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Assessing working conditions using Fuzzy Logic

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Abstract

Working condition assessment is required by Dutch law to obtain approval for occupying building. Nowadays this is a manual procedure that is executed after the building has been realized. Experts are needed to interpret the legislation regulations and test these against what they observe. If this procedure is integrated in the design process, then the risk of costly building changes can be reduced. In this article we describe a system that supports automated testing before building construction using fuzzy logic for reasoning on the working condition regulations. The intrinsic character of the regulations often makes it very difficult to use classical rule-based systems. Instead of stating hard and unambiguous demands, the law contains many rules that are open for discussion, that allow alternate solutions or that are simply put rather vague. In this article we demonstrate that fuzzy logic provides a methodology to formalize such regulations. For testing working conditions, input data are needed about the building geometry and material use, building physics (e.g. lighting) and space utilisation. We describe which data are required and how they can be generated using state-of-the-art research and technology. In a case study, the process of implementing typical regulations shows the implications of automated working conditions checking in practice.

Keywords: Fuzzy logic; Legislation regulations; IFC

1. Introduction

The main purpose of the Dutch Working Conditions Act (WCA) [1] is to ensure three things:

1. safety: no acute dangers for people at work
2. health: no long term or chronic physical health risks
3. wellbeing: no psychological problem caused by working conditions

The WCA is specified in juridical and technical detail in the Working Conditions Decree and the Working Conditions Order. The Decree contains many rules and regulations that are formulated in a general way. Only the intention of the rules is explained, not the means to achieve compliance. Some parts of the Decree are specified in more detail in the Order, giving threshold values for dangerous materials, specifying rules regarding working with computer terminals and hoisting cranes amongst others.

One of the most important tools the WCA provides to establish the level of safety is the Risk Inventory and Evaluation (RI&E). The Inventory has to be performed on a regular basis and verified by a certified professional, preferably within the organization. Usually, an Occupational Health and Safety Professional will analyze an organization and study the building during a thorough inspection tour, using a standardized method which is very often combined with a survey amongst the buildings' users. The most commonly used methods make use of an extensive checklist in which many facets are considered, among which:

1. The policies on absenteeism.
2. Sound levels.
3. Lighting and daylight.
4. Indoor climate and ventilation.
5. Physical labour.
6. Workplace layout.
7. Machinery and tools.

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8. Toxic and other hazardous materials.
9. Rest-regime.
10. Qualified First Aid personnel and fire-drills.

Based on those findings, a list of problems is drawn up. These are evaluated based on an 'odds and effect' principle: what are the odds an accident will occur, and what are the effects should it occur. Based on these results a list of prioritized action list is compiled.

As can be seen, the actual building is only part of this list, though not an unimportant one. Whereas policies can be altered easily and machines can be replaced if they do not comply with the WCA, changes to the building are often very expensive and on occasion even impossible. This is one of the reasons why a check of the building beforehand could prevent a lot of problems from even occurring.

Currently the WCA laws are written in natural language. It contains many rules that are open for discussion, that allow alternative solutions, or that are simply put vague. This makes the rules very hard to formalize in the traditional rule-based way. The focus of this research project is to find a way in which this can be done such that the computer can reason with the WCA laws. An RI&E performed by a WCA professional is a highly interactive, subjective process that requires a lot of knowledge, good insight and a healthy dose of good judgment. To enable a computer to perform at the same level would be all but impossible. The problem is tackled by using Fuzzy Logic [2] to encapsulate the non-formal WCA-regulations. This allows for reasoning at a more 'natural' level, using linguistic variables and incomplete or imprecise data. An example of the WCA is presented below:

Article 5.4 Seating accommodation

An appropriate seating accommodation is provided for an employee who performs labour that is done entirely or partially seated.

As can be seen from the example, the WCA contains very vague regulations that require expert knowledge to be tested. It is not stated what an appropriate seating accommodation is, nor which proportion of work falls under 'partially seated' to make this rule apply.

Many of the regulations of the WCA deal with the indoor climate, such as the requirements for daylight and fresh air. These regulations refer to different NEN/NEN-EN or ISO standards, such as NEN-EN-ISO-7730, "Ergonomics of the thermal environment". This norm utilizes the term "Predicted Mean Vote" which is an indication for the amount of complaints that might occur. The general rule is that this amount should in principle never exceed a ten percent limit (there is a 150 h contingent per season in which it is allowed). Apart from the annoyance caused by indoor climate problems, there's also the chance of people becoming ill. Even though for example a slightly too low temperature is not an immediate serious problem, it can eventually lead to psychological complaints. In economical terms this causes a reduction in productivity and a higher degree of absence. The Working Conditions Act (WCA) is primarily concerned with the human well-being component and not with economical ramifications, but there is of course a connection between the two aspects.

