ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A COMPUTATIONAL MODEL FOR ACCOMMODATING SPATIAL UNCERTAINTY: PREDICTING INHABITATION PATTERNS IN OPEN-PLANNED SPACES

Ph.D. THESIS

Aslı ÇEKMİŞ

Department of Architecture

Architectural Design Programme

SEPTEMBER 2014

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A COMPUTATIONAL MODEL FOR ACCOMMODATING SPATIAL UNCERTAINTY: PREDICTING INHABITATION PATTERNS IN OPEN-PLANNED SPACES

Ph.D. THESIS

Aslı ÇEKMİŞ
(502082024)

Department of Architecture

Architectural Design Programme

Thesis Advisor: Prof. Dr. Işıl HACIHASANOĞLU

SEPTEMBER 2014

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MEKANSAL BELİRSİZLİĞİN ÇÖZÜMÜNE YÖNELİK SAYISAL BİR MODEL ÖNERİSİ: AÇIK PLAN MEKANLARDA KULLANIM ÖRÜNTÜSÜNÜN TAHMİNİ

DOKTORA TEZİ

Aslı ÇEKMİŞ
(502082024)

Mimarlık Anabilim Dalı

Mimari Tasarım Programı

Tez Danışmanı: Prof. Dr. Işıl HACIHASANOĞLU

EYLÜL 2014

Aslı ÇEKMİŞ, a **Ph.D.** student of ITU **Graduate School of Science, Engineering and Technology**, student ID **502082024**, successfully defended the **dissertation** entitled "**A COMPUTATIONAL MODEL FOR ACCOMMODATING SPATIAL UNCERTAINTY: PREDICTING INHABITATION PATTERNS IN OPEN-PLANNED SPACES**," which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Işıl HACIHASANOĞLU** ....
İstanbul Technical University

Jury Members : **Prof. Dr. Gülen ÇAĞDAŞ** ....
İstanbul Technical University

Doç. Dr. Birgül ÇOLAKOĞLU ....
Yıldız Technical University

Doç. Dr. Göksenin İNALHAN ....
İstanbul Technical University

Yrd. Doç. Dr. Suzan GİRGİNKAYA AKDAĞ
Bahçeşehir University

....

Date of Submission : 15 August 2014
Date of Defense : 29 September 2014

To my grandmother,

FOREWORD

This research was financially supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK); grant no 2211 and 2214, and also by ITU Research Fellowship Programme. The thesis also developed by the work undertaken at CASA, University College London in United Kingdom and The University of Newcastle in NSW, Australia.

August 2014

Aslı ÇEKMİŞ
(M.Sc.)

TABLE OF CONTENTS

Page

ABBREVIATIONS

ABM : Agent Based Model
CA : Cellular Automata
CCTV : Closed-circuit Television
COA : Center of Area
COS : Center of Sums
CW : Computing with Words
D : Density (Population)
dOLP : Distance from the Order Line Point
dVP : Distance from the Viewing Point
FASO : Fuzzy Architectural Spatial Objects
FIS : Fuzzy Inference System
FSO : Fuzzy Spatial Objects
GIS : Geographic Information Systems
HVAC : Heating, Ventilation and Air Conditioning
ID : IDentifier
MF : Membership Function
MOM : Mean of Maxima
OLP : Order Line Point
UCL : University College London
VGA : Visibility Graph Analysis
VI : Visual Integration
VP : Viewing Point

LIST OF TABLES

Page

LIST OF FIGURES

Page

A COMPUTATIONAL MODEL FOR ACCOMMODATING SPATIAL UNCERTAINTY: PREDICTING INHABITATION PATTERNS IN OPEN-PLANNED SPACES

SUMMARY

Predicting spatial occupancy and users' behaviour has always been an important field of research. A range of computational models have been developed for analysing spatial inhabitation and human activities, which are typically focussed on macro-patterns, often in cellular or linearly-organised spaces. Few models exist for simulating where people will cluster within complex environments. One reason for this relates to the inherent uncertainty associated with spatial attributes. This thesis proposes a computational model for predicting patterns of inhabitation in ill-defined spaces which are the subject of higher levels of uncertainty. Such spaces are common in large exhibition and conference halls, airport foyers and the concourses of train stations. They are free, open-planned spaces which are not divided into defined rooms by doors or walls, but accumulations of various sub-functions and their virtual sub-spaces within an overall environment. Since the configuration does not define strict patterns of usage, the task of modelling these patterns becomes more difficult. As a novel approach, fuzzy sets theory is used in the model as the means for handling uncertainty; for both the expression of vague spatial configuration and for the analytical estimation of how people spatially behave.

A total space could, hypothetically, be seen as a fuzzy set where each sub-space (and its sub-function) is a fuzzy subset. The smallest unit of this space, which can accommodate a person, is an element or member. Any member in the two-dimensional space belongs to a sub-space with a membership degree $0 \leq x \leq 1$. So, a member can belong to more than one sub-space and a sub-space can be comprised of members with various differing membership degrees. The membership degree is defined by the possibility of a person in that spatial unit; as being present in that sub-space and involved in that sub-function. The sub-spaces in the model are defined as "fuzzy architectural spatial objects" (FASOs). They comprise points, lines, regions and complex regions in buildings, which possess similar features. Having three different zones in a simple fuzzy region, all of the spatial units have the membership degree of $x = 1$ in the core, $0 < x < 1$ in the indeterminate boundary and $x = 0$ in the exterior. This describes the possibilities of being wholly or partly involved in the activity, or being totally disengaged from it. The zones are virtually constructed in the space. The borders between them are fuzzy; not demarcated physically but through conceptual separations that are flexible and permeable to members. So, those objects are neither stable in size nor in shape; they are able to enlarge, diminish, move, merge, separate or disappear, or additionally transform into each other. They change by the free flow of possibilities of involvement or engagement in the space. The practical value of the notion of FASOs in the model is that they provide a spatial representation of the prediction of those possibilities. The possibility of presence is

linked to the membership degree of a spatial unit of a certain FASO, so; spatial usage (inhabitation patterns) could be conceptualised as being about the memberships in a spatial set coupled with the capacity to map the whole space accordingly.

On this basis, the model calculates the possibilities of presence using a fuzzy inference system (FIS) which operates through some parameters (inputs) and logical postulates (if-then rules) that reflect a specific usage function of features, objects and people in the space. The outputs of the FIS are the membership degrees of all the spatial units in the whole space. Later, the model visualises the distribution of possibilities in order to make the FASOs appear on the given plan. The result of the model is a spatial usage map which shows the zones that in all likelihood there will be a person or persons, and the zones that signify a remote possibility of people in those parts of the space. Also it is possible to make deductions about the quality of spatial usage when we interpret the topological relations among the FASOs. The model is structured to be open-ended, to accommodate additional parameters and logical rules as required. In this way the model is capable of mapping different combinations of spatial usage; another set of space, function and user. Any change in the input variables and control statements will make the FASOs change. Then it is possible to compare different predictive maps and to evaluate them for various altered conditions.

After a detailed explanation of the computational process of the model, which is run in MATLAB software, the thesis demonstrates a case study. One of the major exhibition spaces in Istanbul; Tophane-i Amire is analysed when a popular travelling exhibition is on display; the Salvador Dali Exhibition. Appropriate parameters are chosen from the sets of morphological features and functional requirements, also visitor profile and population, which affect the spatial occupancy in the exhibition hall. The logical rules are listed which create meaningful links between inputs and the output -the membership degree of a FASO. Three usage maps are generated depending on different population densities in the space. The results and accuracy of this application of the model are also discussed in the thesis. According to the findings about usage of space for the Dali Exhibition in Tophane-i Amire, the spatial arrangement and layout is efficient for a lower visitor density in terms of the fulfilment of function and the quality of display, but insufficient to adapt to higher densities. From an architectural perspective, the predictive maps broadly replicate the observed usage of space. So, the occupants’ behaviour and the pattern of inhabitation could be foreseen (and problems potentially avoided) by modelling the FASOs and their topological relations. Accordingly, the thesis suggests more future work related to the case study; such as modelling and comparing alternative display layouts of the exhibition for a better installation, and analysing the flexibility of the exhibition hall by modelling different exhibitions that have taken place.

The model can also be used for different functions and typologies; where there is a constant flow of people like in an airport foyer. Additionally, the applications are not limited to only an architectural scale and for open planned interior environments, the model can also be utilised for cases of urban studies, like the usage of public squares and parks. But, the proposed model cannot be used for the analysis of divided cell-like spaces or fixed furnished settings like a theatre, where the configuration eliminates uncertainty by strictly imposed usages of space.

While several parts of the model build directly on previous research, its significance is found in the way it deals with spatial uncertainty. For any specific condition of space, function and users, the model draws a very real-life picture of the spatial usage. This capacity of the FASO model to map the potential limits and character of the uncertainty implicit in space is necessary, as a decision tool both at the preliminary design stage to provide feedback to the concept project, and during the building's occupation to forecast problems and make operational adjustments. This type of analysis can be used to assist architects, designers, operators and users, as well as students and educators who need to be able to assess the performance and flexibility of such spaces. However, it must be acknowledged that the proposed model is still under development, needing a much larger set of examples and a more detailed correlation analyses between the predictions of the model and actual behaviour patterns. While further evidence is needed, along with refinement of the model, to confirm its application, it still offers a rare way of approaching the analysis of uncertain spaces; a way to test the total space and whether it is adaptable to change by measuring its capacity under differing space, function and user related conditions.

MEKANSAL BELİRSİZLİĞİN ÇÖZÜMÜNE YÖNELİK SAYISAL BİR MODEL ÖNERİSİ: AÇIK PLAN MEKANLARDA KULLANIM ÖRÜNTÜSÜNÜN TAHMİNİ

ÖZET

Bu tez çalışmasında mekansal belirsizlik üzerine odaklanılarak, bu durumdaki kullanım örüntüsünün tahminine ve sunumuna yönelik bir bilgisayar modeli geliştirilmiştir. Mekansal belirsizlik, mekan biçimleniminin net ve kesin işlevsel ayrımlar ortaya koymadığı açık-serbest planlı tasarımlarda görülür. Buna örnek olarak çok amaçlı salonlar, geniş sergi salonları, tren garları ya da havalimanları verilebilir. Bu mekanlar kısımlara ayrılarak bölünmediğinden ancak alt işlevler ve onların alt mekan kümelerinin biraraya gelmesi ile tanımlanabilirler. Mekansal belirsizlik kullanıcı davranışı ve kullanım şemalarının ortaya dökülmesini de daha zor ve karmaşık hale getirmektedir. Öte yandan, mimarlar esnek ve değişime adapte olabilmiş mekanlar için kullanım yönünden belirleyici olmayan tasarım yaklaşımlarını tercih etmektedirler. Ancak bu tarz mekanların da farklı işlev, düzenleme ve kullanıcı gruplarına göre nasıl yaşayacağını tahmin etmek ve öngörebilmek, gerek tasarım aşamasında gerekse kullanım esnasında oldukça önemli bir ihtiyaçtır. Bu noktadan hareketle tezde, mekansal belirsizlik; bulanık mantık ve bulanık küme teorisi içinde ele alınmış, ve kullanım simülasyonu yapabilecek özgün bir model önerisinde bulunulmuştur. Amaç, öncelikle total mekan içindeki insanların alt mekansal kümelerde bulunma olasılığını hesaplamak; ve daha sonra tüm olasılık dağılımlarını uygun şekilde görselleştirmektir. Böylece belirsizlik faktörüne rağmen tasarımcılar, işletmeciler ya da kullanıcılar -hatta tasarım eğitimi içinde öğrenciler ve eğitimciler de- mekanın nicel ve nitel performansı üzerine karar verebilecek somut veriler elde etmiş olacaktır.

Literatürde mekansal kullanım ve kullanıcı hareketi üzerine birçok metod ve model önerisinde bulunulmuştur. Özellikle kompleks, dinamik ve lineer olmayan mekansal sistemlerin ve karmaşık kullanıcı davranışlarının tahmini için etmen tabanlı modeller, hücresel otomatlar, sosyal kuvvet modelleri, bifurkasyon ve kaos teorisine dayalı yöntemler, özellikle belirsizliğin stokastik sürecini inceleyen Markov zinciri ve Monte Carlo metodları gibi birçok yaklaşım öne sürülmüştür. Mekan sentaksı teorisi ve morfoloji tabanlı çalışmalar da kullanım ve davranış örüntüleri hakkında hipotezler oluşturmuştur. Ne var ki hâlâ, geniş, serbest ve açık plan tasarımların mekan analizine yönelik tek ve kapsayıcı bir yöntem geliştirilememiştir. Bunun en önemli nedenleri mekan kurgusundaki belirsizliğin dikkate alınmaması ya da işleme dahil edilememesi, ve kullanım şemasını oluşturan tüm mekansal, işlevsel ve insani faktörlerin birarada değerlendirilememesidir. Tez çalışması bu açığı gidererek; mekansal belirsizlik içinde gerçeğe en yakın kullanım düzenini verebilecek uygun tahmin modelinin geliştirilmesini hedeflemiştir. Tez; teori, yöntem, model ve modelin uygulaması aşamalarını içeren oldukça geniş ve kapsamlı bir araştırma sunmaktadır.

Çalışmada ilk olarak belirsizlik kavramı ve belirsizliğin tasarım içindeki yeri irdelenmiştir. Belirsizlik; fizik, matematik, ekonomi ve coğrafya gibi birçok disiplinin çalışma alanında önemli bir yer tutmaktadır. Araştırmacılar belirsizliği tanımlamaya, ölçmeye ve sistemlere dahil hale getirmeye çabalamaktadır. En genel tanımıyla belirsizlik, muğlak, kuşkulu ve kararsız olan bir durumu ifade etmek için kullanılmaktadır. Eksik ve hatalı bilgi, bilgi kaynaklarına veya ölçüme dayalı tutarsızlıklar, bulanıklık, sembolik/dilsel anlaşmazlık, çeşitlilik, sınıflandırma yanlışlıkları, rastlantısallık, ayrıca insana ve araştırmacıya bağlı öznel faktörler belirsizliğin sebepleri arasında sıralanabilir. Belirsizliğin nedeni hem olası sonuçlar hem de kullanılacak yöntem açısından önemlidir. Belirsizlik, yapılı çevrenin oluşumunda ve mimarlık pratiğinde de bulunmaktadır. Tasarım düşüncesi, sonucu başta bilinmeyen ve doğrusal ilerlemeyen bir süreçte ortaya çıkar. Mimarın birçok farklı girdi ve sorunsalı muğlak ve kişisel bir biçimde harmanlaması yaratıcılıkla doğrudan ilişkilidir. Tasarımın ilk safhalarındaki eskizler ve konsept modeller ile kavram haritaları ve yerleşim diagramları keskin biçimler ve teknik çizimlerden farklı olarak düşüncenin kurumsal ana hatlarını ve bağlamsal ilişkileri ortaya koyar. Bu araçlar belirsizliğin tasarım sürecindeki ifadeleridir.

Öte yandan belirsizlik tasarım konsepti olarak da ortaya konmuştur. Belirsizliğin yapının yaşamındaki değişimlere adaptasyonu şeklinde ele alınması ilk kez 1960 lara kadar uzanır. Özellikle Archigram ütoyopyalarında belirsizliğe; bitmemiş, gelişebilen ve değişebilen mimariye gönderme yapılır. Yıllar içinde farklı akımlar ve projeler bu fikri desteklemiş ve geliştirmiştir. Bilgisayar destekli tasarım akışkan, dinamik ve sürekli mekanların ve formların öne sürülmesini sağlamıştır. Esneklik konsepti belirsizliğin mimari ifadesinde önemli yer tutar. Esnek mekanlar ve sistemler tasarlamak değişime; yeni durum ve ihtiyaçlara cevap verebilmek açısından önemsenmiştir. Özellikle modern mimari söylemde yer edinen bu yaklaşım, Le Corbusier, Mies van der Rohe ve Frank Lloyd Wright gibi ünlü mimarların manifestolarında ve yapılarında vardır. Açık planlı tasarımlar ise esnekliğin mekansal karşılığı olarak öne sürülmüştür. Mekansal bağlantısallık, bütüncüllük ve çok işlevlilik açık plan tasarımların en belirgin karakteristiğidir. Yine modernist üslupta önemli yer edinen açık planlar duvar ve diğer tüm bölücü elemanları reddederek radikal bir özgürlük getirmiştir. Açık, total planlar ev, ofis ve müze gibi çok farklı tipolojilerde ve büyüklüklerde uygulanmıştır. Böyle mekanların belli işlev, düzen ve yoğunlukta nasıl kullanılabileceğini öngörmek ve haritalamak belirsizliğin doğru biçimde ele alınmasına ve ölçülmesine bağlıdır.

