Fuzzy computing for layout design in ill-defined, uncertain spaces

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Layout design has been supported by some computational tools, where fuzzy systems have been approved as an appropriate method to handle uncertainty in the early design stage. In this paper, a new mathematical model depending on the fuzzy logic and sets theory is proposed to assist in layout design. The model distinctly deals with spatial uncertainty in open planned designs, where there is no clear layout configuration or definite patterns of usage. The model calculates the possibility of occupancy according to space, function and user related parameters and logical rules. It also visualises the architectural plan as being comprised of sub-spaces formed by the distribution of those possibilities. Sub-spaces are characterised as "Fuzzy Architectural Spatial Objects" (FASOs). As a result, layouts are represented as an accumulation of FASOs showing a certain inhabitation pattern. Various layouts can be generated within the identity of FASOs. Architects can evaluate the layouts and propose new ones by organising the FASOs on the plan and considering their relations. After describing the model the paper demonstrates an application which aims to design a proper layout for a major exhibition hall in Istanbul.

Keywords: *Spatial uncertainty, Open-plans, Inhabitation patterns, Layout design, Fuzzy Architectural Spatial Objects (FASOs)*

INTRODUCTION

Spatial uncertainty is prevalent in fluid and continuous spaces, where an entire space is occupied in a holistic way, and multi-functionality plays an important role. It is experienced in free and open plan designs that are not divided into cell-like rooms by doors or walls. This lack of clear spatial configuration makes the task of modelling inhabitation patterns complex and difficult. The few equivalent methods to handle spatial uncertainty include space syntax and relevant morphological theories, agent-based models, simulations of gaze dynamics, behaviour maps, and GIS-tracking and GPS. Recently, a new approach depending on fuzzy computing was introduced by Cekmis et al. (2014) to predict and simulate occupational behaviour in response to higher levels of uncertainty. Seeing open plans as an ensemble of various temporary 'sub-functions' and their virtual 'sub-spaces,' "Fuzzy Architectural Spatial Objects" (FASOs) was devised to represent sub-spaces.

FASOs were characterised as fuzzy subsets within complex environments. A FASO was a spatial entity that is comprised of persons whose possibility of presence changes from 100% (completely present) to 0% (completely absent). By using fuzzy reasoning, the proposed model was capable of calculating and visualising the FASOs on plans according to certain parameters; thereby mapping the possible spatial usage in ill-defined, uncertain spaces. The model was applied to analyse the inhabitation patterns of the "Dali Exhibition" in "Tophane-i Amire Exhibition Hall," Istanbul, and its efficiency was tested against observed behaviour.

The capacity of the model showing how an open planned space will be occupied can be used in the preliminary design stage to provide feedback to the project at hand. Accordingly, the aim of this research is to suggest the model as a layout planner in the design process. The model presents architectural plans as the scatter of the FASOs to assist in layout design. The model can generate numerous layouts for total spaces based on usage prediction. Architects could decide on one of them by evaluating the sizes and relations of the FASOs, for any aspect such as functional requirements. This property of the model is exercised through a case study. The layout of the "Palladio Exhibition" in "Tophane-i Amire Exhibition Hall" was designed for the installation of the seventeen wooden architectural models of the buildings by Andrea Palladio, the famous 16th century Italian architect.

Considering the uncertainty and ambiguity in the early design stage, fuzzy modelling was used for the floor plan designs. Koutamanis (2007) proposed a digital equivalent of analogue sketching which allows designers to register and manipulate imprecise and uncertain information. The fuzzification of crisp forms created more flexible and adaptable shapes by expressing degrees of tolerance, incompleteness and uncertainty. Bayraktar and Cagdas (2013) proposed a digital design tool which allowed creating sketch-like footprints. The user could create layouts made of bubbles for the spaces needed. The bubbles were moving dynamic parts which had fuzzy boundaries. The vague definition of the placement of the spaces brought more opportunities in the design process. Those approaches focused on not losing the uncertain or creative language of sketches and concept models in the preliminary design stage. The abstract level of the layout idea was converted into a digital representation. However, the layout planning by the model introduced in this paper does not follow the architects' intentions but the patterns of inhabitation. The model does not deal with uncertainty in the way floor plans are designed but the spatial uncertainty inherent in the floor plans of total spaces. In that sense, the model creates 'layouts' for open plans, where architects intentionally leave the interior configuration unplanned, without sketches or any other descriptive material, in order to create more adaptable and flexible systems for changing environments.

