Automated Fuzzy Inference Lighting System

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Introduction

For the following project, De Montfort University has requested for an automated 'lighting' system that will help control and manipulate the lighting in the Computer Science laboratories at gateway house. The system should be implemented using a fuzzy inference system that determines the lighting of the room based upon a variety of inputs. The initial inputs will possibly include the number of people in the room, lighting in the room (determined by the lux) and the time of day. This will then be processed into the fuzzy system to determine the outputs to control the intensity of the lighting and the number of lights that will be turned on. The initial outputs were decided based upon the specification provided by De Montfort University that stated the system should take into consideration power saving and should also use the least amount of lights whenever possible.

There are two proposed models that will be used for the implementation of the system to compare which one is more successful and suitable for this project. Firstly the Mamdani fuzzy inference method which uses a number of 'if-then' rules to control how the system will react to different scenarios. For example, adjusting the intensity of the lights to low if the room is already bright. The Mamdani process consists of five steps including the following:

1. Fuzzify input variables
2. Apply fuzzy operator
3. Apply implication method
4. Apply aggregation method
5. Defuzzification

(Chonghua, 2015)

The second proposed model will be the Sugeno model. The Sugeno model is similar to the Mamdani, however it only has four inference steps. The first three of which are the same as the Mamdani model followed by the final step, which is weighted average of rules strength and consequents. The main differentiation between the two models is that the Sugeno produces an output that consists of a linear or constant expression (MathWorks, 2016).

Literature Review

Introduction

In order for the project to be successful it is important to research previously conducted work, specifically similar systems to provide credence to the proposed system. This will help support the design decisions used for the implementation. Furthermore, it will also give a chance to assess the initial inputs and outputs to certify whether they are suitable for the project or if they need to be altered.

Existing Systems

Panjaitan and Hartoyo created a lighting system that took consideration of electrical energy consumption. Although the system was created for a variety of buildings and not for a few rooms, one of the inputs was based upon the illumination level (lux) within the room(Panjatian & Hartoyo, 2011) which supports the idea of the using the same input for the proposed system as this can help control the intensity of the lighting.

Kiyanfar and Loftibonab designed their light controller to control the number of lamps in a room depending on the number of people. This instantly shows similarities for the proposed system as it will involve manipulating lights based upon the number of people in a room. The light controller took the inputs, number of people and light intensity, then produced the output for the light intensity(Kiyanfar & Lotfibonab, 2012). This supports the idea of using the number of people as an input as this primarily will be used to determine how many lights will be turned on.

The intelligent lighting system produced by Mutua and Mbuthia, similarly to the system of Panjatian and Hartoyo was created in relation to energy consumption. The system used LEDs to produce light for a given room space(Mutua & Mbuthia, 2015). Although this was created for both indoor and outdoor lighting, the input of the illumination was also used for this system, which further strengthens the idea for the proposed input.

Literature Reflections

After completing the research and finalising the reviewing of literature it is important to reflect on the lessons learnt throughout. Reflection will help to ensure that the design decisions for the proposed system are viable.

The majority of the literature review was based upon existing systems. The systems reviewed had various similarities to this project, such as the illumination, number of people and intensity inputs. The first system reviewed which was created for buildings controlled the intensity of lighting, however it did not take into consideration the number of people that present. So for example if one person walked past, all of the lighting would turn on. The idea for the proposed system is to have the minimum number of lights possible, which will help ensure the power saving requirement is met, therefore it is important to have an input based around this idea.

The second system reviewed was the most similar to the proposed system as it involved controlling lights based upon how many people were present. Although the idea of the system was similar the overall product was not, as the output consisted of only the intensity. Similarly to the first system there was no real consideration for the number of lights that would be on.

The final system reviewed was similar to the first one, although there was consideration for energy consumption and power saving, the number of lights and the number of people were not used for the system.

Conclusion

The literature review helped with the design decisions for the system. Overall the majority of the chosen inputs and outputs for the proposed system were supported by the work of others and previous systems, so for this reason they will be implemented. In spite of the fact that the input time of day was not used in any of the systems reviewed, it will still be used for the proposed system as this will be a key input to determine the lighting in the room.

The systems highlighted throughout the literature review were used merely for supporting the initial inputs and outputs. The proposed system holds no intention of replicating or building upon the work conducted by others.

Lighting System

The proposed system will be implemented using both the Mamdani and the Sugeno models. The reason to create the system using both models is to determine the maximum success of the system, in other words which model does it work better with. The inputs, outputs and the rules of the system will also remain the same throughout for both models to ensure a fair comparison is conducted during the testing phase. The inputs and outputs will build upon the reflections of the literature review.

