LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT

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Industrial Engineering and Management

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FUZZY CONTROLLER IN A BAKERY

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ABSTRACT

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Fuzzy controller in a bakery

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The most basic consepts of fuzzy logic. In addition, adaptive neuro-fuzzy inference system (ANFIS) is presented. It is applied in empirical part of the work along with Mamdani's inference system. The goal is to use the methods to control dough's temperature in a bakery. Optimizing the dough temperature ensures homogenous and high product quality. According to initial tests it seems that fuzzy controller performs well in the baking environment.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT

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Tuotantotalouden koulutusohjelma

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Sumea säätöjärjestelmä leipomoon

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Työssä käydään läpi sumean logiikan keskeisimpiä käsitteitä. Työssä esitellään myös sumean logiikan ja keinotekoisten neuroverkkojen yhteinen sovellus ANFIS. Työn soveltavassa osassa luodaan säätöjärjestelmä hyödyntäen ANFIS:ta sekä Mamdanin inferenssisysteemiä. Tavoitteena on hyödyntää järjestelmää säätelemään taikinan lämpötilaa ja siten taata tasainen ja korkea tuotelaatu. Alustavien testien mukaan sumea säätöjärjestelmä vaikuttaa toimivan hyvin kyseissä sovelluskohteessa.

ALKUSANAT

Tahdon kiittää leipomoa, jonne sain tulla tekemään tämän lopputyöni. Olen kiitollinen, kuinka vapaat kädet sain muovata aihettani sekä tehdä tutkimuksia leipomossa. Kiitos viralliselle ohjaajalleni Hannalle, joka oli tarvittaessa tavoitettavissa ja järjesti asioita, kun minulla oli tarve. Kiitos koko leipomon henkilökunnalle, kuinka hyvin ja avosylin otitte minut mukaan porukkaan ja autoitte, kun minulla oli tarve. Monet naurutkin olen saanut kanssanne nauraa niin kahvipöydässä kuin linjalla. Erityisen isosti haluan kiittää automaatioinsinööriä Jannea, joka oli kuin käytännön ohjaajani työssä. Hän opasti ja kertoi linjasta ja leipomosta valtavalla tieto-taidollaan, mutta ennen kaikkea opasti ja tuki oikeaan suuntaan, jos välillä meinasin hukata pallon. Kiitos!

Iso kiitos myös Pasille ja koko Lappeenrannan teknilliselle yliopistolle. Kiitos erinomaisesta tuesta, avusta ja kaikesta teoriaopetuksesta Pasi, jota tämän projektin ja jo maisteriopintojen aikana annoit. Kannustuksesi työn aloituksessa valoi minuun kovasti uskoa, kun työn aloitus leipomossa jännitti, kiitos valoisasta asenteestasi. Yliopistoa haluan kiittää loistavasti järjestetyistä opinnoista pitkän matkani aikana. Nämä kuusi vuotta sisältävät paljon hyviä muistoja yliopistolta ja ennen kaikkea ihania ystäviä.

Olen valtavan onnekas, kun minulla on maailman ihanin äiti, joka on myötäelänyt, tukenut ja kannustanut sekä tämän projektin että koko elämäni aikana. Olet äiti minulle ollut aina tuki ja turva, jo silloin kun talutit minut 18 vuotta sitten ihkaensimmäisenä koulupäiväni kouluun ekalle luokalle. Nyt, kun viimeistelin opintoja, olet edelleen ollut vierelläni tukemassa. Sitä tukeasi olen tarvinnut tämän projektin aikana enemmän kuin koskaan aiemmin. Kiitos äiti.

Kiitos myös sinulle Tero, minun mieheni, joka olet seisonut rinnallani yliopiston alkuvaiheista asti. Olet aina kannustanut ja tsempannut tällä yliopistomatkalla. Tukesi on auttanut minut monesta vaikeasta hetkestä yli. Kiitos, kuinka kärsivällisesti olet ollut mukana tässäkin projektissa taustatukena. Kiitos myös rakkaat lapsemme Senni ja Eelis täydellisistä mindfulness-harjoituksista, joita olette minulle antaneet, kun olemme leikkineet leikkejänne. Rakkaus, jota minulle annatte joka päivä, on parasta koko maailmassa. Äiti rakastaa teitä niin, niin paljon.

Lahdessa 2.5.2020, Roosa Huotari

Table of contents

1. INTRODUCTION

The aim of this thesis is to make a fuzzy controller to be used in certain part of bakery production. The system's idea is to standardize dough and then bread quality and in addition reduce bakers' work and response. Standardizing dough quality ensures baking process to flow without unplanned pauses, reduces production losses and more importantly rises and maintains high product quality.

In a bakery baking conditions like room temperature and flour humidity change during the year which affect straight on the bread quality. These changes may cause waste in the bakery if bread quality varies too much. A baker can affect a quite much to the bread quality when she or he adjusts the production settings according to the bread dough and her or his experience. It would be ideal if the production line could adjust itself according to the circumstances creating more uniform bread by reducing waste and bakers' response. In addition, self-steering production line could help to fulfil one of the key strategies, product quality.

1.1. Earlier research in this field

Lofti Zadeh introduced in 1965 a new concept: fuzzy sets. Previously calculations were based on a thought that something is either true or false. This was very black and white thinking. In this context Zadeh brought all the shades of grey into that black and white world. His fuzzy sets were an extension to the bivalent world meaning that when earlier things were calculated with zeros and ones, now they can have partial memberships to the classes. Usually memberships are between a unit interval [0,1]. After that fuzzy sets and soft computing have been under research widely. (Dote 1995, p. 50; Klir and Yuan l995) Fuzzy logic has numerous amounts of applications from unmanned helicopters to weather forecasting systems and from pattern recognition to medical diagnosis (Singh *et al.* 2013, p. 1).

In history there have been several kinds of trends to improve production lines worldwide. One of the most popular way has been Lean and its several different tools. For example, Khaled and Mapa (2012) introduced how they implemented Lean tools into a bakery having good results. This thesis is done into a bakery in which they have also used different Lean tools broadly in their production and management, but fuzzy methods are not utilized yet. The improvement projects have concentrated on developing the product flow. In other words, the focus has been more on technological improvements like conveyors, not that much on product quality. This project approaches the production development via product quality development. If the product can be produced in a way that it has standard quality, then also the process flows well. In this thesis fuzzy logic is used in order to reach the goal.

According to several different researches it looks like fuzzy logic applications are widely used in food industry already. Several of the applications seems to be used in supervising the product quality. There are also applications in bakery conditions. In 1999 Davidson, Chu and Ryks investigated how Adaptive Neuro-Fuzzy Inference System (ANFIS) could be used for supervising quality of chocolate chip cookies. They created model for three variables which are used for estimating and evaluating how the cookie production had gone. One of the key findings was how difficult it is to create models based on definitions of people. They found out that the customers' opinions of the results were biased because they based their opinions mainly on the cookies' colour neglecting the size and amount of chocolate chips. In addition, Perrot *et al.* investigated (2000) cookie baking process and estimated the success of the process using fuzzy methods. Unlike Davidson, Chu and Ryks, Perrot *et al.* managed to build with very simple model accurate and robust system even though the baking process is highly complex.

1.2. Research framework

The basics of fuzzy methods and how they are applied to the bakery are introduced in this thesis. There are experiments done in order to investigate how bread dough acts in different situations. That knowledge helps to understand the production line better and to find potential needs for improvements. This thesis concentrates on one production line of the bakery. The line is used normally during the research and all the investigations and experiments are done besides it.

1.3. Aim of the research and research questions

The aim is to build a fuzzy controller for certain part of the line. Finding the proper part of the line to build the controller bases on interviews and experiments done in the bakery. Interviews and experiments reveal in which places some improvements should be considered and how they could be implemented on the line. The fuzzy controller means a system which is trained with real-life data gathered from the bakery production line and which can steer settings according to circumstances. This system should standardize the bread production and reduce bread waste.

It is good to notice that the focus is not on (physical) waste work like reducing walking and lifting that bakers do on the line. The target of the project is more on developing the line smart and then get more fluent process flow and achieve end result quality improvements. Research questions are:

1. Which are the critical points in the production line where measurements and supervision should be done?

2. Which variables affect on the bread dough and the end product?

3. How to set fuzzy membership functions for the variables found in question 2?

4. Which kinds of instructions/rule base should be written for the system?

5. What kind of fuzzy control system is needed here?

In question 1 the critical points mean “real and physical” points in the production line like conveyors. Those points should be chosen so that they are important for the bakers in their everyday work; where they walk and supervise the quality of dough, bread or process and steer the production line parameters accordingly.

Question 2 is more about investigating circumstantial things like temperature of the air or temperature of used water. Which variables are followed currently, are they controlled somehow and what kind of effect they have on the dough? Is there probably something that affects on dough or bread quality which is not or cannot be followed at the moment?

Question 3 is about more thorough investigation of the variables found in question 2. This will be an iterative phase to find proper membership functions.

In question 4 are investigated how to make proper rule base for the system. The target is to find how to connect the fuzzy sets found in question 3 into a proper system. The instructions are for example: “If dough’s temperature is HIGH then add COLD water”. The controller needs correctly built rule base.

In question 5 it is a purpose to create a fuzzy controller based on all the steps presented ahead. The results of the fuzzy controller are evaluated basing on how well the controller manages to homogenize and standardize the dough quality. Most likely this needs a test between some process steps because the results cannot be followed at the end of the end product. During the long process there are several other variables and factors that affect on the end product so it cannot be pointed out so straightforward which change affected on what and how.

1.4. Research methods and material

Most of the theory is collected from LUT Finna database. Bakery related info is collected by interviewing bakery staff, doing tests in the bakery and following data sensors from the line.

First, production line and its bakers are observed; where do the bakers walk, what indicators do the bakers follow up, how do the bakers act if something happens and what are their basic work tasks. The bakers will be interviewed at the same time in order to gain knowledge on their work. It is also interesting what do the bakers think about their job on that line and is there something they would like to change. Findings of this project step are gathered in the chapters 3.1 and 3.3.

After gaining the basic knowledge it is investigated what kind of data does the production line produce already, where that data is stored and how is it used currently. The bakers' experiments of the line are compared to the current measuring system; are all the key variables measured that the bakers need on their work or should some measure devices be added on the line to get as wide and deep picture of the process as possible. These findings are written in chapter 3.4.

After having a proper measurement system done, big data will be gathered from the production line. If needed, there will be performed experiments with dough in the bakery's own laboratory so that possible assumptions can be confirmed. Findings from big data are partly presented in 3.5 and they are also used when planning the fuzzy controller in chapter 3.6.

After proper analyzation a plan will be made in which part of the line this thesis needs to focus on more and build the fuzzy controller for it. This means exploiting machine learning on MATLAB and training a model with it. In addition, other parts of the line will be investigated more in order to plan development ideas for them. At the end there will be a fuzzy controller and plan for the rest of the line. The fuzzy controller is presented in chapter 3.6.

1.5. Research structure and boundaries

This paper consists of two parts, theory and practical case study. All important tools of fuzzy methods which are used in this thesis are presented in chapter 2. In chapter 3 first are introduced the bakery, then introduced the investigations and experiments and finally planning, building a controller and evaluating it. During the thesis several different tests are performed to gain information how does the dough behave in certain circumstances. Those results are used for finding the proper place for the controller. In chapter 4 the answers for research questions and limitations of this research are presented. Finally, chapter 5 is a summary of the whole project, results and plans in a nutshell.

2. THEORY: Fuzzy methods

”A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one.” wrote L. A. Zadeh in 1965 (p. 338) about fuzzy sets. It was an extension to the classical notion of sets, crisp sets (Chang *et al*. 2012, p. 1850).

According to fuzzy logic things are not about either true (1) or false (0) like in bivalent logic. In fuzzy logic it is something in between these two (0-1), most often from a unit interval [0,1], and the question is how much something belongs to a certain class. (Klir and Yuan 1995) In other words the concept is about partial truths and truth values between “completely true” and “completely false” (Tosun, Dincer and Baskaya 2011, p. 5554). Charles C. Ragin (2000, p. 88) says that this is the reason why fuzzy sets are so powerful; it allows researchers to act more freely when they do not have to decide whether something belongs fully to a class or not. With fuzzy sets they can calibrate between the unit interval [0,1] without abandoning basic theoretic principles like-sub-set relations. (Ragin 2000, p. 88)

2.1. Calculating membership degrees

There are different types of fuzzy membership functions. Fuzzy membership functions can be sinusoidals (wave shaped), L-shaped, R-shaped, triangulars, trapezoidals or bell-shaped (AlKheder and AlRukaibi 2020, p. 3). In figure 1 is presented three different fuzzy membership functions.