The paper first describes the notion of the FASOs and introduces the fuzzy computational model. Later, the layout planning capacity of the model is explained through an application.

THE MODEL AND THE FASOS

The novel approach uses the fuzzy logic and sets theory as the appropriate method to deal with uncertainty; in both the expression of sub-spaces as FASOs and in assigning the possibilities of people involved in those sub-spaces.

Fuzzy systems are ideal for expressing spatial identity of open-plans, since fuzzy logic is based on the notion of partial (relative) truth, and fuzzy sets have imprecise boundaries different from crisp sets, thereby allowing gradual membership. A total space could, hypothetically, be seen as a fuzzy set where each sub-space (and its sub-function) is a fuzzy subset. The whole, two-dimensional space is 'the universe of discourse' of the fuzzy set. The smallest unit of this space, which can accommodate a person, is an element or member. Spatial units (centroids) are obtained when the architectural plan is divided using a 50 by 50 cm grid. Centroids can reside in more than one sub-space with different membership degrees ($0 \leq x \leq 1$); consequently a sub-space can be comprised

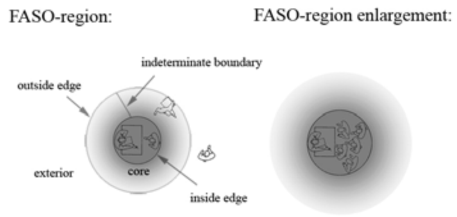


Figure 1
A FASO

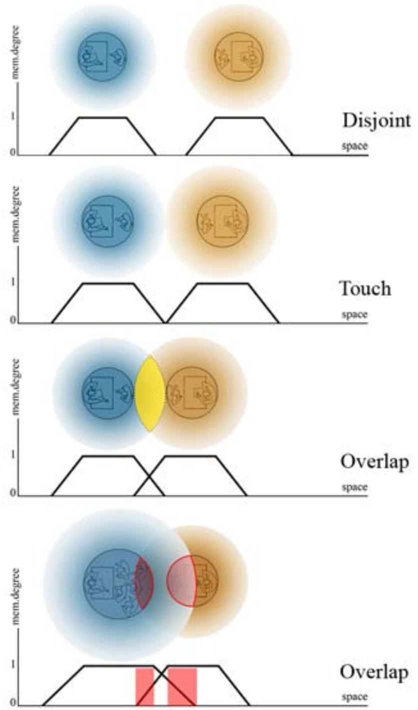


Figure 2
Topological relations

of members with various differing degrees of belonging. This is the fundamental attribute of spatial uncertainty, where no physical boundaries of sub-spaces exist and people can fulfil multiple functions within different sub-spaces simultaneously.

The sub-spaces in the model are defined as FASOs, adopted from the concept of "Fuzzy Spatial Objects" (FSOs) which are used by geographers to apply the value of the multiple membership capacity into the spatial entities. This conceptual tool is proposed to identify architectural spaces with imprecise or vague spatial attributes. The fuzzy objects are comprised of fuzzy points, lines and regions. As the most relevant, a FASO-region has three zones comprised of spatial units with different membership values in the fuzzy set: "the core" ($x = 1$), "the indeterminate boundary" ($0 < x < 1$) and "the exterior" ($x = 0$); which describes the possibilities of being wholly or partly involved in the activity (sub-function), or being totally disengaged from it. These zones of a region are virtually constructed in the space. The borders between the zones are not demarcated physically but through conceptual separations that are flexible and permeable to members. They support a free flow of possibilities of involvement or engagement in the space. So, the FASOs in space are neither stable in size nor in shape; they are able to enlarge, diminish, move, merge, separate or disappear. They may also transform into each other. The topological relations of the FASOs, including disjoint, touch (meet) and overlapping, help to make deductions about the use of space (Figure 1 and 2).