Input Variables

The inputs for the system will be used to make an accurate decision when manipulating the lighting system. There are three chosen inputs for the proposed system, as these were identified to be the most suitable and necessary. The function that was used to portray all the input fuzzy sets was the Trapezoidal shaped membership function, the reason for this was because it gives a clear representation of the changes that occur in a smooth yet effect manner. Furthermore, it is simple to identify the start, increase and decrease of the sets. The inputs include the following:

Number Of People

The number of people will be given a maximum range of 50. The reason for this is that a typical laboratory has a total of 16 computers, an example scenario could be the room being full, with 3 people per computer working together which gives a total number of 48, therefore it is logical to round this to the nearest ten. The system will use the values provided to measure the level of membership the number of people has to 'PeopleInRoom'. The categories of this are:

- **Empty** - There are no people in the room.
- **Low** - There are between 1 to 20 people in the room.
- **Medium** - There are between 15 to 30 people in the room.
- **High** - There are between 25 to 40 people in the room.
- **Full** - There are between 35 to 50 people in the room.

Lighting In Room

The lighting in the room will be determined by an integer using the measurement of lux. Lux is the unit used for describing luminosity. The values for the lux were determined by using the Microsoft data set provided on the official website as a guide. The values provided range from 0(Pitch Black) to 100,000(Direct Sunlight)(Microsoft, 2017). The system will use the values to measure the level of membership the lux has to 'LightingInRoom'. The categories of this are:

- **Pitch Black** - The lux is 0, there is no lighting in the room therefore, the room is pitch black.
- **Dark** - The lux starts at 0 and increases to 300, continues towards 375 and then decreases until 1000.
- **Normal** - The lux starts at 350 and increases to 400, continues towards 5000 and then decreases until 5100.
- **Bright** - The lux starts at 4900 and increases to 5000, continues towards 30,000 and then decreases until 30,100.
- **Very Bright** - The lux starts at 29,000 and increases to 30000, continues towards 100,000 (Direct Sunlight).

Time Of Day

The time of day will be determined by the minutes in a day(1440). Although, the time of day changes throughout the year which could have an impact on the lux levels, specific rules will be developed to counter this problem. The system will use the values provided to measure the level of membership the time of day has to 'TimeOfDay'. The categories of this are:

- **EarlyMorning** - Starting from midnight, increasing to approximately 2.00am and then decreasing for 5.00am.
- **Morning** - Starting from 4.00am, increasing to 7.00am, continuing to approximately 10.00am and then decreasing for 12.00pm.
- **Afternoon** - Starting approximately 11.00am, increasing to 12.30pm, continuing to around 16.00pm and then decreasing for 18.00pm.
- **Evening** - Starting approximately 16.30pm, increasing to 17.30pm, continuing to around 20.00pm and then decreasing for 21.00pm.
- **Night** - Starting at 20.00pm, increasing to 22.00pm, continuing to 00.00am.

Output Variables

The outputs of the system will be responsible for adjusting the lighting system as required. There are two outputs chosen for the proposed system. The reason for choosing two outputs instead of one was to fulfil the power saving requirement highlighted earlier. If there was only one output(intensity or number of lights) then this requirement would not be met. The function for highlighting both output fuzzy sets was the Triangular shaped membership function, the reason for choosing this was because the sets are easier to define manually, which ensures that the maximum range of the full intensity or the number of lights on are not left un-catergorised. The outputs include the following:

Intensity

The intensity will be given a maximum value of 100 and will be determined by percentage. The value of 100 will portray the lights as being turned on to their full power. The system will use the values provided to measure the level of membership the intensity has to 'Intensity'. The categories of this output are:

- **Off** - 0%, there is no intensity.
- **Low** - 17-33%, the intensity is low.
- **Medium** - 33-50% - the intensity is medium.
- **High** - 66-95% - the intensity is high.
- **Full** - 95-100% - the intensity is full(maximum).

Number of lights on

The number of lights on will be given a maximum value of 9. This value was determined by a typical computer science laboratory at De Montfort University that has a total of 9 lights. Although this value is for these specific laboratories, it can be adjusted to suit another larger or smaller room. The system will use the values provided to measure the level of membership the number of lights has to 'NumberOfLightsOn'. The categories of this output are:

- **None** - 0, there are no lights on.
- **Low** - 0-3, there are a low amount of lights on.
- **Medium** - 3-5 - there are a medium amount of lights on.
- **High** - 5-7 - there are a high amount of lights on.
- **All** - 7-9 - all the lights are on.