Fuzzy logic has been research as a technology that can support both the fuzziness of the WCA regulations and the crisp building data. The building data consists of geometrical data (e.g. space dimensions), physical data (e.g. temperature) and organisational data (e.g. number of persons). To test the feasibility of this approach we developed a prototype WCA compliance tester. Our system only focuses on those parts of an RI&E that have to do with building related risks The objectives are: (1) to give the architect and project developer an insight in possible WCA-issues, and (2) to give the WCA-expert a certain leverage with an objective 'second opinion' that supports his conclusions. A selection was made that reflects the different types of regulations in the law, ranging from precisely described minimal dimensions (such as the width and height of emergency exits) to subjective, vague, emotional requirements (such as privacy in open office spaces).

The outline of the article is as follows. First we discuss related research in the field of code checking and safety evaluation. Next we present the software architecture of the WCA compliance tester we developed and specifically how fuzzy logic technology is applied. In a case study the process of implementing typical WCA regulations in fuzzy rules is described in detail. In the conclusion section we discuss the feasibility of automated WCA compliance checking with regard to current legislation formalisation and building model standardisation.

2. Related research

Related work is found in two areas namely Building code checking and Construction safety evaluation. Building code checking research has focus on the problem how to represent the building data and the code data in such a format that it allows for automated checking. Noticeable research projects are from Woodburry et al. [3] and from Yang and Li [4]. The first apply typed feature structures and logic programming that are used to implement the building data as well as the building code. The latter follow an object oriented approach utilizing existing technologies for the building data, namely IFC [5], and for the building code, namely JESS [6]. A well known example from practice is the CORENET (CONstruction and Real Estate Network) project [7]. In this project a system named e-PlanCheck was developed for automated code compliance checking. The core of the system is the IFC Building model repository [5]. However, since the IFC model is not sufficient for code checking, the model is extended with so-called FORNAX objects. The FORNAX objects encapsulate the IFC object and add the higher level semantics that are necessary for code-checking. Construction safety evaluation focuses on the human activities that take place on the construction site, which might lead to hazardous situations dependent of the type activity and the actual circumstances. Systems have been developed to predict if such situations might occur using construction planning and a database of historical data about accidents as input. Examples of such research are [8,9].

Work conditions assessment differs from the above research because it aims to investigate the quality of the work environment for an employee or visitor rather than the building code as such.

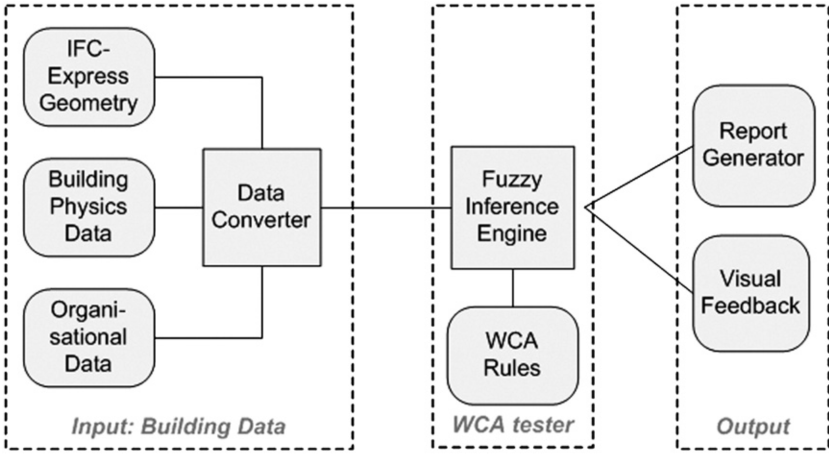

Fig. 1. WCA test modules.

Also, in contrast with building codes we can observe a higher degree of implication and ambiguity in WCA than is used in building code checking and construction safety evaluation. Therefore we opted for a different approach, namely Fuzzy Logic, to research whether this is a feasible technology for testing WCA regulations.

3. WCA-compliance test

The WCA compliance test consist of the following modules: the input module, where all required input data are collected from other recourses and converted input into a single format, the actual WCA tester application that contains the WCA rules and two types of output: textual and graphical. These modules are subdivided into smaller components as presented in Fig. 1, which are discussed in detail below.

