concentration of water-air has to be kept within a certain range. The products cause heat which has to be removed and water has to be added or removed from the air when adjusting the relative humidity. The removal of heat and the addition (or removal) of water cause heat and mass flows. These flows then have to leave the system. This is illustrated with the *sink* blocks. In this description the real (measured) value is compared to the target and depending on the difference a decision is made whether heat or mass should be added or removed. The important questions that remain are now:

- How and when to remove heat from the products (the source)?
- How and when to add or remove mass (water) to or from the air around the products?

7.4 The search for alternative solutions

The previous figures showed that heat has to be removed from the products or that a difference in temperature is needed. This implies that a body or fluid of lower temperature has to made contact with the products. In the actual system cold outside air is send through the products. Heat flows from warm to cold so the cold air will take over the heat from the products. An interesting aspect is also the *sink* element, especially when removing heat. A certain amount of heat is being removed and maybe it is worth studying whether this heat should be "thrown away" or used/stored for other purposes. The figures also show that it is not necessary to think in terms of cooling but that thinking in terms of removing heat is also possible. Figure 7.7 showed that to cool down the products a ΔT was needed. The issue of removing heat and, maybe, store this heat for other purposes brings the idea of cold storage. This technology gives the possibility to store heat in the summer and use it in the winter. The opposite, storage of cold in winter for use in summer, is also possible. This could be used as a back up when the outside temperatures are not low enough for cooling. The smallest, and cheapest, cold storage system offered by GeoComfort[8] costs € 47.250,- with average annual service costs of € 1.275,-. This system would offer a cooling power of 45 kW. Notice that the actual costs of using the systems are not included. Comparing these costs with the relatively low energy costs (figure 6.4) of the actual system suggests that applying this technology, for a food storage warehouse like the one described in this project, is not profitable. Such a high investment is also unattractive since the storage warehouse is used for only seven months a year.

The design also depends on the biological heat of the products. As was shown in chapter 5 when the biological heat is relatively low it may be sufficient to ventilate early in the morning. In general it can be expected that the temperature will be low enough around this time. When the biological heat is relatively high ventilation will be needed every day. The ventilation periods will also be longer since it will cost more effort to cool down the products. In this case some active form of cooling should be installed.

[8] GeoComfort is a company specialized in the technology of storing heat or cold in the ground for later use. Website: www.geocomfort.nl

8. Conclusion

Rapid prototyping

This thesis showed how a model can be built of a physical system and how that model can be used for design. Climate control strategies can be developed and designed in these models for simulation. These simulations gave the possibility of testing different strategies and different design parameters in a short period of time, without having to build any prototype. Only a few amount of resources were needed to understand the system, think solutions of how to control the process and to test ideas. The time for this process is also short since, for example, a month can be simulated in approximately 7 minutes (on a Pentium 4, 3.00 GHz).

The most interesting advantage shown in this thesis is the possibility of modelling a system in a program like SIMULINK and letting it generate the C-code. The relative simple modelling in SIMULINK and the code generation option can make it possible to build different models for different clients according to their needs. Modelling this in SIMULINK would make this job relatively easy and fast. The time between idea and implementation is considerably reduced by the possibility of designing in SIMULINK and letting it generate the programming code. Custom-made code can be created and even implemented much faster! This part was shown with a first SIMULINK prototyping model, appendix A4. The most important aspects for climate control in the potato storage warehouse were modelled in SIMULINK and downloaded into the HC12 microprocessor. With some simple electronic devices (potentiometers) climate conditions were "imitated" with a control panel and some LEDs, a motor and a ventilator connected to the microprocessor represented the climate control actions. These were determined by the control strategy in the model and the inputs from the control panel. **No programming in C-code was needed!!!**

Climate control

The innovative idea was to use weather forecasts to determine the best moment for ventilating the products in a food storage warehouse. Simulations showed that the biological heat of these products has the biggest impact on temperature change. Simulations also showed that when the biological heat is relatively high (>20 W/ton) the use of the weather forecast is not possible because the products will warm up too fast. A biological heat of 9 W/ton was also tested, making the use of the weather forecast possible. Chapter 6 showed the results and compared them with a normal feedback system. Tests showed that the costs differences were not significant. Other figures showed that both methods have advantages and disadvantages. Using predictions keep the temperature of the products closer to the ideal storage temperature. This is the case for the later months. In the first months the system had difficulty with keeping the temperature within an acceptable range. The feedback system did not show this problem; however the temperature of the higher products was not as close to the ideal storage temperature as when using the weather forecast. A possible reason is the fact that the control system (with weather forecast) only ventilates at 3:00 in the morning. If the temperature at that moment is not low enough the control system will wait until the next day. The system does not account for the possibility of a decrease in temperature in later hours.

The simulations also made it possible to create figures and tables with specific information about how the system works. In a short period of time specific, useful, information can be gathered by designers. The information can also be showed to clients. By this more interaction with the client is possible at early stages of the design process. Clients can also tell if they are happy with the design before building a prototype.

Reflection

At the start of this project it seemed a very good idea to use temperature predictions for the climate control of a potato storage warehouse. At a certain moment one would determine if it is better to delay the ventilation of the process and wait for a colder day. However simulations showed that the biological heat has a great impact on the temperature change. When the biological heat was relatively low no significant differences could be achieved with this idea.

It was nice to get more experience with SIMULINK and experience by myself how important model building and simulations can be. It is sometimes amazing how well a model can describe a real system. Of course one has to remember that it is just a simplification of the reality. Amazing was also the complexity of what seems a simple system like a food storage warehouse. Chapter 4 can show this and keep in mind that not al factors that affect the temperature or humidity were modelled.