The model serves to calculate and visualise the membership values in spatial units thereby revealing the FASOs on an architectural plan. Both phases are run in MATLAB. Membership degrees are calculated through a fuzzy inference system of pre-set parameters and logical postulates which conceptualize possible occupational behaviour. The method of fuzzy reasoning is used, since spatial uncertainty is not related to frequency or randomness (which requires probability theory) but to the inherent complexity and indeterminacy of human usage of space.

The parameters affect the membership degree of a centroid by either increasing or decreasing the possibility of a person's presence in that spatial unit. They can be grouped into three areas: space, function and user. These are the main factors shaping the formation of a FASO. These parameters are the inputs, and predicates on which the logical postulates in the calculation process are based.

The calculation side of the model is undertaken

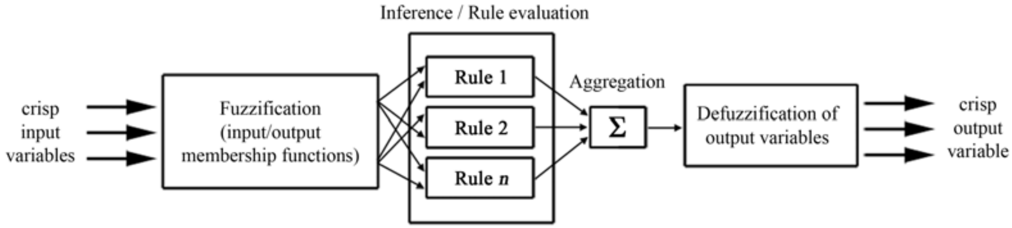


Figure 3
The FIS process

using a fuzzy inference engine; including a fuzzy inference system (FIS) and, input data file which is the whole list of parameter variables of all the spatial units. The FIS takes the input data which it processes using fuzzy reasoning and set theory through a series of control rules to calculate the output data; the membership degree. The FIS involves five steps: fuzzification, rules, inference process, aggregation and defuzzification. Figure 3 shows the flow of the process of FIS.

When the overall calculation process is completed, a list of outputs of all centroids is produced as a precursor to visualisation. After the outputs are arranged on a matrix that corresponds to the spatial units on the architectural plan, two-dimensional interpolation is applied in order to provide a robust visualisation in terms of sensitive colour gradients and higher image resolution. The image process of the model makes the FASOs appear by representing their core, exterior and intermediate values on a heat map. In practical terms the colours describe the likelihood of people being present in a sub-space. When the visualisation process is completed, the total space is illustrated as an accumulation of the FASOs with different sizes and shapes indicating the probability of inhabitation.

The model mapping spatial usage provides a framework, as it is open to the addition of new rules and parameters to suit specific conditions. As a case study, the Dali Exhibition (from 23 December 2011 to 26 February 2012) in Tophane-i Amire Exhibition Hall was analysed by using the model. Tophane-i Amire is a historical building in Istanbul and houses various major touring exhibitions (Figure 4). It has a rectangular symmetrical plan scheme of 1150 m^2, which, despite its pillars, can be regarded as an open plan. The Dali Exhibition contained 121 drawings hung on display walls (Figure 5).