Belirsizliğin matematiksel ifadesi için birçok yöntem mevcuttur. Bunlar arasında olasılık teorisi, istatistik, klasik küme teorisi, bulanık küme teorisi, olabilirlik teorisi, kaba küme teorisi ve kanıt kuramı sayılabilir. Belirsizliğin ölçümünde kullanılan en yaygın metod: olasılık teorisi olayların sonuçları ile ilgili bilinmezliğe odaklanır ve rastlantısallık içindeki tüm olası neticeleri listeler. Oysa, önerilen modelde de kullanılan bulanık küme teorisi olayların kendilerindeki muğlaklıkla ilgilenir. Bu; bir değişkenin kazanma ihtimalinin hesabı yerine, o değişkenin ne olduğu ve nereye ait olduğu ile ilgili bir değerlendirmeyi kapsar. Bulanık küme teorisinin kuramsal temelini bulanık mantık oluşturur. İlk kez 1970 lerde Aristo ikili çıkarım mantığına alternatif olarak Lotfi A. Zadeh tarafından önerilen bulanık mantık; ortanın dışlanması ilkesini redderek kısmi ve nispi doğru (gerçeklik) savını öne sürer. Olaylar ya “o” ya da “diğeri” şeklinde net sonuçlar ve sınıflamalar yerine hem “o” hem de “diğeri” olabilecek şekilde tarif edilir; böylece bulanık kümeleri klasik kümelerden ayıran temel yaklaşım ortaya çıkar. Öyle ki, bir bulanık küme klasik kümeden farklı olarak belirsiz sınırlara sahiptir. Dolayısıyla bir bulanık küme farklı üyelik derecelerine sahip elemanlardan (olaylardan) meydana gelir; ve bir eleman aynı mantık çerçevesinde birden fazla kümeye ait olabilir.

Bulanık mantık ve küme teorisi uygulamaları için MATLAB bilgisayar programı kullanılmaktadır. Bulanık Çıkarım Sistemi (BÇS) basit sebep-sonuç ilişkileri üzerinden kompleks davranışları modelleyebilir. BÇS beş aşamadan oluşur, bunlar sırayla şöyledir; 1. Bulanıklaştırma (giriş değişkenlerine üyelik fonksiyonlarının atanması), 2. Kural tabanı (girdiler ve çıktı arasında eğer-ise kontrol kurallarının belirlenmesi ve gerekirse "ve, veya, değil" işlemlerinin uygulanması), 3. Çıkarım motoru (her bir kuralın öncü bölümlerinin hesaplanıp sonuç (bulanık) alt kümelerinin oluşturulması), 4. (Bulanık) Harmanlama (sonuç (bulanık) alt kümelerinin tek bir (bulanık) küme oluşturacak şekilde birleştirilmesi), ve 5. Durulaştırma (bulanık çıktının uygun yöntemle (örneğin; en büyük üyelik, ağırlık merkezi ya da ağırlıklı ortalama) kesin sayıya dönüştürülmesi). Sugeno ve Mamdani en çok kullanılan iki çıkarım sistemi çeşididir, aralarındaki tek fark Sugeno yönteminin kural sonuçlarını bulanık değil sabit ve doğrusal vermesi böylece durulaştırmaya gerek olmadan hesaplamayı bitirmesidir.

Bulanık mantık birçok alanda uygulandığı gibi mimaride de belirsizliğe dayalı problemlerin çözümü için önerilmiştir. Özellikle tasarım aşamasında eskizlerin özet ve öznel dilini bilgisayara aktarmak, ve tasarım ortamını dijital olarak yaşatabilmek için bulanık mantık ilkeleri kullanılmıştır. Öte yandan, belirsizliğin tasarıma aktarılmasında da bulanık yaklaşıma başvurulabilir. Yapı elemanlarının geleneksel ve kesin birleşimlerinden akışkan formlara ve iç içe geçen mekanlara gelindiğinde bulanık sınırlar ve kısmi üyelikler karşımıza çıkar. Tez çalışması da açık plan mekanları bu mantıksal ve matematiksel yaklaşım üzerinden anlamaya çalışmıştır. Bulanık mantık ve küme teorisi öneri modelde hem mekansal belirsizliğin ifadesinde hem de kullanım olasılığının hesaplanmasında kullanılmıştır.

Model öncelikle kavramsal olarak açık plan mekanların bulanık küme teorisine dayanan bulanık mekansal objelerden meydana geldiğini; ve bu objelerin de mekansal, işlevsel ve kullanıcı odaklı birtakım parametrelere göre oluştuğunu öne sürmüştür. Hipoteze göre, bölücü elemanlarla parçalanmamış total bir açık plan bir bulanık kümedir, ve her alt işlev ve onun alt mekan öğesi bir bulanık alt küme (üyelik fonksiyonu) tanımlar. Planda bir insanın bulunabileceği en küçük mekansal birim küme elemanıdır, bu; verilen plana 50 x 50 cm ünitelerden oluşan bir grid konulmasıyla elde edilebilir. Bir insanın belirli bir mekansal ünitede bulunma olasılığı o küme elemanının ilgili alt işlev ve alt mekana ait olma derecesini ifade eder. Mimari olarak mekansal alt kümeler "bulanık objeler" olarak tanımlanmıştır. Bulanık obje kuramı ilk kez coğrafyacılar tarafından sınırları net olmayan uzamsal nesnelere yönelik kullanılmıştır. Örneğin, Amerika eyaletler haritasındaki sınırlar net ve keskinken bir havadurumu haritasında farklı hava koşulları arasındaki geçişler daha yumuşaktır; birden fazla duruma ait ortak alanlar ve içiçe geçen ara bölgeler vardır. Bulanık obje nokta, çizgi ya da bölge olabilir. Bir bulanık bölge $x = 1$, $0 < x < 1$ ve $x = 1$ şeklinde farklı üyelik derecelerine ait elemanların oluşturduğu çekirdek, ara zon ve dış alandan oluşur. Bulanık objeler esnektir; büyüklükleri ve biçimleri değişebilir. Objeler arasındaki topolojik ilişkiler olgunun bütünü ve genel durum hakkında yorum yapabilmemizi sağlar. Coğrafi ölçekte ele alınan bu objeler, tez çalışmasında açık planların alt mekan parçalarının özelliğini anlatmak için uygun bir araç olarak görülmüş ve mimari mekana adapte edilmiştir. Bu sanal objeler mekan elemanlarının dolma olasılığını yansıtacaktır. Bu bağlamda mekan kullanımını; başka bir deyişle elemanların üyelik derecelerini etkileyecek faktörler önem kazanır. Bu faktörlerden biri alt işlev odağından fiziksel uzaklıktır. Mekanın yapısal, görsel, algısal vb. özelliği de bir kriter olabilir. İşleve ait nitel ve nicel faktörler de düşünülmelidir (örneğin alt işlev sayısı ve hizmet kalitesi gibi). Ayrıca mekan kullanıcılarının fiziksel, sosyal ve davranışsal durumları ile nüfus faktörü kullanım şemasının bulunmasında oldukça etkilidir.

Modelin bilgisayar destekli hesaplama ve görselleştirme süreci MATLAB programında gerçekleştirilir. İlk aşama mekan birimlerinin (noktaların) üyelik derecelerinin BÇS kullanılarak hesaplanmasıdır. Öncelikle, belirli bir mekan, işlev ve kullanıcı durumundaki kullanım örüntüsünü oluşturacak uygun parametreler seçilir. Her nokta için parametre değeri, diğer gerekli gözlem, deney ve ek hesaplamalar ile elde edilerek girdi data dosyası hazırlanır. Aynı anda, girdiler ve çıktı arasındaki mantıksal ilişkiler belirlenir. BÇS önceden anlatıldığı gibi uygulanır ve sonuçta her grid noktasına ait $0 \leq x \leq 1$ üyelik dereceleri belirlenmiş olur. Görselleştirme kısmı üyelik derecelerine göre mekansal birimlerin kırmızı-yeşil-mavi skalasında renklendirilmesidir. Sonuçta, insanların mekandaki noktalarda bulunma ihtimaline göre farklı zonlardan oluşan mekansal objeler elde edilmiş olur. Farklı büyüklük ve biçimdeki bulanık objelerden meydana gelen yeni plan bir kullanım haritası sunmaktadır. Objeler ve aralarındaki topolojik ilişkiler farklı amaçlar için yorumlanıp, tasarım verisi olarak kullanılabilir. Parametre değerlerindeki değişiklikler (örneğin popülasyondaki artış) her seferinde yeni haritalar oluşturacak; böylece farklı dizim, aktivite ve yoğunluk durumları değerlendirilebilecektir.

Tez, kapsamlı bir alan araştırması içermektedir. Model, İstanbul'da Tophane-i Amire sergi salonunda Salvador Dali sergisinin mekansal kullanım örüntüsünün tahmini ve simülasyonu için kullanılmıştır. Tophane-i Amire yenilenmiş eski bir top dökümhanesi olup 1150 m^2 lik yığma bir yapıdır. Sadece sekiz kagir sütunla bölünen dikdörtgen simetrik açık plan tasarımı birçok sergiye ev sahipliği yapmaktadır. Bunlardan biri de 23 Aralık 2011 – 26 Şubat 2012 tarihleri arasında gösterilen Dali sergisidir. 121 adet küçük boyutlu resim, kolonlar arasına yerleştirilen bölücü duvarlarla oluşturulmuş sergi düzeninde temalarına göre asılmıştır. Mekanın ayrıntılı rölövesi yanında, sergileme süresi boyunca fotoğraflar ve video kayıtları alınmıştır.

Uygulamada, öncelikle bu vakadaki kullanıcı davranışını etkileyecek parametreler saptanmıştır. Resim izleme noktasına olan uzaklık, görsel bütünleşme değeri ve ziyaretçi popülasyonu faktörleri yanında, ayrıca sergi salonunda oluşabilecek kuyruklar ve toplanmalar için dolaşım rotası izine olan uzaklık parametresi de seçilmiştir. Mesafeler ArcMap programı, görsel bütünleşme değerleri de Depthmap yazılımı aracılığıyla hesaplanmış ve mekan noktalarının girdi değerleri elde edilmiştir. Popülasyon ise az, orta ve çok yoğun zamanlardaki ziyaretçi sayımından bulunmuştur. Çıktı üyelik derecesi ve girdiler arasındaki mantıksal ilişki şu şekilde kurulmuştur: uzaklık azaldıkça, görsel bütünleşme arttıkça ve popülasyon yükseldikçe üyelik derecesi artar; ve tersi yönde üyelik derecesi azalır. Sugeno tipi BÇS kullanılarak her nokta için sonuç üyelik dereceleri hesaplanmış ve görselleştirme sürecinin sonunda bulanık mekansal objeler ortaya çıkmıştır. Bu haliyle plan tanımlanan mevcut duruma ait bir kullanım haritası sunmuştur.

Uygulama üç farklı popülasyon düzeyi için tekrarlanmış ve sonuçta elde edilen planlar değerlendirilmiştir. Az yoğun haritada planın büyük bölümü bulunma olasılığının düşüklüğünü gösterecek biçimde mavi skalada (dış alan) resmedilmiştir. Mekansal birimler ara zonlarda farklı alt işlevlere ait olsa da, bulanık objeler çakışmadan ferah ve belirgin bir kümelenme oluşturmuştur. Ayrıca görsel bütünleşmenin yüksek olduğu noktalarda oluşan mekansal objeler düşük olan noktalara göre daha büyüktür; bu da mekan diziminin ve görsel bağlantılılık ölçütünün kullanım üzerindeki etkisini vurgulamaktadır. Çok yoğun haritada farklı olarak dikkat çekici değişimler görülmektedir. Mekandaki tüm noktalar artık en az % 25 dolu olma potansiyeli kazanmıştır. Daha fazla kişi barındırma ihtiyacı bulanık objelerin çekirdeklerini genişletmiştir. Tam üyelik zonları birbiri içine geçerek küme niteliğini bozmuştur. Alt işlev mekanlarının üst üste binerek aynılaşması mimari olarak sıkışık ve konforsuz bir tablo çizmiştir. Ayrıca bu haritada tematik resim gruplarının başlarında ve dolaşım rotaları üzerinde kuyrukları ve toplanmaları temsil eden yeni mekansal objeler ortaya çıkmıştır.

Tezde, tahmin haritalarının, gerçek kullanım verileri ile karşılaştırılarak, sağlanması yoluna gidilmiş; böylece, modelin bu alan araştırması üzerinden etkinliğinin ve işlevselliğinin ispatlanması hedeflenmiştir. Farklı yoğunluk zamanlarında çekilen fotoğraflardaki kullanıcı dağılımları; toplanmalar, oluşan kuyruklar ve sıkışıklıklar bulanık mekansal objeleri onaylamaktadır. Bunun yanısıra, tez çalışması modelin sistemli gerçeklemesi için ek analizlere başvurmuştur. Az, orta ve çok yoğun bir zamanda, insanların sergi salonunda bulunduğu noktaların plana işlenmesi ile mekandaki bir anlık kullanım durumu elde edilmiştir. Bu planlar modelin verdiği tahmin haritaları ile çakıştırılmış ve insanların, beklendiği gibi yüksek üyelik derecelerine sahip noktalarda gezdiği görülmüştür. Gerçek kullanım durumuna ait planların, kullanıcı hareketine bağlı olarak, değişen her an için farklı bir yerleşim göstereceği kesindir, ancak bu planların da işlenen örneklerin varyasyonları olup yine tahmin haritalarını doğrulayacağı öngörülmüştür. Bu bağlamda tek bir an yerine bir zaman dilimi ele alınarak başka bir analiz daha yapılmıştır. Orta yoğunlukta, bir saatlik süre içinde ardışık 30 video görüntüsündeki dolu noktalar katmanlar halinde plana işlenmiş ve model çıktısı ile karşılaştırılmıştır. Deney (gelişigüzel deneme) yoluyla elde edilen asıl olasılık değerleri öneri dağılımla eşleşmiş; kullanım örüntüsünün yoğunluğu uyuşmuştur. Gerçek kullanım durumlarıyla örtüşen tahmin haritaları göstermiştir ki Tophane-i Amire sergi salonu Dali sergisinin az ziyaretçisi olduğu zamanlarda elverişli ve uygun bir ortam sunarken, sayı arttıkça oluşan kalabalık sergi deneyimini olumsuz yönde etkilemektedir. Şüphesiz ki, modelle sağlanan bu kullanım öngörüsü en çok tasarım aşamasında (sergi henüz kurulmadan) faydalı olabilir. Farklı sergileme düzenleri ve olası yerleşimler modellenip, alternatif planlar değerlendirilebilir. Böylece mimar ya da küratör karar verme sürecinde gerçeğe oldukça yakın verilerle hareket etmiş olur.

Sonuç olarak, tez çalışması mekansal belirsizlik içinde açık plan tasarımların kullanım örüntüsünün tahminine yönelik bir model geliştirmiş ve bu modeli ayrıntılı bir uygulamayla denemiştir. Model, farklı mekansal, işlevsel ve kullanıcı durumlarına, uygun parametre ve kurallarla adapte olabilecek esnek bir çerveye sahiptir. Elde edilen neticeler modelin yerinde tahminler yaptığını ve etkin bir sistem kurduğunu gösterse de, yeni uygulamalar ve sağlamalarla daha gelişmiş ve ileri bir seviyeye ulaşabileceği düşünülmektedir.

1. INTRODUCTION

This chapter gives an introduction to the thesis and proposed model. First of all, the scope and the motivation of the research are explained. Later, previous approaches are discussed followed by the aim of the present model. In the last section, under the title of “The Methodology;” the hypotheses, methods and procedures are given, also an outine of the thesis is presented.

1.1 The Scope and Motive of the Research

The present research focuses on the uncertainty inherent in spatial composition. This uncertainty is prevalent in fluid and continuous spaces, such as in free and open planned designs where an entire space is occupied in a holistic way, but multi-functionality still plays an important role. Such spaces are common in large exhibition and conference halls, airport foyers and the concourses of train stations. These spaces are not divided into defined rooms by doors or walls, but rather spatial modelling, coupled with material and colour changes, which act to separate various sub-functions and sub-spaces within an overall environment. This lack of clear spatial configuration prompts the uncertainty present in inhabitation patterns and it also makes the task of modelling these patterns complex and difficult.

This type of uncertainty is a by-product of the freedom that exists in the way people use architectural space, which is often regarded as an asset, and deliberately manifested by architects for the sake of promoting flexibility and adaptability. However, despite its benefits, a need to map the potential limits and character of the uncertainty implicit in such spaces is necessary, both at the preliminary design stage to provide feedback to the concept project, and during the building’s occupation to forecast problems and make operational adjustments. So, an appropriate model showing the patterns of potential usage is expected to be appreciatively used as a design decision tool by anybody who needs to assess the performance and capacity of total spaces, including; architects, operators, managers and occupants (users) as well as design students and educators.

1.2 Previous Work

In the last few decades researchers have developed a variety of analytical methods, data mining processes, parametric tools and visualisation techniques for supporting spatial occupancy and behavioural mapping (Batty et al., 2013, Cheshire and O'Brien, 2013). Human activity has been both predicted and simulated in terms of environmental interaction within a building (Fujii and Tanimoto, 2004) and pedestrian movement through space, especially during an evacuation (Fang et al., 2011). Expert systems have provided suggested means for modelling spatial usage for any design decision and evaluation process, in order to replicate human behaviour (Rosenman et al., 1991, Rosenman and Gero, 1993). On the other hand, spatial usage has been fundamentally linked to the morphology of space (Hillier and Hanson, 1984). In this tradition, researchers have used topological relations, isovist properties and syntactic measurements to consider inhabitation and movement patterns as well as perceptual and cognitive schemas (Turner, 2003, Penn, 2003, Ostwald, 2011).