It was also great to see and learn how SIMULINK can generate the programming code of a model built by just simple blocks. The nice part was that I was able to see how a SIMULINK model would work in reality. This was possible by downloading the code into a microprocessor (HC12) and see the effect on the LEDs or other output pins.

Making the Adelaide toolbox work was very time consuming and frustrating. After weeks of trying it seemed that an additional, simple, electronic circuit was necessary. Fortunately Tamer discovered this before we gave up. There were also times in where some values in some of the source files needed to be adjusted. This was caused by the size of the SIMULINK model. These problems show that although it is relatively easy to work with SIMULINK and learn the process of code generation and downloading someone with experience in this area should be around to discover small problems that can come up.

It would be interesting to study how the presented design methodology, with rapid-prototyping, will work in reality for this problem. Maybe in the future VDH can integrate this approach in their design process. A potato storage was the example but the methodology can of course be applied to different products and systems. It is expected that the design time can be reduced and that less resources will be needed. A time study can be done to compare the design time when SIMULINK and code generation is used with the actual design time.

Also interesting would be the use of abstract problem description in practice. Companies that use abstract functions or elements to describe design problems can be approached to investigate whether the advantages described in this thesis were also realised. It can also be interesting to see how these functions can help model building in SIMULINK, abstract thinking can help model building since that is also an abstract process. Maybe it can help to think in terms of SIMULINK blocks.

References

1. Simons, J.L., industrial engineering lectures

2. Baarda, D.B, de Goede, M.P.M, 2001, Basisboek methoden en technieken, Wolters-Noordhoff, Groningen

3. De Leeuw, A.C.J., 2000, Bedrijfskundig Management: primair proces, strategie en organisatie, Van Gorcum, Assen

4. In 't Veld, J., 1998, Analyse van organisatieproblemen: een toepassing van denken in systemen en processen, Educatieve Partners Nederland, Houten

5. Pahl, G., Beitz, W., 1996, Engineering design: a systematic approach 2nd ed., Springer-Verlag, London

6. Ulrich, K.T., Eppinger, S.D., 2003, Product design and development, third edition, McGraw Hill, Boston

7. www.answers.com

8. Incropera, F.P., DeWitt, D.P., 1990, Fundamentals of heat and mass transfer, John Wiley & Sons, New York

9. Smith, J.M., Stammers, E., Janssen, L.P.B.M, Fysische transportverschijnselen 1, Delft University Press, Delft

10. Keesman, K.J., Diederik, P., Lukasse, L.J.S., 2003, Optimal climate control of a storage facility using local weather forecasts, Control Engineering Practice, volume 11, issue 5, 505-516

11. Robinson, S., 2004, Simulation: the practice of model development and use, John Wiley & Sons, Chichester

12. http://www.agf.gov.bc.ca/resmgmt/publist/300series/331000-4.pdf

13. Gottschalk, K., Chalabi, Z.S., Day, W., Young, P.C., 1996, Mathematical modelling of the thermal behaviour of stored potatoes & developing of fuzzy control algorithms to optimise the climate in storehouses, Proceedings of the 2nd IFAC ISHS workshop on mathematical and control applications in agriculture and horticulture, No. 406, 331-339

14. Laguerre, O., Ben Amara, S., Flick, D., 2006, Heat transfer between wall and packed bed crossed by low velocity airflow, Applied Thermal Engineering, volume 26, issue 16, 1951-1960

15. http://www.gnb.ca/0029/00290050-e.asp

16. Isermann, R., 2005, Mechatronic systems fundamentals, Springer-Verlag, London

17. Bentley, J.P., 1995, Principles of measurement systems 3rd ed, Prentice Hall, Harlow

18. Swanson, G.A., 2004, Accountability and the governance of business alliances, Tenessee Tech University, International Council on Systems Thinking in Management (ICSTM)

19. Hubner, C., 1991, PATO cursus sensoren, TU Eindhoven

20. Logothetis, N., Wynn, H.P., 1989, Quality through design: Experimental design, Off-line quality control and Taguchi's contributions, Clarendon Press, Oxford

21. Park, S.H., Zhang, G., Zheng, 1995, H., A new method of analysis for parameter design in quality engineering, Total Quality Management, vol. 6 issue 1

Appendix A1. Parameter Design

Designing a product with the ability to maintain consistent performance over a range of conditions, regardless the way it is manufactured or used is called *robust design* [6]. A robust system is not sensitive to factors that can have an unwanted effect on the performance. These factors are also called *noise factors*. In the robust design process specifications are set for the product in order to accomplish the desired performance while reducing the noise effects. The specifications are also called *design parameters* and the search for the desired set of specifications is called *parameter design*. From now on the term parameters will be used when discussing design specifications. A parameter is any product or process variable that is directly or indirectly relevant to the product performance. The use of the term specifications will be used when discussing the performance or characteristics that the users expect (and demand) from the product [6]. The combination of parameters that makes a system insensitive to noise and keeps the desired performance is the *robust setpoint*. In most cases there will be many possible combinations of parameters but some combinations are more sensitive to noise than others. The goal then is to find the combination that makes the system the least sensitive to noise.

Taguchi

In this chapter a short summary is given about Genichi Taguchi and his approach to robust design. The approach developed by Taguchi uses *design of experiments (DOE)* [6] methods when designing parameters. Parameters that are controllable and the most important noise factors are first identified. These are then varied during experiments to find robust setpoints. This approach tries to take advantage of the nonlinear behaviour of systems when changing the parameters. As shown in figure A1.1, deviations from e.g. parameter x_0 may have less impact on performance than deviating from parameter x_1.