3.1. IFC-geometry

An increasing number of software developers support IFC import/export. In this project Autodesk/Revit version 9 was used. Although the latest IFC standard (version 2 edition 3 at the time of this writing) is quite extensive, it's unlikely to assume that all data for WCA compliance testing is included. In practice, like in the CORENET system, additional data needs to be added or must be inferred from the available data. In the limited case study in this research project (see Section 4) all data could be retrieved from the IFC model generated by Revit.

3.2. Building physics: light conditions

EcoTect was used for light calculation. Unfortunately this program does not support IFC import. Therefore the model was converted into a (3D Studio Max) 3DS format. In order to simulate artificial lighting a number of light-sources have been placed in the model as well. For the resolution of the calculation, a grid size of 0.50 m squared was selected, which resulted in approximately $80\times60=4800$ squares. Even at this resolution the calculation process took many hours. EcoTect offers the possibility to export the data generated by the Lighting Analysis calculation in a very simple format; each row in the output file contains the values of all the grid-fields (expressed in Lux).

3.3. Organisation

For generating the organisational data, we applied the USSU (User Simulation of Space Utilisation) system developed at EUT [10]. On the lowest level, USSU uses nodes which are locations where a task can be performed. One or more nodes are placed in a so-called abstract-space (room, hallway, ect.) An abstract-space

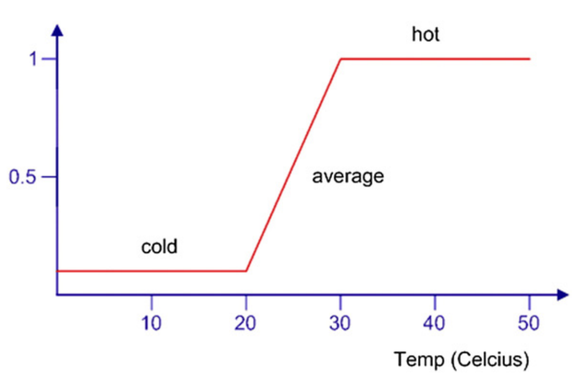

Fig. 2. Fuzzy set of Temperature: X-axis=temp in Celcius, Y-axis=degree of membership.

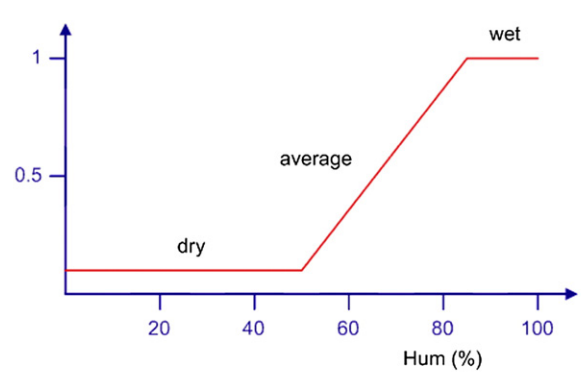

Fig. 3. Fuzzy set of Humidity: X-axis=hum in %, Y-axis=degree of membership.

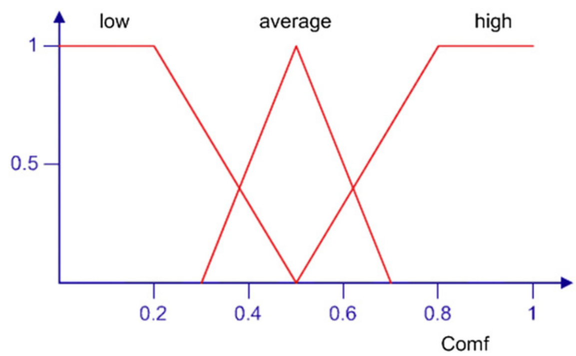

Fig. 4. Fuzzy set of Comfort: X-axis = comfort (normalised), Y-axis = degree of membership.

can also contain other abstract-spaces, e.g. the abstract-space 'Floor' contains all spaces on that floor in the building. Each individual in an organisation has a role and associated to that role, a list of activities. A set of AI modules in USSU generate a schedule for each individual. Consequently, the schedule consists of activities that are part of the role definition (called the 'skeleton activities') of that person complemented with arbitrary activities such as getting a drink, taking a bathroom break, smoking a cigarette etc. (those are called 'intermediary' activities). The scheduler also takes interaction between people into account, for instance when planning a meeting or a presentation. For this project a set of eight of these daily schedules were used as basis to determine: (1) the number of hours a room is occupied each day, (2) the amount of people that use a certain corridor, and (3) the number of people working in the room.