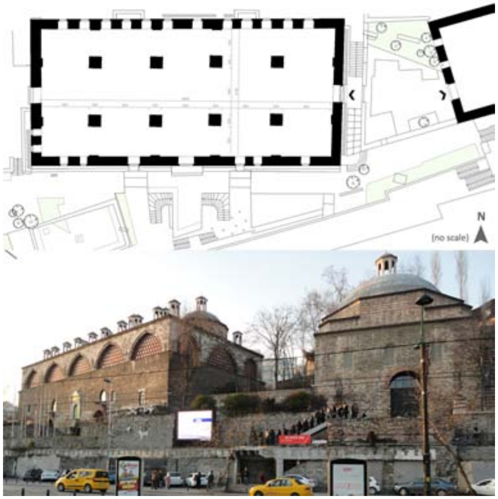


Figure 4
Tophane-i Amire
Exhibition Hall

In this application, 2849 centroids of both the habitable and uninhabitable dots on the 37x77 grid were identified. Four key parameters were selected; space related parameters: the distance from the viewing point, the distance from the order line point, visual integration, and a user related parameter: population. Some parameters were deliberately not chosen; like the function related inputs; "the number of exhibits" since it was fixed for the duration of the exhibition, and "popularity" since all the pieces of art in the collection were prominent and on a par with each other. The fact that people chose to attend the exhibit was also taken as a basis to ignore personal preference parameters.

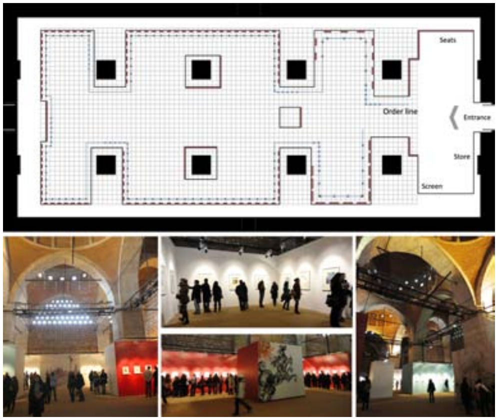


Figure 5
The Dali Exhibition

FIS was built as a four-input, one-output, and forty five-rule analysis problem. For each centroid, it transformed the crisp inputs to fuzzified inputs (fuzzification: input to inputmf), then to fuzzy outputs (evaluation of the fuzzy control rules: inputmf to outputmf), and finally to the single crisp output (aggregation and defuzzification: ouputmf to output). The list of 2849 membership degrees proceeded to visualization. The visualisation processes were operated according to the guideline issued earlier.

The exhibition space was then represented as being comprised of FASOs showing the possible inhabitation pattern of that specific condition. The process was repeated three times for the three visitor population density values; low, middle and high (Figure 6). The other inputs remained constant, since the display layout did not change. As the result of three usage maps, the spatial arrangement of the Dali Exhibition in Tophane-i Amire was efficient and effective for a lower population density, but it was less so for much higher densities. The crowd began to undermine the proper engagement with the art objects in functional terms, as three or more people were involved in the same sub-function. Also, the queuing zones blocked the view when they formed around display walls and interrupted the visitor flow on the main circulation paths. By using photographs and video recordings, the efficacy of the models was tested. The predictive maps broadly replicated the observed usage of space. The model captured well what was happening in the real space.

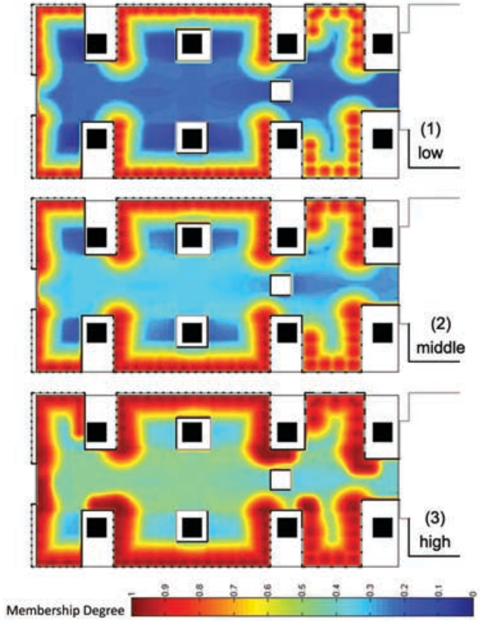


Figure 6
The results of the Dali Exhibition

In sum, the pattern of inhabitation pertaining to higher density levels could be foreseen (and potentially avoided) by modelling the FASOs and evaluating their topological relations. The disadvantages caused by the increased population could be eliminated through minor adjustments, such as hanging paintings with a wider gap between them or simply taking the fake column away to remove the corridors. Alternative layouts could also be modelled and evaluated before the installation. Following this notion, the next section will focus on the layout planning capacity of the model by analysing a different exhibition in the same hall.