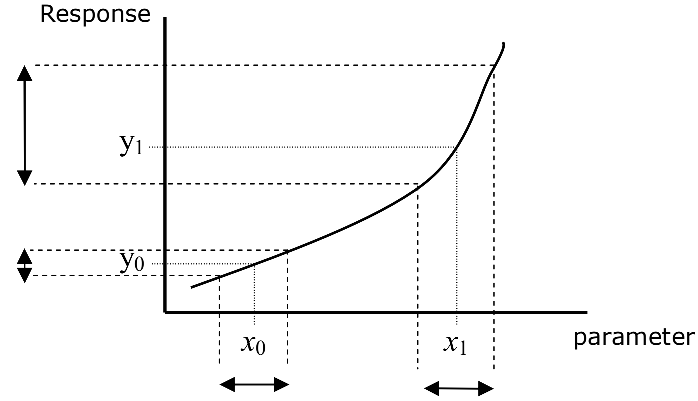


Figure A1.1 Response to parameter *x*.

Design of experiments consists of the following seven steps:

1. Identify control factors, noise factors and performance measures
2. Formulate an objective function
3. Set up an experimental plan
4. Run the experiments
5. Analyse the results
6. Select and confirm setpoints
7. Evaluate and repeat steps

<u>Step 1. Factors</u>

Control factors (CF) are design variables that can be controlled by designers and that can be varied (in a controlled manner) during experiments.

Noise Factors (NF) are those variables that cannot be controlled during the manufacturing or use of the product. The goal is to make a design that works well regardless of the values for these factors. Sometimes it is possible to simulate noise in a controlled way during experiments.

Performance measures are measures used to quantify how the product works in order to make (statistical) analysis possible. In general specifications are used as performance measures because chosen parameters have a certain impact on specifications. A product can have a long list with specifications so most of the times two or three of the most important ones are chosen. The performance measures can be divided in *target performance measures* (TPM) and *noise performance measures*

(NPM) [20]. TPM are measures of the process mean, they can be used to identify the control factors that affect the performance mean. NPM are measures of the performance variability, showing which control factors change the performance variability.

In this step designers have to decide which factors and performance measures will be used during the experiments.

Step 2. Objective function

A function is formulated in terms of the performance measures, which most of the time has to be maximized or minimized (e.g. minimize product dimensions). A target value for the function is also possible. Most of the times the performance measures are transformed into a signal-to-noise (S/N) ratio. The following possibilities exist when using a S/N ratio [20, 21]:

Symbols

y = measured value for a performance measure

n = number of measurements

- When smaller is better: minimizing the objective function

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

- When larger is better: maximizing the objective function

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$$

- When realizing a target value is desired

$$\frac{S}{N} = -10\log\left(\frac{\overline{y}^2}{s^2}\right), \quad \text{where } \overline{y} = \sum_{i=1}^{n} \frac{y_i}{n} \text{ and } s^2 = \sum_{i=1}^{n} \frac{(y_i - \overline{y})^2}{n-1}$$

Step 3. Experimental plan

In situations where the costs of experimenting are relatively low a large number of experimental trials can be run. The study of many factors with many different values and combinations is than economically feasible. When the costs are high an efficient experimental plan has to be developed in order to simultaneously change several factors at once. *Orthogonal arrays* are usually used to run such experiments. When using orthogonal arrays only specific values for the control factors are used. The number of different values that a factor can have is called the level. With orthogonal arrays many factors can change in value simultaneously. Taguchi prefers the use of two or three level orthogonal arrays. Figure A1.2 gives an example of a two level orthogonal array with seven factors. When it is possible to simulate noise the a distinction can be made between control factors and noise factors, as was described in step 1. When it is not possible to simulate noise the array consists only of control factors. One can expect the noise to be naturally present.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**Performance**
1	0	0	0	0	0	0	0	P_1
2	0	0	0	1	1	1	1	P_2
3	0	1	1	0	0	1	1	P_3
4	0	1	1	1	1	0	0	P_4
5	1	0	1	0	1	0	1	P_5
6	1	0	1	1	0	1	0	P_6
7	1	1	0	0	1	1	0	P_7
8	1	1	0	1	0	0	1	P_8

Figure A1.2 L8 orthogonal array

7 factors: A-G

2 levels:

1 = maximum value

0 = minimum value

Step 4. Running experiments

In this step the product or system is tested under the conditions described by the rows of the experimental plan. Ulrich and Eppinger suggest to randomize the sequence of the experiments to prevent any systematic trend in the results because the factors are being varied in a systematic way.

Step 5. Analysis

Statistical techniques are mostly used to analyze the results gathered by the experiments. A popular technique is *analysis of means*. For each factor the mean of the performance (mean effect, E) is calculated, only taking into account the rows for

which the specific factor keeps the same value (level). The main effect for factor A1 in figure 2 is the mean of the performance for rows one to four.
Another, faster, technique is Pareto analysis. Here the square difference in S/N between the different levels of the factors is calculated. The ratio of the difference for each factor compared with the total difference determines a contribution ratio (%) for each factor.
Analysis of variance (ANOVA) is the most used technique by Logothetis [20].