Since USSU does not import IFC models, a manual check had to be performed, to ensure a consistent naming and numbering of rooms to allow for the WCA-compliance test to be performed. USSU uses an XML-file format to export its data. There are two types of files required for the WCA-compliance testing:

1. The description of the building model and the hierarchy of abstract-spaces and nodes.
2. The activity-schedule itself, containing the list of all scheduled activities of all people in the virtual organization. This consists of a list of activity entries. An activity entry holds information about the location in which the activity is taking place, and the duration.

3.4. Fuzzy rules engine

There are two places where knowledge is modelled in a fuzzy rule-based system. The one is in the membership curves, where the boundaries for the different fuzzy sets are specified. Possible sources are surveys (or statistical data), literature, common sense or expert knowledge. The other place is in the rules that are defined for the inference system (e.g. IF A THEN B). Usually these are composed by someone with expert knowledge in combination with a knowledge engineer.

Let's assume we want to implement the following Fuzzy Logic rules:

1. IF temp IS hot OR hum IS wet THEN comfort IS low
2. IF temp IS average AND hum IS average THEN comfort IS high

Then we need to specify two input variables, namely temp (Fig. 2) and hum (Fig. 3) and one output variable, namely comfort (Fig. 4). For each variable the fuzzy sets and the mathematical expression for the membership function are defined. The temp variable consists of three sets: cold, average, hot. Similarly the hum variable and comfort variable are determined. Often simple linear functions are used to represent a continuous fuzzy set as show in the Figures.

Suppose that we know that the temperature is 27 °C and the humidity is 75%. If we look up these values in the membership curves we can see, that the temperature would be somewhere around 0.7 and the humidity around 0.8.

For the evaluation of the OR and AND clauses from Rule 1 and Rule 2 respectively, w apply the classical fuzzy set theory [2]. In this case max (0.7, 0.8) = 0.8 (see Fig. 5: left), and min(0.7, 0.8) = 0.7 (see Fig. 5: right).

Now we can aggregate the two results into one schema. To determine the output variable we apply Mamdani's Center of Gravity (COG) method [11]:

$$COG = \frac{\int \mu_A(x)x dx}{\int \mu_A(x) dx} \quad (1)$$

In this example it's a rather simple calculation since the shape of the area is very simple (as can be seen in Fig. 6: left). The resulting comfort value has a higher Degree of

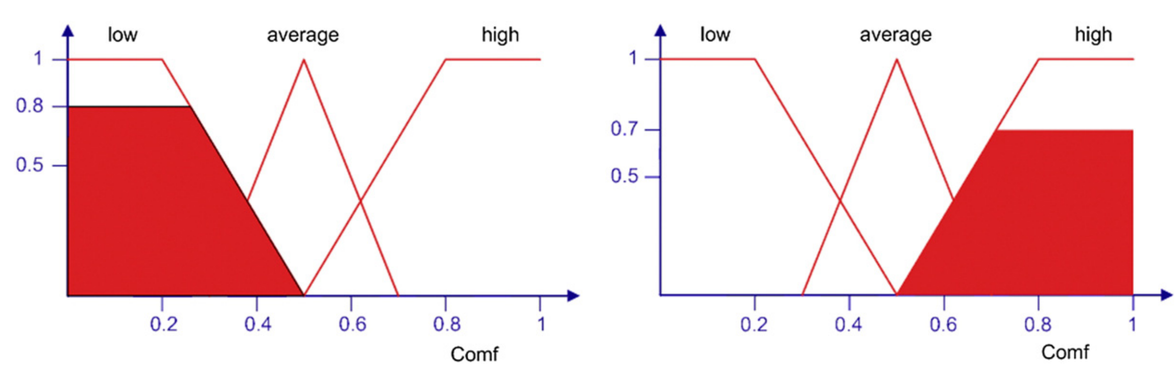

Fig. 5. Degree of membership after evaluation of Rule 1 (left) and Rule 2 (right).