Rules

To determine which input sets the data falls into, it is important to develop rules. The rules are all based upon the 'if-then' then Mamdani model supplies. To fulfil the requirements expected from De Montfort University, it was necessary to create rules that would manipulate the system accordingly, regardless of the day or time of year. The general outline of the rules included the following:

- **Lights/Intensity Off** - These rules were developed for whenever the room had no people in it.
- **Low Intensity / Low-Medium-High Lights** - These rules were created for when the room had low/medium/high people in it and the lux was bright in the early morning, morning, afternoon or evening.
- **Medium Intensity / Low-Medium-High lights** - These rules were created for when the room had low/medium/high people in it and the lux was dark/normal in the early morning, morning, afternoon or evening.
- **High Intensity / Low-Medium-High lights** - These rules were created for when the room had low/medium/high people in it and the lux was pitch black/dark in the early morning, night or evening.
- **Maximum Setting** - These rules were created for when the room was full in the evening or at night and the lux was pitch black.

There are a total of 66 rules, that have been created specifically to maximise the success of the system for any time of the year and for practically any given scenario.

The full set of rules can be found in Appendix A and the figures of the fuzzy sets can be found in Appendix B.

Testing And Evaluation

Once the system has been created, using both the Mamdani and Sugeno models it is important to test and evaluate them both. The tests will be conducted through using the data stored in an XML file, which will be passed to the Mamdani system. The same values will then be entered into the Sugeno system. The results can then be compared and contrasted to determine the best fit for De Montfort University. The XML file contains data that is both valid and invalid to see how each system responds, the good and bad data is color-coded in the XML provided, this file can be found in Appendix C

Testing

Valid Inputs

The valid inputs were based upon realistic scenarios that could occur at anytime throughout the year. These were generally constructed based upon the rules that had been created, this helped to ensure that the correct expected outputs were being produced. Some of the results from the tests are listed in the following table:

Table 1: Shows the three valid inputs of data followed by, the two outputs

Model	**NumberOfPeople**	**LightingInRoom**	**TimeOfDay**	**Intensity**	**NumberOfLights**
Mamdani	0	0	1200	0%	0
	4	300	1100	83%	2
	30	25000	900	17%	6
	40	0	1040	100%	8
	50	0	1200	100%	9
	43	670	1300	50%	5
Sugeno	0	0	1200	0%	0
	4	300	1100	72%	2.4
	30	25000	900	30%	7
	40	0	1040	100%	9
	50	0	1200	16%	1.5
	43	670	1300	0.5%	4.5

Invalid Inputs

The invalid inputs were based upon near impossible scenarios such as, the room lighting being very bright at night. The reason for creating these was to determine how the systems would react to unlikely events. Some of the results are listed in the following table:

Table 2: Shows the three invalid inputs of data followed by, the two outputs

Model	**NumberOfPeople**	**LightingInRoom**	**TimeOfDay**	**Intensity**	**NumberOfLights**
Mamdani	0	90000	1200	0%	0
	0	0	400	0%	0
	5	10000	1440	50%	5
	50	50000	0	0%	0
	30	0	1000	90%	7
	45	10000	1300	0%	0
	20	0	450	50	5
Sugeno	0	90000	1200	0%	0
	0	0	400	0%	0
	5	10000	1440	0.5%	4.5
	50	50000	0	0%	0
	30	0	1000	30%	2.33
	45	10000	1300	0.5%	4.5
	20	0	450	0.5%	4.5

There were a total of 31 tests conducted, the full test results can be found at Appendix C.

Defuzzification Methods

Defuzzification is a process that converts the degrees of membership of output linguistic variables into numerical values(NationalInstruments,2010). There are five defuzzification methods which include centroid, bisector, mom, som and lom (Middle-Small-Largest of maximum). Each method was tested with small basic data to see how the outputs varied. Once again to make all the tests fair the data was kept the same throughout. The results from this are shown in the following table:

Table 3: Shows the inputs and outputs of data per defuzzification method

Method	**NumberOfPeople**	**LightingInRoom**	**TimeOfDay**	**Intensity**	**NumberOfLights**
Centroid	10	6000	600	17%	2
	50	0	1200	98%	8
Bisector	10	6000	600	17%	2
	50	0	1200	98%	8
Mom	10	6000	600	17%	2
	50	0	1200	98%	8
Som	10	6000	600	17%	2
	50	0	1200	96%	7
Lom	10	6000	600	17%	2
	50	0	1200	100%	9

Although the results from the tests are very similar, the chosen defuzzification method for this system will be the largest of maximum(lom), primarily because this is the only one that allows the system to be used at its maximum capacity for when the room is full (highest intensity and all the lights on).