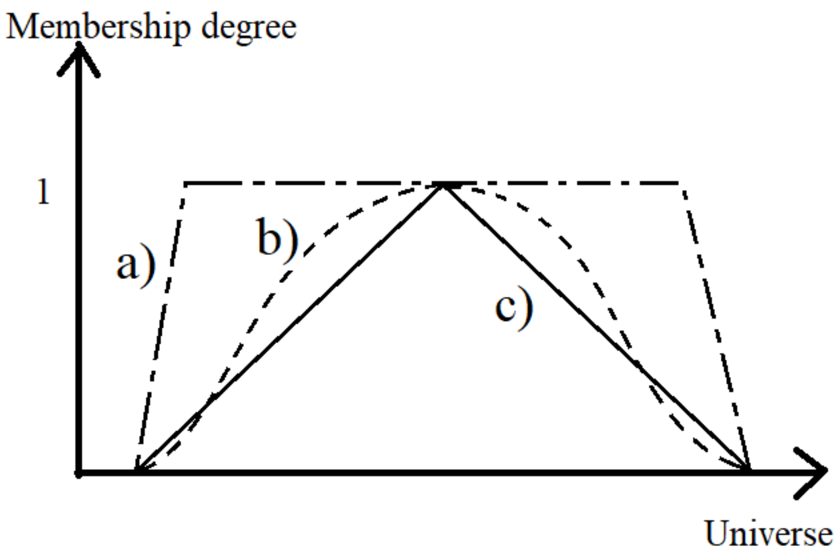

Figure 1. Different kinds of fuzzy membership functions. a) present trapedzoidal membership function, b) bell-shaped and c) triangular. Adaption of Kouatli's (2008, p. 173) figure.

Shape of the fuzzy membership function defines how the membership degree is calculated for an element. Alonso (2020) defines membership degree: "A membership function for a fuzzy set A on the universe of discourse x is defines as μ_A:X → [0,1], where each element of x is mapped to as value between 0 and 1. This value, called membership value or degree of membership quantifies the grade of membership of the element in x to the fuzzy set A." In this thesis trapedzoidal fuzzy membership functions are used in the controller because they present well wide temperature areas. Wide temperature areas are needed in the controller because they present the needed areas sufficiently. For trapezoidal fuzzy sets membership function is calculated according to equation (1) (Mattila 2002):

$$\Pi = (x;\ \alpha, \beta, \gamma, \delta) \ = \left\{ \begin{array}{c} 0 \ if \ x < \ \alpha \\ \frac{x-\alpha}{\beta-\alpha} if \ \alpha \ \leq x \leq \beta \\ 1 \ if \ \beta \ < x \leq \ \gamma \\ \frac{\delta-x}{\delta-\gamma} if \ \gamma \ < x \leq \delta \\ 0 \ if \ x > \ \delta \end{array} \right\} \qquad (1)$$

which are defined by lower limit α, upper limit δ, a lower support limit β and an upper support limit γ, and where $\alpha < \beta < \gamma < \delta$.

Calculations go mainly in the same way even the shape of the fuzzy set changes. The most important thing is to find suitable membership function to describe linguistic states properly. Different shapes of fuzzy sets can be even mixed if needed in a model.

2.2. Applying fuzzy set theory to real life

In the figure 2 is presented the difference between fuzzy and crisp sets. Fuzzy membership functions partly intersect each other but crisp sets have “sharp” edges. For example, temperatures are between T_1 and T_2 so that the whole temperature range is split into 5 pieces according to linguistic terms. When saying any temperature value between those T_1 and T_2 that value can be set clearly only one of the crisp sets from ‘very low’ to ‘very high’. Putting that same value on figure 2’s a) it is not obvious whether that value belongs to one group fully or two groups at the same time. For instance, temperature can be partly ‘medium’ and partly ‘low’ at the same time. These fuzzy sets enable more realistic modeling of actual situation.

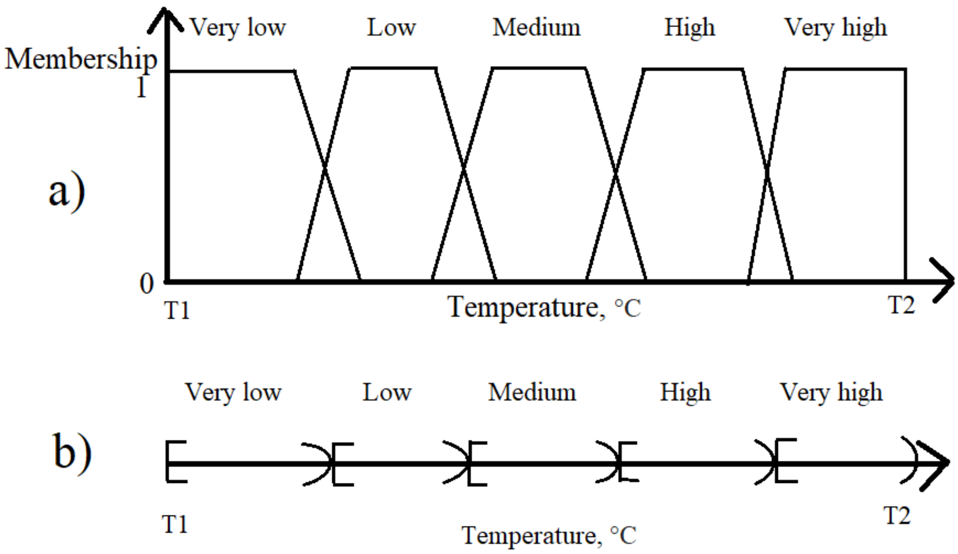

Figure 2. Adaption of Klir and Yuan's (1995) picture present how fuzzy sets differ from crisp sets. Different linguistic states for temperature are modeled with a) fuzzy sets and b) traditional crisp sets.

Linguistic concepts like warm, hot, small, light and tall are often represented by fuzzy sets (Trillas *et al.* 2012, p. 105). With fuzzy sets there is no need to decide whether a room is very warm or very cold. Fuzzy sets allow modeling the situation in which the temperature can be between these two states. For example, "room temperature belongs to the class very warm with membership degree of 0.70".

Linguistic concepts related to a temperature are presented in figure 3. Temperature has some limits, minimum is T_1 and maximum T_2. For example, when considering about the room temperature T_1 could be 0 °C and T_2 could be 50 °C like in the figure 3. Sets are equally spaced in this example but they could have unequal spacing, for instance the group medium could be much wider compared to others.

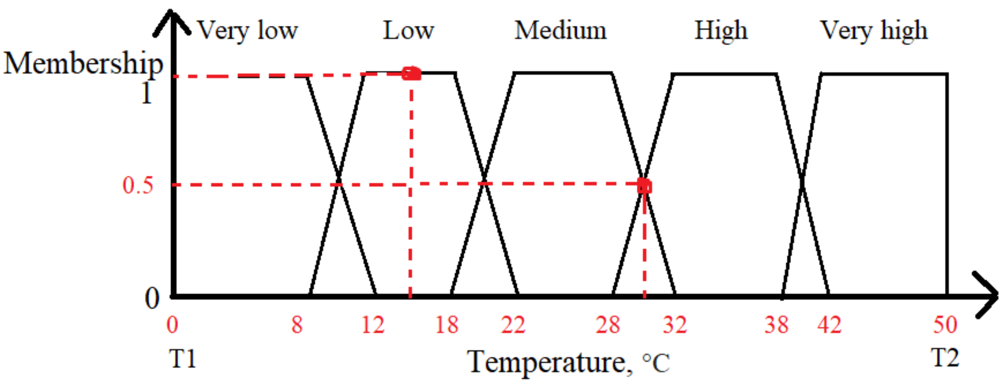

Figure 3. An example of temperature variation with five linguistic states. Temperature varies between 0 °C and 50 °C.

In figure 3 are presented couple of examples with red. If temperature is 15 °C it would get full membership degree (1) to the class "Low" and then it does not belong to any other classes. If the room temperature is 30 °C it belongs partly (with 0.5 membership degree) to the class "Medium" and with same membership degree to the class "High". This same kind of classification of variables could be done according to other linguistic states also like height, weight, humidity, age etc.

Rules can be created related to the built fuzzy sets, for instance: "If room temperature is LOW then turn heater on" (Trillas *et al*. 2012, p. 105), or "If room temperature is HIGH then use cold water in baking". These rules are the basis for example a controller which can steer settings correctly for some purpose (Trillas *et al*. 2012, p. 105), for instance production settings so that the result is optimal.

2.3. The basic connectives

The basic connectives of fuzzy logic are union, inclusion, intersection and complementation. Bede (2013, p. 6) presents that when Zadeh at first introduced these connectives, intersection and union were based on the max and min operations. These connectives were generalized in detail later on. By exploiting the features of fuzzy sets different and powerful methods are created. Assume F(X) denoting the collection of fuzzy sets on a universe of discourse X. Assume also that A and B are set of elements which construct the fuzzy sets and A, B ∈ F(X).

Union

Union of A and B (denoted as A ∪ B) means the fuzzy set containing the elements of A or B or both (Belohávek and Vychodil 2005, p. 1). Bede (2013, p. 6) present the fuzzy set C to be union of A and B:

$$C(x) = (A \cup B)(x) = \max\{A(x), B(x)\}, \forall x \in X \tag{2}$$

Inclusion

If every element of A belongs to B, A is said to be a subset of B and denoted as $A \subseteq B$. (Belohávek and Vychodil 2005, p. 1). Bede (2013, p. 6) present the fuzzy membership degree A being included in B if

$$A(x) \subseteq B(x), \forall x \in X \tag{3}$$

Intersection

Intersection of A and B (denoted as A ∩ B) means the set containing elements from both A and B (Belohávek and Vychodil 2005, p. 1). Bede (2013, p. 6) present the fuzzy set C to be the intersection of A and B:

$$C(x) = (A \cap B)(x) = \min\{A(x), B(x)\}, \forall x \in X \tag{4}$$

Complementation

Bede (2013, p. 6) present the complement of A accordingly:

$$\bar{A}(x) = 1 - A(x), \forall x \in X \tag{5}$$

Implication

Implication method define how consequent fuzzy set is calculated. Consequent fuzzy set refers to the conclusion which is got from a known fact. In Mamdani's fuzzy inference system the minimum is used. In Larsen's method fuzzy implication is modeled with product operation instead of using minimum. (Luukka 2019c) For composition is used the max-product operator (Anon 2010). According to Luukka (2019c) the change is small in practice but may simplify fuzzy inference model a lot.

Luukka (2019c) presents an example how an individual output of *k*th rule can be calculated using Larsen's implication:

$B^k(x) = \alpha_k \cdot B^k(x)$, *where* α_k *is the firing level for kth rule* (6)

2.4. Mamdani's Fuzzy Inference System

Hamam and Georganas (2008, p. 4) present some advantages of Mamdani Fuzzy Inference System (FIS) compared to the Takagi-Sugeno FIS. Mamdani FIS is described with words: ”expressive power, easy formalization and interpretability, reasonable results and relatively simple structure, intuitive nature of rule base, for multiple-input-single-output and multiple-input-multiple-output system, and the output can be either fuzzy or crisp.” (Hamam and Georganas 2008, p. 4)

Luukka (2019a) presents an example: Consider two inputs, x_1 and x_2 (antecedents) and a single output y (consequent) with collection of r linguistic IF-THEN proportions, this is an example of simple fuzzy system. The rules are presented in the form:

IF x_1 *is* A^k_1 *and* x_2 *is* A^k_2 *THEN* y *is* B^k *for* $k=1,2,\ldots, r$. (7)

In this A^k_1 and A^k_2 are the fuzzy sets of *k*th antecedent pairs and B^k is the fuzzy set of *k*th consequent. The firing level for the *k*th rule can be calculated using *min* to model "and" connective in premise for the crisp inputs x_{10} and x_{20}:

$\alpha_k = \min\{A^k_1(x_{10}), A^k_2(x_{20})\}$. (8)

The output of *k*th rule can be calculated $B^{pk}(y) = \min(\alpha_k, B^k(y))$. (9)

These individual rule outputs B^{pk}, can be aggregated into single overall system output by using disjunctive system of rules:

$B(y) = \max\{B^{p1}(y), B^{p2}(y), \ldots, B^{pr}(y)\}$ (10)

Defuzzification is needed in order to get a single crisp output. This can be done for example using Center of Gravity (COG):

$$y_0 = \frac{\int_Y yB(y)dy}{\int_Y B(y)dy} \tag{11}$$

(Luukka 2019c)

2.5. Takagi-Sugeno Fuzzy Inference System

Sometimes Takagi-Sugeno FIS can be called Sugeno FIS only or Takagi-Sugeno-Kang FIS. Takagi and Sugeno created their first FIS and presented in 1985 (Takagi and Sugeno 1985, p. 116) and Sugeno presented one kind of model with Kang in 1988 (Sugeno and Kang 1988).