Figure 7
The Palladio Exhibition

THE MODEL FOR LAYOUT DESIGN

In this case study the fuzzy computational model is advanced to support design decision on layout planning. The Palladio exhibition (from 29 November to 31 December 2010) in Tophane-i Amire was a collection comprised of seventeen wooden architectural models (Figure 7). This exhibition was intentionally chosen for this research. Unlike pictures that need to be hung, the total space was maintained without any additional separators or dividing walls. The objects could be freely moved and arranged in the exhibition space. So, spatial uncertainty was clearly apparent, also the occupational behaviour became more complex and difficult to foresee. However, the FASO of each of the seventeen sub-functions is expected to be read clearly, while their influence on layout planning can be easily understood.

The creator proposed a spatial layout for the Palladio exhibition, that the architectural models of different sizes were placed in the entire space except the four corner areas where the screen equipment was located (Figure 8). The display objects seemed to be arbitrarily distributed on the plan, but the No17, which was the largest exhibit, was solely placed in a big axial partition. Additionally, the entrance was designed at the opposite side from where the entrance for the Dali Exhibition was.

In this application, the 42x97 grid (50 by 50 cm) on the plan contained 4074 centroids. Three key parameters were selected. The first one was the space related parameter: the "Distance from the sub-function" (D). The relative proximity to the object would raise the possibility of a person being present in the sub-space. This parameter formed the basic and the same FASO for all exhibits without the effects of other inputs. "Visual integration" (V), the second parameter, was also a space-related parameter. Depending on the syntactic property of the space, the pattern of integration showed how much a person could see from certain points, those where movement was more exploratory and desirable. So, the FASOs residing in highly integrated zones of the space would be much bigger in order to support a higher possibility of presence. The last parameter: "Model" (M) was a qualitative factor from the function related set. Since the architectural models' sizes and details were all different from each other, the 'length of time' people spent involved in an activity and their presence in the relevant spatial unit would change. Some parameters were deliberately not chosen. For example, "Population" was not used this time, because the objective was to create the FASOs for layout planning; to see their abstract self-forms and relations, not how they would change when the number of people in the space increased.

The calculation side of the model was comprised of FIS and input data file. The data file was the list of parameter variables of all the centroids. The distance