Evaluation

Mamdani VS Sugeno

After conducting fair tests for both of the systems using valid and invalid data it is apparent that the Mamdani system would be more suitable for De Montfort University. The reasons for this are because, for valid inputs the Mamdani system adjusts accordingly and fulfils the power requirement highlighted earlier, for example when the room had 30 people and it is was bright during the afternoon the intensity was set to a low with 17% and only 6 lights were turned on. For the same set of values the Sugeno system returned 30% and 7 lights turned on, which although is still acceptable it falters in comparison to the Mamdani. Furthermore, in relation to the invalid data both systems returned similar outputs. However, the Sugeno resulted in decimal figures for example 4.5, which will not be possible for the proposed system as only whole numbers are accepted.

Another clear differentiation between the systems found during the testing was that if there were 6 people in the room and the room was dark during the evening the Mamdani system would correctly adjust the intensity to 50% and the number of lights would be 2. On the other hand for the same data the Sugeno system returned 148% for the intensity and 6.92 for the lights, this is clearly not possible as the intensity exceeded the maximum limit of 100%.

In support of the Sugeno system, it did react correctly for when there were no people in the room as it set the intensity to 0% and the number of lights on to 0. However, when the rooms were portrayed to be dark and full, the system did not produce the correct outputs. For example there were 50 people in a pitch black room at night, the system set the intensity to 16.7%, with only 1.5 lights on. The Mamdani on the other hand returned 100% for intensity with all the lights turned on, which was the expected output.

The examples provided can be found in the results tables given at Appendix C

Critical Reflection & Conclusion

Introduction

After the creation, testing and evaluation of the systems it is important to critically reflect on the implications of the chosen system and how could it have been improved throughout the development life-cycle.

Reflection

Although the system performs quite well on the whole, there are still small minor changes that could be addressed for the long term. The main noticeable issue is that when there is 1 person in the room, 3 lights seem to turn on, a better output would have been 1. Furthermore, in all of the tests conducted there were none that returned the number of lights on as only 1. This might have possibly been different if during the development the system stuck with the initial inputs. There was an important aspect changed throughout the development of the system. The system initially was supposed to have four inputs, the fourth being the time of year, which would have been determined by the season. The reason for eliminating this input was because the rules system would have been unmanageable, this was noticed mid-way through the development phase. Furthermore, it became apparent that the system could still react as it should by using only the lux. To further tackle the input elimination, specific rules were created that would cover the changes in lighting the days have throughout the year for example, in the summer it gets dark at a later time in comparison to the winter when it gets dark earlier. (Appendix A)

Conclusion

Overall the system performed successfully when applied to the given specification. The initial inputs and outputs decided were supported by the conduction of the literature review, as this allowed the opportunity to assess previous work to gain a better understanding of how the proposed system could perform to its maximum potential. The two models that were used for the systems gave the chance to analyse and assess how they reacted to the given data, in which the tests showed that the Mamdani is the most suitable option for De Montfort University.

The system that has been created can be successfully applied to any given room or building, for which one would only have to change the ranges of the inputs and outputs. So for example to apply this system to a lecture hall in the Hawthorn building, the people limit would change to approximately 100, and the number of lights limit would be around 15.

For future testing, it would be useful to use real-life data, as this would give a proper evaluation of the systems overall performance.

References

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Appendix A Rules List

```
%Lights/Intensity Off Rules
LO1= [1 0 0 1 1 1 1]; %If (PeopleInRoom is Empty) then (Intensity(%) is Off)(Number Of Lights On is None)
LO2= [2 5 0 1 1 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Very Bright) then (Intensity(%) is Off)(Number Of Lights On is None)
LO3= [3 5 0 1 1 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Very Bright) then (Intensity(%) is Off)(Number Of Lights On is None)
LO4= [4 5 0 1 1 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Very Bright) then (Intensity(%) is Off)(Number Of Lights On is None)
LO5= [5 5 0 1 1 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Very Bright) then (Intensity(%) is Off)(Number Of Lights On is None)

%Low Intensity / Low Lights
LI1 = [2 4 1 2 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is EarlyMorning) then (Intensity(%) is Low)(Number Of Lights On is Low)
LI2 = [2 4 2 2 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Morning) then (Intensity(%) is Low)(Number Of Lights On is Low)
LI3 = [2 4 3 2 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Afternoon) then (Intensity(%) is Low)(Number Of Lights On is Low)
LI4 = [2 4 4 2 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Evening) then (Intensity(%) is Low)(Number Of Lights On is Low)


%Low Intensity / Medium Lights
LI5 = [3 4 1 2 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is EarlyMorning) then (Intensity(%) is Low)(Number Of Lights On is Medium)
LI6 = [3 4 2 2 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Morning) then (Intensity(%) is Low)(Number Of Lights On is Medium)
LI7 = [3 4 3 2 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Afternoon) then (Intensity(%) is Low)(Number Of Lights On is Medium)
LI8 = [3 4 4 2 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Evening) then (Intensity(%) is Low)(Number Of Lights On is Medium)

%Low Intensity / High-Full Lights
LI9 =  [4 4 1 2 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Bright)  and (TimeOfDay is EarlyMorning) then (Intensity(%) is Low)(Number Of Lights On is High)
LI10 = [4 4 2 2 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Bright)  and (TimeOfDay is Morning) then (Intensity(%) is Low)(Number Of Lights On is High)
LI11 = [4 4 3 2 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Bright)  and (TimeOfDay is Evening) then (Intensity(%) is Low)(Number Of Lights On is High)
LI12 = [4 4 4 2 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Bright)  and (TimeOfDay is Afternoon) then (Intensity(%) is Low)(Number Of Lights On is High)

LI13 = [5 4 1 2 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is EarlyMorning) then (Intensity(%) is Low)(Number Of Lights On is All)
LI14 = [5 4 2 2 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Morning) then (Intensity(%) is Low)(Number Of Lights On is All)
LI15 = [5 4 3 2 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Evening) then (Intensity(%) is Low)(Number Of Lights On is All)
LI16 = [5 4 4 2 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Bright) and (TimeOfDay is Afternoon) then (Intensity(%) is Low)(Number Of Lights On is All)
```