Takagi-Sugeno fuzzy models are described by using if-then rules like Mamdani model (Jassbi *et al.* 2007, p. 1). According to Benzaouja and El Hajjaji (2012, p. 2) these rules represent a nonlinear system's local input and output relations. Takagi-Sugeno fuzzy model is proven to be a universal approximator of nonlinear dynamic systems. Its main characteristic is that the model takes into account "the partition of nonlinear systems by a set of linear models so that the overall nonlinear behaviour of the system can be obtained by the fuzzy blending of the set of subsystems." (Benzaouja and El Hajjaji 2014, p. 2)

Hamam and Georganas mention in their article the advantages of Takagi-Sugeno FIS to be compared to Mamdani FIS: "Possibility to use algorithms that automatically optimizes the Takagi-Sugeno FIS (e.g. in ANFIS in MATLAB), better processing time because of weighted averages replaces time-consuming defuzzification, computationally efficient and accurate, more robust with noisy input data like sensor data, flexible and adequate for functional analysis because of continuous structure of output function." (Hamam and Georganas 2008, p. 4) These same kind of characteristics are also introduced by Jassbi *et al*. (2007, p. 2)

In Luukka's course material (2019b) are presented some basics how calculations related to Takagi-Sugeno inference system can be performed. Consider two input single output first order Takagi-Sugeno model. First order refers that the output function $f(x,y)$ is a linear function of x and y. If the model were zero order model, it would mean that $f(x,y)$ is constant. Now, the inputs are x_1 and x_2 (antecedents) and output z (consequent). A fuzzy system is described with a collection of r linguistic if-then rules accordingly:

$$IF\ x\ is\ \mathrm{A}^k\ and\ y\ is\ \mathrm{B}^k\ THEN\ z^k = f_k(x,y)\ for\ k = 1,2,\ldots,r \tag{12}$$

In the equation (12) A^k and B^k are fuzzy sets representing the *k*th antecedent pairs and z^k the *k*th consequent. Firing level for the *k*th rule can be calculated for the crisp inputs x_0 and y_0 and using *min* for modelling "and" connective in premise:

$$\alpha_k = min(\mathrm{A}^k(\mathrm{x}_0),\mathrm{B}^k(\mathrm{y}_0)) \tag{13}$$

The output is crisp, given by the function $z = f(x,y)$. Each of the rule provides their own outputs, which is for the *k*th rule output:

$$z_k = p_k x_0 + q_k y_0 + c_k,\ where\ p_k,\ q_k\ and\ c_k\ are\ constants \tag{14}$$

In order to get single output from all the rule outputs, weighted average can be used as defuzzification method:

$$z = \frac{\alpha_1 z_1 + \alpha_2 z_2 + \dots + \alpha_r z_r}{\alpha_1 + \alpha_2 + \dots + \alpha_r} \tag{15}$$

(Luukka 2019b)

2.6. Adaptive neuro-fuzzy inference system (ANFIS)

According to Karaboga and Kaya (2019, p. 2264) along with fuzzy logic, another significant artificial intelligent technique is artificial neural network (ANN). It consists of artificial neurons, imitating human brain. It learns with samples; modelling a system starts with training a model with train data. Test data is used for supervising the success of the model. The ANN model can be considered to be good if the model has low error rate in test data. Error is calculated from the difference between the real output and the predicted output. Still, the disadvantage of the technique is inability to explain the value of the weights belonging to ANN model. (Karaboga and Kaya 2019, p. 2264)

Combinations of fuzzy logic and ANN are called neuro-fuzzy systems. Several of neuro-fuzzy systems for different purposes are published according to Vieira *et al.* (2004). Jang presented Adaptive Neuro-Fuzzy Inference System (ANFIS) in 1993 (Jang 1993) which is one of the most popular neuro-fuzzy systems nowadays (Karaboga and Kaya 2019, pp. 2264-2265). ANFIS combines ability to learn and relational structure from ANN to decision-making mechanism of fuzzy logic. This combination eliminates for example the problem of inability to explain the obtained weight values in ANN models. (Karaboga and Kaya 2019, p. 2264)

In figure 4 the structure of one type of ANFIS is presented. Jang presents (1993, pp. 665-666) that premise and consequence are the two parts which forms the network structure of ANFIS. Premise parameters are used in layer 1 and consequence parameters in layer 4. Training the model means determining proper parameters to these two parts utilizing the optimization algorithm. Karaboga and Kaya (2019, pp. 2267-2268) present several different training algorithms for the premise part. In 1993 Jang used a derivative based hybrid learning algorithm as training algorithm and determined consequence parameters with least squares error. That is why hybrid learning is the most used method for training the ANFIS (Karaboga and Kaya (2019, p. 2267).

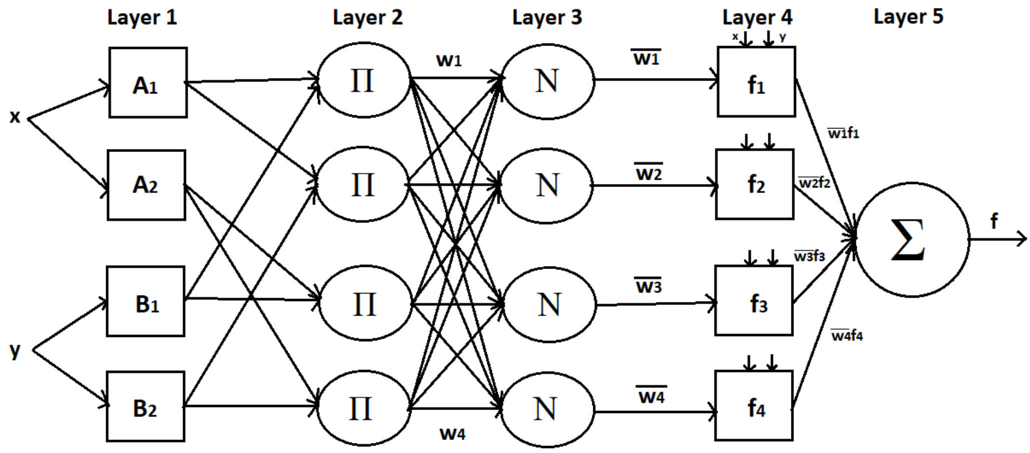

Figure 4. Structure of type 3 ANFIS. Model contains two inputs and one output. Caption of Karaboga and Kaya's figure (2019, p. 2266).

Fuzzy inference systems perform so called fuzzy reasoning which starts in premise part (Jang 1993, pp. 665-666). Jang (1993, p. 668) mentions that there are several different types of fuzzy reasoning proposed in the literature. However, Jang suggests that most of the fuzzy inference systems can be classified into three types depending on how they perform fuzzy reasoning. Type affects on consequent part of the fuzzy reasoning. Type 1 forms the overall output as weighted average of each rule's crisp output, type 2 derives the overall fuzzy output by applying max operation to the qualified fuzzy outputs and type 3 uses Takagi-Sugeno's fuzzy if-then rules. In that type each rule gives an output which is a linear combination of input variables and a constant term. (Jang 1993, p. 668) Ahmadi-Nedushan (2012, p. 668) states that fuzzy inference systems can be divided into two groups, Mamdani and Takagi-Sugeno. In these two models, consequents are different and then procedures of aggregation and defuzzification differ accordingly. The layers for type 3 ANFIS are explained next:

Layer 1

This layer is called fuzzification layer. In premise part input variables are compared to the membership functions in order to get membership values of each linguistic model. (Jang 1993, pp. 665-666) Parameters in this layer are called premise parameters (Jang 1993, p. 673). Membership degree can be calculated as presented in chapter 2.2. Other shapes like bells and triangular-shaped membership functions could be also used (Jang 1993, p. 673).

In other words, the output of this layer is the membership value O_i^1 of fuzzy set A_i (cold, medium, hot etc.). “It specifies the degree to which the given x satisfies the quantifier A_i”. (Jang 1993, p. 673) Jang (1993, p. 673) uses equation:

$$O_i^1 = \mu_{Ai}(x) \quad (16)$$

Layer 2

This layer is called rule layer (Karaboga and Kaya 2019, p. 2266). In the layer membership values of the premise part need to be combined together using some specific T-norm operator (usually min or multiplication). The output of each node represents the rule’s firing strength. (Jang 1993, pp. 665-666, 674) Jang (1993, p. 673) presents multiplication in the following way:

$$w_i = \mu_{A_i}(x) \times \mu_{B_1}(y), i = 1,2 \quad (17)$$

In practice multiplication is basically same as modeling connective AND using *min* (intersection).

Layer 3

This layer is called normalization layer. Normalized firing strengths are calculated to each rule. The normalized value is obtained by using the ratio of the ith rule's firing strength to the total of all firing strengths. (Karaboga and Kaya 2019, pp. 2266-2267) Jang (1993, p. 674) present the equation (18) for calculating the normalized value:

$$output3_1 = \bar{w}_i = \frac{w_i}{w_1+w_2+w_3+w_4} \quad i \in \{1,2,3,4\} \tag{18}$$

Layer 4

This layer is called defuzzification layer (Karaboga and Kaya 2019, p. 2267) According to Jang (1993, p. 675) in each node of this layer are calculated weighted values accordingly:

$$output4_i = \bar{w}_i f_i = \bar{w}_i\,(p_i x + q_i y + r_i) \tag{19}$$

$\bar{w}_i$ used in this layer is the output of the normalization layer. $\{p_i, q_i, r_i\}$ are referred as the consequence parameters. Each rule has one more consequence parameter than it has inputs. (Jang 1993, p. 675) Basically, Larsen's implication is used for connecting premise and consequence parts.

Layer 5

This layer is called summation layer. By summing all the outputs obtained for each rule in defuzzification layer provides the actual output of ANFIS. (Karaboga and Kaya 2019, p. 2267) They also present the equation (20) how the result is calculated. It is weighted average of the outputs.

$$output5_i = overall\,output = \Sigma\bar{w}_i f_i = \frac{\Sigma_i w_i f_i}{\Sigma_i w_i} \tag{20}$$

3. CASE BAKERY

This thesis focuses on automating a part of bread production line in a bakery. The part is not decided beforehand so it must be investigated in which part of the line this thesis should concentrate on.

3.1. Introducing the company and bread line

Fuzzy logic theories are used in the bakery in order to improve their current processes. The case bakery is one of the leading companies in Finland when it comes to bread and bun making. In this thesis one production line of the bakery is considered. The volumes of the production line are impressive. The bakery concerns this project in the line as a pilot project for their further investigations and development projects.

The baking process itself is similar to one when baking at home but these steps are performed in practice differently; in baking industry automated baking line does the biggest work. Baking process steps both in bakery and at home are: ingredients are added and mixed, dough rests for a while before shaping to bread, dough rests again, is baked in the oven and then cooled down before packing. Those process steps are presented into table 1 and figure 5.

Table 1. Process steps and their descriptions.

STEP NUMBER	NAME OF THE PROCESS STEP	DESCRIPTION
1	Dough mixing	Ingredients are added and mixed.
2	Dough rest	Mixed dough rests for a while on conveyors.
3	Dough dosing to the line	Dough is dosed to the line as a flat dough mat.
4	Shaping the bread	Flat dough mat is cut into bread pieces.
5	Proofing in the prover	Dough rests again but as a shaped bread piece this time. Temperature and humidity are controlled in the prover.
5	Bake in the oven	Bread pieces are baked in the oven after the proofing.
6	Cooling down the bread	Bread pieces need be cooled down in order to avoid sticking the saw and forming condensation water in the bags.
7	Packing to the bags	Bread pieces which meet strict quality requirements are packed to the bags.
8	Packing bags for transportation	Bags are packed into big transportation boxes that protect bread bags during the transportation.

Process steps presented in the table are put into figure 5 which shows the ordering of the process steps again and imitates what kind of product flow is on the line. In 2. dough rest is only dough, after 3. dough dosing and 4. shaping raw bread pieces go to the 5. prover. After the prover the bread pieces are still raw (in figure 5 slices are still light colored) but after 6. bake in the oven the bread pieces are ready, notice the color change in the figure 5. Those ready breads are moved to the 7. Cooler and then to packing.