To respond to the challenges associated with working with complex, dynamic and non-linear systems, new mathematical methods and techniques have been devised; including agent-based models, cellular automata, social force models, the methods depending on bifurcation theory and chaos theory, also other stochastic methods of Markov chain and Monte Carlo. Agent-based modelling is an individual-centric modelling which establishes a connection between the active entities (agents) and their behaviour. An agent-based model (ABM) is used to investigate bidirectional flow evacuation, where pedestrian speed is determined by the speed of the leading agent and the surrounding agents (Dai et al., 2013). Cellular automata (CA) are discrete and decentralized systems consisting of large numbers of simple identical components with local connectivity. A two-dimensional CA model is applied to simulate the process of evacuation with respect to the kin behaviour, which results in backtracking (Yang et al., 2005). A social force model is another microscopic approach for pedestrian behaviour. According to this idea, behavioural changes are guided by social forces; not simply the effects of the environment (e.g. other pedestrians or borders) but essentially the motivation to act which evokes the physical production of an acceleration or deceleration (Helbing and Molnár, 1995). The theory of bifurcation is the mathematical study of the nature and properties of sudden shifts in behaviour, which is mostly applied in nonlinear dynamical systems.

For example, the mechanism of crowd jamming is demonstrated by using catastrophe theory, a branch of bifurcation theory (Xiaoping et al., 2010). Chaos theory is the study of apparently random or unpredictable behaviour of systems that are highly sensitive to initial conditions -a paradigm popularly referred to as the butterfly effect. Accordingly, the occupant's response pattern is chaotic; minor changes may create a greater change of the occupant's attitudes (Lu et al., 2010). Markov chain describes a random process (usually characterized as memoryless) from one state space to another. The Markov chain method is used to generate stochastic occupancy schedules within a building by using statistical properties of occupancy such as the time of morning arrival and night departure (Wang et al., 2011). Monte Carlo method like Markov chain refers to a stochastic process and relies on repeated random sampling to obtain numerical results. A Monte Carlo modelling approach is developed to establish a realistic simulation of how the spaces are actually used according to survey statistics (Degelman, 1999).

However, despite such advances in spatio-temporal analysis there are few equivalent models for handling patterns of inhabitation within complex structures including large, free or open planned architectural spaces and open public urban spaces. Those that do exist are typically derived from the methods associated with space syntax and relevant morphological theories (Shpuza and Peponis, 2008, Bhatia et al., 2012), agent-based models (Shelhorn et al., 1999), simulations of gaze dynamics (Wong et al., 2012), behaviour maps (Marusic, 2011) or GIS-tracking and global positioning systems (Gong and Mackett, 2011). But, there is still no single accurate method for mapping usage of this kind of spatial structure. This is in part due to the inefficiencies in handling uncertainty which exists as an inherent feature of architectural systems, those which organize space as not being limited to distinct boundaries (Arabacıoğlu, 2010), thus consequently complicating the capacity to model or analyse patterns of spatial behaviour and occupancy.

Concerning this situation, the present work aims at a suitable approach for predicting and simulating spatial inhabitation in response to higher levels of uncertainty which are associated with particular, complex, spatial structures. The proposed computational model is intended to be capable of replicating actual behavioural schemas and showing possible occupancy in free, open-planned, total spaces.

1.3 Methodology of the Thesis

In this study, spatial usage is conceptualized as the distribution of the possibilities of people present in the whole space. The single possibility value of a person being in the smallest spatial unit is linked to the membership degree of that unit in belonging to a certain sub-function and sub-space. The sub-space set is characterised as a fuzzy sub-set, which is comprised of spatial units with various degrees of membership ($0 \leq x \leq 1$). To express this quality, “Fuzzy Architectural Spatial Objects” (FASOs) are devised. These objects, having the types “points,” “lines” and “regions,” are virtually constructed, special sub-spaces which have different membership zones that are not demarcated by crisp boundaries. Based on these assumptions, the patterns of inhabitation are related to the capacity to map an uncertain environment according to the possibilities of presence; thereby representing the given plan as an accumulation of the FASOs. In this way, the complex nature of spatial behaviour and occupancy can be foreseen; and the uncertainty attributed to the space can be measured and expressed.

Following this conceptual premise, the model first calculates the probability of people being involved in a sub-function and sub-space within a larger space, and then visualizes the distribution of those possibilities across the whole space.

The thesis postulates that uncertainty is most appropriately dealt with by using fuzzy logic while analysing spatial usage in ill-defined volumes. As a suitable mathematical tool for measuring uncertainty, Fuzzy Inference System (FIS) is used for calculating the possibility of presence. The inference system gives membership degrees by operating through certain space, function and user related parameters, and logical rules defining the relations between inputs and output. By overcoming the challenges and inefficacies of previous methods, a FIS combines all factors effecting spatial inhabitation; not merely using morphology and isovist properties of syntax theories or occupancy behaviours of singular agents. Also, unlike the stochastic processes, a vague and limited knowledge with simple control rules provides accurate outcomes, without any need for statistical data to make probabilistic estimations.

With the possibilities acquired via the inference system, the FASOs numerically emerge in the space. But, at the second stage they have to be visualised by colouring each unit according to its membership degree. Thus, the given plan is modified as a heat-map showing the likelihood of people involved in the sub-functions. It denotes the spatial usage map, which can be architecturally interpreted by evaluating the differing size and shape of the FASOs and the topological relations among them.

The proposed model is introduced in the thesis by following the steps: the conceptual development, operational procedure, also an application and verification, and finally an overview of further research. As the case study, the model is run to simulate spatial usage at different population levels in a major exhibition hall when a popular travelling exhibition is on display. The visual and statistical data belonging to the actual occupancy is obtained. The model is tested by comparing the predictive maps with the plans showing the exact usage in a single time frame and overlapping across a sequence of times.

In regard to the frame of the research, the thesis is organized into four parts. Figure 1.1 illustrates the flow of the research with all the concepts and relations the thesis encompasses. Part 1 (Chapters 2 and 3) discusses the relevant literature for the theoretical and methodological base of the proposed model, highlighting the links between the uncertainty embedded in design issues and their treatment by fuzziness. Part 2 (Chapter 4) is allocated for the explanation of the model. Uncertainty and fuzzy sets in space, the idea of the FASOs, and also space, function and user related parameters effecting spatial usage are explained first, followed by the entire computational process of the model: the calculation and visualisation components, which are both run in MATLAB software. Part 3 (Chapter 5) examines the other parts of the model. The model was applied for a specific set of features, objects and people within a space, to produce the FASO map of this condition. To evaluate the quality of spatial usage the process was repeated three times for different population densities. Since the parameter: “the number of visitors” changed, new FASO maps were obtained. The related diagram seen in Figure 1.1 stresses this flexibility of the model as it provides an analytical framework for architecture. It is open to the addition of new rules and parameters to map every space-function-user combination for a given plan. In this way it is possible to compare different predictive maps and to evaluate them for various altered conditions. This part additionally includes the validation of the model for this application, and also suggests other possible practices for the space and layout examined in the case study. The final part (Chapter 6):

“Conclusion” ends the thesis argument on the point that the model is a promising tool for analysing inhabitation patterns in uncertain, ill-defined spaces. This chapter also mentions future research proposals using the model for different typologies and scales.

A much shorter version of this research was recently published in the scientific journal “Building and Environment” (Çekmiş et al., 2014). At different progressive stages, the work was also presented in several national and international meetings such as CASA Seminar in London (Çekmiş, 2012). But, this thesis now provides the most comprehensive and current resource for those who will conduct new applications or attempt to improve and develop the model.

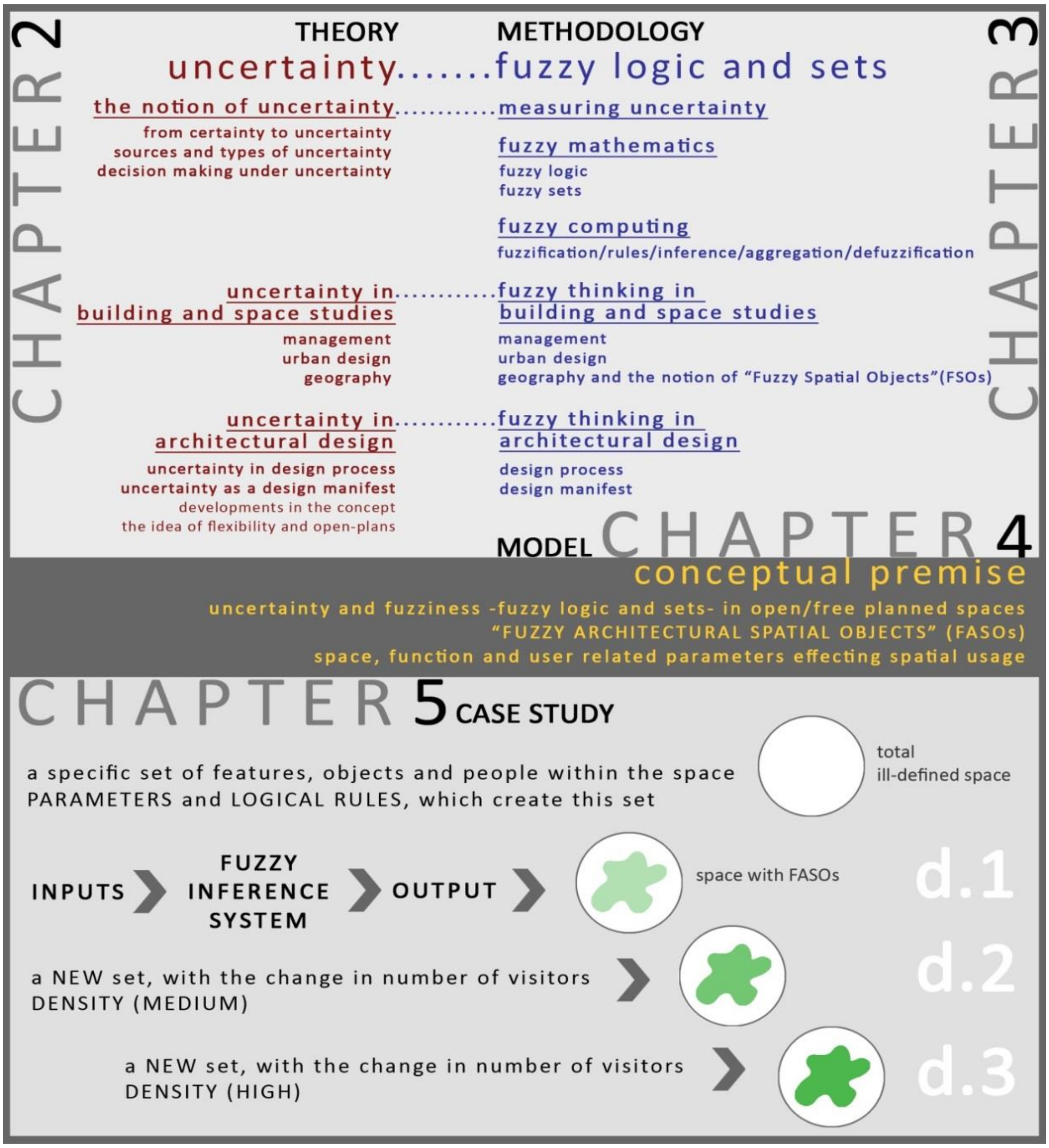


Figure 1.1 : The model research.

2. UNCERTAINTY

This chapter demonstrates a review of literature pertinent to the present research. Uncertainty in space and design forms the theoretical background of the proposed model. The first section in this chapter gives an expanded meaning of uncertainty. The following section reviews uncertainty in management, urban studies and geography. Later, the concept is elaborated within architectural design by identifying uncertainty both as an inherent feature of the design process, and as a design manifest advocating adaptability to change.

2.1 The Notion of Uncertainty

Uncertainty is a term handled in different disciplines including physics and mathematics, also engineering, economics, geography and psychology. Keeping its own terminology, each field endeavours to identify, quantify and incorporate uncertainty. According to Chao and Ayyub (1998) uncertainties in engineering systems can be attributed to ambiguity due to non-cognitive sources (e.g physical randomness) and vagueness due to cognitive sources (e.g definition of parameters). Within the same discipline, Lovell (1995) puts uncertainty in a place between complete ignorance and possession of sure knowledge. From an economist perspective, uncertainty reflects our lack of sureness about something or someone, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome (Epstein, 1999). In GIS literature, Zhang and Goodchild (2002) use uncertainty as an umbrella term for errors, randomness and vagueness. From the fields of neuroscience and psychology, Glimcher (2004) refers to unpredictability as the irreducible uncertainty in human behaviour depending on an indeterminate nonphysical process. In a broad sense, the term uncertainty is used to express the state of being vague, ambiguous, hesitant and cloudy; or the lack of clarity, exactness and precision.

2.1.1 From certainty to uncertainty

Until the twentieth century Newtonian mechanics was regarded as the foundation of physics. According to Laplace (1902) if we know the present state of the universe (with all the forces that compose it and within the effect-cause relation) it would be possible to apply the same formula both to the movement of the greatest bodies of the universe and those of the lightest atom; and, "nothing would be uncertain and, the future, as the past, would be present to its eyes". But, this strong determinism which represents the universe as a very precise clock is shaken by two great breakthroughs in physics; the theory of general relativity and quantum mechanics. Relativity that was conceived by Albert Einstein has changed profoundly our ideas of time-space and matter-energy. The idea of quantum theory was discovered by Max Planck, and developed by a group of physicists. Niels Bohr, one of the pioneers, says that quantum systems demand the overlapping of several complementary descriptions such as the duality of "this is a wave" and "this is a particle" (Peat, 2002). So, as Polkinghorne (1994) summarised, the universe; the system we live in became to be perceived as cloud-like rather than clock-like due to the uncertainty in nature as well as in science.

In 1927, Werner Heisenberg outlined that one cannot simultaneously measure with absolute precision both the position and the momentum of an electron at any given instant. He argued that every measurement destroys one part of our knowledge gained by previous measurements, so the precision of the measurement of a particular property makes the other more imprecise; more inexact or uncertain (Cassidy, 2009). The reciprocal relationship between the indeterminacy of these two measurements has become known as "(Heisenberg's) Uncertainty Principle". And because of this uncertainty, it is seen as impossible to know both the present position and momentum of an electron for certain, and consequently its quality at any future time.

Within the same century, a new uncertainty arose in mathematics itself. Everything started in 1900 with the famous paradox of Russell; 'the set of all sets that are not members of themselves,' which leads to a contradiction since it must be a member of itself, and nonmember of itself. This paradox was important because it undermined the naive set theory –the fundamentals of mathematics, and it was required to consider tackling such antinomies. On the other side, David Hilbert proposed a research project –known as “metamathematics,” or “Hilbert’s program” (Science et Vie, 1997). He wanted -the mathematicians- to formulate a solid logical foundation in order to demonstrate the ‘consistency and completeness’ of mathematics. He applied the rules of logic to the mathematical theorems, as supposed; every statement or judgment is either true or false –if statement A is false; then not A is true. However, a negative answer was given to Hilbert’s program by Gödel, a young Austrian mathematician. In 1931 he published “incompleteness theorem,” a landmark discovery as powerful as Einstein's theory of relativity. For him, there is a statement which says neither A nor not A is true (like the self-contradictory paradoxes). In an abstract way, Gödel’s theorem tells that there are mathematical truths that can never be proved. Alan Turing took the problem in a different way and much deeper than Gödel. He used computer, which was implicit in Gödel’s paper, by claiming that any computation that a human being can perform should be possible to do using a machine (Turing machine) –as Hilbert mentioned ‘a mechanical procedure’. And in 1936, he showed ‘the halting problem’ when he asked what is impossible for such a machine (Chaitin, 2007). So, the axiomatic theory of Hilbert ends in failure by being both incomplete and undecidable.

Furthermore, nonlinear structures and dynamic systems in both mathematics and physics were expressed by two novel approaches; chaos and complexity. Nonlinearity does not satisfy the superposition property, homogeneity and proportional cause-effect relation. In nonlinear systems, small changes in causal elements can lead to dramatically different outputs (Byrne, 1998). Dynamic systems are also highly sensitive to initial conditions (butterfly effect) and rendering long-term predictions are impossible in spite of their deterministic nature. Hence, the behaviour of dynamic and nonlinear systems is generally chaotic and complex. Especially many natural systems are observed as chaotic structures. Not surprising that the foundation of chaos theory is settled in 1961 by Edward Lorenz, who is a meteorologist. Complexity as a wider concept leads to new fields related with uncertainty such as neural networks, cellular automata, robotics and genetic algorithms.