More about the mentioned statistical techniques can be found in appendix A1.1 and A1.2

Step 6. Selection and confirmation

The analysis can show the design team which factors have a positive effect on the performance so they can select the values that make the system the most robust. This is accomplished by selecting the values for the factors that simultaneously improve performance and decrease the variability. In the case of Pareto analysis the factors that cumulatively take account for 80-90% of the total difference have a significant impact on the performance variability. These factors should get priority when choosing the setpoint. The levels for those factors with the highest S/N ratio are then chosen.
It can happen that a setpoint is chosen that was not tested during the experiments. An experiment or simulation should be run to be sure that the setpoint provide the desired results.

Step 7. Reflection

In many design problems one experimental round is enough to find appropriately robust setpoints. However, it may be worthwhile to do some more experimentations to further optimize performance. Experiments could be done for example with values that lie between the maximum and minimum values in a two level experiments. The design team can also experiment with factors that where skipped in step one.
Hereafter designers should reflect on the whole parameter design process and ask themselves if the right experiments where done or if the results are acceptable. They should also decide whether repeating the whole process is necessary.

Criticism on Taguchi

The most remarked issue about Taguchi's parameter design is the assumption that the factor effects are independent, without interaction between factors. The assumption states that there are no interactions or that they are so small that they can be neglected. Taguchi also prefers to study as many factors as possible instead of many interactions. It is, however, possible to investigate the effect of interactions by adding extra columns to figure A1.2 as shown in figure A1.3. In this example the interactions between factors A and B and between A and C are investigated. The level for the interactions is simply the product of the levels of the two factors. Further analysis remains as was described in step five.

	A	**B**	**AB**	**C**	**AC**	**D**	**E**	**F**	**G**
1	0	0	1	0	1	0	0	0	0
2	0	0	1	0	1	1	1	1	1
3	0	1	0	1	0	0	0	1	1
4	0	1	0	1	0	1	1	0	0
5	1	0	0	1	1	0	1	0	1
6	1	0	0	1	1	1	0	1	0
7	1	1	1	0	0	0	1	1	0
8	1	1	1	0	0	1	0	0	1

Figure A1.3 L8 orthogonal array with interactions (AB and AC)

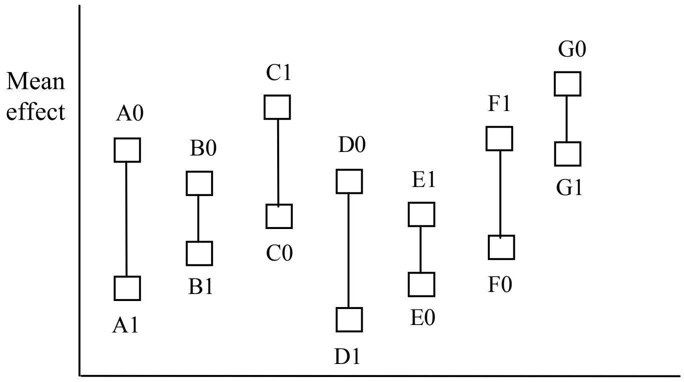
Appendix A1.1 Analysis of means

	A	B	C	D	E	F	G	Performance
1	0	0	0	0	0	0	0	P_1
2	0	0	0	1	1	1	1	P_2
3	0	1	1	0	0	1	1	P_3
4	0	1	1	1	1	0	0	P_4
5	1	0	1	0	1	0	1	P_5
6	1	0	1	1	0	1	0	P_6
7	1	1	0	0	1	1	0	P_7
8	1	1	0	1	0	0	1	P_8

$$E_{A0} = \frac{P_1 + P_2 + P_3 + P_4}{4}$$

$$\vdots \qquad \vdots$$

$$E_{G1} = \frac{P_2 + P_3 + P_5 + P_8}{4}$$



If objective function has to be minimized choose levels A1, B1, C0, D1, E0, F0, G1

If objective function has to be maximized choose levels A0, B0, C1, D0, E1, F1, G0

Appendix A1.2 Pareto analysis

	A	B	C	D	E	F	G	SN
1	0	0	0	0	0	0	0	SN_1
2	0	0	0	1	1	1	1	SN_2
3	0	1	1	0	0	1	1	SN_3
4	0	1	1	1	1	0	0	SN_4
5	1	0	1	0	1	0	1	SN_5
6	1	0	1	1	0	1	0	SN_6
7	1	1	0	0	1	1	0	SN_7
8	1	1	0	1	0	0	1	SN_8

Factor	A	.....	G	Total
Sum at factor level 0 1	 A_0 A_1		 G_0 G_1	
Square of difference	$(A_0-A_1)^2$	.....	$(G_0-G_1)^2$	$T=(A_0-A_1)^2+\ldots+(G_0-G_1)^2$
Contribution ratio (%)	$\frac{(A_0-A_1)^2}{T}\cdot 100$	.....	$\frac{(G_0-G_1)^2}{T}\cdot 100$	100

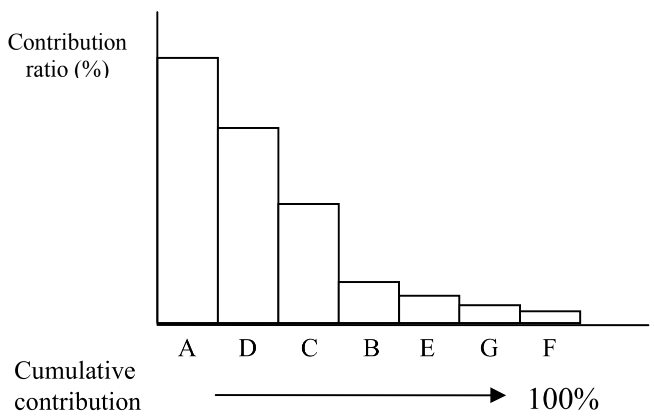
$A_0 = SN_1 + SN_2 + SN_3 + SN_4$

: :

: :

$G_1 = SN_2 + SN_3 + SN_5 + SN_8$

Now a diagram can be drawn in sequence of high contribution ratio to low contribution ratio. Also calculate the cumulative contribution ratio.