Figure A.1: Rules 1-21, presented with the code & plain text representation

```
%Medium Intensity / Low Lights
MI1 = [2 2 1 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is EarlyMorning) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI2 = [2 2 2 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Morning) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI3 = [2 2 3 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Afternoon) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI4 = [2 3 1 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is EarlyMorning) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI5 = [2 3 2 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Morning) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI6 = [2 3 3 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Afternoon) then (Intensity(%) is Medium)(Number Of Lights On is Low)
MI7 = [2 3 4 3 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Evening) then (Intensity(%) is Medium)(Number Of Lights On is Low)

%Medium Intensity / Medium Lights
MI8 =  [3 2 1 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is EarlyMorning) then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI9 =  [3 2 2 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Morning) then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI10 = [3 2 3 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Afternoon) then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI11 = [3 3 1 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is EarlyMorning) then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI12 = [3 3 2 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Morning) then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI13 = [3 3 3 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Afternoon then (Intensity(%) is Medium)(Number Of Lights On is Medium)
MI14 = [3 3 4 3 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Evening then (Intensity(%) is Medium)(Number Of Lights On is Medium)

%Medium Intensity / High-Full Lights
MI15 = [4 2 1 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is EarlyMorning)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI16 = [4 2 2 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Morning)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI17 = [4 2 3 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Afternoon)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI18 = [4 3 1 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is EarlyMorning)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI19 = [4 3 2 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Morning)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI20 = [4 3 3 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Afternoon)  then (Intensity(%) is Medium)(Number Of Lights On is High)
MI21 = [4 3 4 3 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Evening)  then (Intensity(%) is Medium)(Number Of Lights On is High)

MI22 = [5 2 1 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is EarlyMorning)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI23 = [5 2 2 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Morning)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI24 = [5 2 3 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Dark)   and (TimeOfDay is Afternoon)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI25 = [5 3 1 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is EarlyMorning)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI26 = [5 3 2 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Morning)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI27 = [5 3 3 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Afternoon)  then (Intensity(%) is Medium)(Number Of Lights On is All)
MI28 = [5 3 4 3 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Normal) and (TimeOfDay is Evening)  then (Intensity(%) is Medium)(Number Of Lights On is All)
```

Figure A.2: Rules 22-49, presented with the code & plain text representation

```
%High Intensity / Low Lights
HI1 = [2 1 1 4 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is EarlyMorning) then (Intensity(%) is High)(Number Of Lights On is Low)
HI2 = [2 1 5 4 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is Low)
HI3 = [2 1 4 4 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is Low)
HI4 = [2 2 4 4 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is Low)
HI5 = [2 2 5 4 2 1 1]; %If (PeopleInRoom is Low) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is Low)

%High Intensity / Medium Lights
HI6 = [3 1 1 4 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is EarlyMorning) then (Intensity(%) is High)(Number Of Lights On is Medium)
HI7 = [3 1 5 4 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is Medium)
HI8 = [3 1 4 4 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is Medium)
HI9 = [3 2 4 4 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is Medium)
HI10= [3 2 5 4 3 1 1]; %If (PeopleInRoom is Medium) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is Medium)

%High Intensity / High-Full Lights
HI11 = [4 1 1 4 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is EarlyMorning) then (Intensity(%) is High)(Number Of Lights On is High)
HI12 = [4 1 4 4 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is High)
HI13 = [4 1 5 4 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is High)
HI14 = [4 2 4 4 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Evening) then (Intensity(%) is High)(Number Of Lights On is High)
HI15 = [4 2 5 4 4 1 1]; %If (PeopleInRoom is High) and (LightingInRoom(Lux) is Dark) and (TimeOfDay is Night) then (Intensity(%) is High)(Number Of Lights On is High)

%Maximum Setting
MS1 = [5 1 5 5 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Night) then (Intensity(%) is Full)(Number Of Lights On is All)
MS2 = [5 1 4 5 5 1 1]; %If (PeopleInRoom is Full) and (LightingInRoom(Lux) is Pitch Black) and (TimeOfDay is Evening) then (Intensity(%) is Full)(Number Of Lights On is All)
```