In terms of uncertainty, another great development occurred in the discipline of geometry with the movement towards the non-Euclidean geometry. And the most recent development in geometry is fractals which was first introduced by Benoit

Mandelbrot. It had emerged from the pursuit of regularity of irregularity (order beneath chaos). Fract[ion]al geometry is seen as the best existing mathematical descriptions of many complex natural forms. In his book, Mandelbrot (1983) starts with “Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line”. His studies of irregular patterns explored a quality of self-similarity; symmetry across scale (Gleick, 1987). Fractals from natural compositions to artefacts are studied in numerous disciplines; such as biology, art and architecture.

2.1.2 Sources and types of uncertainty

Incomplete-incorrect information or knowledge, disagreement between information sources (contradiction), fuzziness, symbolic-linguistic imprecision, variability and randomness are mostly indicated as the sources of uncertainty. Measurement (methods and techniques) and human factor (assumptions and personal predicates of observer/researcher) problems can also give rise to uncertainty. Identifying the source of uncertainty is a critical task for estimating its consequence –its effect on the final outcome.

Many researchers have categorized uncertainty into different types depending on the origin of its occurrence. Rolston (1988) expresses four types of uncertainty: a. uncertain knowledge (having only a heuristic knowledge regarding some aspect of the domain); b. uncertain data (even being certain of the domain knowledge, there may still be uncertainty in the data); c. incomplete information (necessity to make decisions based on incomplete information); d. randomness (the condition that some domains are inherently random). On the other hand, uncertainty does not merely imply the lack of the qualities of the inputs (data, information or knowledge), but also it is related with the signification, categorisation and interpretation of those inputs. For instance, a researcher investigating about the elderly has accurate and certain biological age data whilst there stands a big uncertainty in the taxonomy of the ‘old.’ Or, ‘cold’ refers to different subjective perceptions of having low temperature by a researcher in Egypt and another in Canada, apart from the measured certain degree Celsius. Disregarding uncertainty by putting crisp borders to the concepts such as age and temperature gives rise to errors and misunderstandings due to the ignorance of the cognitive and reasoning scheme of humans, personal biases and cultural variations; also the natural facts of the world and their indubitable presence in the science.

Aleatory and epistemic uncertainty is another well-known distinction (Oberkampf et al., 2004). Aleatory uncertainty arises from the inherent variation associated with the physical system or environment, and the mathematical representations that are mostly used to handle aleatory uncertainties are probability distributions. The knowledge of experts cannot be expected to reduce aleatory uncertainty although their knowledge may be useful in quantifying the uncertainty. Thus, this type of uncertainty is sometimes referred to as irreducible uncertainty. Tossing a coin or rolling a dice is a statistical example of aleatory uncertainty. On the other side epistemic uncertainty derives from a missing part of the physical system or environment. The term is used to define any lack of knowledge or information in any phase or activity of the modelling process. This type of uncertainty can be eliminated or reduced to a certain extent by gathering relevant data or conducting sufficient research.

Lo and Mueller (2010) propose an elaborated taxonomy of uncertainty, which tries to cover a wide spectrum of intellectual pursuits. The distinguished levels start with “Complete Certainty” which refers to the realm of idealized determinism, that all past and future states of the system are determined exactly. Level 2: “Risk without Uncertainty,” 3: “Fully Reducible Uncertainty,” 4: “Partially Reducible Uncertainty,” 5: “Irreducible Uncertainty” follows on gradually. And finally 6: level ∞ “Zen Uncertainty” describes attempts to understand uncertainty as mere illusions.

In his book “Les sciences de l'imprécis” in 1990 Moles (2004) put emphasis on uncertainty as an important fact in science, and it is pretty easy to witness. The null hypothesis typically indicates 1/n proportion of n numbered options (equal rates). However, a simple reasoning, an external data, or at least a wispy sense will change the proportion assigned to each option; hence, that type of knowledge although it is imperfect, incomplete or so primitive, yet it is not ‘null.’ Uncertain knowledge is better than to know nothing. In this respect, any subjective knowledge or any kind of data that reduces the covalent options (creates difference) has to be the object of science. On the other hand, under the taxonomy of uncertainty, Moles (2004), describes uncertain phenomena which are somehow not associated with the objectivity of science. He mentions the fields in which the things are uncertain at present and will probably remain uncertain for a long time; subconscious and subliminal matters are cited as examples. Also, uncertainties in some areas such as religions and beliefs are revealed with the support of sociology and psychology. This approach shows the inherent uncertainty in our way of life and our frame of mind, besides the explicit uncertainty in mathematical formulations.

2.1.3 Decision making under uncertainty

Uncertainty is intrinsically linked to problem solving and decision making both in science and in everyday life. Our decision making depends on the concept of utility – a measure of the desirability, or of the various consequences of our actions (Jordaan, 2005). Rendering optimal is another crucial issue for decision making under uncertainty. Most problems (especially design problems themselves) are multiobjective in nature, where one is interested in simultaneously optimising two or more conflicting objectives. For example the goals of low cost and high quality are generally mutually exclusive. Another topic of interest is the relation between uncertainty and risk for decision makers. Knight (2009) puts emphasis on interdependence and says “uncertainty must be taken in a sense radically distinct from the familiar notion of risk, from which it has never been properly separated.” Profit is labelled as the key which pushes a person to take risk. Risk is present in every circumstance of uncertainty as a result of unpredictable outcomes and inaccurate measurement of loss. Yet, uncertainty is associated with the incident, and it is an intrinsic feature of nature. Risk, contrarily, is about the actions and the outcomes. Uncertainty is the same for all who deal with it, but risk depends on the choice that a person opts for, as in the example: the possibility of raining is uncertain for everyone; but the risk of getting wet is specific to one person.

Experiments on human cognition and decision mechanisms indicate that people avoid unknown probabilities in decisions under uncertainty; named as ‘ambiguity aversion’ (Camerer and Weber, 1992). Especially some unpleasant outcomes of risky choices make people uncomfortable; and they regard them as undesirable situations which one needs to reduce or minimize. However, vagueness (fuzziness) and imprecision is inherent in our daily life. And for simple, quick and practical decisions human thinking and judgement works well with uncertainty. This refers to the ‘linguistic uncertainty’. Lootsma (1997) says that while people think and decide, a considerable amount of imprecise information with a quantitative connation is transmitted via natural language. And, he lists the frequency indicators as well-known examples: “almost never, rarely, sometimes, often, mostly and almost always,” which are all meaningful in a particular context only. The question of whether a man is short, somewhat taller, rather tall, tall, or very tall depends on the situation (in comparison with whom). So, graded judgement should also be considered within a particular framework. Additionally, those qualifications -tall- and set of categories -tall men- are identified within a shared social consciousness, which also creates the communication.

Objectivity which eliminates personal biases, a priori commitment and emotional involvement is often attributed to the property of science and scientific measurement. But subjectivity exists in each theory, measurement and concept. All the theories and philosophies (or discovery of ideas) are the outcomes of a subjective mind, as the whole (scientific) world is interpreted through our own way of understanding. And, the perspective, feelings, past experience and knowledge (of the expert) as the components of individual subjectivity plays an important role in decision making. All uncertainties derived from subjectivity result in both fuzziness (e.g. “the square is crowded”, here the subject is square), and probabilistic uncertainty (e.g. “the probability of the square being crowded is high”, here the subject is the probability).

2.2 Uncertainty in Building and Space Studies

The built environment is always subject to uncertainty arising from many factors related to human actions, risk factors and the nature of the phenomenon.

2.2.1 Management

Uncertainty is a key challenge in managerial works, especially in construction projects (Chapman and Ward, 2011), which have a specific set of objectives and constraints such as a proposed time and budget. Project management acts to find a compromise between all inputs and possible outputs in the face of uncertainty. Uncertainty also has an immense impact on disaster and emergency management strategies. Almost all disasters pose uncertain and complex processes that are uneasy to foresee and to be prepared against its results. Along with uncertainty as the probabilities of events occurring, predictions are frequently based on incomplete and, often, statistically inadequate records (Granger, 2000). Additionally, uncertainty has a decisive role in environmental and natural resource management (Cardinall and Day, 1998) together with economy and society based developments.

2.2.2 Urban design

Uncertainty is crucial in urban studies; including planning, city structure and public space. Batty (2007) says “system of cities are no longer thought of as being ‘complicated’ but rather ‘complex,’ in that there is always uncertainty about the outcome of processes of change that originate from the bottom up”. Public space always has a fluid and dynamic configuration, as it naturally represents social life. Cupers and Miessen (2002) stress that public space and urbanity have always been connected to “disorder, functional heterogeneity and diversity.” Public spaces are (should be) places where the individual and the community can openly and freely meet and interact. Highly structured, programmed, and controlled spaces in the contemporary city threaten the city’s public connectivity; its openness and unpredictability. Sennett (2007) argues that the over-determination both of the city’s visual forms and its social functions result in the “Brittle City;” a closed system, which ignores evolutionary growth and change in time. It is experienced in Le Corbusier's “Plan Voisin” for Paris where rigid images and precise delineations remove the urban imagery. However, the idea of “Open City,” influenced by Jane Jacobs’ urban studies, attaches uncertainty and complexity to the design of cities. Sennett describes the systematic elements of an open city as “passage territories,” “incomplete form” and “development narratives” –which if those three are incorporated is “democratic”.

2.2.3 Geography

Researchers in the discipline of geography are the first to discuss the notion of spatial uncertainty. A vast majority of research is conducted on uncertainities in spatial choice, behaviour and decision-making in human cognitive and perceptual processes. Imperfect situations in spatial data sources, data (information), classification, analysing, representing and mapping in geographic information systems (GIS) are also examined. For Couclelis (1996) the imperfection may derive from one or all of the following variables: the observer or its means of observation, the application purposes, and the characteristics of the phenomenon. Campari (1996) describes the space as an "ensemble" of elements and entities with uncertain boundaries, and their determination depends on the context in which the elements and entities are observed. Bordogna et al. (2006) stress that spatial entities characterised by either unsharp boundaries or sharp boundaries whose positions are ill-known are forced into rigid representations which are embodied as artificial boundaries or disregard relevant irregularities. However, spaces are rarely defined and delimited in such a decisive manner.

2.3 Uncertainty in Architectural Design

In this section, uncertainty in architectural design is addressed as being in the emergence of the design idea, and as being the purpose of design itself. The major concern here is the blurring boundaries in architectural form and space, which prompts uncertainty in the shape grammar and in the spatial configuration.

2.3.1 Uncertainty in the design process

Uncertainty is inherent in the design thought. According to Schön (1987) designers, architects in particular, make representations of something non-existent, "something to be brought to reality," dealing with unknown and uncertain variables, constraints and consequences that, throughout designing, may be discovered and defined. In the beginning, the final outcome is always uncertain and designing is a continuous process of definition and discovery in a constant loop of construction, surprise, analysis, criticism and reconstruction. This continuous endear is named as "reflection-in-action". The designer deals with uncertainty through reflecting on his own actions, reframing the unexpected outcomes throughout the process. This open-ended process is like a 'trial and error' method in which the designer's reflection on each trial is a new starting point for the next trial; and new meanings and directions for the last artifact. Stiny (2008) strongly relates 'uncertainty' to the concept of 'ambiguity'. For him, it is not possible to know in advance what you are going to see and do next; ambiguity is an unavoidable factor within the design process. And he claims that although ambiguity causes "misunderstanding, confusion, incoherence and scandal," it is not possible to be creative without it. He argues against the logical notion of counting, standardizing and analysing, which traditionally has attempted to reduce ambiguity as much as possible. Rather, he proposes assuming, using and promoting ambiguity as a method for supporting creative design processes. Lester and Piore (2004) also relate uncertainty and ambiguity to the concept ‘innovation’. For a designer the world “appears so complex and uncertain that not even the possible outcomes are known”. Innovation derived from uncertainty and ambiguity is used as an initial resource out of which new ideas emerge. Additionally, Özkar (2004) in her thesis discusses that uncertainties and reasoning can be handled simultaneously in design education to benefit creativity –through abstract forms, not fixed elements and structures by saying: “Design students should understand the creative process as a thought process that explores uncertainties and redefines constraints”.

The language of sketches and conceptual models in the preliminary design stage, also the bubble and zoning diagrams express the abstraction levels of the idea by retaining uncertainty and ambiguity for the final project. They show all primary relations, initial decisions including relative sizes and forms as well as syntactic composition before they are moulded into exact shapes and strictly defined spaces at the end. Figure 2.1 shows the concept models belonging to an architectural design studio (Çekmiş and Hacıhasanoğlu, 2011), where students exercised basic design principles by deferring secondary decisions in a more uncertain and vague way when compared with the final projects.

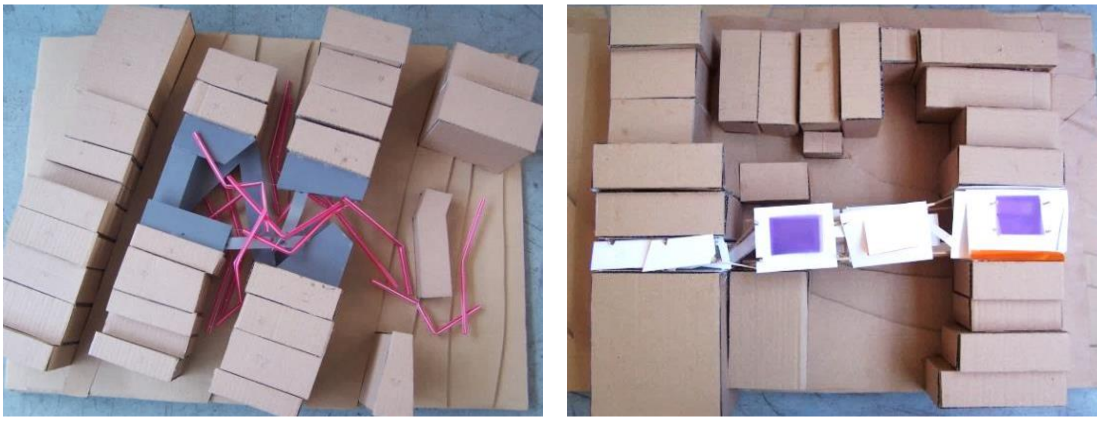


Figure 2.1 : Concept models (Çekmiş and Hacıhasanoğlu, 2011).

2.3.2 Uncertainty as a design manifest

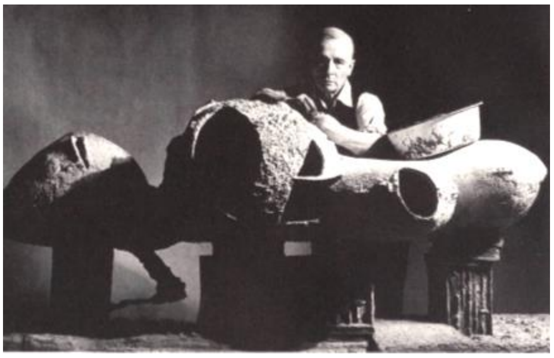
Besides the uncertainty and its innovative stimulation during the design process, uncertainty can be attributed to the design idea itself. Price (2003) proposes that uncertainties convert from the abstract design concept to the physical life of a building. That is an enterprise of transforming indeterminate situations into indeterminate physical solutions.

2.3.2.1 Developments in the concept

The concept of indeterminacy was proposed by architects in the 60s and 70s as a way to assume and address the problems related to the uncertainty of change during the life of a building. Archigram and its allies promoted utopic ideas and a new architecture sympathetic to uncertainty, incompleteness and emergent situations (Sadler, 2005). John Weeks brought the word “indeterminacy” to architectural discourse with his project for the Northwick Park Hospital in London, 1961-64. He proposed an additive mode of indeterminacy, in which endless and extendable modular pavilions were able to grow linearly and thus were free to adapt to arising needs throughout their lives (Hughes, 2000). Within ten years Archigram extended the notion of indeterminacy. A member, Peter Cook (1999) told: “Architecture can be much related to the ambiguity of life. It can be throw-away or addictive; it can be ad-hoc; it can be more allied to the personality and personal situation of the people who may have to use it”.

Frederick Kiesler’s projects; Endless House and Universal Theatre (Figure 2.2) in the 1960s are theorised around the concepts of continuity and endlessness (Phillips, 2008). Kiesler proposed responsive architecture modulated to an evolving set of parameters that could expand and contract in correlation to varied spatial needs simultaneously within one continuous form. With the design of Universal Theatre, he attempted to create an inclusive spatial atmosphere that diffused the physical and social boundaries of architecture. Elasticity served as an important metaphor for Kiesler as it guided his practice beyond the limited scope of fixed static structures.

In 1970, the term “kinetic architecture” was introduced by William Zuk and Roger H. Clark (1970). They took several ideas developed in the 1960s from construction, engineering, planning, robotics and aerospace, and implied control and shape modification through mechanical movement. For them, architecture can be defined as a “three dimensional form-response to a set of pressures,” and therefore kinetic architecture is the mechanical modification of the shape according to the change on these pressures. They classify “incremental architecture” as the chance to envision a range of possible states and buildings open to accept new, outside elements which may not have existed at the time of the original inception. They also define "deformable architecture" as the chance to meet a variety of functions where at the time of the original design it is only necessary to predict a range of future changes which may occur.