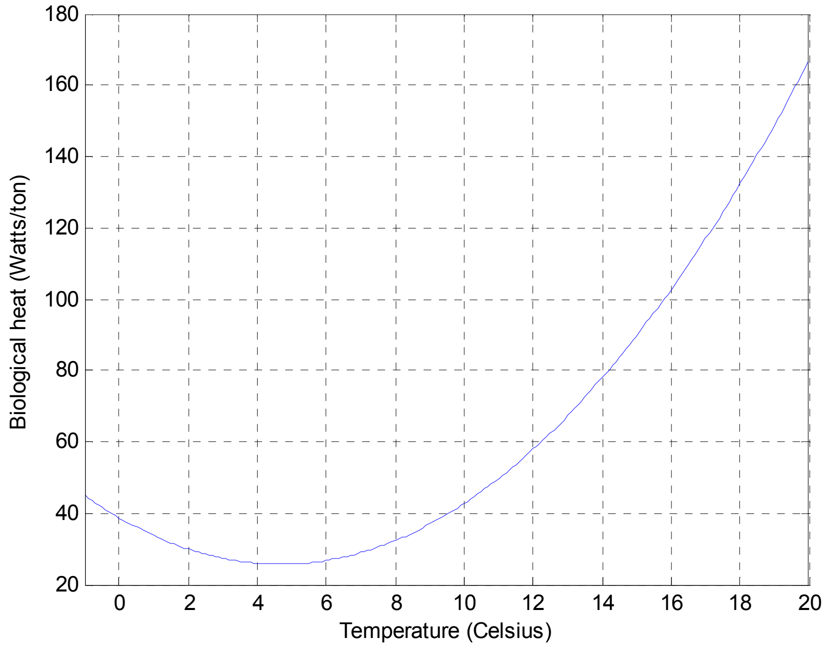
Appendix A2. Biological heat potatoes

Omnivent (interview with F. Schra)

40 W/ton

Gottschalk [13]

$q_{bio}(T) = 38.7 - 5.6 \cdot T + 0.6 \cdot T^2$ [W/ton] T = temperature (°C)



http://www.tis-gdv.de/tis_e/ware/gemuese/kartoffe/kartoffe.htm

Increase of 0.25 °C/day => ≈10 W/ton

http://home.planet.nl/~nhuijts/Loods.html

Increase 0.22 °C/day => ≈9 W/ton

British Columbia, ministry of agriculture and food

http://www.agf.gov.bc.ca

16.9 – 19.9 W/ton

Appendix A3. Results experimental design

Ex	**Costs (€)**	**Avg. T_{low} (K)**	**SD. T_{low} (K)**	**Avg. T_{high} (K)**	**SD. T_{high} (K)**	**SN_{low} (dB)**	**SN_{high} (dB)**
1	182.60	277.61	0.31	278.17	0.17	-59.16	-64.08
2	210.90	277.76	0.21	278.19	0.13	-62.44	-66.68
3	155.70	277.86	0.35	278.45	0.20	-57.93	-61.15
4	180.90	277.93	0.31	278.42	0.25	-58.96	-61.08
5	180	277.96	0.36	278.39	0.28	-58.11	-59.81
6	161.70	277.95	0.29	278.42	0.24	-59.52	-61.21
7	168	277.52	0.29	278.17	0.18	-59.52	-64
8	210.30	277.72	0.24	278.19	0.16	-59.63	-64.93

Appendix A4. SIMULINK model for prototyping

Figure A4.1 shows a first SIMULINK model for climate control that was downloaded into the microprocessor. The figure shows only the higher level of the model. On this level the outside temperature (T_o), the temperature of the products (T_{high}, T_{low}) the difference between T_{high} and T_{low} and the outside relative humidity determine if ventilation is needed. This is checked in the if-block. The action to be taken according to the inputs is determined by the blocks inside the if-action subsystems. These are the lower level models. The temperature under the floor, or channel temperature, T_f can be found inside the if-action block responsible for ventilation with outside air. Remember that this temperature is not a condition for ventilation but determines the opening of the ventilation windows.

A couple of important things can be noticed in the higher level model: functions blocks (Fcn), a gain block and a hysteresis blocks (relay). The function and the gain blocks are used to convert the input value from the ADC into a corresponding temperature or relative humidity value. The ADC can only give values between 0 and 5. In this case these input values are converted into temperature values between -10 and 20 °C. The other input is converted into a value between 0 and 100 %, the relative humidity. The hysteresis block makes sure that the ventilation process is started when Thigh is above a certain value and stopped when Thigh is below another value (see chapter 5.3).

The model is downloaded into the microprocessor and the processor is connected to a control panel (input). On the panel the input voltage of the ADC can be varied. Some LEDs, a ventilator and a motor are also connected to the microprocessor (output). With these one can see how the downloaded model works when the input is varied. No programming (in C-code) is needed!!!