Figure A.3: Rules 50-66, presented with the code & plain text representation

Appendix B Fuzzy Sets

Mamdani

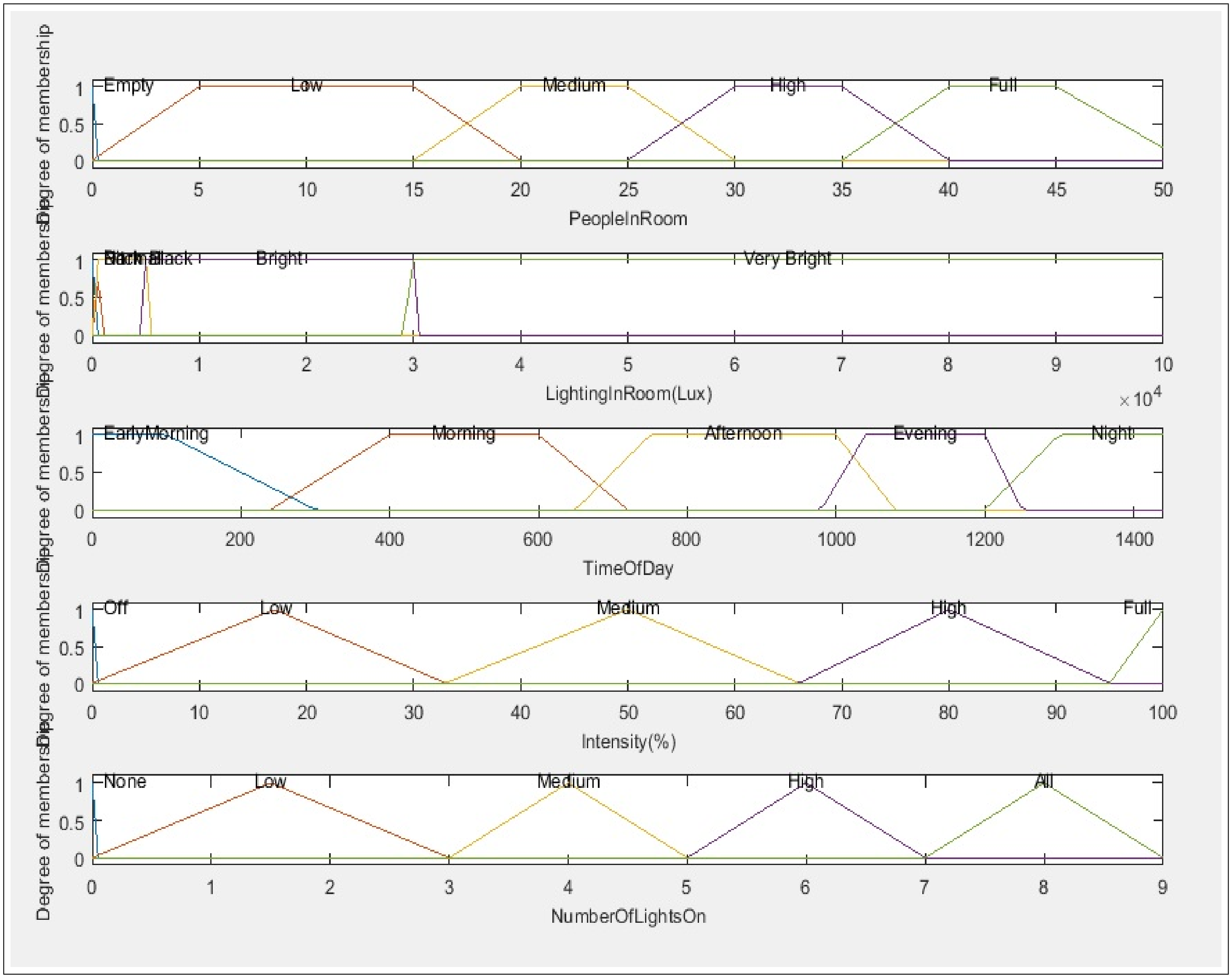

Figure B.1: Fuzzy Sets - Mamdani Model System

Sugeno

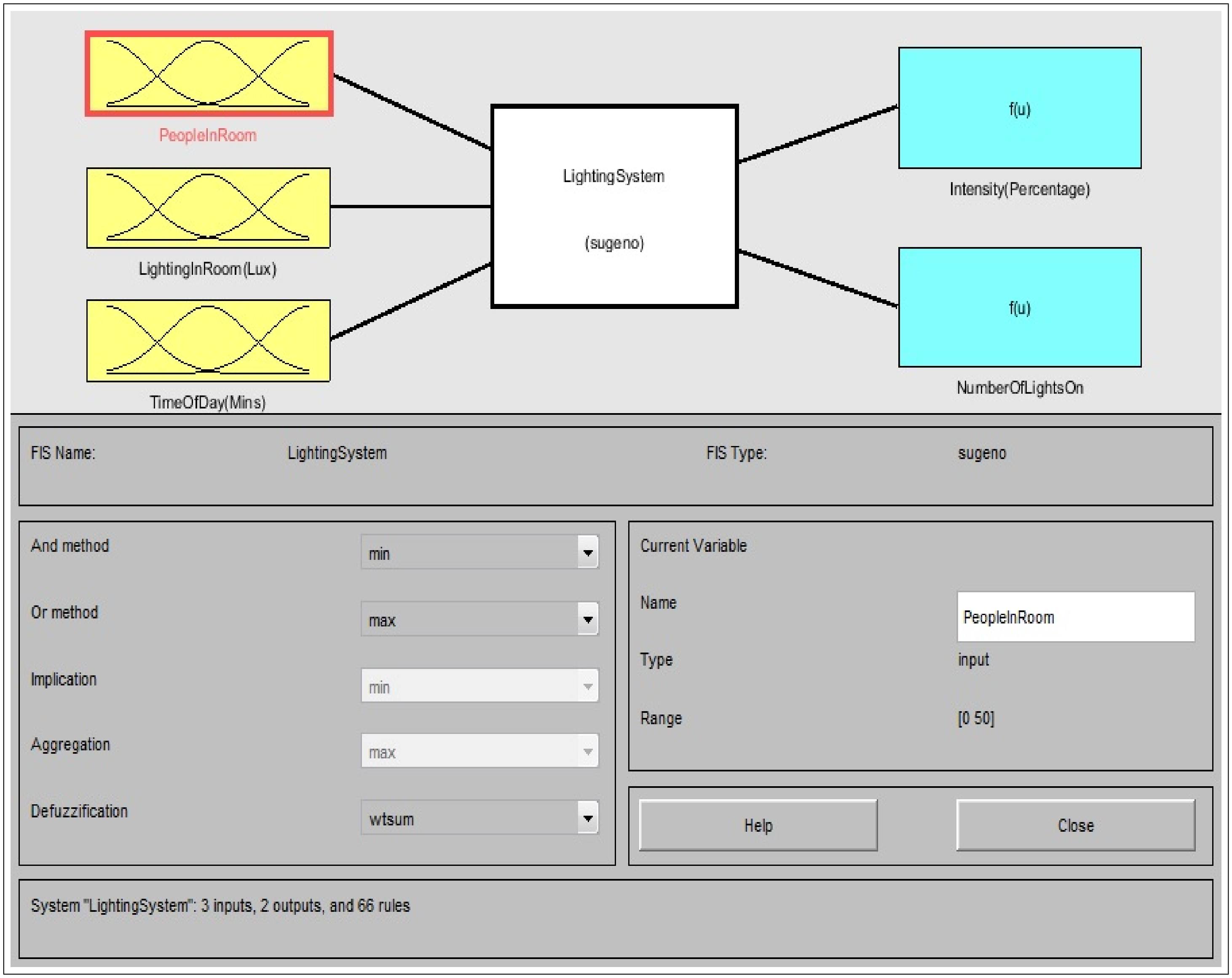

Figure B.2: Fuzzy Sets - Sugeno Model System

Appendix C Full Test Results

XML Tests File

Keys
Data used only for the Mamdani model
Good Inputs – Very Realistic Possible Scenarios Used For Both Mamdani and Sugeno Systems (Testing)
Bad Inputs – Near Impossible Scenarios (Used For Further Testing)
Statements translated into plain English to make them easier to understand