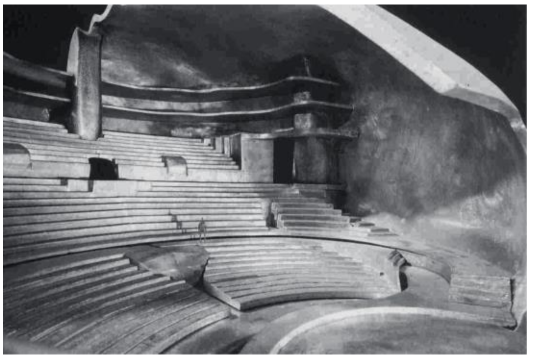


Figure 2.2 : Endless House and Universal Theatre (Phillips, 2008).

As the use of computerized form-generation tools in the architectural design process enhanced, new concepts regarding the design of the architectural form increased. The notion of indeterminacy, in-becoming and continuity used in early proposed models have shifted with the advent of cyberspace to an extent that a building itself is uncertain in terms of shape and space. In 1991, Marcos Novak wrote an inspiring article named "Liquid Architectures in Cyberspace." He expressed that, "Cyberspace is liquid. Liquid cyberspace, liquid architecture, liquid cities… Liquid architecture is more than kinetic architecture, robotic architecture, architecture of fixed parts and variable links. Liquid architecture is an architecture that breathes, pulses, leaps as one form and lands as another." For Novak, form belonging to liquid architecture is contingent on the interests of the beholder without doors and hallways. A liquid architecture in cyberspace is also a dematerialized architecture. This architecture tends to the pattern quality of music composition beyond the space, form and light.

Open Source Architecture (O-S-A) proposed "The Hylomorphic Project," which the concept uncertainty is in the creation of form (Iris, 2008). The research discusses the concept of uncertainty as a method in architectural design processes, where computerized calculations serve as the creative force in designing the architectural form. The design process includes a meaningful dimension of uncertainty regarding the product at the end of the process (Figure 2.3). Furthermore, that approach refers to processes in which this dimension of uncertainty is intrinsic to the computational process in itself. Given the complexity of the calculation and the embodiment of indeterminacy within the computational process, the discussion is of uncertainty as a method and a process and of the potentiality of the method with regard to design. The design process of The Hylomorphic Project serves as a platform for unpredictable and extraordinary results that would not have otherwise been possible.

Figure 2.3 : The Hylomorphic Project (http://www.o-s-a.com/portfolio/the-hylomorphic-project/).

Rosenberg (2009) uses "Scissor-pair Transformable Structures," first invented in the 1960s, to explore the generation of uncertain spaces and behaviours. The "Centre Scissor-Pair" is the basic configuration for simple transformable structures (Figure 2.4). Scissor-pair Transformable Structures are mechanisms able to change as they follow a sequence of states, changing physically from one overall shape to another in a continuous process, offerring the chance to design and build indeterminate physical solutions. Rosenberg claims that the use of these types of structures in architecture constitutes an opportunity to materialize the dual condition of uncertainty; the one during the design process and the one during the life of the building.

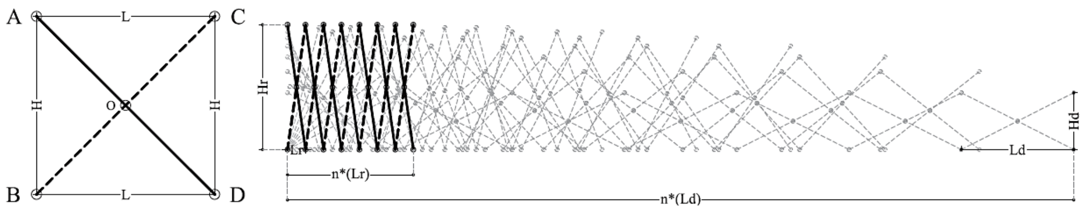


Figure 2.4 : Scissor-pair Transformable Structures (Rosenberg, 2009).

2.3.2.2 The idea of flexibility and open-plans

The idea of flexibility is clearly an architectural response to uncertainty. Designing a flexible system is seen as a method for managing uncertainty. In general, the term flexibility is applied to an object which is pliable and yielding. In architecture and design the term flexibility does not refer to the physical characteristics of material (pliability or rigidity), but rather the tendency to change in order to suit new conditions and requirements.

In the beginning of the 20^{th} century, Frank Lloyd Wright developed his Prairie-style domestic architecture influenced by Japanese design of flowing spaces; their unfettered integration by sliding walls and open-plans. Those years his books were owned by emerging modernist designers including Peter Behrens, Le Corbusier, Walter Gropius, Mies van der Rohe and Otto Wagner (Kronenburg, 2007). The idea of flexibility was conceived as a missing part of functionalism of modernity. Against the presumption that all parts of a building should be destined for specific uses, recognition that not all uses could be foreseen at the moment of design made 'flexibility' a desirable architectural property. Gropius advised that the architect should conceive buildings not as monuments but as receptacles for the flow of life which they have to serve; and his conception should be flexible enough to create a background fit to absorb the dynamic features of our modern life.

Associated concepts of flexibility

Flexibility is associated with many concepts in design. The phenomenon of '*change*' is at the core of flexibility. Kronenburg (2007) claims that flexible buildings are intended to respond to changing situations in their use, operation and location. This is architecture which adapts, transforms, moves and interacts with its users; not the one which is static, stagnates, restricts and inhibits. He says that change constantly takes place in economic, social, and cultural life. Change occurs (1) in the environment around the buildings, (2) in the way they are used, and (3) in the purpose beyond recognition. And flexible architecture is designed for 'responsive' living.

Flexibility is related to the capacity to accommodate the different size of dwelling which is expanding or shrinking, which we may call '*elasticity*'. The concept of elasticity is concerned with the study of changes in the floor area, spatial requirements and the shape of the dwelling. According to Moharram (1980), elasticity can be achieved in two ways – by 'add-on' (adding new space to the overall space already given), and by ‘add-in’ (adding spaces to the interior of the building without changing the existing area).

‘*Scaleability*’ also describes a property of space for expansion and contraction. For example, Brubaker (1998) notes how schools may require annexes and additions to meet the needs of increased enrolment or curricular alterations.

‘*Versatility*’ is the ability to provide for multiple uses of space. This approach deals with two variables; space and time. Space may be used either for several functions at the same time, or for different functions at different times. It requires the interchangeability of functions in the space. According to Monahan (2002) cafeterias, auditoriums and ‘multi-purpose rooms’ signal one mode of versatility, but versatile spaces such as these run the risk of homogeneity.

Flexibility and ‘*variability*’ are essentially complementary. Flexibility refers primarily to the adaptation to change, while variability refers to change as such. Various configurations allow for different users of the same unit to choose a different layout from multiple options. Habraken (1976) devised variations as the systematic design of support structures that led to the design of the module. Dluhosch (1973) stressed that variability of use is achieved by the manipulation of objects either in a personalized manner or by design.

‘*Modifiability*’ is the spatial property which invites active manipulation and appropriation. Maccreanor (1998) states the need for physical change in housing emerges due to two reasons. Housing units are expected to offer freedom of choice (typological variety) for users having a diversity of lifestyles prior to occupation. Secondly, they should provide the opportunity to make adjustments or modifications (adaptability/flexibility) according to changing wishes and demands over time.

‘*Adaptability*’ which is the ability of individual modifications to suit new conditions is used for theorists; occasionally in a similar meaning and overlap with flexibility. However, there also exists a controversial conception about terms. Maccreanor (1998) identifies flexibility that does not imply the necessity of endless change and breakdown of accepted formula. And adaptability is a different way of viewing flexibility” which refers to “transfunctional[ity] and multifunctional[ity]”. For housing projects, Schneider and Till (2007) describe flexibility as achievement by altering the physical fabric of a building, and adaptability as achievement by designing rooms or units so that they can be used in a variety of ways. In short, adaptability is related to the use of space. Flexibility, on the other hand, is defined as suitability for different physical arrangements, which is valid not only for the interior but also for the exterior adjustments of the unit itself.

'*Evolvability*' which is a unique term in system engineering extends the viewpoint of design. Evolution is a word most commonly associated with the concept of incremental change of an entity over time. And system evolvability is the ability of a system to adapt in response to changes in its environment, requirements and implementation technologies. In a similar sense, evolvable spaces and buildings can change and adapt to altering circumstances during their life cycles. Evolvabilitiy in architecture particularly refers to an imaginative adaptiveness; a capacity to deal with the unforeseen just like nature always does.

The notion of '*affordances*,' coined by the psychologist James Gibson in 1977 to indicate the actionable properties the environment offers to an animal, is applied to architecture and buildings in order to represent functionality and usability (Koutamanis, 2006). Human interaction with the built environment is largely conditioned by the affordances of building elements and spaces. "The multi-level abstraction and the flexibility of choice implied by the underlying functional patterns are essential for the correlation of designers' and users' perception of affordances." Maier et al. (2009) suggest that the idea of affordance may serve as a conceptual basis and unifying framework for architectural theory, design and practice.

The concept of '*permanence*' is introduced into architectural discourse in Vitruvius' Ten Books of Architecture as 'firmitas' (Touw, 2006); mass and solidity crafted to endure eternally. As a contemporary notion, dynamic permanence through a flexibility of location and, potentially, of function; involves all scales from building parts to entire buildings.

'*Fluidity*' represents the design of space for the flow of individuals, sight, sound, and air. Open spaces are well-known designs to provide fluidity. Fluidity may be interpreted as the diffusion or intertwining of building elements or functions. Also the texture of space, the meaning and the sense is possibly translocated. Change, fluidity and movement is conceived as the unifying feature of architecture today and ‘dynamism’ is in the centre; as dynamic inhabitants, materials, structures, connections and associations (Harris, 2002).

‘*Movement*’ is a strong term which refers to the dynamism of flexible architecture. It is also the keystone of 20th century utopias. It inherently bears the potential of mobility. For Archigram, mobility was important and omnipresent, even for the urban landscape that became a “Walking City”. Buildings can form new clusters anywhere to deal with the changing demands of a city. Yesterday’s offices could change into tomorrow’s museums and kindergartens.

‘*Functionality*’ is a blurred term within its relation with flexibility. Flexibility was first coined in the modernist age as a hope of redeeming functionalism from deterministic excess by introducing time and the unknown. Forty (2000) sets forth the confusion in the meaning of flexibility which is based on two contradictory roles: “it has served to extend functionalism and so make it viable” and “it has been employed to resist functionalism.”

Open-plans

Forty (2000) identifies three types of architectural flexibility: by spatial redundancy, by technical means, and as a political strategy. Hill (2003) adds one more: the open-plans. Spatial redundancy is well explained by Koolhaas and Mau in S, M, L, XL (1995). Flexibility is the creation of margin – excess capacity that enables different and even opposite interpretations and uses. Spatial redundancy is a feature owned, for example by Baroque palaces, where rooms were not dedicated to specific uses. Suggesting a loose fit between space and use, the open-plan is similar to flexibility by spatial redundancy, but unlike flexibility by technical means, in that change of use is less dependent upon a physical transformation of the building than a change in the perception of the user (Hill, 2003).

An earlier example of the open-plan can be Villa Madama (in the 1510s) by Raphael and Antonio de Sangallo. According to Evans (1997); the villa was, in terms of occupation, an open plan permeable to the numerous members of the household, because all its rooms can be public and permeable to movement. He attributed this design approach to the way of life which is evident in the 16th century, displaced in the 19th century by the corridor plan, “which is appropriate to a society that finds carnality distasteful, which sees the body as a vessel of mind and spirit, and in which privacy is habitual… In this respect modernity itself was an amplification of nineteenth century sensibilities." Modernist open plan does not reflect a society which prompts 'carnality;' however the interconnectivity of spaces is apparent in both the Villa Madama and the Barcelona Pavilion (Hill, 2003).

Japanese architecture was better known to early modernists; also the open plan. 'Fusuma,' sliding partitions in traditional Japanese house was praised by Gropius. There is no "circulation space" as we understand it; connections are made between rooms, each room is an antechamber (anteroom) to another and names can be given to rooms based on the uses to which they are put at a given time of day (Rabeneck et al., 1974). Furniture is mostly lightweight and movable, such as beds which are only brought out when in use, and the rest of the time they are folded away. However Hill (2003) criticizes the adaptation of Japanese (and Korean) architecture to the modernist open plan in terms of being misinterpreted and having hardened their spatial, social and environmental "porosity;" the unique characteristic of the connection between inside and outside.

In the early 20th century the 'open plan' became a key site in modernist architecture. Its most extreme versions, without rooms or doors, seemed to symbolise a radical and unprecedented freedom. The "free plan" or "plan libre" as the opening up of spatial composition was also the third of the "Five points of a new architecture" published by Le Corbusier in 1927 to promote his ideas at the Weissenhof in Stuttgart. The free design of the ground plan is managed by interior walls placed wherever required; each floor being entirely independent of the rest. The open, flowing space of this free plan was central to the work of leading modernist architects. While exploring the potential of this pattern, Mies van der Rohe pushed it further by proposing the idea of a "column-free universal space" to be deployed at every scale from the house to wide mayor public buildings. Crown Hall (Figure 2.5), which was completed in 1965, is a pure rectangle with a 36.6 x 67 m wide floor plan enclosing a column free interior space (Cohen, 1996). Lots of diverse scaled projects by different architects represent this concept such as the Hangar Project by Wachsmann, 1953 and Eames House by Charles Eames, 1949.

Both past and present, spaciousness and flexibility of open plans are appreciated in many projects, especially for the typologies incuding houses and offices, also the exhibition areas of galleries and museums. The architectural design of exhibition areas plays a critical role in facilitating visitors' encounters with the displays. Open planned projects provide a wide range of possibilities in the arrangement of art objects and of combinations for engagement between visitor and art object. The Pompidou Center (Figure 2.6), as a competition project, gains its significance by virtue of its flexible design which identifies the relation between the collection and the exhibition space. The juxtaposition of different functions under the containment of huge, undivided voids reflects the initial idea's focus on the concept of flexibility (Silver, 1994). The space of any part of the museum's differentiated program can be enlarged or shrunk with respect to the changing needs of these functions.

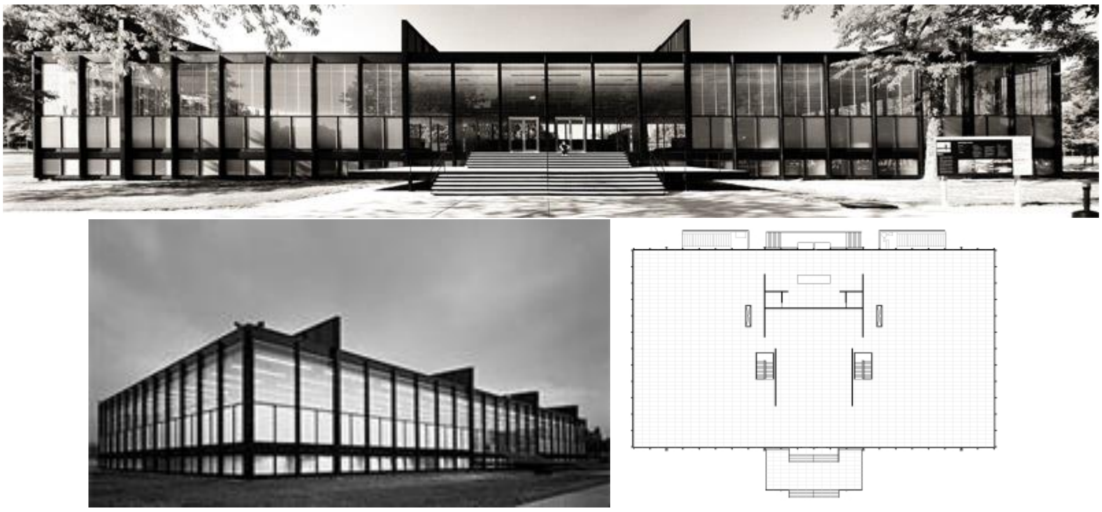


Figure 2.5 : Crown Hall (Cohen, 1996).