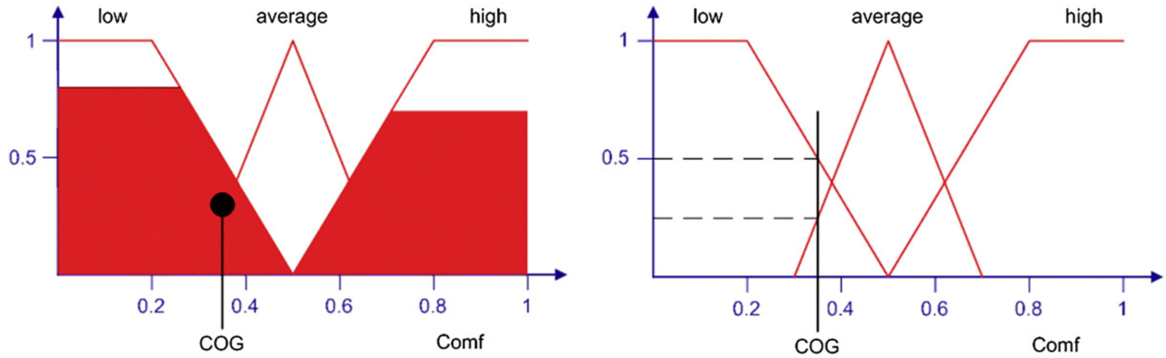

Fig. 6. Fuzzy set of Output variable Comf: *X*-axis = comfort (normalised), *Y*-axis = degree of membership.

membership for ‘low’ than for ‘average’. Thus the defuzzyfied outcome in this case is a ‘low’ comfort. If more rules would have applied to this particular case, the resulting graph could have been more complex and the calculations less straightforward. For more elaboration on this subject refer to refer to [12].

The implementation of Fuzzy Logic in this project was done with the use of the Matlab Fuzzy Logic Toolkit. Each of the building components in the building model that are tested has its own Fuzzy rule sets. The Matlab toolkit requires each component instance to be subject of the applicable rule set. The outcome of the WCA test is exported to a (plain-text) .FIS-file containing an output vector for each compliance check (see Fig. 7). The output vector contains the value for the degree of membership of the tested WCA condition.

3.5. Report generator and visual feedback

After the test has been run, the user can select ‘view results’ to send the IFC-file to the viewer. The viewer, which is available through the official IFC site [5], offers many options to hide and display several parts or categories in the model. This allows every object to be inspected. The building objects that are not compliant with the WCA regulation have a red colour property. Wireframe rendering mode (Fig. 8) proves the easiest way to show all invalid entities at once.

4. Case study

As a case study we took the ninth floor of our faculty building. This floor contains 26 rooms for the scientific staff and open office spaces for PhD students. Because the floor plan is very deep, there

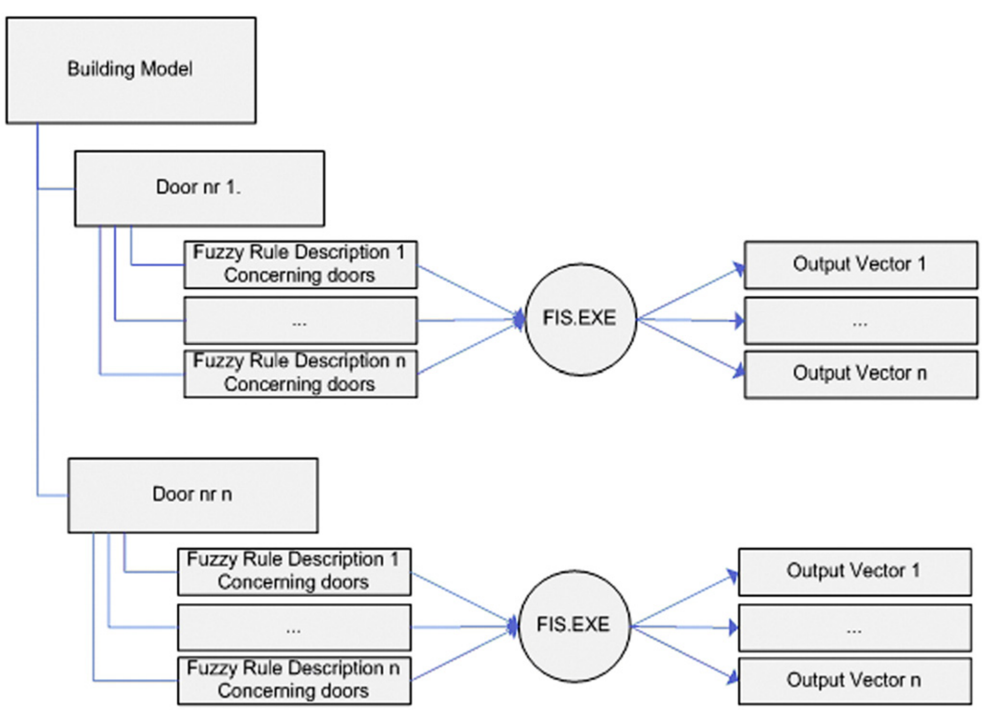

Fig. 7. Fuzzy rules engine.