Number Of People	Lighting In Room (Lux)	Time Of Day (Mins)	
0	300	600	
0	5500	1200	
0	29000	870	
0	0	100	
1	0	1440	
5	374	1000	
10	6000	600	
20	50000	250	
25	374	1100	
28	0	1250	
30	5000	489	
33	155	715	
36	34000	1222	
38	2000	1305	
40	29000	950	
41	2555	321	
45	1231	546	
47	55466	1210	
50	5464	240	
0	0	1200	(No people in the room, room is pitch black at night)
0	300	200	(No people in the room, room is dark in the early morning)
1	0	1200	(One person in the room, room is pitch black at night)
4	300	1100	(Four people in the room, room is dark in the evening)
6	600	1000	(Six people in the room, room is normal in the afternoon)
8	5000	600	(Eight people in the room, room is bright in the morning)
10	80000	400	(Ten people in the room, room is very bright in the morning)
16	2500	750	(Sixteen people in the room, room is normal in the afternoon)
25	600	200	(Twenty-five people in the room, room is dark in the early morning)
30	25000	900	(Thirty people in the room, room is bright in the afternoon)
32	60000	500	(Thirty-two people in the room, room is very bright in the morning)
30	0	650	(Thirty people in the room, room is pitch black at night)
33	0	1400	(Thirty-three people in the room, room is pitch black at night)
35	375	750	(Thirty-five people in the room, room is dark in the afternoon)
31	3300	1050	(Thirty-one people in the room, room is normal in the afternoon)
28	7000	250	(Twenty-eight people in the room, room bright in the early morning)
34	70000	1000	(Thirty-four people in the room, room is very bright in the afternoon)
40	0	1040	(Fourty-people in the room, room is pitch black in the evening)
43	670	1300	(Fourty-three people in a room, room is dark at night)
46	4000	150	(Fourty-six people in the room, room is normal in the early morning)
48	10000	800	(Fourty-eight people in the room, room is bright in the afternoon)
50	45000	620	(Fifty people in the room, room is very bright in the morning)
50	0	1200	(Maximum setting test – full room, pitch black at night)
50	0	1040	(Maximum setting test – full room, pitch black at evening)
0	90000	1200	(No people in the room, room is very bright at night)
0	0	400	(No people in the room, room is pitch black in the morning)
5	10000	1440	(Five people in the room, room is bright at night)
50	50000	0	(Fifty people in the room, room is very bright in the early morning)
30	0	1000	(Thirty people in the room, room is pitch black in the afternoon)
45	100000	1300	(Fourty-five people in the room, room is very bright at night)
20	0	450	(Twenty-people in a room, room is pitch black in the morning)

Figure C.1: XML file color-coded with the valid and invalid inputs

Test Results

Table C.1: Test results for the Mamdani model system

Model	NumberOfPeople	LightingInRoom	TimeOfDay	Intensity	NumberOfLights
	0	0	1200	0%	0
	0	300	200	0%	0
	1	0	1200	92%	3
	4	300	1100	83%	2
	6	600	1000	50%	2
	8	5000	600	50%	2
	10	80000,	400	0%	0
	16	2500	750	53%	2
	25	600	200	58%	5
	30	25000	900	17%	6
	32	60000	500	0%	0
	30	0	650	50%	5
	33	0	1400	80%	6
	35	375	750	50%	6
	31	3300	1050	50%	6
Mamdani	28	7000	250	29%	7
	34	70000	1000	0%	0
	40	0	1040	100%	8
	43	670	1300	50%	5
	46	4000	150	54%	8
	48	10000	800	25%	8
	50	45000	620	0%	0
	50	0	1200	100%	9
	50	0	1040	100%	9
	0	90000	1200	0%	0
	0	0	400	0%	0
	5	10000	1440	50%	5
	50	50000	0	0%	0
	30	0	1000	90%	7
	45	100000	1300	0%	0
	20	0	450	50%	5

Table C.2: Test results for the Sugeno model system

Model	**NumberOfPeople**	**LightingInRoom**	**TimeOfDay**	**Intensity**	**NumberOfLights**
Sugeno	0	0	1200	0%	0
	0	300	200	0%	0
	1	0	1200	18%	0.6
	4	300	1100	72%	2.4
	6	600	1000	148%	6.92
	8	5000	600	90%	6
	10	80000	400	0%	0
	16	2500	750	60%	3.4
	25	600	200	0.5%	4.5
	30	25000	900	30%	7
	32	60000	500	0%	0
	30	0	650	0.5%	4.5
	33	0	1400	90%	7
	35	375	750	90%	10.5
	31	3300	1050	82.5%	9.63
	28	7000	250	3.75%	0.75
	34	70000	1000	0%	0
	40	0	1040	33.3%	3
	43	670	1300	0.5%	4.5
	46	4000	150	0.5%	4.5
	48	10000	800	15%	4.5
	50	45000	620	0%	0
	50	0	1200	16.7%	1.5
	50	0	1040	0%	0
	0	90000	1200	0%	0
	0	0	400	0%	0
	5	10000	1440	0.5%	4.5
	50	50000	0	0%	0
	30	0	1000	30%	2.33
	45	100000	1300	30%	9
	20	0	450	0.5%	4.5