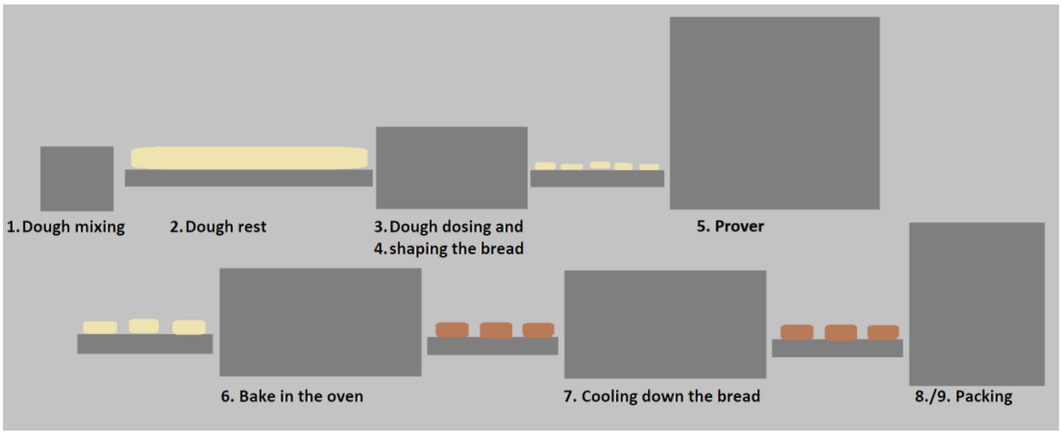

Figure 5. Simplified picture of automated baking process.

The process is highly automated. This process runs continuously and there is dough or bread at each of these process steps all the time. This is possible with several different kinds of conveyors, photocells (optical sensors) and good software. Dough or bread is followed via photocells when conveyor moves the dough or bread onwards on the line. Software is for bakers to supervise the line and to make proper adjustments to the process parameters.

Even though the process is highly automated it still needs manual work and constant observation. Bakers' duty is to ensure that dough and bread fulfil certain requirements in each process step like dough must be certain temperature and bread piece needs to have correct weight. Finding a balance for raw bread piece weight is important because raw weight needs to be high enough (bakery cannot sell underweighted packages) but not over-weighted (this is waste cost for the bakery). A baker must follow these certain measures and act according to them. The baker also ensures line to work properly. For instance, sometimes dough or flour dust may block the view of photocell which causes a pause in the production until the photocell is cleaned. In addition, there may be several other interference situations, such as dough gets stuck to the machines, raw materials do not come to the dough mixing or the oven breaks down. These kinds of situations need fast acting and many times assistance from other production lines.

3.2. Research approach and gaining the material

The target is to find ways to automate the process more. It would reduce human labour and error and at the same time improve product quality and process flow. Then a baker does not need to think the condition of dough or bread and adjust process parameters because the machine does it itself instead. This allows continuous and exact action always during the baking process. When baking process parameters are always set correctly by the machine, quality of end product can be expected to improve. In addition, when dough acts in the line as expected it helps production process to flow better without interruptions.

This project starts first by interviewing bakers about what kind of process baking is and how the bread line works. After understanding the basics of the process, the target is to find critical points and variables related to them. Those points are places where a baker checks the quality of bread dough and reacts according to it. By using the information gained from the interviews, proper measurement system can be planned to the production line. The measurement system should supervise certain variables and their changes.

The system collects automatically enormous amounts of data on almost everything in the process. During this project it is also investigated whether current measurements are enough or should there be couple of measurements more. Currently all that process related data is for the bakers to follow if they need it for example to investigate a problem in production line. It is needed to investigate if the current measuring system is enough or should there be more measuring devices on the production line. Current measuring system is validated according to the interviews of the bakers.

Proper measuring system makes it possible to investigate if there are some hidden patterns or causal relationships between variables. There are no proper studies done in the bakery on which variables causes what on the production. That is why one of the targets of the thesis is to find these causal relationships between variables and exploit the knowledge from them. The second target is to build a fuzzy controller to the production. Its purpose is to steer certain point of the process independently so that a baker does not need to calculate optimal process parameters. Still, it must be investigated first which part of the line the fuzzy controller is needed most.

3.3. Wisdom of interviews

When interviewing the bakers three major problems came up related to the baking process:

1) **Living raw materials**. Raw materials are living and never exactly the same which causes the dough to act differently and makes it difficult to standardize the end product. These small differences are difficult or impossible to detect from the dough in the beginning. In other words, for example yeast has each time different “activity level” and it may change during storage. That is why each day when bread is made the amount of yeast (which is set to the system) used in the baking process affects slightly differently: one day the bread may rise a bit more than in another day.

2) **Complex structure**. Many variables affect on many things at the same time and it is difficult to find the actual causal relationships on changes. That is why it is almost impossible to track down which one of the variables caused the bread to rise poorly in the prover for instance. It could be bad yeast, too

sore sourdough, too warm room temperature combined to too warm dough, too cold machines (problem especially in the production starts) or bad settings in the prover.

3) **Long time before changes are visible**. If something happens right at the beginning of the line, it is visible later on the dough or even as late as in the end product. If some process parameters are then changed because of end product is not good enough it takes a couple of hours before the changes are visible in the end product again. For example, if bread rises badly on the oven the problem is on the bread rise earlier on the line. This can be fixed by adding more temperature on the prover or checking the yeast levels from the very beginning. This means at least 1 hour production to be waste or in the worst case 2 hours of waste production before the parameter changes are visible on the end product. Because it takes such a long time before changes are seen on the end product, there may be instances when a baker adjusts the parameters again before the first changes are even seen. This makes it impossible to track down the causal relationships again when nobody knows how the first change affected and where on the production line comes the bread with new parameter changes.

3.3.1. Initial causal relationships

Interviews give basic knowledge how relationships are assumed to be and how do bakers react on certain occasions on the line. There seems to be mainly four places on the line in which the bakers follow the dough or bread quality and change process parameters according to them. These places are marked in the process figure 6 accordingly A) Dough mixing, B) After pressing the shape, C) After the prover and D) After the oven. In this thesis these four stages are called as critical points because decisions made in those places have a great impact on the end result, in other words they are important places to supervise the process flow.

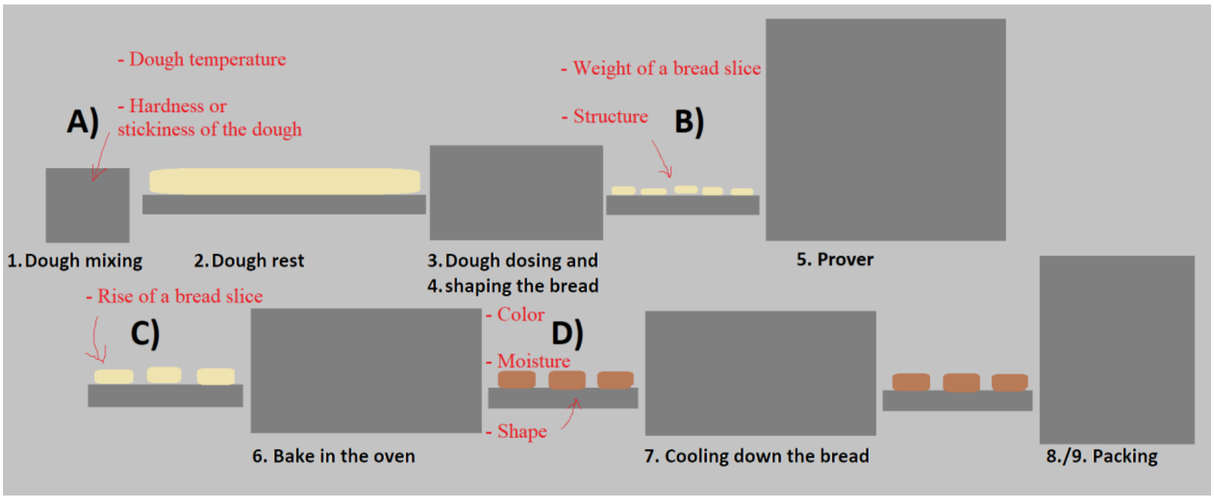

Figure 6. Process with four critical points A, B, C and D. Variables that the bakers follow during the process are written in red and pointed with arrows in which place they exactly appear.

In those four places which are presented in figure 6 may be several different variables to be followed. These variables, how they are measured or observed and which variables have an effect on them are listed in the table 2. The list is gathered from the interviews so it is good to remember that there may be some other factors that affect on certain variables than only these listed ones.

Table 2. Critical points are listed and explained which variables are followed in them currently, how they are followed and which may affect on them.

LOCATION	VARIABLE	MEASURING SYSTEM	WHAT AFFECTS ON IT?
A) Dough mixing	Dough temperature	Continuously and automatically on the line	Room temperature, raw material temperature
	Room temperature	No measurement	Time of the year and week
	Dough hardness or stickiness	Comparing dough movement to the stick	Ash content, falling number, gluten quality, amount of water and flour
B) After pressing the shape	Weight	Manually carrying a sample to the scales	Proofing during the rest, dough dosing on the line
	Structure	Manually carrying a sample to the measurement plate	Relationship of water and dough, proofing on the line
C) After the prover	Rise	Visual inspection	Temperature and moisture in the cabin, rise on the line earlier, yeast quality, dough structure
D) After the oven	Color	Visual inspection	Oven temperatures

The table 2 confirms the complex structure of baking process. Many of the variables can cause same kind of problems on the end product and it is difficult to track down which variable caused what on the end product. Still those are only the variables that a baker can follow currently on the line. There are several other known and unknown factors during the whole production process that affect on the end product.

3.3.2. Critical points and variables

The line is highly automated but there are some points where a baker is still needed almost continuously. According to interviews and supervising the line, it seems that there are four critical points on the line. Of course, the baker needs to supervise the process in whole: their duty is to ensure everything goes well through the line. These four critical points are places where bakers need regularly and repeatedly to concentrate more and change the process parameters according to dough or bread. Location and variables followed were presented in the figure 6. According to critical points and the variables presented in figure 6 the bakers steer the baking process by changing parameters on the line. Temperature, weight and structure are measured using measurement devices, but all the other measures are done by rule of thumb without more precise measures, mainly only qualitatively by looking. Each of these variables are explained thoroughly next.

Temperature of the dough is critical in the process. It has strict limits in which it must be and there is continuous measuring system in the line. Deviations have straight impacts on the rise of the bread. If dough is too cold, the yeast cannot work properly because of two reasons: it does not work in cold circumstances and the dough is also too hard for yeast to rise. If dough is too warm the yeast works too actively during the first rest and does not have "power" to rise the bread more later on during the second rest. Then the bread does not fulfil its quality limits. In addition, if dough is too hot, it kills the yeast and bread does not rise at all. Deviations are caused by raw material temperature deviations and room temperature changes.

Correct **hardness** of the bread dough is important for smooth process flow and good end result. Too hard dough does not rise properly and bread is tough and flat. In addition, it causes problems in shape hitting when the machine has problems to hit hard enough in order to get bread shape hit to the dough mat and vice versa: if the dough is too soft it gets stuck on the machines. The bakers follow the hardness of the dough using a horizontal stick. The stick is a manual mark on the line for a baker: if dough is too soft, it is in a different place compared to the stick versus if the dough is too hard. In figure 7 is presented how the dough may act compared to the stick if it is too soft or too hard.

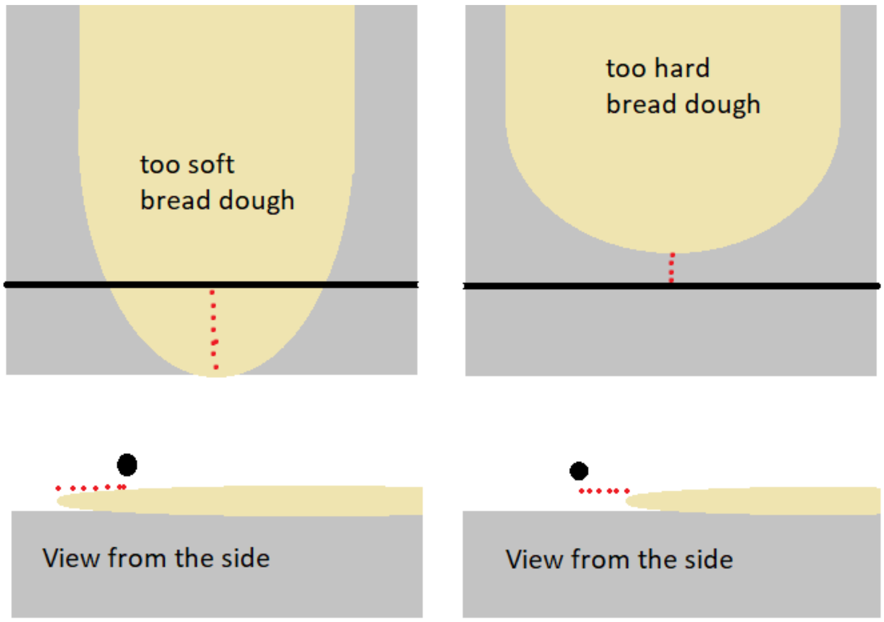

Figure 7. The view of too soft and too hard doughs on the line compared to the stick. The first pictures are from above the line, the latter ones are views from the side of the line.