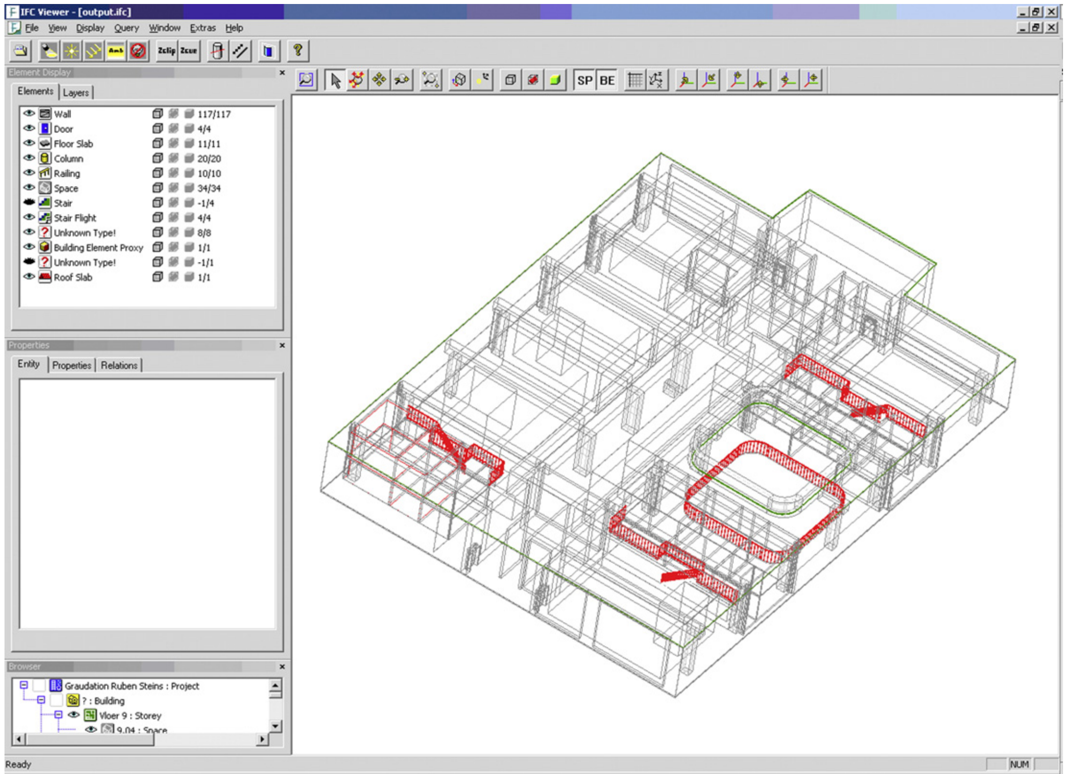

Fig. 8. A model with WCA-invalid objects showing red.

is an atrium which provides daylight. Some offices can only be reached by stairs. The existing WCA regulations consist of thousand (simple and complex) checks. Because we are looking at a proof of concept, we selected seven different types of checks that are fairly representative for the WCA checks. The seven WCA checks are:

1. Dimensions of emergency exits.
2. Size of offices with regard to working hours.
3. Privacy problems on open work floors.
4. See-through windows in doors.
5. Adequate fencing around voids.
6. Sources of pollution (e.g. laser-copiers).
7. Lighting level in office spaces.

In the following section we give a comprehensive description of one WCA check in the system as an example. The appropriate WCA-policies are given, as well as the Fuzzy variables and membership curves.

4.1. WCA-check: size of offices with regard to working hours

The Working Conditions Order, 2.4 states: 'Each firm must have a policy stating in what way the personal privacy of individuals is guaranteed'.