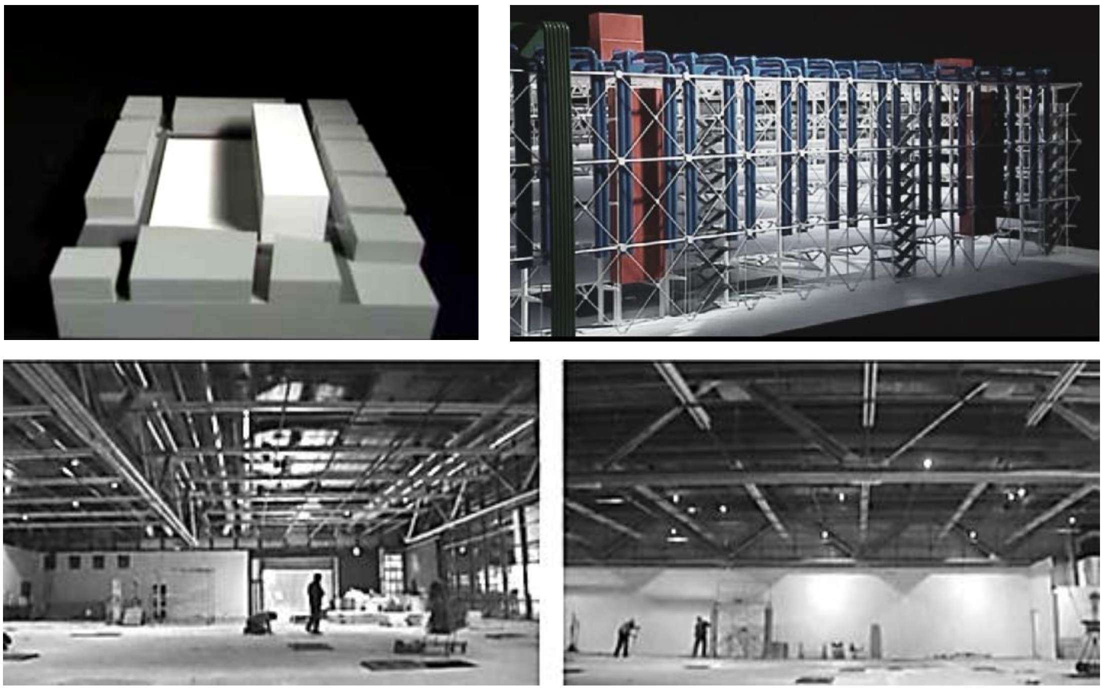


Figure 2.6 : The Pompidou Center (Erkaya, 2008).

Peponis et al. (2004) concentrated on open plan exhibitions and the effect of exhibition layouts on visitors' spatial behaviour. This study focuses on the effects of accessibility and visibility on visitor movement paths and engagement with display objects. Physical boundaries connect or separate spaces, and reflect ‘structures’ in a building program. Thus, the “disposition and arrangement of boundaries” structure permeability in space and organize accessibility patterns in a building configuration (Peponis et al., 1997). However, in open plan museums, physical boundaries are less prominent. Path choice is particularly critical for open plan museums where visitors' spatial behaviour is less determined by partitions or other physical constraints, but where some implicit boundaries are recognized through visibility (Kaynar, 2009).

2.4 Chapter Summary

This chapter revealed that uncertainty exists in daily life, in almost every real world problem, and science did no longer endeavour to reach precise and exact conclusions. By addressing the concept within three different fields; complex processes of management, fluidity of social city forms and the notion of spatial uncertainty were introduced. But this chapter comprehensively investigated uncertainty in architectural design encompassing the areas of design process and design manifest. The significant point in this part was the idea of flexibility and emergence of flexibility as open-plans, which will be referred to throughout the rest of the thesis.

Overall, in this chapter the theoretical part of the proposed model was illustrated by exploring uncertainty in many aspects. The following chapter will review the methodological base of the model. Fuzzy logic and fuzzy sets are proposed as the appropriate way of handling uncertainty.

3. FUZZY LOGIC AND FUZZY SETS

This chapter first introduces some methods and techniques proposed for modelling uncertainty, and later elaborates on fuzzy logic and the theory of fuzzy sets as the most suitable approach to be used in the spatial model. The computational tool for applying fuzzy reasoning is immediately explained in the following section. The last sections are allocated for literature review of fuzzy logic and sets methods in management, urban studies and geography, also fuzzy thinking in architectural design with respect to the previous chapter.

3.1 Measuring Uncertainty

The expression of uncertainty in measurement is a challenging aspect for researchers. There is a substantial and growing body of research focusing on the mathematical treatment of uncertainty. Probability theory, statistics, classical set theory, fuzzy set theory, possibility theory, rough set theory and evidence theory (Dempster-Shafer Theory) can be cited as well-known methods for measuring uncertainty.

“Probability theory” is the essential tool of mathematics to deal with random problems. Its root is in a gambler’s dispute in the 17th century, but was clarified by Kolmogorov in the 20th century via a treatment of probability theory on an axiomatic basis for statistics and stochastic processes (Li and Du, 2007). The outcome of a random event cannot be determined before it has materialised, whilst we are able to have an idea about the outcomes. We assign equal probabilities to each finite number of possible outcomes of that chance experiment. For example when we toss a coin, both the possible outcomes H (heads) and T (tails) has the probability of 1/2. If the randomness of the case is not structured in this way, the experiment is repeated a large number of times -trials- with an expectation of probability distribution among the possible outcomes –frequency concept of probability (Grinstead and Snell, 1997).

“Statistic” which is also used as a tool to measure uncertainty is conceptually related with the probability theory. Probability is interested in predicting the likelihood of future events, while statistics involve the analysis of the frequency of past events

(Skiena, 2001). Hence, a statistician makes observations and gathers data to reach rules about future matters (who looks backwards), the reverse of what a mathematician using probability does (who looks forward).

“Classical set theory” brings a fundamental concept needed for uncertainty analysis. A set is a collection of items or elements from a universe of interest. In set theory, an object is either a member of a set or not; which refers to classical or crisp sets (Ayyub and Klir, 2006). It expresses the uncertainty through the use of sets of mutually exclusive potential alternatives. However, crisp set theory is not capable of representing uncertainty in many cases in terms of description and classification.

“Fuzzy set theory” is an outgrowth of classical sets. Fuzzy sets have imprecise boundaries different from crisp sets. Thus, the membership in a fuzzy set is gradual rather than abrupt, which is labelled as the membership function (Klir and Wierman, 1999). Fuzzy logic and set theory was coined by Lotfi A. Zadeh in 1965 as an alternative for binary logic. This approach allows partial belonging -values in the interval [0 - 1]; from the highest level of compatibility (1) to non-compatibility (0).

“Possibility theory” was introduced as an extension of fuzzy sets by Zadeh (1978). It uses possibility to describe uncertainty instead of probability; grounding that imprecision that is intrinsic in natural languages (also in human decisions) is possibilistic rather that probabilistic.

“Rough set theory” was developed as a way to describe uncertainty where the classical sets fail. Those sets were first described by Pawlak (1991) by proposing a formal approximation of a crisp set through a pair of precise subsets: the lower and the upper approximation. Theories of fuzzy sets and rough sets are derived from classical set theory in favour of modelling vagueness and ambiguity. However, a fundamental question arises concerning their relationships and differences. Rough sets pertain to the indiscernibility between objects due to the equivalence relation, while fuzzy sets deal with the ill-definition of boundary of an objects group (Yao, 1998). As Zadeh (1998) told, a fuzzy set may be viewed as a class with unsharp boundaries, whereas a rough set is a crisp set which is coarsely described.

“Evidence theory” (Dempster-Shafer theory) was reinterpreted and published by Glenn Shafer in 1976 as an extension of the work of Arthur Dempster (Shafer, 1976). The theory is based on two ideas in principle; belief and plausibility as measures of uncertainty. Plausibility of an event depends on the quality of belief which measures the strength of the evidence of experiments or of any other reliable source. And the degree of a belief (belief function) of an event is known through the combination of independent pieces of information from different sources.

There exist generally multiple types of uncertainty within the same (design) problem. The source of uncertainty you deal with determines the methodological approach you should use –among those which have been briefly introduced above. The theory of fuzzy logic differs from the other methods in several important ways that also make it ideal for the proposed spatial model, even though it is less well known in architecture than probability theory and statistics. The next section presenting fuzzy logic and fuzzy sets highlights those advantages and convenience.

3.2 Fuzzy Mathematics

As the most commonly known tool of measuring uncertainty, probability theory (or allied methods like statistics and evidence theory) models a type of uncertainty which is related to the '*events*' –about their results which will either occur or not. Probability theory proposes a quantitative analysis of random and frequent phenomena. However, fuzzy set theory models a different kind of uncertainty. It refers to the uncertainty which cannot be described by endless trials and experiments; that is the vagueness and ambiguity inherent in the '*facts*' (such as natural formations). Instead of modeling a variable's likelihood of achieving a specific value (Talley, 2008) fuzzy set theory indicates to which group a variable or alternative belongs. In a nutshell, fuzzy logic enables a qualitative analysis of intrinsically uncertain phenomena.

3.2.1 Fuzzy logic

Fuzzy logic is the conceptual foundation of fuzzy sets. Zadeh (1975, 1979) says that fuzzy logic is not fuzzy; it is a precise logic of imprecision and approximate reasoning. It can be seen as an attempt at formalization and mechanization of two remarkable human capabilities (Zadeh, 2008): the capability to converse, reason and make rational decisions in an environment of imperfect information, and the capability to perform a wide variety of physical and mental tasks without any measurements and any computations.

Fuzzy logic is based on the notion of partial or relative truth which fluctuates between completely true and completely false –different from the conventional dual logical statement which is either true or false, but not in between (Zimmermann, 2001). The bivalence in logic, as well as science and mathematics, which identifies a world of black and white, dates back to the ancient Greeks; Aristotle's binary logic postulates the law: it is either "A" or "not A;" it can't be "A" and "not-A" (the law of excluded middle). The critical response to this logical assumption has always existed, before Aristo and later; as like in the belief system of Buddha seeing the world filled with contradictions; in the rhetoric of the sophists in Greek; and in the wax argument by Descartes. The state of being both A and not-A defines a situation of intermediate. As Kosko (1993) states: "Everything is in flux. Everything flows…there are the atoms in between…The finger shades into the hand, the hand shades into the wrist, the wrist into the arm. Earth's atmosphere shades into space. The mountain crumbles into a hill and in time crumbles into a plain". So, in the world of black and white, there exists gray "from accurate to inaccurate as they change". But, the probability theory, first proposed to handle this type of uncertainty, does not support the grays; instead it is about the events which are black or white; occurs and not occurs. Aristotle's law of A or not-A is fundamental in the probability theory, whereas the "fuzziness" in fuzzy logic denotes grayness between black and white –referring to multivalence; the quality of having many values. Overall, fuzzy logic can be cited as a multivalued logic, where the principle of theory depends on the matter of degree including truth (set membership). Then, it formulizes the approximate reasoning.

Zadeh (1997) mentions three basic concepts of human cognition which are granulation, organization and causation; "granulation involves decomposition of a whole into parts; organization involves integration of parts into a whole; and causation relates to the association of causes with effects." And, humans are capable of making rational decisions in an environment of imprecision, partial knowledge, partial certainty and partial truth by using fuzzy information granulation. So, fuzzy logic is highly effective and successful in dealing with real-world problems. Fuzzy logic prompts a qualitative analysis referring to linguistic thinking. Humans employ words in computing and reasoning, arrive at conclusions expressed as words – different from the traditional sense of computing that involves manipulation of numbers and symbols. The concept of "Computing with Words" (CW) (Zadeh, 1996) is an assignment of words to numbers (membership values and functions); and an assignment of numbers to words. The information is conveyed by a collection of propositions expressed in a natural language. There are a number of word categories; nouns (e.g. age), adjectives (e.g. young), adverbs (e.g. very) and verbs in natural language. The adjectives and adverbs define the noun as a matter of degree. The epistemological and ontological foundation of fuzzy logic relies on this representation of meaning and knowledge (Türkşen, 2006).

3.2.2 Fuzzy sets

Fuzziness is mathematically expressed by fuzzy sets to capture the idea of partial membership. The classical (crisp) set theory is incapable of modelling linguistic vagueness and imprecision. Because, a set is a collection of distinct objects –each single element can either belong to or not belong to a set. This refers to the Aristotelian logic; the law of A is either true (1) or false (0). All the elements in a set are completely equal in terms of their belonging to the set. For instance, the set ‘age’ has subsets (the collections of elements within a set): “old,” “middle-aged” and “young,” which are strictly separated from each other. The universe of discourse X covers all the ages a human can be, any age value $x \in X$ is the member of only one subset x, MF = 1; and non-member of the other subsets x, MF = 0. For instance x = 35 is either young or middle aged. So, in traditional bivalent set theory, there exists a sharp distinction between members and non-members of a set.

Considering two classical sets A and B defined on the universe X, the basic operations that can be performed are;

The *union* (3.1), called logically as OR, represents all the elements that reside in either the set A, the set B or both sets A and B;

$$A \cup B = \{x | x \in A \text{ or } x \in B\} \tag{3.1}$$

The *intersection* (3.2), called logically as AND, represents all the elements that simultaneously reside in both sets A and B;

$$A \cap B = \{x | x \in A \text{ and } x \in B\} \tag{3.2}$$

The *complement* (3.3), called logically as NOT, represents all the elements that do not reside in the set A;

$$\overline{A} = \{x | x \notin A, x \in X\} \tag{3.3}$$

As distinct from the traditional bivalent sets, in a fuzzy set the truth ranges in value between 0 and 1, as it refers to the partial truth. A fuzzy set contains elements that have varying degrees of membership. So an element can reside in more than one set with different membership degrees according to its degree of belonging (Şen, 2009). This idea is in contrast with classical set theory that members of a crisp set would not be members unless their membership was full or complete (MF = 1). An element in a fuzzy set has a membership value in the interval of [0, 1], thus a fuzzy set (3.4) is characterized by 'membership functions':

$$A = \{(x, \mu_A(x)) \mid x \in X\} \qquad \textbf{(3.4)}$$

The fuzzy set "age" (nouns), for instance, has fuzzy subsets (or membership functions): "old," "middle-aged" and "young" (adjectives) which overlap (Zadeh, 2008). And any age value is identified by membership degree $0 \leq x \leq 1$ according to it belonging to the membership function (Figure 3.1). In the real world, the adjectives such as young, middle aged and old refer to continuous numerical scales, as $x = 35$ can be both young and middle aged, very or slightly. This reality; this type of uncertainty arising from the vagueness and imprecision of the fact itself can mathematically be expressed by fuzzy sets. In relation to fuzzy logic, the membership function is the granulation of data (or knowledge), while adverbs such as very and slightly indicate the degree attached to label partial truth –membership degrees in fuzzy sets.

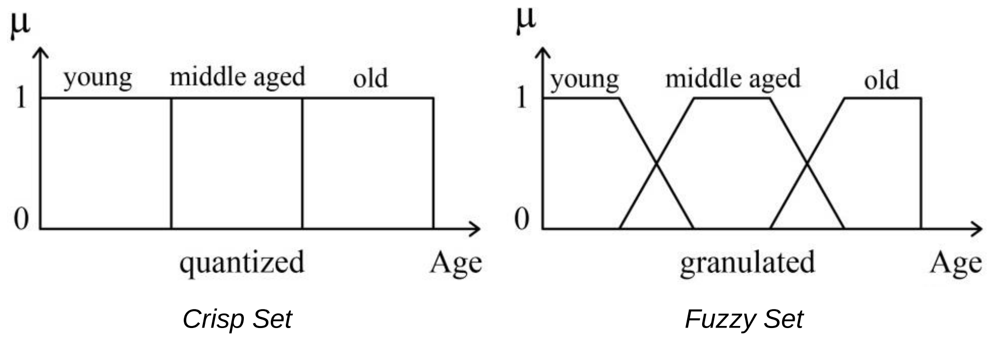


Figure 3.1 : The granulation of age (Adapted from Zadeh, 2008).

In Figure 3.2, fuzzy set properties are seen on a trapezoidal membership function. Each member has a membership degree in a fuzzy set A within the interval [0, 1], such as a_1 MF = 0.5 and a_2 MF = 1. The "α-cut" of fuzzy set A is the crisp set $^{\alpha}A$ that contains all the elements of the universal set X whose membership degrees in A are greater than or equal to (or only greater than) the specified value of α. The set of all levels $\alpha \in [0, 1]$ which represents distinct α-cuts of the given fuzzy set A is called a "level set" of A. The "support" of fuzzy set A within a universal set X is the crisp set that contains all the elements of X that have a nonzero membership degree in A. The "height," *h*(A), of fuzzy set A is the largest membership degree of any element in that set. Fuzzy set A is called "normal" when *h*(A) = 1, and it is called "subnormal" when *h*(A) < 1 (Klir and Yuan, 1995). Besides this *vertical view* of a fuzzy set as a membership function, seen in Figure 3.2, another view is to consider a fuzzy set as a nested family of classical subsets via the notion of level-cut, named as the *horizontal view* of a fuzzy set (Dubois et al., 2000). The idea is to fix a positive threshold α and to consider as members of the set the elements with membership grades above the threshold. Moving the threshold in the unit interval, the family of crisp sets $\{\mu_a: 1 \geq \alpha > 0\}$ is generated (Figure 3.3).