In the figure 7 is presented how the dough can act compared to the stabile stick. Too soft dough flows too far away from the stick. If the dough is too hard it does not spread on the line at all. If the dough is optimal it is placed right under the horizontal stick. The bakers follow this stick by eye occasionally.

Weight is important for two reasons: it is regulated by law that it needs to be followed and documented the result. Another reason is that it is question of money for the company. The bread cannot be too light because the bakery cannot sell under-weighted products. On the other hand, if the bread is over-weighed it costs huge amount of money yearly because it is waste to produce more than enough for each of the bags. At the moment weight is measured regularly by taking a sample by hand from the line and carrying it to the scales.

Structure means testing how soft or hard the current bread dough is. In practice, it is performed regularly by taking couple of raw bread pieces from the line and pressing them with certain measuring device. Now, structure measuring is used only for testing whether it could replace measuring FE from the beginning of the production line. Bakers are advised that if the bread pieces do not meet the quality limits, they need to follow the situation and do the test again after a while. Dough quality varies continuously so that after five minutes the results may be back to normal. That is the reason why the bakers should not change the dough mixing parameters immediately even when the results exceeds the limits.

Rise in the prover is followed by viewing the bread by eye before it goes to the oven. If bread does not rise enough, there may be several different reasons from earlier stages: weakly active yeast, too warm or too cold dough or the settings in the prover to be inappropriate. Sometimes bread can rise too much. Both these conditions cause bread pieces to have wrong shape after the oven. The fastest way to try to fix the rises is to set the prover settings. If adjusting the parameters of the prover does not help fixing the problems on dough rise, changes can be done to the raw material dosing in the dough mixing. Because the line is long, bread rests for a while first on a conveyor (during process step 2. dough rest) and then in prover, it takes about 1.5 hours before any changes are seen on the dough quality.

Color, moisture and shape of a bread piece tell a lot what has happened during the production. Color reveals most about how the baking in the oven has succeeded and if malt extract is dosed properly, moisture about baking in the oven and success of dough making and shape about dough’s rise in different locations. For example, if the baked bread has risen in the oven too much there might have been problem in the rise during the first or second rest.

There are still variables that have straight impact on bread dough quality and the end product, but they are not followed during the baking process. These variables are assumed to be between certain quality limits and then their effects to be handled during the baking process. Following those variables on the production line continuously is very difficult or even impossible. On the list below are presented six additional variables which have a big effect on the dough and bread. However, there still may be several other variables more which have an effect on dough quality too but are not found yet.

1. Flour properties
2. Room temperature and humidity
3. Temperature and humidity of the prover
4. Yeast quality
5. Sourdough properties
6. Gluten quality

First, **flour properties**, is crucial because it affects on how the dough behaves during the rest of the line. For instance, sometimes flour has lower ash content and/or falling number which means that the dough does not absorb water normally. Then the dough is stickier than usually and causes problems later on the line. Low falling number also causes the bake in the oven to fail when the bread does not solidify properly (Salovaara *et al.* 2017, p. 59; Salovaara 2008, pp. 36-38). On the contrary if flour absorbs water more than usually the dough is too hard and there will be different kinds of problems on the line. Too soft dough gets stuck on the machinery while too hard dough is difficult to shape to bread and it does not rise normally. Flour properties are very difficult to track because they need laboratory tests. Bakers have to trust that the flour properties are between certain limits.

Room temperature and humidity can be measured but they cannot be managed well enough in the big bakery hall. Especially the room temperature is the problem because it varies over 10 °C during a week. The temperature varies through the year even more because of hot summers and cold winters. The problem is that if the room is too warm the bread rises too much during the first rest. This affects on the rise later on the line and then to the shape of the bread. The baker needs to pay attention to room temperature every day when selecting water temperature to the dough. That temperature affects straight to the temperature of the dough. If the room is very hot the dough needs to be cooler and vice versa if the room is very cold.

Temperature and humidity of the prover can be followed and changed more easily and more accurately than the temperature of the room. However, more thorough measurements in the prover reveals that the circumstances in there are not homogenous. Temperature rises a lot when going only a couple of meters upwards in the prover. And because the temperature rises then humidity drops down there. The second proofing in the prover is important for the bread so that it would achieve correct shape and structure in the oven.

Yeast quality is like flour properties: the quality and activity of it varies between each of the batches and even during the same batch. That is why it does not help to steer the production according to yeast activity test results that yeast provider delivers with the batch. If there are problems in the rise the amount of yeast can be slightly changed but it needs to be first confirmed that there are not problems for instance in the dough temperatures because they affect also on the rise. The activity of the yeast cannot be followed during the process because it needs laboratory tests. That is why the bakers need to follow how the dough behaves. Unfortunately, problems in yeast are many times seen as late as just before or after the oven.

Sourdough is done using the end of last sourdough, yeast, flour and water. It has two kinds of fermentation reaction: lactic acid fermentation and alcohol fermentation. Lactic acids reduce the pH of the sourdough. This is important for bread to give it taste and microbiological shield against mold. (Salovaara *et al*. 2017, p. 120) sourdough is done in big containers and it lasts for about four hours before new sourdough container is taken to the use. Each of these containers have slightly different sourdough mixture and these changes are seen on the end product. For example, if the sourdough is too sour it disturbs or even kills the yeast and then the bread does not rise normally. There are no possibilities to follow the sourness of the sourdough on-line from the line at the moment. In addition, mixing ratio of flour and water varies during one container even though there is mixing in the sourdough container. In other words, in the beginning of the container the sourdough taken from it may be thicker or diluter than the end of the sourdough from the same container.

Gluten is added to bread in order to improve end product's quality properties. Gluten quality varies between batches and it needs laboratory tests in order to solve the properties. Gluten has huge impact on dough's water absorption. This can be seen as too wet or dry dough even though recipe is same. That is the reason why it needs to be followed visually during the dough mixing how does the dough look like. On the other hand, there are other factors too which affect on water absorption of the dough, for example flour properties.

3.4. Measurement system in the line

During the long production process there are several factors that affect on the end product. It is said that almost 90 - 95% of the end result, bread, is done in the beginning, more precisely at dough mixing. That is why it is important to focus on the very beginning of baking process in order to create as homogenous dough as possible because the biggest changes to the dough are done there. When the changes are made in the beginning of baking process, it is easier try to define adjustments on the dough quality during the rest line than try to fix the totally bad dough properties on the production line when big changes are impossible. If something happens on the dough mixing it may not be even fixed anymore during the rest of the process. That is why this thesis focuses investigating more the dough mixing and also the fuzzy controller is done for that part.

In the production line there are couple of measuring devices for bakers to follow. In order to investigate more dough mixing and its variables, following measures from the system should be exploited:

1. water temperature
2. dough temperature
3. sourdough temperature

Based on the critical points found in interviews couple of measuring devices are added to the production line. These devices are used to measure the following variables:

4. hardness (distance from a laser, see figure 8)
5. flour temperature
6. room temperature
7. moisture of dough

Data is collected from these seven sensors once in every minute for data mining. These points are chosen so that the process could steer itself automatically with the values got from these measurement points. Before that it is necessary to find the relationships between parameters, values and the result.

These variables can help to handle the problem of dough making: two key changes in the dough are temperature and hardness. In order to build a fuzzy controller for dough making it is investigated what causes changes in dough temperature and hardness.

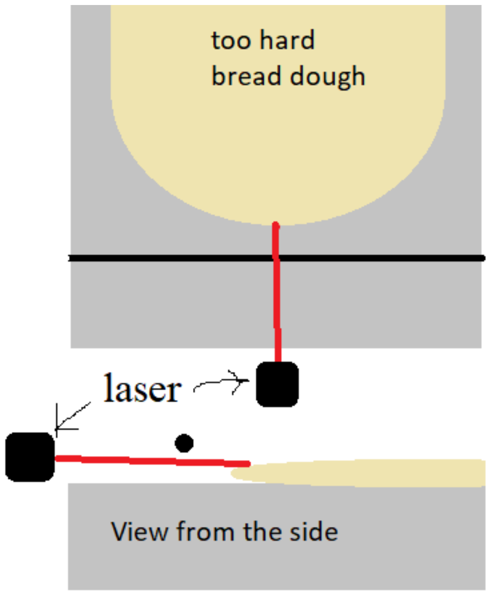

Figure 8. Place of the laser.

Three key ingredients of the dough are water, flour and sourdough. Data collected from the measurement system can be used for investigating how much key ingredients' temperatures vary and cause changes to the dough temperature. In addition, it must be ensured that currently used horizontal stick to measure hardness is working. It is done by using optical sensor to get movement of the dough in millimetres. In figure 8 it is presented how the optical sensor, laser, is placed on the production line. This way it measures the movement of dough accurately.

Distance value got from the laser is compared to value of FE. FE means farinograph, it is a measure for dough properties (BakerPedia 2020). It basically tells about dough's viscosity (Salovaara *et al.* 2017, pp. 56-57). Each dough(/bread quality) has its own limits for FE in which it has to be. FE is "official" measure for hardness of the dough. FE limits are set by recipe designers and they are followed regularly by laboratory tests.

3.5. Finding essential variables for the controller

At the moment biggest problems that cause waste on the line are related to the dough quality. Everything that happens right in the beginning of the line are visible later in the process. In the beginning the dough may seem visually homogenous but it may act entirely differently causing the end product to be good or inappropriate.

The question is, are there some small changes on the baking which cause dough act differently later on the line and how these small details can be handled.

This thesis concentrates on the dough mixing. The goal is to homogenate the dough temperature and hardness. At the moment bakers follow two measures of dough, 1) temperature and 2) hardness with distance compared to the horizontal stick. To optimize the dough mixing there are two kinds of fuzzy controllers needed, one for temperature and one for hardness. There are several variables which affect on them. Part of these variables were followed by using the measurement system built in chapter 3.4. The data from the measurements was used to analyze which of the variables followed could be used for fuzzy dough temperature controller or fuzzy dough hardness controller. The variables are presented next and evaluated whether they can be used in fuzzy controllers for temperature or hardness.

3.5.1. Water temperature

Water temperature is essential for the dough. Almost one third of the ingredients added to the dough in mixing is water. Water is the only way to control the temperature of the dough. Water temperature should be controlled with a controller in order to homogenize the dough temperature. Bakers need to pay attention especially when machinery is cold after a longer pause. Then they need to use warmer water than normally is used in the dough and on the contrary when it is a hot day colder water is used. It is a baker who needs to follow the temperature of the dough (and temperature of the room) and adjust water temperature according to it. Set values for water temperature varies between 29 °C to 35 °C. The baker does not know temperatures of raw materials and that is why she or he does not take them into account when setting the water temperature.

3.5.2. Dough temperature

Dough temperature is measured continuously from the line. It is important to keep it as precisely as possible on 31 °C (in practice between 30 °C and 32 °C) because otherwise the dough acts very differently later on the line. Too cold dough does not rise well or at all and too hot dough rises too much. In both cases the structure and shape of the end result are destroyed.

Proofing problems of the dough and bread are related in two ways to dough temperature. First is caused by yeast and the second hardness of the dough. Yeast activity depends on dough temperature: if dough is warm yeast works more actively than in cold dough. Hardness can be caused of several reasons like flour and gluten properties but also dough temperature affects on it. According to performed tests FE exceeded its limit almost immediately when the dough temperature was too low or too high. In addition, yeast and the hardness of the dough relate to each other: If dough is too hard the yeast cannot rise it because the yeast is not "powerful" enough to rise very hard dough.

Dough temperature can be affected by changing the temperature of water used in the dough. Problems come up when there is a pause (short or longer one) on the line because then raw materials and machinery get cold and they remain cold for a while after a new start. It is difficult to approximate the optimal temperature for water without knowing the exact temperatures of the raw materials and room temperature. Even then it is impossible for a baker to take into account everything and calculate which is the optimal water temperature in order to get dough with optimal temperature. This is done by trying some water temperature and following how does the dough temperature develop. If there is a long pause in production line the water needs to be much warmer than normally during the run because all the machines are cold and it takes a time before warm dough warms them up to normal temperature.

According to the results of data mining it seems that after each longer pause dough temperature is too low almost a whole day before it reaches the target level. When measuring this with manual thermometer from the same place it took only 6 minutes from the start the dough to reach correct temperature. This means that the current temperature sensor in the production line is placed so that it is disordered because of its place. It should be set to the better place so that it can react faster to the temperature changes. When ensuring proper function of the thermometer it eases bakers' work when they can rely on system. Proper function of thermometer ensures also unbiased data from the line and makes it possible to develop automatic controllers for dough temperature.