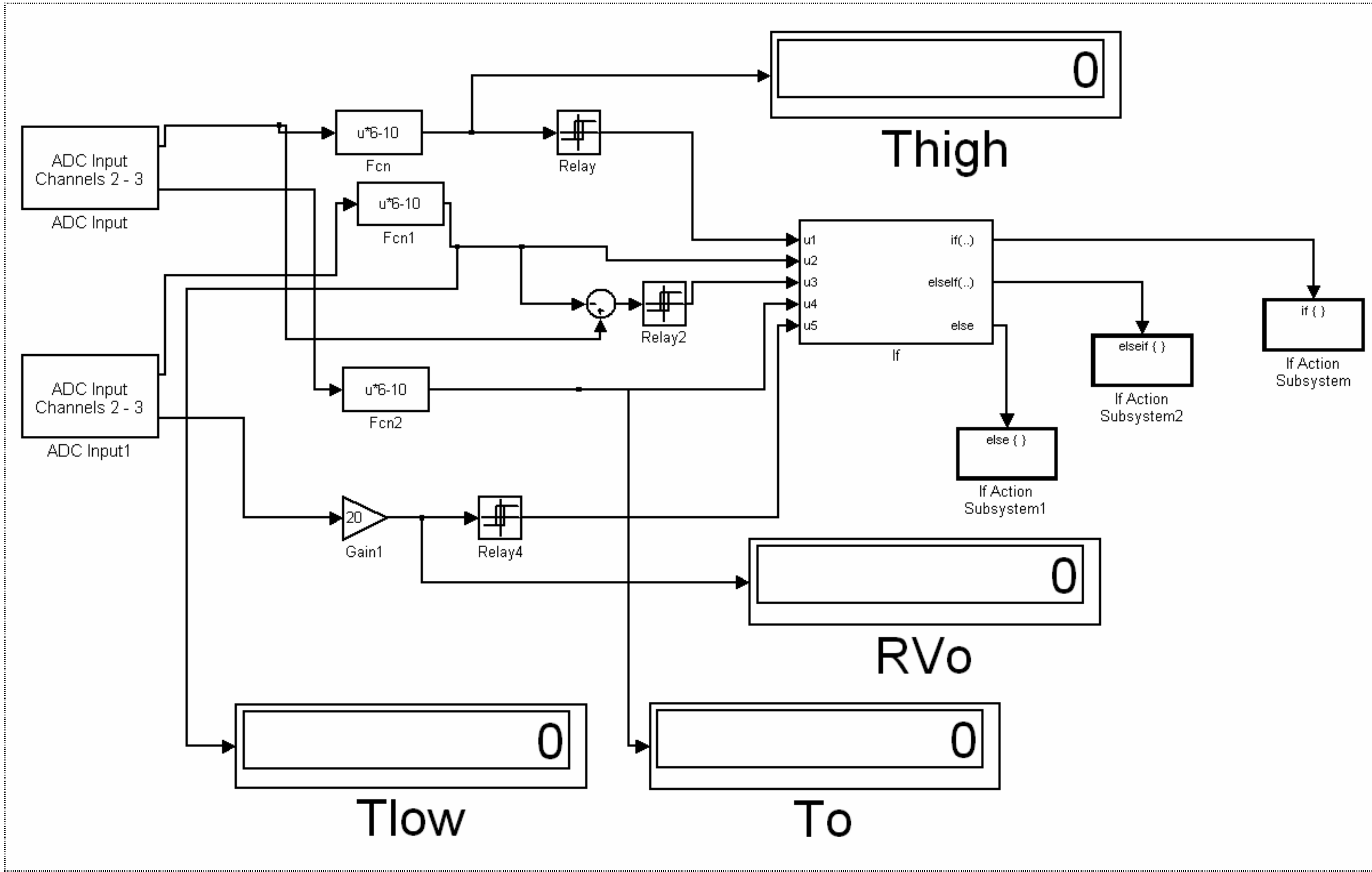


Figure A4.1 SIMULINK climate control model for prototyping

Appendix A5. Comparison of results

Comparison of costs for a system using forecasts and cooling down T_{high} to 5 °C (scenario 1) with a normal feedback system (scenario 2)

Significance level: 5.0%

Replication	Scenario 1 result	Scenario 2 result	Difference	Cum. mean difference	SD	Confidence interval: Lower interval	Confidence interval: Upper interval	Conclusion
1	204	217.51	-13.51	-13.51	n/a	n/a	n/a	n/a
2	272.4	321.4	-49.00	-31.26	25.095	-256.73	194.22	No difference
3	263.5	245.3	18.20	-14.77	33.618	-98.28	68.74	No difference
4	182.9	213.6	-30.70	-18.75	28.581	-64.23	26.73	No difference
5	173.4	188.6	-15.20	-18.04	24.803	-48.84	12.75	No difference
6	160.7	156.7	4.00	-14.37	23.940	-39.49	10.76	No difference
7	165.1	168.4	-3.30	-12.79	22.251	-33.37	7.79	No difference

Appendix A5. Comparison of results

Comparison of costs for a system using forecasts and cooling down T_{high} to 4.5 °C (scenario 1) with a normal feedback system (scenario 2).