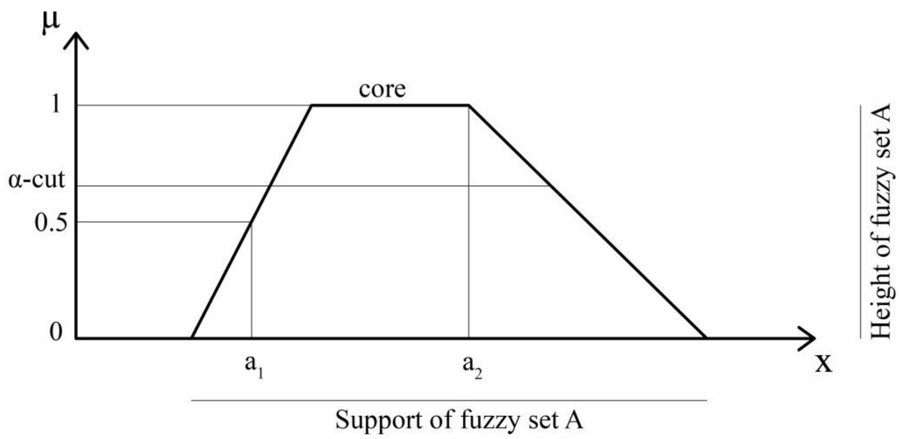


Figure 3.2 : A fuzzy set, vertical view.

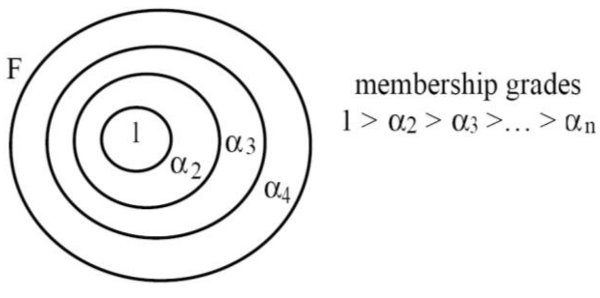


Figure 3.3 : A fuzzy set, horizontal view.

Considering two fuzzy sets A and B defined on the universe X, the basic operations that can be performed are (Çelikyılmaz, 2008);

The *union* (3.5) is defined by the maximum of membership functions;

$$A \cup B = \mu_{A \cup B}(x) = \max [\mu_A(x), \mu_B(x)] \qquad \textbf{(3.5)}$$

The *intersection* (3.6) is defined by the minimum of membership functions;

$$A \cap B = \mu_{A \cap B}(x) = \min [\mu_A(x), \mu_B(x)] \qquad \textbf{(3.6)}$$

The *complement* (3.7) is for A^c is defined as follows;

$$\mu_A{}^c(x) = 1 - \mu_A(x) \qquad \textbf{(3.7)}$$

To make a comparison, Figure 3.4 illustrates a graph to show the difference in the logical operations between two-valued logic; crisp logic and multivalued logic; fuzzy logic (MathWorks, 2013a).

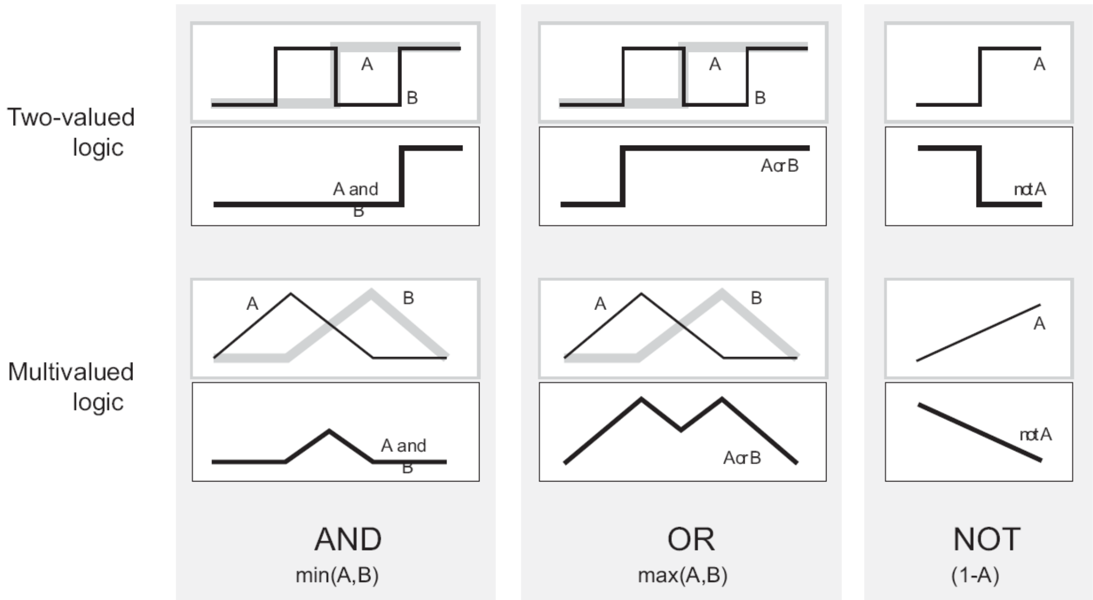


Figure 3.4 : Logical operations (MathWorks, 2013a).

In sum, fuzzy sets are the mathematical representation of fuzzy logic –the mental representation of reality. The facts such as age and temperature in natural language are expressed by resolving intermediate categories between notations such as true/false; young/old and cold/hot. Classical logic and crisp sets are too rigid to account for such categories that membership is a gradual notion rather than an all-or-nothing matter. In that sense, fuzzy logic and fuzzy sets provide an alternative to binary logic and precise numbers.

3.3 Fuzzy Computing

The fuzzy logic and sets capabilities can be exercised by using MATLAB. MATLAB (matrix laboratory) developed by MathWorks is a high-level language and interactive environment for numerical computation, visualization, and programming. “Fuzzy Logic Toolbox” provides functions, graphical tools, and a Simulink block for analyzing, designing, and simulating systems based on fuzzy logic (MathWorks, 2013a). The toolbox lets the user model complex system behaviors using simple logic rules, and then implement these rules in a fuzzy inference system (FIS).

Fuzzy inference is a method that interprets the values in the input vector and, based on user-defined rules, assigns values to the output vector. The FIS involves five steps: fuzzification, rules, inference process, aggregation and defuzzification. Figure 3.5 shows the flow of the process of the fuzzy inference system.

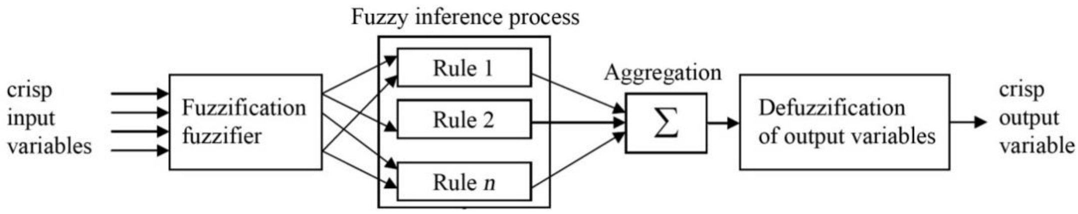


Figure 3.5 : Fuzzy inference system (Adapted from Raol, 2010).

The most commonly seen inference methods are Mamdani (Mamdani and Assilian, 1975) and Sugeno (Sugeno, 1985). The first two parts of the FIS; fuzzifying the inputs and applying the fuzzy operator are exactly the same in both methods. The difference lies in the consequents of their fuzzy rules: Mamdani fuzzy systems use fuzzy sets as rule consequent whereas Sugeno fuzzy systems employ linear functions of input variables as rule consequent (Sivanandam et al., 2007).

3.3.1 Fuzzification

In FIS, each input is defined as a fuzzy set which is characterized by its membership functions (MFs); this is the “subset”. So the input variable, which is always an integer numerically limited to the universe of discourse, is fuzzified by being assigned a membership degree: $0 \leq x \leq 1$ (Figure 3.6). This conversion of a Boolean quantity to a truth value by using the sets of input MFs is named as the fuzzification process. Fuzzification is applied for each input, and the rest of the inference process operates with the fuzzified input variables.

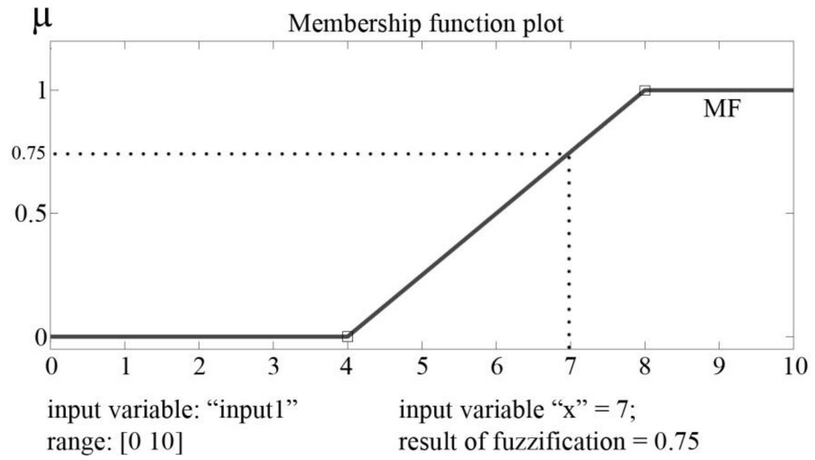


Figure 3.6 : Fuzzification.

Fuzzy logic toolbox includes eleven built-in membership function types. The straight line membership functions: triangular membership function (trimf) and trapezoidal membership function (trapmf) have the advantage of simplicity. A triangular membership function is defined by the variables a, b and c, where a is the left intercept (mf = 0), b is the center peak (mf = 1) and c is the right intercept (mf = 0). Trapezoidal membership function is used when the left or the right intercept or the center peak coverts into an interval of values (mf = 1) (Hines, 1997).

Notably the output can also be defined as a fuzzy set with MFs if the Mamdani-type inference is operating. However, in the Sugeno type of FIS, the system supports the output membership functions, which are either linear or constant.

3.3.2 Rules

The second step is generating the rules. To obtain the output in FIS, inputs are processed using a set of "IF-THEN" conditional statements (fuzzy control rules), which are written in the following form: If (input is MF x) Then (output is MF x). The if-part of the rule is called the antecedent or premise, while the then-part is called the consequent or conclusion. If the antecedent of a rule has more than one part, inputs are connected by logical operators – "AND", "OR" and "NOT" – where needed. Also, it is possible to weight one rule relative to the others in order to make it more effective in the inference system.

A 'relation' is a set of ordered pairs. Relations express connections between different sets, and they are a convenient tool for creating if-then rules (Kecman, 2001). *R* as a crisp relation matrix in Table 3.1 (a) shows the association or interconnection between fruit color and state. This relation matrix can be interpreted as an existing empirical set of If-then rules:

R_1 If the tomato is green, then it is unripe.

R_2 If the tomato is yellow, then it is semiripe.

R_3 If the tomato is red, then it is ripe.

However, a better interconnection between fruit color and state is given by a fuzzy relational matrix in Table 3.1 (b). Fuzzy relations between sets (inputs and output) are defined in linguistic variables expressing various degrees or strengths of associations, interactions and interconnections. The elements of the relational matrix are degrees of membership, that is, possibilities, or degrees of belonging, of a specific pair to the given relation R. So, R_1 can be written as follows:

R_1 If the tomato is green, then it is unripe (μ = 1), possibly semiripe (μ = 0.5), and unlikely to be ripe (μ = 0).

Table 3.1 : Relation matrixes (Kecman, 2001).

	R (crisp)	unripe	semiripe	ripe
	green	1	0	0
	yellow	0	1	0
	red	0	0	1
(a)				
	R (fuzzy)	unripe	semiripe	ripe
	green	1	0.5	0
	yellow	0.3	1	0.4
	red	0	0.2	1
(b)				

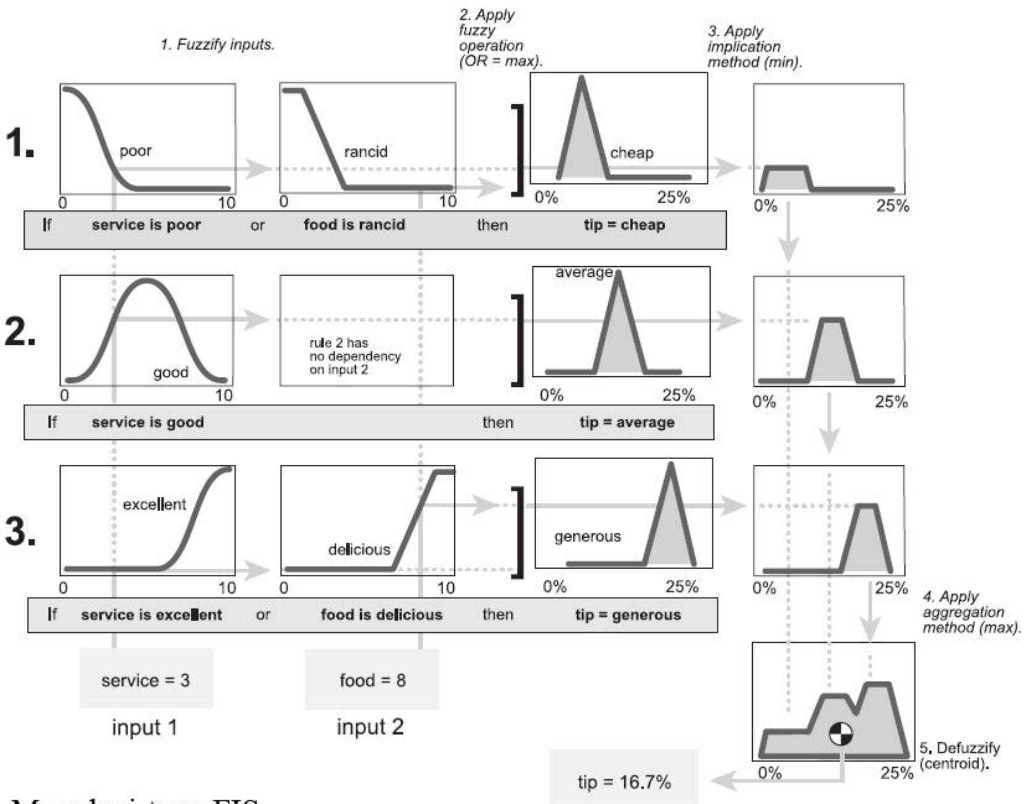
Fuzzy rule base consists of the rules that would be used in the inference process. All possible rules can be generated automatically by combining all the membership functions of the inputs and output (Şen, 2009). Expert opinion, training data and also the degree of belief (Nguyen and Walker, 2006) are the ways to validate the rules, as well as to eliminate or weight them. These three methods are crucial in architectural applications of fuzzy inference models, especially for predicting human behaviour and inhabitation patterns.

3.3.3 Inference, aggregation and defuzzification

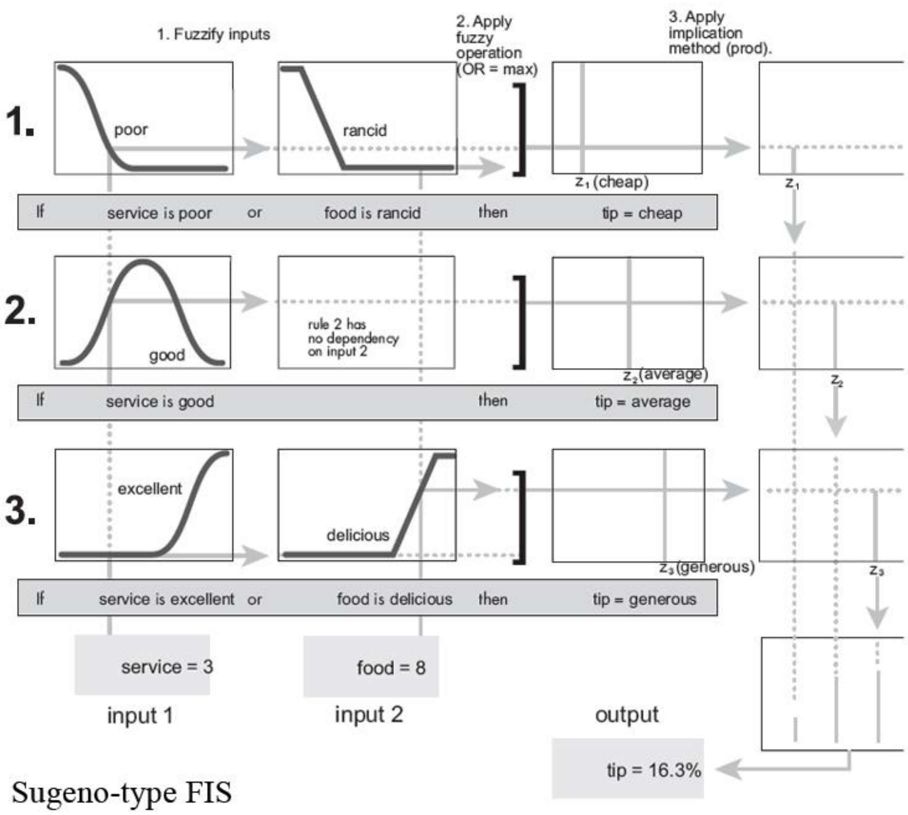
After the fuzzification and rules application steps, the FIS goes through the last three processes. The inference process -also called as implication or rule evaluation- determines an output by evaluating the rules. This describes how the membership function of the input variable (its antecedent condition) influences the result (its consequent condition). This is managed by an algorithmic process wherein for each rule the 'firing strength' (the degree to which the antecedent part of a fuzzy rule is satisfied) is computed (MathWorks, 2013a). Thereafter, the output value of the rule is computed.