3.5.3. Sourdough temperature

Sourdough's temperature varies between 25.8 °C and 39.5 °C. This temperature is measured from the dough mixing place, just before the sourdough is mixed to the dough. One of the reasons may be long, cold pipes which are not covered anyway from the sourdough containers to the dough mixing places. Salovaara *et al*. (2017, p. 120) present an experiment done in a bakery of Primula in 1980 that changes only couple of °C in sourdough temperature cause radical changes on pH, yeasts and so on. That is why the changes in sourdough temperatures come probably because of the effect of cold pipes. If the changes in temperatures were that big in sourdough containers the sourdough may be ruined. After each planned or unplanned pause and sourdough container change, pipes get cold and cool down the sourdough moved to the dough when the process is started again. The pipes are so long that there are 280 kilograms of sourdough between sourdough container and dough mixing place. Covering the sourdough pipes could help to smooth the sourdough temperatures radically and then help to standardize the temperature of the dough.

One third of dough's ingredients is sourdough. That is why all the changes in sourdough will most likely be seen in dough quality and temperature. Sourdough's temperature needs to be taken into account when choosing correct water temperature for the dough, in other words sourdough temperature can be used for fuzzy dough temperature controller. If sourdough is very cold the water used in dough should be warmer so that it ensures that the dough temperature stays high enough.

3.5.4. Hardness of the dough

Horizontal stick is used for supervising how soft or hard the dough is. The basic idea of the stick was presented in chapter 3.3.2. The bakers observe how the dough is placed compared to the stick and if needed, they adjust the amount of water or flour on the dough. If dough is too soft, water is reduced and amount of flour increased and vice versa if dough is too hard.

The horizontal stick was replaced with optical distance sensor (SICK dt50) which tells exact movement on millimetres how much the dough really moves on the line. The official and better measure for hardness of the dough is farinograph. Farinograph is done regularly almost daily for the dough by a laboratory technician on the laboratory. This is the most accurate way to measure the condition of dough hardness. Samples were taken from the line regularly and compared to the results from the FE to the distance values from the sensor. The values of sensor did not change that much even though FE exceeded its limits. More investigations on the production line confirmed the results; adding water to the dough reduced FE far too low but the optical sensor did not record any exceptional movement of the dough on the production line. According to these results, horizontal stick or optical distance sensor cannot be used for estimating hardness of the dough or fuzzy dough hardness controller.

3.5.5. Flour temperature

Almost one third of the dough is flour. If there are big changes in flour temperature, it could be seen in dough temperature. The knowledge from flour temperature could be used for selecting optimal water temperature. If temperature of flour is hot, water should probably be slightly colder than normally to ensure that dough's temperature remains between optimal values.

Proper thermometer was set to the production line in order to measure flour temperature just before mixing it to the dough. Using big data collected from the thermometer it turned out that flour temperature varies much, from 19 °C to 25 °C. Flour temperature can be used as a variable in fuzzy dough temperature controller.

3.5.6. Room temperature

According to interviews room temperature varies a lot. This was confirmed with data mining. Every week temperature drops down by the end of the week (Friday) and on the contrary temperature rises quickly between Sunday and Monday. This is caused by machinery. When almost all production in the bakery ends on Friday, the temperature of the hall falls drastically. But when all the production lines are back on track on Sunday or Monday, the hall warms up quickly and room temperature rises. This causes temperature to vary between 20 °C to 32 °C every week.

Room temperature is important for dough. The dough rests 30 minutes in room temperature and goes through the line which takes about 10 minutes. 40 minutes is such a long time that it will be seen on dough's quality when comparing dough which has been 40 minutes in 20 °C or in 32 °C. Bakers will take room temperature into account at some level when they set the water temperature for the dough. They do not have thermometers, but they will act according to their experience about how warm or cold the dough should be. Then the bakers estimate the temperature for water so that it warms dough enough or cools it down. Room temperature should be used for fuzzy dough temperature controller in order to adjust the dough temperature optimal.

3.5.7. Moisture of dough

Exact moisture of the dough is measured by laboratory technician occasionally. An experienced baker can see to some extend if the dough is too moist or dry. Still, the moisture cannot be seen only by eye because it needs laboratory tests. As small change as 0.6% can change dough's properties drastically. Moisture seems to be connected to FE at some level. The drier the dough is, the harder it becomes.

Couple of experiments were performed in order to test how much does the moisture affect on FE. According to tests there seems to be clear relationship between moisture and FE. After having these kinds of results, it was investigated if moisture measuring device were better measure for dough hardness than horizontal stick. Flour and gluten properties affect on how much water the dough can absorb. This dough property could partly be supervised with moisture measurement device. Capacitive moisture sensor was used for testing how accurately it can detect changes in moisture of the dough. Even though several different test arrangements were tested, the results of moisture measuring were inaccurate. The moisture measuring device should be investigated more but currently it cannot be used for fuzzy dough hardness controller because it does not estimate hardness of the dough reliably.

3.6. Fuzzy controller

From the four critical points which were presented in 3.3.2. A) dough mixing B) after shaping C) after prover D) after oven, this project concentrates on the first one, the dough mixing because it has the strongest effect on the end result. The dilemma in the production line is that dough quality varies too much causing the production problems.

Two biggest reasons for dough quality variation are changes in dough temperature and dough hardness. Both are currently followed on certain level, but those ways should be improved. Temperature varies too much because lack of forecast from raw material temperatures and it does not take into account surroundings like room temperature. In addition, the temperature measuring system should be improved because at the moment the thermometer on the production line reacts too slowly on changes in dough temperature. Hardness is measured using horizontal stick but that measure turned out not to work properly.

In this thesis a fuzzy controller for steering the water temperature is created. Controlling the water temperature is important because it is the only way to control the temperature of dough. The model performs calculations in MATLAB and uses big data gathered from the production line for steering temperature of the dough automatically. Controller for dough hardness cannot be done before finding variables that can be used for predicting hardness (FE) of the dough.

Fuzzy controller can be useful in this kind of environment because it enables smooth steering of the line parameters according to several different variables. In addition, it can be predictive way to steer the line compared to one where changes are done after there is a change in dough temperature. With a fuzzy controller the changes to the production parameters can be done already when measuring devices reveal changes in temperatures of raw materials. It then ensures dough quality to be smooth.

3.6.1. Controller for water temperature

Dough temperature must stay between 30 °C and 32 °C. The challenge is that the room temperature, temperature of the machinery, raw materials' temperatures and bakers' different settings causes dough temperature to be unstable. A baker needs to follow the dough temperature regularly and set water temperature manually with her or his best knowledge. It is good to notice that in some cases those limits, 30 °C and 32 °C must be exceeded. Baker must take into account if the room temperature is very low for example after a longer cleaning pause. Then the machines, and also raw materials, are so cold that it cools down the dough. Sometimes the situation is other way around and the circumstances for baking are so hot that the dough must be little bit cooler than normally.

In figure 9 is presented a week from the dataset gathered from the line. Weekend is seen after minutes is 4200 from the start. Even though used dough water temperature is higher than normally, the temperature of dough is not high enough because of cold raw materials. The thermometer shows the changes in dough temperature a bit slowly which may affect on dough temperature results. However, here dough temperature is observed only in dough mixing. Most likely there would be even more variation in dough temperature if the temperature were measured also after the dough rest. In addition, it looks like flour temperature changes are caused by the room temperature variation. It should be investigated, why does sourdough temperature vary so much continuously. Temperature variation of sourdough may have huge impacts on dough quality because it changes the sourdough's properties, like acids.

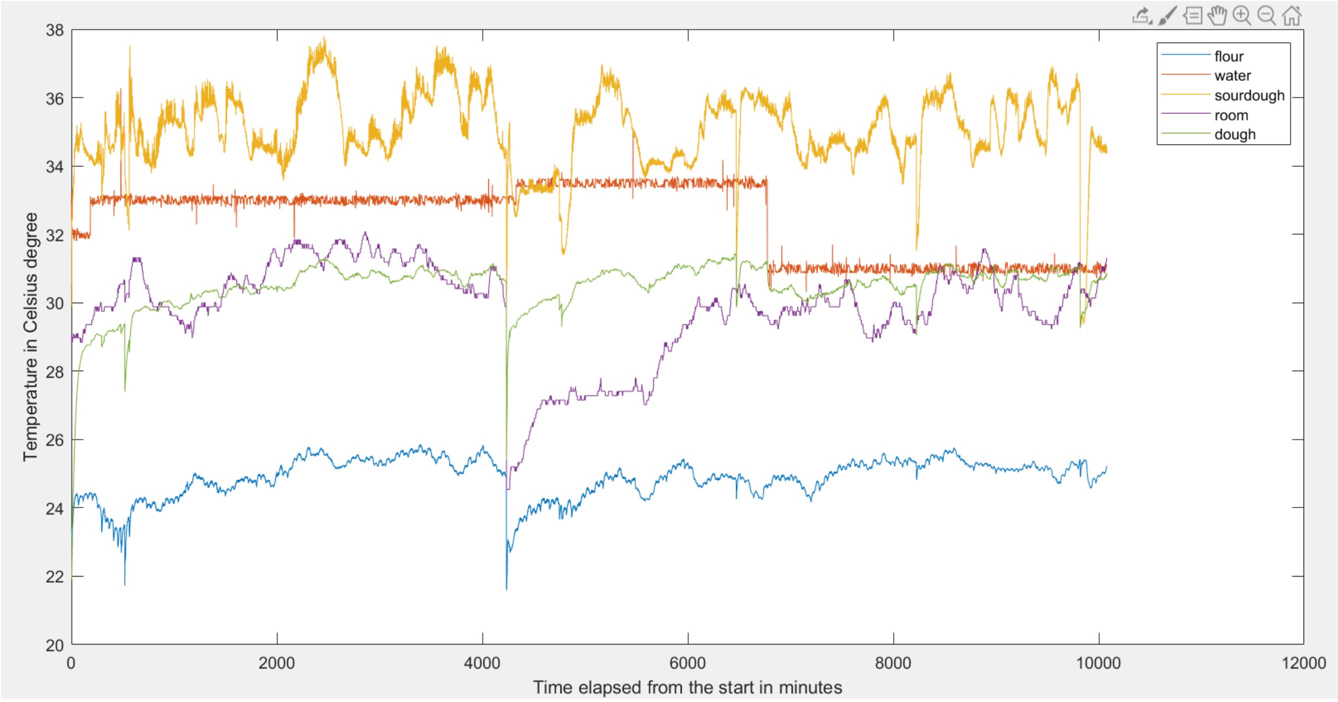

Figure 9. Variable temperatures from a week. Measuring started on Wednesday and weekend is seen after 4200 minutes from the start.

If a baker does not remember to follow the temperature and dough is baked with wrong temperature, it causes a lot of problems later on the line. In the worst case all the bread is ruined. There is a clear need for automated water temperature controller which takes into account raw materials' temperatures, room temperature and current temperature of the dough automatically.

Data

There are 64607 rows of input and output data pairs gathered from the measurement system on the production line. The data is pre-processed so that all the lines during the production pauses and 5 minutes after them are removed. In addition, output values are moved two rows downwards because it takes about two minutes before raw material temperature changes are visible on dough temperature.

ANFIS

Input variables are temperatures of water, sourdough, flour and room. Output variable is dough temperature. In other words, ANFIS is used for estimating the temperature of dough according to the circumstances. This model can be used for stabilizing the dough temperature variation. Stabilization can be reached by adjusting water temperature used for the dough.

Most of the settings for Takagi-Sugeno FIS part of the ANFIS are used as default settings. For example, AND operator method is product of fuzzified input values and OR operator method maximum of fuzzified input values. Product implication (how consequent fuzzy set is calculated) and sum aggregation (how rule consequents are combined) are always used in Takagi-Sugeno systems in MATLAB. Crisp output is calculated using weighted average of all rule outputs. In figure 10 it is drawn a simplified version of MATLAB's fuzzy inference process with these settings. In that example, there are only 2 variables, dough and room temperatures, with three membership functions.