Significance level	5.0%

Replication	Scenario 1 result	Scenario 2 result	Difference	Cum. mean difference	SD	Confidence interval: Lower interval	Confidence interval: Upper interval	Conclusion
1	204.9	217.51	-12.61	-12.61	n/a	n/a	n/a	n/a
2	274.7	321.4	-46.70	-29.66	24.105	-246.23	186.92	No difference
3	277	245.3	31.70	-9.20	39.311	-106.86	88.45	No difference
4	168.6	213.6	-45.00	-18.15	36.750	-76.63	40.33	No difference
5	200.4	188.6	11.80	-12.16	34.531	-55.04	30.71	No difference
6	145.4	156.7	-11.30	-12.02	30.887	-44.43	20.40	No difference
7	178.6	168.4	10.20	-8.84	29.420	-36.05	18.36	No difference

Appendix A6. Abstract functions and elements

Table A6.1 Rodenacker: general functions

Connect	Joining or fastening something together
Separate	Making something to become parted (from something else)
Channel	Directing or guiding something along a desired course

Table A6.2 Isermann: elements of technical processes

Source	Element that delivers an output quantity from a large supply
Transformer	Element that takes up a quantity and deliver it again in the same form, without storing it
Converter	Element that takes up a quantity in a certain form and delivers it after conversion into another form, without storing it
Sink	Element that takes up a quantity and consumes it in the same or another form completely or in a substantial portion
Storage	Element that takes up a quantity and delivers it again in the same form

Table A6.3 Roth: general functions

Change	Giving something a different form or appearance
Add	Joining or uniting something (or things) so as to increase size, quantity, quality or scope
Connect	Joining or fastening something together
Distribute	Spreading or diffusing over an area
Channel	Directing or guiding something along a desired course
Transform	Changing into a different form, substance or state
Guide	Showing the way, lead
Store	To accumulate and set aside for future use

Table A6.4 Krumhauer: general functions

Change	Giving something a different form or appearance
Increase	Making or becoming larger
Decrease	Making or becoming smaller
Connect	Joining or fastening something together
Branch	Separating, diverging
Channel	Directing or guiding something along a desired course
Stop	---
Store	To accumulate and set aside for future use

Table A6.5 Koller: General functions

Change	Giving something a different form or appearance
Change back	---
Change direction	Changing the course or route
Increase	Making or becoming larger
Decrease	Making or becoming smaller
Couple	Link, something that joins or connects two things together
Interrupt	To stop, break the continuity
Join	Putting or bringing together so as to make continuous or form a unit
Separate	Making something to become parted (from something else)
Assemble	Bringing or calling together into a group or whole
Divide	= separate
Channel	Directing or guiding something along a desired course
Isolate	To set apart or cut off from others
Collect	Accumulate
Scatter	To distribute loosely
Rectify	Correcting by calculation or adjustment
Oscillate	Varying between alternate extremes, usually within a definable period of time
Conduct	Serving as a medium for conveying (transmission)
Insulate	Preventing the passage of heat, electricity, or sound into or out of
Absorb	Consuming, retaining without reflection or transmission
Emit	To send out
Store	To accumulate and set aside for future use
Empty	Holding or containing nothing

Table A6.6 Miller: critical subsystems of living systems

Subsystems that process both matter, energy and information

1.	*REPRODUCER*	The subsystem that carries out the instructions in the genetic information or charter of a system and mobilizes matter and energy to produce one or more similar systems.
2.	*BOUNDARY*	The subsystem at the perimeter of a system that holds together the components that make up the system, protects them from environmental stresses, and excludes or permits entry to various sorts of matter-energy and information.

Subsystems that process matter-energy

3.	*INGESTOR*	The subsystem that brings matter-energy across the system boundary from the environment.
4.	*DISTRIBUTOR*	The subsystem that carries inputs from outside the system or outputs from its subsystems around the system to each component.
5.	*CONVERTER*	The subsystem that changes certain inputs to the system into forms more useful for the special processes of that particular system.
6.	*PRODUCER*	The subsystem that forms stable associations that endure for significant periods among matter-energy inputs to the system or outputs from its converter, the materials synthesized being for growth, damage repair, or replacement of components of the system, or for providing energy for moving or constituting the system's outputs of products or information markers to its suprasystem.
7.	*MATTER-ENERGY STORAGE*	The subsystem that places matter or energy at some location in the system, retains it over time, and retrieves it.
8.	*EXTRUDER*	The subsystem that transmits matter-energy out of the system in the form of products or wastes.
9.	*MOTOR*	The subsystem that moves the system or parts of it in relation to part or all of its environment or moves components of its environment in relation to each other.
10.	*SUPPORTER*	The subsystem that maintains the proper spatial relationships among components of the system, so that they can interact without weighing each other down or crowding each other.

Subsystems that process information

11.	*INPUT TRANSDUCER*	The sensory subsystem that brings markers bearing information into the system, changing them to other matter-energy forms suitable for transmission within it.
12.	*INTERNAL TRANSDUCER*	The sensory subsystem that receives from subsystems or components within the system markers bearing information about significant alterations in those subsystems or components, changing them to other matter-energy forms of a sort that can be transmitted within it.
13.	*CHANNEL AND NET*	The subsystem composed of a single route in physical space or multiple interconnected routes over which markers bearing information are transmitted to all parts of the system.
14.	*TIMER*	The clock, set by information from the input transducer about states of the environment that uses information about processes in the system to measure the passage of time and transmits to the decider signals that facilitate coordination of the system's processes in time.
15.	*DECODER*	The subsystem that alters the code of information input to it through the input transducer or internal transducer into a "private" code that can be used internally by the system.
16.	*ASSOCIATOR*	The subsystem that carries out the first stage of the learning process, forming enduring association among items of information in the system.
17.	*MEMORY*	The subsystem that carries out the second stage of the learning process, storing information in the system for different periods of time, and then retrieving it.
18.	*DECIDER*	The executive subsystem that receives information inputs from all other subsystems and transmits to them outputs for guidance.
19.	*ENCODER*	The subsystem that alters the code of information input to it from other information processing subsystems from a "private" code used internally by the system into a "public" code that can be interpreted by other systems in its environment.
20.	*OUTPUT TRANSDUCER*	The subsystem that puts out markers bearing information from the system, changing markers within the system into other matter-energy forms that can be transmitted over channels in the system's environment.