The feeling of privacy is very subjective and has to do with many aspects. The (fuzzy) rule must give a valued result stating whether privacy problems are likely to appear. Today the WCA

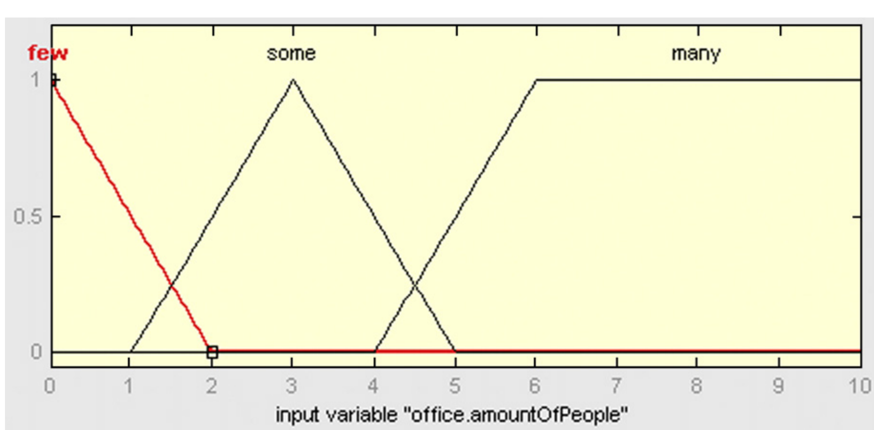

Fig. 9. Fuzzy set of office.amountOfPeople: X-axis = office.amountOfPeople, Y-axis = degree of memberschip.

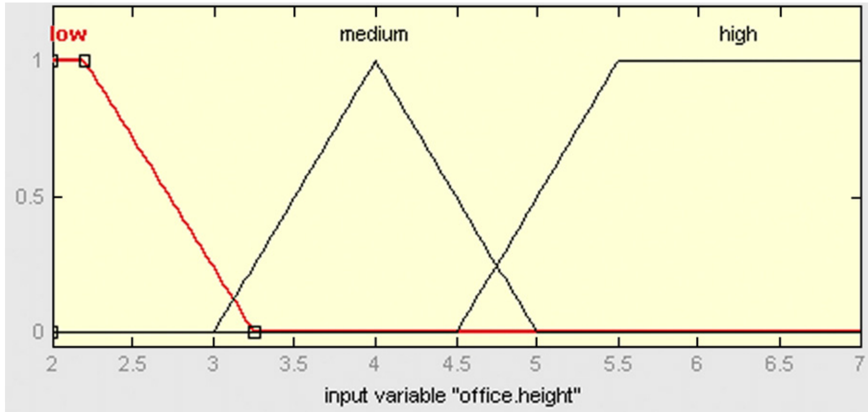

Fig. 10. Fuzzy set of office.height: X-axis = office.height in meter, Y-axis = degree of memberschip.

expert is responsible for making an interpretation of the working conditions order in the context of the specific situation. Since there are no precedents in this field our only reference to make an interpretation using literature from environmental psychology [13] and building physics [14]. Finally we checked our interpretation with the WCA expert of the university office. It is important to notice here that although the following rules have been confirmed by the WCA expert, there is a fair chance that another WCA expert would come up with different results, because as stated in the introduction, the interpretation is subjective. In our case study the following relationships were assumed:

- In offices that are shared by many people, the chance that privacy problems occur is higher.
- Rooms with high reflective ceilings and walls cause more sound resonance. Higher sound level means more inconvenience, which results in less privacy.
- Rooms adjacent to busy corridors suffer from higher sound levels, resulting in more inconvenience.
- Rooms next to windows give a higher feeling of privacy, since people have a visual escape away from the office space.

These relationships were translated into input variables and membership functions. Input variable one, 'office.amountOfPeople' categorizes the amount of people that have to share an office space to few, some or many, depending on the given value (Fig. 9):

The second input variable, 'office.height' gives an indication of the height of the room. This can be either 'low', 'medium' or 'high' (Fig. 10):

Similarly the membership functions for office.adjacentCorrider ('noneOrQuit', 'avarage', 'busy') and vicinity.window ('closeBy', 'avarage', 'farAway') are defined.

There is one output-variable called 'privacyProblems' which indicates the importance and likelihood of possible privacy problems (Fig. 11):

The four input variables with can each take 3 values results in principle into $3 \times 3 \times 3 \times 3 = 81$ rules to define all possible combinations between the input values and the output values. From the stated relationships not all of these rules can be deduced. Some combinations are irrelevant and not accepted as input, but still 60 rules were needed for this working condition order.