Figure 8
The layout of the Palladio Exhibition

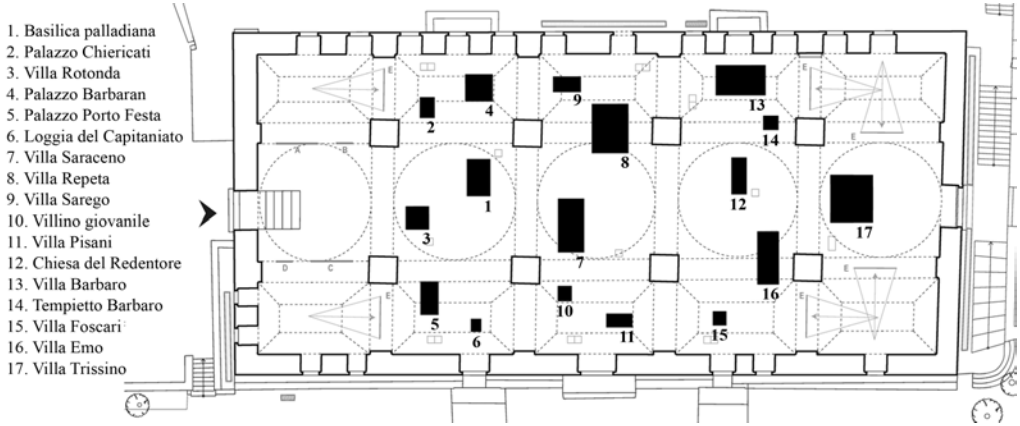


Figure 9
The VGA

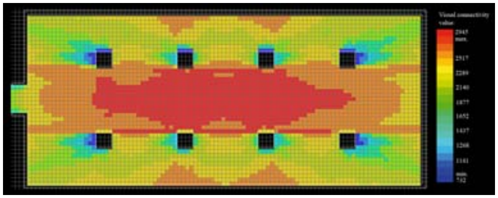
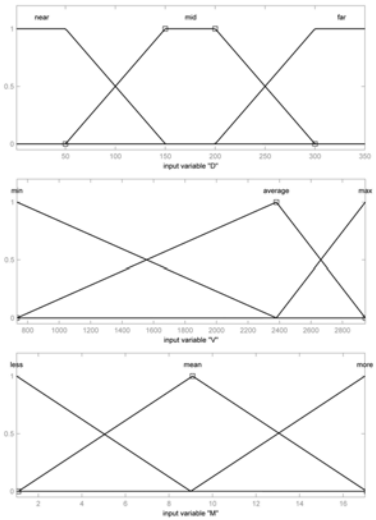


Figure 10
The membership function plots (MATLAB)

from the sub-function was identified as the distance from a certain exhibit and measured by using ArcMap software. To obtain integration values Visibility Graph Analysis (VGA) was run in the UCL Depthmap application (Figure 9). The quality values of the exhibits were scaled from the level 1 to 17; and the centroids within the circle d = 300 of a certain exhibit were affected by its quality.

In FIS, each input was defined as a fuzzy set which was characterized by its membership functions (MFs); this was the subset. As seen in Figure 10, the MFs for "D" were near, middle and far; for "V" were min, average and max; and for "M" were less, mean and more. The output was also translated into the MFs from the lowest membership (mf1 = 0) to the highest membership (mf7 = 1). 27 rules in total were constructed by the combination of the individual logical postulates between each input and output as seen in the following examples:

- If D is near then membership degree is mf7 (high)
- If V is min then membership degree is mf1 (low)
- If M is less then membership degree is mf1 (low)



After the overall calculation process was completed, 4074 outputs proceeded to visualisation. The listed membership degrees of centroids were mapped to a matrix that corresponds to the grid cells on the architectural plan. So, the fuzzy subsets (the FASO sets) were numerically represented in the space. Later, grid-based interpolation was applied to create intermediate values between cells. The complete set of values was assigned colours according to the membership degrees; $0 \leq x \leq 1$.

First, each FASO was individually modelled to see the sub-spaces independently (Figure 11). The FASOs were demarcated by a circle d = 300; outside of this line was defined as "the exterior" where the membership degree was $x = 0$. The zones of the core and the indeterminate boundary within the circle were determined by the parameters: visual integration and the quality of the exhibit. For example, the lowest and highest ranked exhibits No.6 (rank 1) and No.17 (rank 17) have different FASO-regions within their limits. The bigger area was $0.5 \leq x$ (reddish) in No.17 FASO, whereas it was $x \leq 0.5$ (bluish) in the No.6; which demonstrated the possibility of occupancy on those spatial units. Visual integration also affected the formation of the FASOs. For example, although No.7 (rank 14) and No.16 (rank 13) had very similar quality