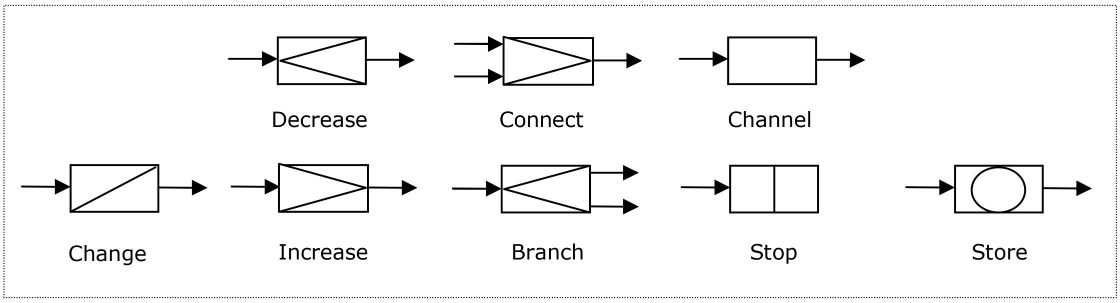


Figure A6.1 Krumhauer: general functions

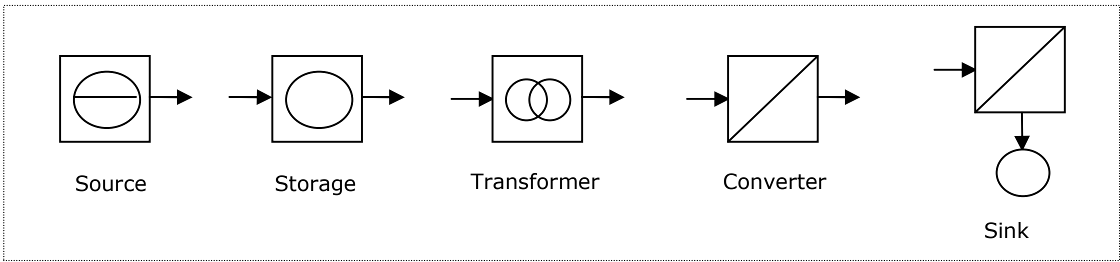


Figure A6.2 Isermann: elements of technical processes

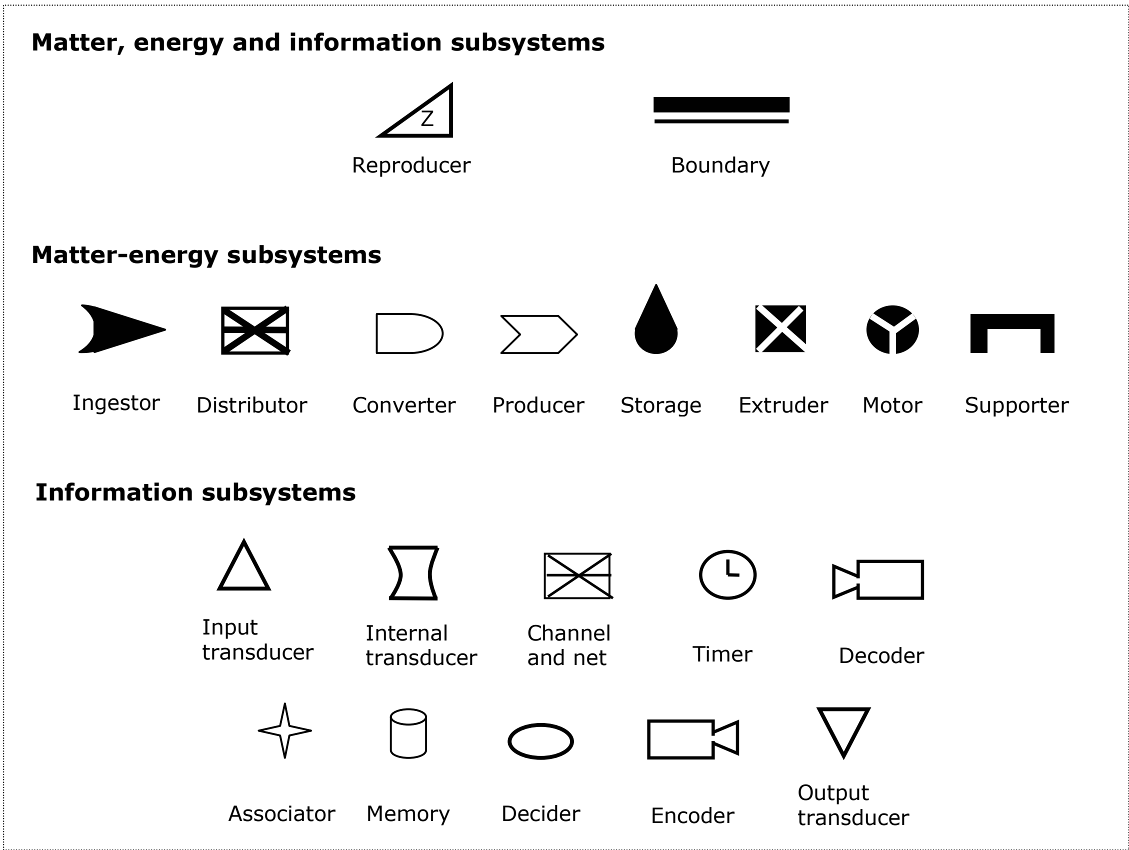


Figure A6.3 Miller: critical subsystems of living systems