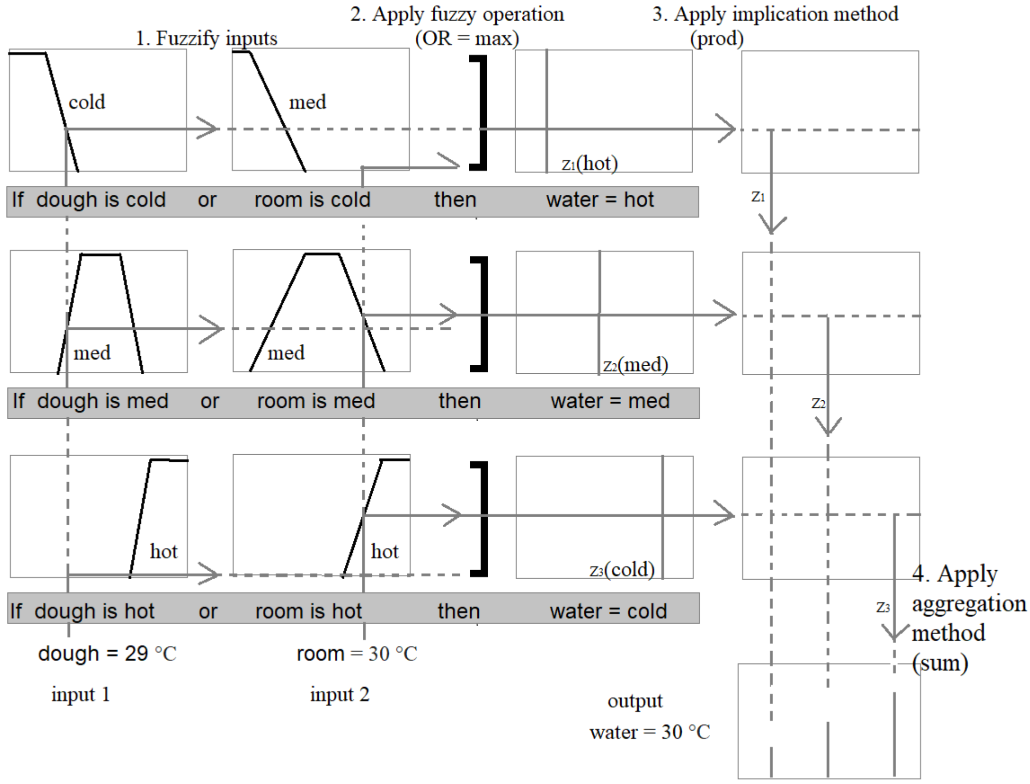

Figure 10. Takagi-Sugeno fuzzy inference process in MATLAB.

Part of the ANFIS settings are modified to the model. Initial FIS structure is changed to three instead of MATLAB's default of two. This means having three membership functions for each variable instead of having two. In other words, each variable has three membership functions. Then there are 81 rules in total formed in the model because there are four input variables (water, sourdough, flour and room) with three different membership functions (cold, medium, hot). In addition, the maximum number of training epochs is increased from MATLAB's default of ten to fifteen. Training epoch defines the amount of iterations while training ANFIS. Rest of the ANFIS options are used with default settings. For example, optimization method is hybrid method which uses least squares estimation for computing output membership function parameters.

The result of training is evaluated with root squared mean error, RMSE. The best performing model is the one which has the lowest RMSE values on test data and is not over-fitting on the data (Kvalheim *et al.* 2017, p.12). The ANFIS with settings described above creates great results in estimating dough temperature according to RMSE values. RMSE value for the model is 0.3148 which indicates model to perform well.

CONTROLLER

Mamdani's fuzzy inference system is created for the dough temperature controller. The controller is built after creating ANFIS. In ANFIS the system optimised the fuzzy sets for the variables so that estimating dough temperature was possible. That model and its fuzzy sets were used for creating the controller for dough temperature. In practise the water temperature needs to be controlled in order to control dough temperature. This means that the controller's input variables are temperatures of sourdough, flour, room and dough and output variable is water temperature. The model takes in temperatures which must be considered in order to define the water temperature added to the dough as well as possible. Well defined water temperature means defining it so that the dough temperature stays stabile even though raw materials' or room's temperatures changes.

Fuzzy sets of sourdough, flour and room temperatures created by ANFIS are copied to the Mamdani's fuzzy inference system. Fuzzy sets for dough temperatures are created based on the expertise of recipe developers; they define that the dough temperature must stay between 30 °C and 32 °C. These fuzzy sets for input and output variables are presented in figure 11.

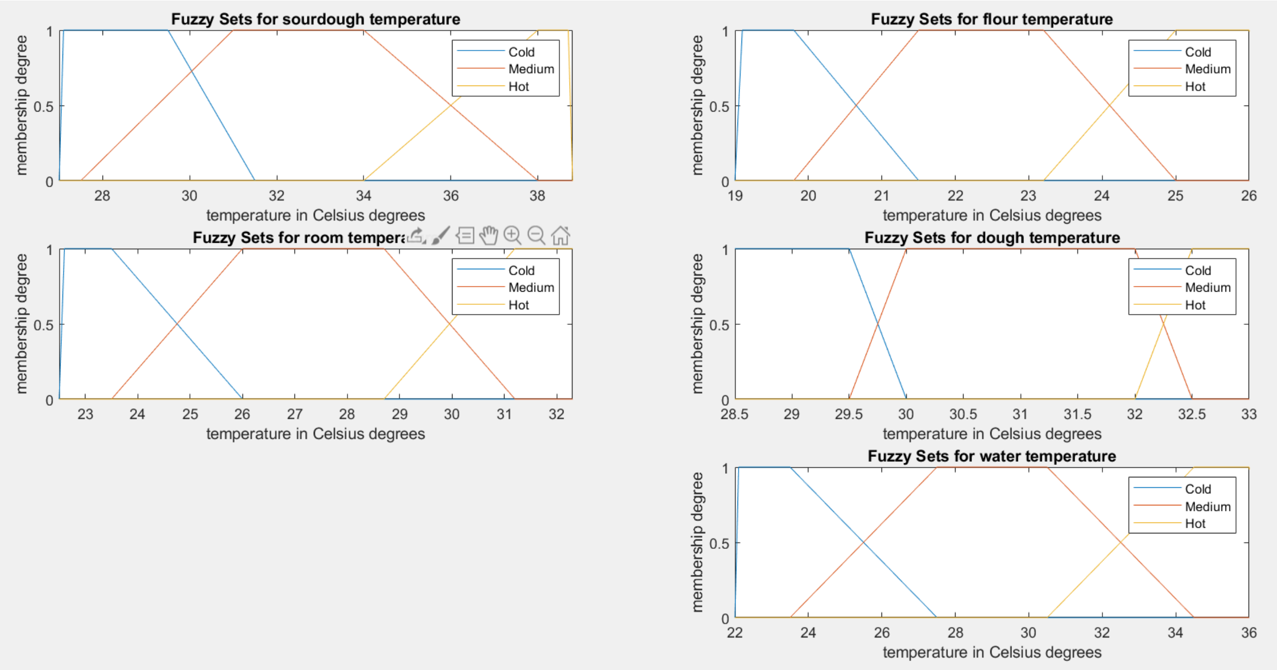

Figure 11. Fuzzy sets for input variables (sourdough, flour, room and dough) and output variable (water).

With four input values and three membership functions in each, it means that there are 81 rules in total. If-then rules are created in iterative process in which first rules are set according to the basic theory of baking. Rules are adjusted to their places iteratively according to the calculation results. Defuzzification in the system is done using discrete Central of Gravity. The output is temperature in Celsius degrees which water temperature should be used to the dough in order to keep the dough at optimal temperature.

RESULTS

The controller is tested qualitatively because of lack of "correct answers" for water temperature settings and inability to do proper tests in continuously operating production line. Qualitative testing of the results is based on the bakers' expertise knowledge and judgement. In practice, the controller is tested with several different input values and the output, is evaluated by couple of bakers does it seem rational.

According to these initial tests it seems that the controller is able to suggest proper water temperatures for different kind of situations in the bakery. The advantages of it could be seen already in a week when temperatures of the raw materials and room are changing radically. However, proper tests are required straight on the production line. According to those results the rules can be adjusted better.

FUTURE OF THE CONTROLLER

In order to test the model more on the line there should be done couple of improvements on the production line. First, thermometer of the dough should be moved to another place on the line so that it measures the dough temperature correctly. Another thing is to think how the model can be entered to the current production system because the current system does not have much of calculating power. If there is not enough calculating power, it could be considered if the calculations are moved to external computer to calculate the result. It would probably be wise to measure the variable temperatures once a minute, calculate new settings and send the result to the system.

3.6.2. Possible other controllers

In this project the fuzzy controller for water temperature was created. Another very important controller is needed for controlling the hardness of the dough in the beginning of the line. It needs thorough investigations how to follow and estimate hardness of the dough reliably. Laboratory technicians have done measurements of dough's temperature, moisture, pH, total titratable acidity and FE. There have been done 79 tests during 2019. The results were used in correlation matrix in order to investigate if there is some variable which explains FE. The results are presented in figure 12.

-0.3415	0.1175	0.1812	0.2004	1.0000

Figure 12. Results of correlation matrix for variable FE in following order: temperature, moisture, pH, total titratable acidity and FE.

According to the correlation matrix none of the variables (temperature, moisture, pH or total titratable acidity) can be used for estimating FE for controller of dough hardness. However, the dataset is so small that reliable conclusions of how much variables affect on each other cannot be made. For instance, the results for the moisture are unconvincing; moisture correlates weakly with FE. It would mean that the wetter the dough is the harder the dough would be. Very low correlation result which does not follow theory is probably incorrect and indicates need for more measurements. Finding proper measurements for the dough hardness and then creating controller for it are important in order to meet the bakery’s goals of having great product quality.

After the two dough properties, temperature and hardness, are under control it would be good to develop a controller for dosing the dough on the line in order to optimize the bread piece weight. This kind of controller would need an automatic weight measuring and probably machine vision in order to optimize the dosing. This may bring savings to the bakery if over-weighted products can be reduced.

After improving the parts of the production line from the beginning, 3D camera could be considered how useful it would be for estimating parameters for the prover. When the proofing is under control possibility to create a controller for the oven should be evaluated. It should be able to control the oven according to the bread’s moisture and colour. However, this controller is very difficult to create because of flour on the breads which disturbs seeing the surface colour of the bread.

4. CONCLUSIONS

All in all, the baking process is a complex set of numerous amounts of variables in which everything affects on everything. Part of the causal relationships are identified but usually the magnitudes of their influences are still a mystery. There should be done several tests in order to understand the causal relationships better. Then the quality of end result can be improved and maintained, huge amounts of money be saved and the production process itself optimized.

In order to automate the whole line, the production line should be divided into parts and developed one part at a time. Each of the parts have their own key variables to follow, for instance hardness of the dough, rise of a raw bread piece and moisture of the end product. It would be recommended to start developing the line from the part A) (dough mixing and rest) towards the part D) (after the oven) and taking care of one part at a time, see figure 5. In practise the first step would be to think in part A) what do we want out of the part, what is the optimal result of part A) before the dough continues to the part B). After that the key measures should be found how it can be measured if the targets of part A) are reached and develop that part according to them. When the dough is homogenised so well that the quality is stabile after part A) it is time to move on to the next part B).

There would be several places on the line in which proper controllers could help automating the production line. Creating controllers need thorough investigations on how the baking variables affect on dough properties. After understanding the causal relationships of the variables, it could be possible to make controllers for the production line and automate it more, piece by piece.

4.1. Answering to research questions

There were five research questions for this thesis. The answers to them are gathered next.

1. Which are the critical points in the production line where measurements and supervision should be done?

There are four critical points in the line in which supervision is mainly done: A) Dough mixing, B) after the shaping the bread, C) after the prover and D) after the oven. Some measurement devices were added to these places so that part of the supervision could be done automatically by a machine. From these four critical points this thesis focused most on point A).

2. Which variables affect on the bread dough and the result (end product, bread)?

There are several variables in the line which affect on the end result; part of them are known and part of them are not even found or are not followed and taken into account anyhow in baking. Even though some of the variables are known the magnitude of their influence should be investigated more, for instance room temperature. Key variables on the line in part A) are dough temperature, dough hardness and room temperature, in part B) weight, in part C) rise (width, height, length) of the raw bread piece and in part D) colour, shape and moisture of the bread piece.

This thesis focused investigating more which variables cause changes in dough temperature and hardness. Variables that affect most on dough temperature are temperatures of flour, sourdough and room. All of them should be taken into account when setting correct temperature for the dough water. Currently they can be followed and used the knowledge for dough temperature controller. In addition, there are several variables that cause variation in dough hardness, for instance flour, sourdough and gluten quality, mixing power and time. Because flour, sourdough and gluten quality cannot be followed straight from the production line, there should be more investigations done in order to find proper way to estimate dough hardness. Before that controller for dough hardness cannot be developed.

3. How to scale each of these variables gained in the question 2?

Variables that are needed in the fuzzy dough temperature controller are flour, sourdough, room and dough temperatures. Limits for dough temperature are set according to the product developers from the bakery. They have set certain temperature limits in which the dough must be. Proper sets for flour, sourdough and room temperatures were found using Adaptive Neuro-Fuzzy Inference System (ANFIS) in MATLAB. Using many rows of input-output data a model was created in the MATLAB.