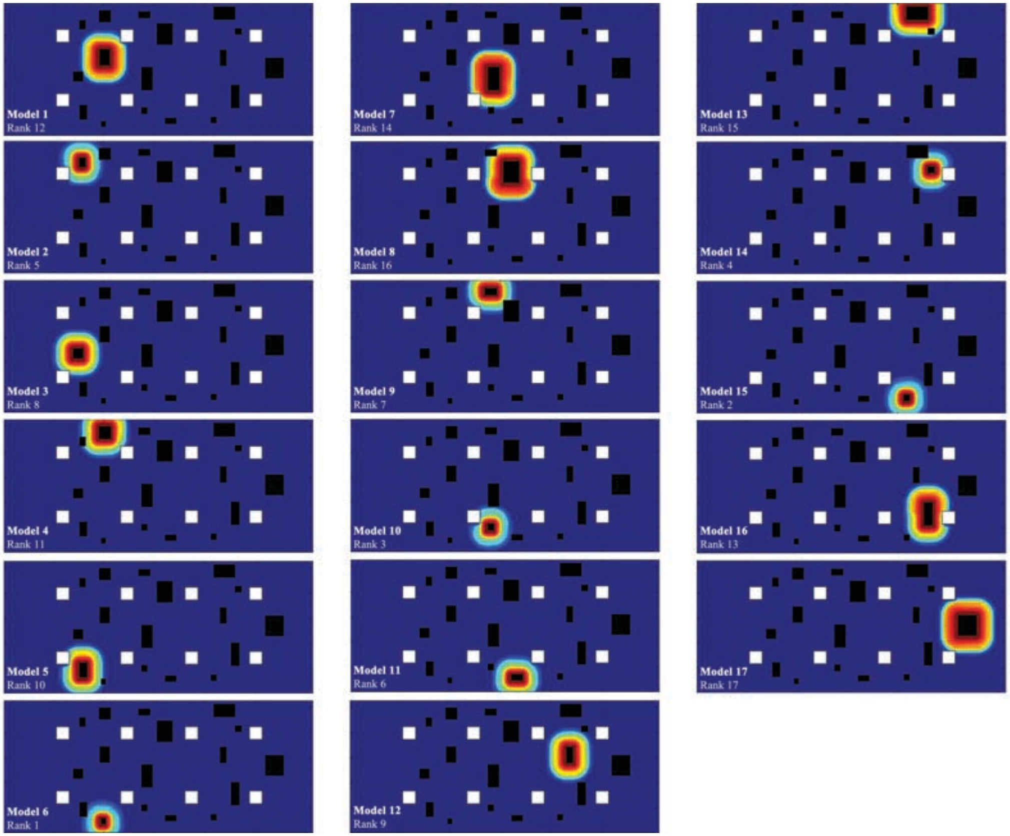


Figure 11
17 FASOs

values, the zones of the regions changes dramatically due to their location in the exhibition space. The difference can also be read at the structure of a FASO itself; like in No.7 and No.8, where the parts of the FASOs coincided with a higher integration value reddened. Additionally, some FASOs such as the objects belonging to No.13 and No.14 were cut since the exhibits were very close to the walls and pillars.