4.2. Running the WCA-compliance test

As described in Section 3, before the WCA compliance test can be run the input data for the test case are prepared, namely the IFC geometry (in Revit), the lighting (in EcoTect) and the organisation (in USSU). The rules are formulated (in Matlab) for the

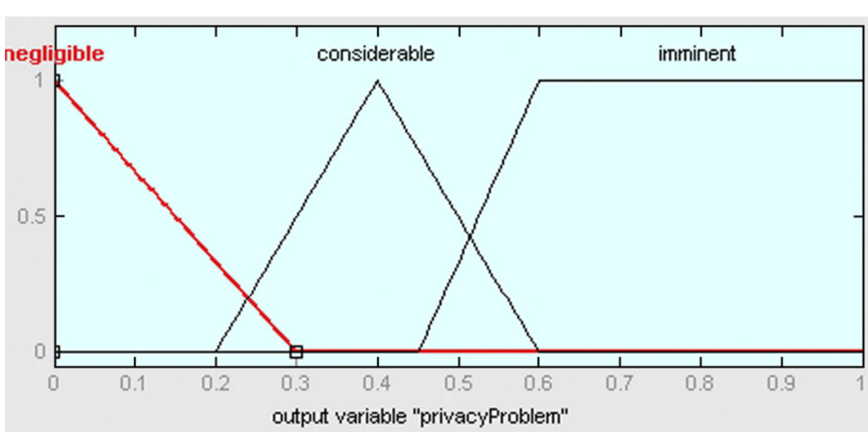

Fig. 11. Fuzzy set of privacyProblems: X-axis = privacyProblems (normalised), Y-axis = degree of membership.

seven WCA checks. The prototype WCA tester reads the input files and calls the Matlab Fuzzy Logic inference engine to execute the rules. The output (conflict with rule nr. X) is exported from Matlab and added to the IFC file. The extended IFC file is imported into the IFC viewer to visually check which building components are subject to WCA compliance test violation.

4.3. Test case results

Running the prototype WCA tester for the seven WCA checks renders the following violations.

- The railings: all railings are marked invalid by the system. The opening between the bars of the railing exceeds the allowed distance. The explanation here is that the prototype system is unable to detect kicking-borders along the bottom or the railings, because they are not part of the IFC model. In case of a kicking-border a bigger distance is allowed.
- The offices: all offices that are only accessible through stairs, are rejected, due to their limited height. The same conclusion was drawn by the official Risk Inventory and Evaluation (RI&E) of the building that was performed earlier. The offices are only allowed to serve as temporary workplaces. In practice however, all these offices are used as permanent workplaces.

5. Conclusions

Building code checking systems are usually based on an extended IFC model and apply classic rule-based systems. In contrast with building codes, working conditions codes are not specified as hard and unambiguous demands. Since to our knowledge no previous attempt has been made of a system that can evaluate WCA-compliance of building models, there was doubt whether this could actually be achieved. The prototype and theoretical design prove that this is feasible. Using well-designed fuzzy rule-based systems, which can be developed by a knowledge engineer and a WCA-expert, the requirements contained in the WCA-legislations can be captured. This often requires the WCA experts to make many conditions explicit that usually are implicitly formulated in the rules. Since the WCA regulation interpretation is subjective it will lead to different rules even within WCA experts. In the Netherlands this problem has been acknowledged and therefore WCA information sheets have been released, that reflect the common understanding on the interpretation between the experts. Although these information sheets have no legal status, in practice they serve as the WCA inspection guidelines. One step further in this process is the development of fuzzy rule sets that can be applied by automated WCA-compliance checking before the building is actually constructed. Rule specification is a very labour intensive process because of the many WCA regulations and the input variables that are part of these. However once this task is done the effort will pay-off because of the re-use of this encoded knowledge with every new building design.

A precondition for automated WCA-compliance checking is the availability of digital building data. Unfortunately, only a limited number of CAD vendors support the IFC standard and often not strictly and to its full extend. Even less IFC support is found in the field of domain specific applications such as needed for the calculation of the physical conditions. Nevertheless, IFC is a good basis for WCA-compliance checking. In practice more intelligent tools are necessary to infer or to collect the required information that cannot be retrieved from the IFC model directly. Much research is going on the domain of Semantic Web technology to support communication and reasoning using IFC data [15]. WCA-compliance checking will benefit from these developments, because fuzzy rule systems fit well within these new technical frameworks.

Finally we believe that WCA-compliance checks prior to the actual building phase will prevent a lot of building-related problems that have a negative influence on workers' safety, health and well-being.

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