4. What kind of instructions/rule base should be written for the system?

Dough temperature is controlled changing the water temperature used in the dough. In order to eliminate dough temperature variation temperatures of the most important raw materials (flour and sourdough), circumstances (room) and current dough must be taken into account in controller. The controller can then set the water temperature so that it buffers the changes in flour, sourdough or room temperatures. All of the variables can be described with three linguistic states; cold, medium and hot. Because there are four variables (flour, sourdough, room and dough temperatures) with three different fuzzy membership functions it means that in the controller there are 81 rules in total. These rules are presented in appendix 2.

5. What kind of fuzzy control system is needed here?

In this thesis Mamdani's fuzzy inference system was used in order to control dough temperature through water temperature. In FIS firing levels were calculated taking intersections from the rules, aggregated the single overall system output using disjunctive system of rules and used Center of Gravity for defuzzification. Controller takes four temperatures (flour, sourdough, room and dough) as inputs and gives proper value for water temperature as output. Proper value means water temperature which would stabilize dough temperature variation. For example, if room temperature is very low at the beginning of week, the controller adjusts water temperature so that the dough temperature remains optimal. In practice the controller could take inputs once a minute and give water temperature as output for the system according to the inputs.

4.2. Limitations of this research

Even though having wide opportunities to do research in the bakery, there were some limitations when performing the investigations. The line is almost continuously running so arranging tests on it is difficult. When there is a production pause the production line is cleaned and using it for tests or production is then forbidden. In addition, part of the tests should be done outside the production hours because the tests would have had an effect on the dough and the end result.

Another limitation related to the technical issues. The production line would have needed two improvements in order to enable testing in real conditions: the dough thermometer should have been moved to another place so that it would have reacted to changes in dough temperature immediately and calculation power of the production system should have been improved. Alternatively the calculations could have been done outside the system.

5. SUMMARY

During writing this thesis 3D camera was investigated, several tests were made of how FE (measure for dough hardness) changes when something is changed in the dough or how that FE changes during the process, data mining was made using couple of different datasets, one of the measures (horizontal stick) was revealed to be a false measure on the line, ANFIS model was trained for estimating the dough temperature, controller for water and then dough temperature was created and tested initially, experiments were done on moisture measuring device and several problems were pointed out on the line.

One of the key results of this thesis is the mapping the baking process. This mapping includes information of the key variables in each process step and the process mapping is used for planning the future for the production line. It seems that the production between dough mixing and bake in the oven should be divided into four parts according to the variables supervised in the production line. Those parts are A) dough mixing and dough rest, B) dough dosing to the line and shaping the bread, C) prover and D) bake in the oven. After the part D) the rest of the production line could be divided into two to three parts. However, this thesis concentrated on parts A) to D) and more accurately on part A) only.

During the process it turned out that in the baking everything starts from the very beginning, dough mixing. The changes in there are seen on latter process steps and then those changes in dough quality are too late to fix. Production line that produces continuously great quality seems to produce dough which has stable temperature and hardness. The impact of those two may be even so great that most of the problems later on the line would disappear if those two are taken under control. That is the reason why it is important to improve dough making process in order to improve and maintain high product quality.

This thesis focused on standardizing dough making by creating a fuzzy controller for water temperature. Adjusting water temperature is the only way to control the dough temperature. The controller is Mamdani's inference system which has four inputs (flour, sourdough, dough and room temperatures) and output is the calculated optimal temperature for the water used in the dough. According to initial tests the controller seems to perform very well in the baking circumstances. If it is implemented on the production line well it could reduce unplanned process pauses when the production flows better and more importantly increase product quality.

In order to exploit the fuzzy controller for stabilizing the dough temperature couple of technical improvements should be done to the production line first. For example, the dough temperature thermometer is not placed properly on the production line. Currently it is placed in a way that it reacts to changes on dough temperature too slowly. Then it is impossible for a software to steer the production parameters if it does not know the current situation correctly. In addition, controller for dough hardness should be also created. In order to do that the proper measures for estimating the FE should be found. Having these two controllers, the dough making would be highly automated and could even steer the process automatically.

MATLAB and its Fuzzy Logic Toolbox turned out to be very powerful set of tools to analyse and build models from numerous rows of raw data. It can provide models to be used as such or it can provide answers to build own kind of model. Fuzzy logic could make it possible to develop the baking process so much that it could steer the process parameters by itself. Still, more tests and investigation are needed to understand the real causal relationships between variables.

Improving and developing the line should start from the beginning of the production line. Once the end product of the first part of the line is homogenized, only then it is wise to move to next part of the line. It makes no sense to start improving the line from the end or the whole line at once. Each small change on the production line should be investigated thoroughly how does it affect on what. This cannot be done if the production line is under development as whole. During the whole baking process there are so many variables that it would be impossible to find out effects of some changes so that other small variable changes would not mess the results.

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Appendix 1

Small baking glossary

Ash Content	Ash is one way to describe the mineral content of flour. It refers to the amount of ash left over after burning certain amount of flour. This is one measure for the flour quality. In Finnish “Tuhkapitoisuus”. (Salovaara *et al.* 2017, p.287; BC Cook Articulation Committee 2015, p. 24)
Falling number	Falling number is a measure for describing α-amylase activity and the level of sprouting in wheat or rye. This is one way to evaluate the quality of the flours. In Finnish “Sakoluku”. (Codinâ, Mironesa and Mironesa 2012, p. 2162; Salovaara *et al.* 2017, p. 59)
Farinograph	A recording dough mixer in a bakery which is used for example defining the consistence, strength and water absorption of dough but the actual emphasis of results used may vary between the mills and bakeries. (Salovaara *et al.* 2017, pp. 56, 275) See FE.
FE	When talking about the result of the farinograph measurement in this thesis term FE is used. The lower the FE the looser the dough and vice versa. See Farinograph.
Gluten	General name for proteins in wheat, rye, barley and triticale. It is like a glue in food which enables food to maintain its shape. (Celiac Disease Foundation 2020) Gluten can be used in bread doughs for improving the baking properties.

Sourdough	Sourdough is one kind of predough for the dough. It is sour because it contains living microbes, especially lactic acid bacteria. In Finnish “Raski”. (Salovaara *et al.* 2017, p. 285)
Total Titratable acidity	Describes the total amount of formed acids in sourdough, dough or bread. In Finnish “Happoluku”. (Salovaara *et al.* 2017, p. 124)

Appendix 2

Fuzzy rules for controller

rule	IF	sourdough	AND	dough	AND	room	AND	flour	THEN	water
1	IF	cold	AND	cold	AND	cold	AND	cold	THEN	hot
2	IF	cold	AND	cold	AND	cold	AND	med	THEN	hot
3	IF	cold	AND	cold	AND	cold	AND	hot	THEN	hot
4	IF	cold	AND	cold	AND	med	AND	cold	THEN	hot
5	IF	cold	AND	cold	AND	med	AND	med	THEN	hot
6	IF	cold	AND	cold	AND	med	AND	hot	THEN	hot
7	IF	cold	AND	cold	AND	hot	AND	cold	THEN	hot
8	IF	cold	AND	cold	AND	hot	AND	med	THEN	hot
9	IF	cold	AND	cold	AND	hot	AND	hot	THEN	med
10	IF	cold	AND	med	AND	cold	AND	cold	THEN	hot
11	IF	cold	AND	med	AND	cold	AND	med	THEN	hot
12	IF	cold	AND	med	AND	cold	AND	hot	THEN	med
13	IF	cold	AND	med	AND	med	AND	cold	THEN	med
14	IF	cold	AND	med	AND	med	AND	med	THEN	med
15	IF	cold	AND	med	AND	med	AND	hot	THEN	med
16	IF	cold	AND	med	AND	hot	AND	cold	THEN	hot
17	IF	cold	AND	med	AND	hot	AND	med	THEN	med
18	IF	cold	AND	med	AND	hot	AND	hot	THEN	med
19	IF	cold	AND	hot	AND	cold	AND	cold	THEN	med
20	IF	cold	AND	hot	AND	cold	AND	med	THEN	med
21	IF	cold	AND	hot	AND	cold	AND	hot	THEN	cold
22	IF	cold	AND	hot	AND	med	AND	cold	THEN	med
23	IF	cold	AND	hot	AND	med	AND	med	THEN	cold
24	IF	cold	AND	hot	AND	med	AND	hot	THEN	cold
25	IF	cold	AND	hot	AND	hot	AND	cold	THEN	med
26	IF	cold	AND	hot	AND	hot	AND	med	THEN	cold
27	IF	cold	AND	hot	AND	hot	AND	hot	THEN	cold

28	IF	med	AND	cold	AND	cold	AND	cold	THEN	hot
29	IF	med	AND	cold	AND	cold	AND	med	THEN	hot
30	IF	med	AND	cold	AND	cold	AND	hot	THEN	hot
31	IF	med	AND	cold	AND	med	AND	cold	THEN	hot
32	IF	med	AND	cold	AND	med	AND	med	THEN	hot
33	IF	med	AND	cold	AND	med	AND	hot	THEN	hot
34	IF	med	AND	cold	AND	hot	AND	cold	THEN	hot
35	IF	med	AND	cold	AND	hot	AND	med	THEN	med
36	IF	med	AND	cold	AND	hot	AND	hot	THEN	med
37	IF	med	AND	med	AND	cold	AND	cold	THEN	hot
38	IF	med	AND	med	AND	cold	AND	med	THEN	hot
39	IF	med	AND	med	AND	cold	AND	hot	THEN	med
40	IF	med	AND	med	AND	med	AND	cold	THEN	med
41	IF	med	AND	med	AND	med	AND	med	THEN	med
42	IF	med	AND	med	AND	med	AND	hot	THEN	med
43	IF	med	AND	med	AND	hot	AND	cold	THEN	med
44	IF	med	AND	med	AND	hot	AND	med	THEN	med
45	IF	med	AND	med	AND	hot	AND	hot	THEN	med
46	IF	med	AND	hot	AND	cold	AND	cold	THEN	med
47	IF	med	AND	hot	AND	cold	AND	med	THEN	med
48	IF	med	AND	hot	AND	cold	AND	hot	THEN	cold
49	IF	med	AND	hot	AND	med	AND	cold	THEN	med
50	IF	med	AND	hot	AND	med	AND	med	THEN	cold
51	IF	med	AND	hot	AND	med	AND	hot	THEN	cold
52	IF	med	AND	hot	AND	hot	AND	cold	THEN	cold
53	IF	med	AND	hot	AND	hot	AND	med	THEN	cold
54	IF	med	AND	hot	AND	hot	AND	hot	THEN	cold
55	IF	hot	AND	cold	AND	cold	AND	cold	THEN	hot
56	IF	hot	AND	cold	AND	cold	AND	med	THEN	hot
57	IF	hot	AND	cold	AND	cold	AND	hot	THEN	hot
58	IF	hot	AND	cold	AND	med	AND	cold	THEN	hot

59	IF	hot	AND	cold	AND	med	AND	med	THEN	hot
60	IF	hot	AND	cold	AND	med	AND	hot	THEN	med
61	IF	hot	AND	cold	AND	hot	AND	cold	THEN	med
62	IF	hot	AND	cold	AND	hot	AND	med	THEN	cold
63	IF	hot	AND	cold	AND	hot	AND	hot	THEN	cold
64	IF	hot	AND	med	AND	cold	AND	cold	THEN	med
65	IF	hot	AND	med	AND	cold	AND	med	THEN	med
66	IF	hot	AND	med	AND	cold	AND	hot	THEN	med
67	IF	hot	AND	med	AND	med	AND	cold	THEN	med
68	IF	hot	AND	med	AND	med	AND	med	THEN	med
69	IF	hot	AND	med	AND	med	AND	hot	THEN	cold
70	IF	hot	AND	med	AND	hot	AND	cold	THEN	cold
71	IF	hot	AND	med	AND	hot	AND	med	THEN	cold
72	IF	hot	AND	med	AND	hot	AND	hot	THEN	cold
73	IF	hot	AND	hot	AND	cold	AND	cold	THEN	med
74	IF	hot	AND	hot	AND	cold	AND	med	THEN	cold
75	IF	hot	AND	hot	AND	cold	AND	hot	THEN	cold
76	IF	hot	AND	hot	AND	med	AND	cold	THEN	cold
77	IF	hot	AND	hot	AND	med	AND	med	THEN	cold
78	IF	hot	AND	hot	AND	med	AND	hot	THEN	cold
79	IF	hot	AND	hot	AND	hot	AND	cold	THEN	cold
80	IF	hot	AND	hot	AND	hot	AND	med	THEN	cold
81	IF	hot	AND	hot	AND	hot	AND	hot	THEN	cold