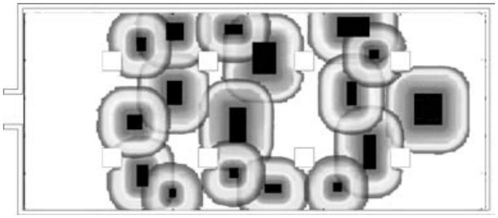


Figure 12
17 FASOs altogether

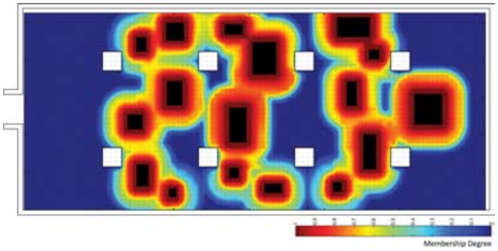


Figure 13
The result of the Palladio Exhibition

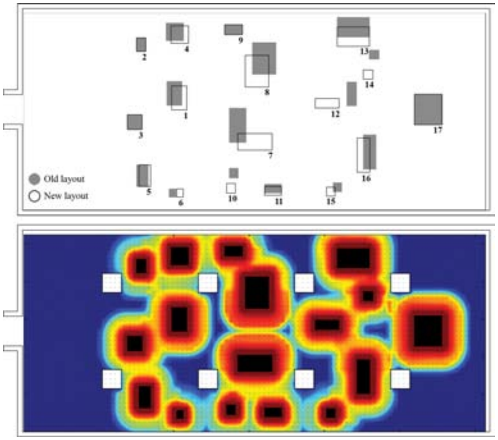


Figure 14
A new layout

In terms of spatial reserve of the sub-function these exhibits were restricted. In Figure 12, the individual FASOs were gathered by decreasing their opacity and converting into grayscale to understand the initial topological relations. It was mostly seen that the FASOs were overlapped, even to an extent that the outside edge covered the other exhibit. For example, the FASOs of No.13 and No.14, also No.8 and No.9 showed this relation. It was rarely seen that the FASOs touched (met), like between No.6 and No.10. In addition, none of the FASOs stood separately; in a relation of disjoint.

To express the overall result, the integrated heatmap of all seventeen FASOs was produced as seen in Figure 13. The parameter "V" was constant for all centroids. However, "D" was accepted as the shortest distance from any nearest sub-function. And in the parameter "M," the centroid affected by more than one exhibit was assigned the value of the highest ranked exhibit. The result shows that the cores of some FASOs merged including No.13 and No.14; also No.8 and No.9. The penetration at the high values of the indeterminate zone (the red and ochre areas) is much more than the penetration at the low values of the indeterminate zone (the blue and turquoise areas). It can be concluded that there is a dense layout of cramped spatial arrangement. Especially the middle axis of the space is expected to be occupied without allowing a proper circulation path. The dark blue areas, which are proposed as hardly inhabited, are clustered rather than sprawling reasonably among the FASOs.

As an alternative, a new layout for the Palladio Exhibition was devised by keeping the main design approach proposed by the creator. Some of the exhibits were moved slightly (such as No.4 and No.13) and some of them were rotated (such as No.7 and No.12). The aim here was to show how the minor changes would result in different patterns, which could not be realized without the FASOs map. In this new layout (Figure 14) the FASOs didn't overlap on the cores but on the lower values of the indeterminate zone as the yellow and bluish connections were prominent on the plan. The density was reduced by the spacious rearrangement of the exhibits, which would provide a more comfortable movement in the space. Thus, the dark blue vacant areas mostly disappeared. Since the exhibits such as No.13 and No.14 were carried away from the walls and pillars, their FASOs were recovered.

It is also possible to model and evaluate diverse layouts. For example, a layout with a deterministic itinerary can be proposed via a clear circulation path in the exhibition space. Or another layout can be proposed to balance the "V" and "M" parameters for the FASOs; as putting the smaller architectural models (low M) in the middle of the exhibition space (high V) and vice versa. In sum, by changing the places of the exhibits numerous FASO layouts that show possible inhabitation can be produced. The creator or architect can select and apply one of them according to certain criteria.

CONCLUSION

This paper introduced a fuzzy computation model as a design decision tool for layout planning in uncertain or ill-defined spaces. Layouts are conceptualised by using fuzzy architectural spatial objects (FASOs) which represent the probability of a sub-space being occupied, as a function of the features, objects and people within the total space. That the model is structured to be open-ended, to accommodate additional parameters and logical rules as required, various layouts can be generated. The evaluation of inhabitation pattern layouts is expected to assist architects to develop more feasible and rational arguments as well as to contribute to their design knowledge.

This research advanced the FASOs as generative-syntactic components in the early design stage, which could be arranged for spatial layouts. In a visionary sense, these FASOs can also be utilized to design the borders of a space; the outer shell of a building. Instead of that the FASOs are delimited by the walls of the building (as they cut in the exhibition space), the built form will transform according to the designed FASOs. So a reverse process is initiated; from FASOs housed in open plans to kinetic and flexible spaces and buildings shaped by the FASOs.

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