After the output of each rule is acquired, the rules must be combined in some manner in order to make a decision. Decisions are based on the testing of all of the rules in a FIS. In the aggregation process, all of the outputs of all the rules are grouped together. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable for Mamdani-type FIS. Since the outputs of the rules are membership functions, they have to be defuzzified for a quantifiable global output value. Selecting a crisp number u* representative of μ_{OUT} (u) is a process known as deffuzification (Tsoukalas and Uhrig, 1997). The most frequently used deffuzification techniques are the centroid or center of area (COA), the center of sums (COS), and mean of maxima (MOM). However, defuzzification is not required for the Sugeno-type FIS, since the outputs of the rules are already single numbers and just need to be combined. The final output of the system is the weighted average of all rule outputs.

Figure 3.7 shows a full-size fuzzy inference diagram; fuzzy inference, aggregation and defuzzification processes for a "tipping problem" in both the Mamdani and Sugeno -type FIS (MathWorks, 2013a). The inference is modelled to decide the tip at a restaurant, according to two inputs: the quality of service and the quality of food. Three rules are defined including both factors: 1. If the service is poor or the food is rancid, then the tip is cheap 2. If the service is good, then the tip is average 3. If the service is excellent or the food is delicious, then the tip is generous. The input variables are; service = 3 and food = 8. The output value is tip = 16.7% for the Mamdani-type FIS, and tip = 16.3% for the Sugeno-type FIS.



Mamdani-type FIS



Sugeno-type FIS

Figure 3.7 : Inference, aggregation and defuzzification (MathWorks, 2013a).

3.4 Fuzzy Thinking in Building and Space Studies

Fuzzy reasoning is used in many fields for understanding and interpretation of the built environment, also to assist qualitative research as well as the mechanism for problem solving and decision making.

3.4.1 Management

Fuzzy techniques are applied in managerial work especially for performance assessments (Chan et al., 2009). For instance, risk analysis -relation between sources and consequences- is conducted by using fuzzy estimations (Tah and Carr, 2000). Fuzzy reasoning is used to evaluate design ideas, projects and planning decisions at any stage. As an example, a fuzzy multi-criteria decision-making model is proposed for the evaluation of end products of the architectural design process by Palabıyık and Çolakoğlu (2012). In emergency management, the fuzzy approach is used in numerous danger scenarios and simulations encompassing pre- and post-disaster studies; from structure or material control and design (Şen, 2010, Güçlü and Yazıcı, 2007) to evacuation modelling (Tan et al., 2009, Zhu et al., 2008), crowd movement (Deshpande and Gupta, 2010) and panic behaviour (Singh, 2006). In the field of environment and natural resource management, recent works apply fuzzy tools to sustainable technologies and eco-design (Vakili-Ardebili and Boussabaine, 2007, Cornelissen et al., 2001). Additionally, many building performance analyses use fuzzy logic for energy, comfort and control management –e.g. for HVAC systems (Kolokotsa, 2007, Alcalá et al., 2009, Bhavani and Khan, 2009).

3.4.2 Urban design

As the applications of linear rationalist planning methods (such as long range land use planning and Euclidean zoning) have failed to solve urban problems of actually complex and non-linear systems, new methodologies are steadily introduced. Fuzzy thinking is appreciated as it is a favourable expression of uncertainty and complexity in city planning, also to the fluidity of public space. Habib and Shokoohi (2009) propose the fuzzy system approach for classification and solving complex urban problems including control, polytely, optimizing, as well as open and decision making problems. Sassen (2010) uses the term “cityness” which is not a western notion of urbanity and refers to the intersection of differences. For her, conceiving cities as fuzzy logic systems will reveal the possibilities of the juxtapositions of different settings, which cannot be managed by applying the formal logic of planners.

3.4.3 Geography and "Fuzzy Spatial Objects" (FSOs)

By geographers, the logical system of fuzziness is seen as an appropriate tool to handle ambiguity, vagueness and imperfection about space. In his oft-cited paper "Fuzzy Sets and Spatial Choice," John S. Pipkin (1978) argues against the classical choice theories with Boolean truth-functional logics, which are becoming increasingly incapable of providing a fully adequate account of the classes of vagueness and ambiguity uncovered by research on spatial cognition. However, the fuzzy set concept is capable of capturing this kind of uncertainty. For instance, inexactness in the perception of distance can be formalized and interpreted as "approximately the shortest" or "reasonably close to". Spatial choice can also be defined as a fuzzy set with membership functions (parking space, service quality and travel time) which are taken as fuzzy subsets –where each fuzzy union or intersection alternative of subsets possesses different behavioural implications. Similarly, Leung (1983) underlines the difficulties encountered in attempting to analyse and predict with exactitude the spatial preference, choice and movement of individuals. In deciding on a mode of transportation, economical, relatively comfortable, good service, and low accident rate may serve as standards, or in determining a place to shop, the basic requirements may be not too far away, relatively high quality products, and reasonable prices. However, there are no exact boundaries demarcating economical in terms of fare, or not too far away in terms of physical distance. Thus, "uncertainty arising from the interpretation and processing of these inexact concepts has nothing to do with randomness but is directly related to fuzziness." Additionally, Thill and Sui (1993) investigate the relevance of fuzzy preferences for mental mapping. Imprecision and ambiguity in individual residential preferences result in the ambivalence and uncertainty to rank the spaces which will construct mental maps (representing aggregate residential preferences in a population). They conclude that interval scales used in rating or evaluating tasks do not force individuals to give a crisp judgement of places, they are more adequate than ordinal scales for mental mapping and for behavioural analysis.

Contemporary researches prove that new capabilities are required in spatial analysis due to the increasing awareness of uncertain situations. “Fuzzy spatial objects” (FSOs) based on fuzzy logic and sets are specifically suggested by virtue of the necessity for an appropriate reasoning in GIS.

Distinct thematic layers carry different information with respect to the same spatial unit. The concept vagueness is related to the nature of the observed spatial phenomenon characterised by some gradual physical, social or cultural property. Many natural features are fuzzy by definition (Bordogna et al., 2006). Our understanding of, and actions in, space are necessarily unable to be described in terms of classical set theory. Boolean logic, a two-valued system subdivides space into a set of mutually exclusive and exhaustive regions with clear-cut boundaries. A region or zone can not be treated as an entity or theoretical construct which is exactly defined and delimited. Geographers consider this problem in relation to landscape features and spatial zones, for instance by querying what a mountain and a valley is when the two are adjacent; which points have to be assigned to the valley and which points to the mountain. There is no strict boundary between these conditions, leading to the value of the “partial truth” and “multiple membership” capacity of the fuzzy set. This is why geographers have adopted fuzzy thinking as a means of analysis.

Schneider (1999) defines fuzzy spatial objects as objects with imprecise or vague spatial attributes (e.g. the temperature areas in a weather map with fuzzy borders), as opposed to crisp spatial objects, those with precise or exact attributes (e.g. U.S. States map with crispy borders). In Figure 3.8, wave heights over the Mediterranean Sea are illustrated on a weather map. According to the map, the wave heights have varying characteristics, which are most dense in the south-west of Italy and clear on the Eastern Mediterranean. The borders of the density regions are indeterminate since the height characteristic changes somewhat gradually (Sözer, 2010).

The most established spatial data types are point, line and region; and fuzzy spatial objects are comprised of fuzzy points, lines and regions (Sözer et al., 2008). A fuzzy point is a point for which an exact position is not known but possible positions are known within a certain area. In Figure 3.9 (a) the expected position of such a point is shown by a black dot and the possible positions are shown by grey dots. For instance, a ship waiting in the queue to cross Istanbul’s Bosphorus is supposed to be found at a certain point but may drift from that position from time to time (move to the grey points). A fuzzy line is a line, the exact shape, position or length of which is not known, but what is known is which area the line must reside in. In Figure 3.9 (b), the centre line, for instance, shows the normal shape of a river. The actual river line can change position and shape due to floods or droughts (seen as the grey area). A fuzzy region is a region with indeterminate boundaries. In Figure 3.9 (c) a typical fuzzy region is depicted and might be used to express the gradual change over a spatial domain for a given attribute (e.g. wave height). Finally, a complex region is a set of regions possibly with holes and multiple components, as seen in Figure 3.9 (d). Foggy regions with clear patches, for example, can be represented as complex regions.

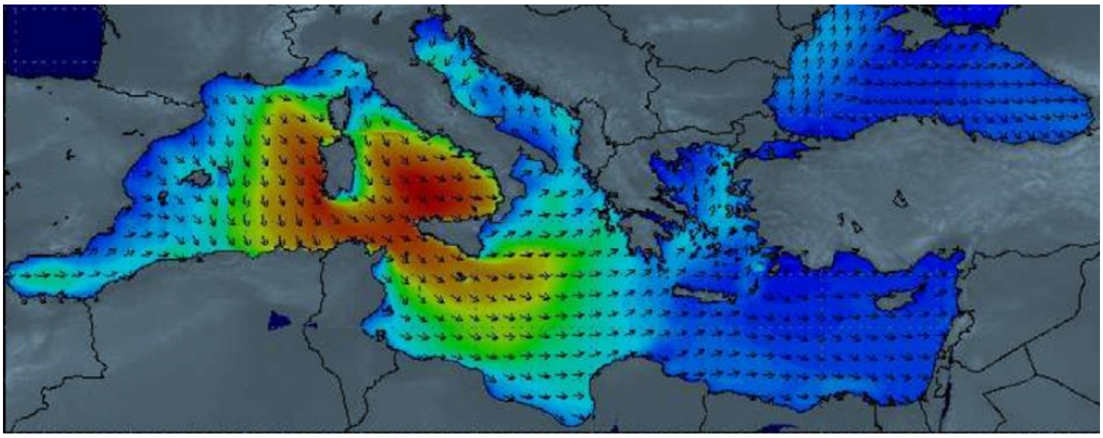


Figure 3.8 : Wave heights over the Mediterranean Sea (Sözer, 2010).

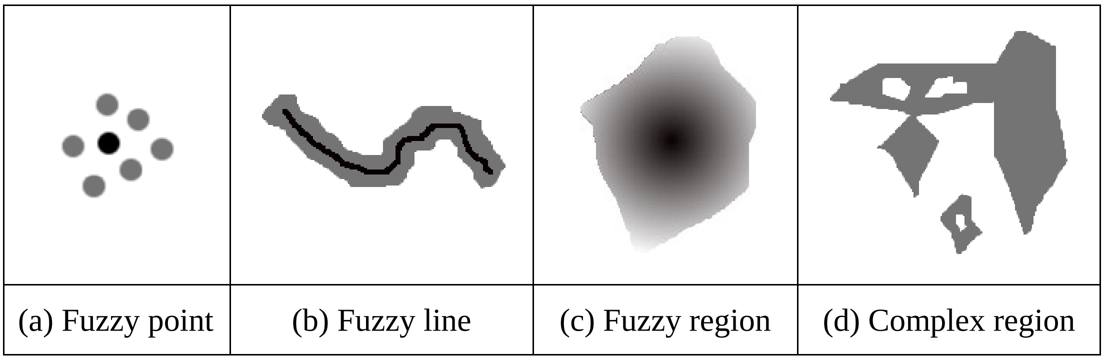


Figure 3.9 : Spatial data types (Sözer et al., 2008).

A fuzzy spatial object is defined by a fuzzy subset of the spatial domain, that is, by a set of spatial elements whose membership is gradual rather than abrupt (Bordogna and Chiesa, 2003). The fuzzy region, which is the most architecturally relevant data type, has three zones comprised of points with different membership values in the fuzzy set (Zhan and Lin, 2003): “the core,” “the indeterminate boundary” and “the exterior”. As the degree of belonging; the membership value of any point in the core is $x = 1$, in the indeterminate boundary is $0 < x < 1$, and in the exterior is $x = 0$ (Figure 3.10). The core is represented by the spatial elements that fully satisfy the property; the exterior by the elements that do not satisfy the property; and the indeterminate boundary by the elements with partial degrees of satisfaction.

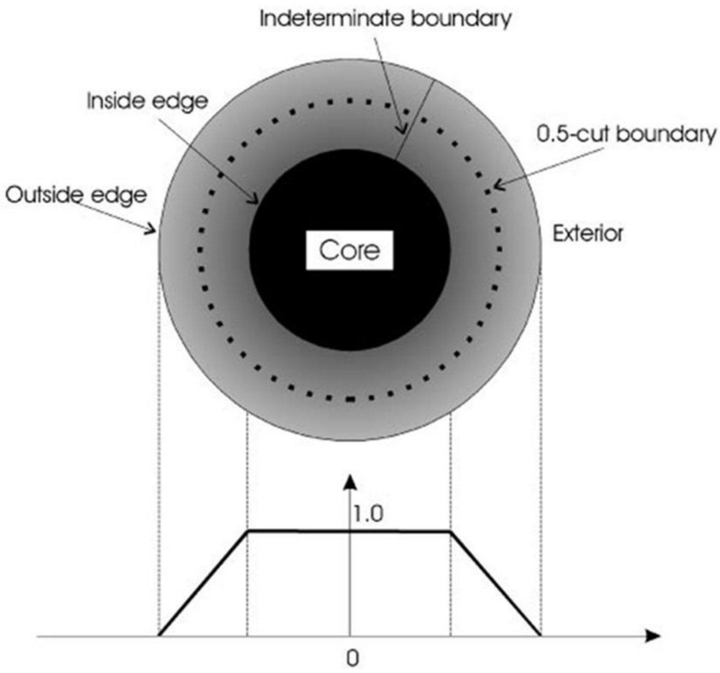


Figure 3.10 : A fuzzy region (Zhan and Lin, 2003).

In geographical space, reasoning on spatial entities is supported by representations that involve direction, topological, ordinal, distance, size and shape relationships (Pullar and Egenhofer, 1988). Topological relations between two dimensional objects are spatial relations that are preserved under such transformations as rotation, scaling and rubber sheeting. Eight meaningful binary topological relations are introduced for crisp regions; disjoint, meet, equal, inside, contains, covers, covered by and overlay (Egenhofer et al., 1994). These relations, known as a 9-intersection model, are based on the intersection between the parts (interior, boundary and exterior) of the regions involved. Tang et al. (2006) adopted the 9-intersection matrix to identify the topological relations for fuzzy spatial objects; for regions, lines and points. The topological relations between fuzzy regions are inevitably fuzzy because of the indeterminate boundaries of the regions involved. Figure 3.11 shows the semantic terminology of the relations between two spatial regions.

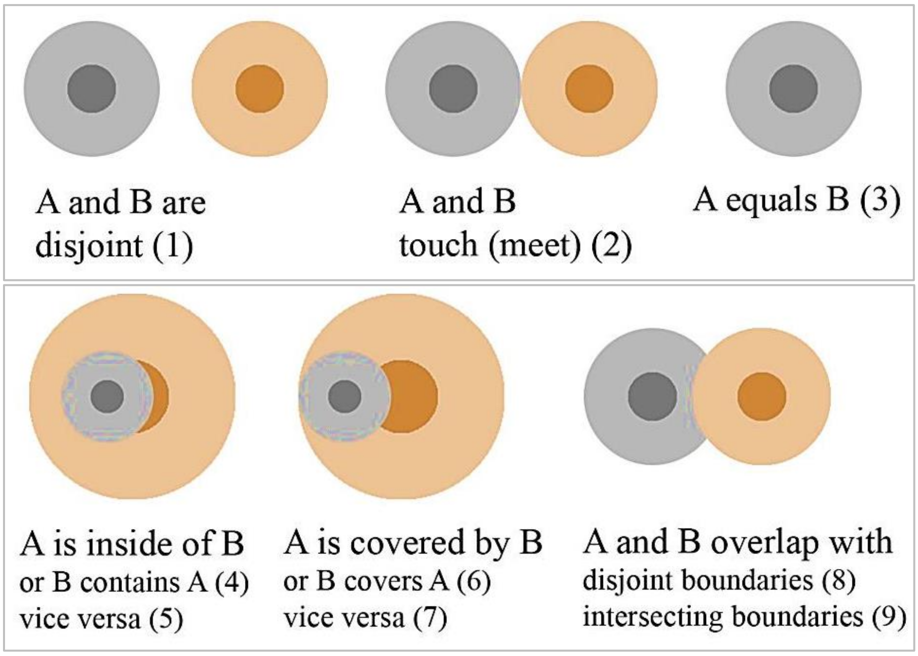


Figure 3.11 : Topological relations between two FSOs.

3.5 Fuzzy Thinking in Architectural Design

3.5.1 Design process

Fuzzy thinking is regarded as a way to model uncertainty in the design process, as Cao and Protzen (1999) propose a FRS_IBIS (Fuzzy reasoning system issue-based information system) computational model to represent design knowledge and architects' reasoning patterns. In an experiment, invited designers are asked to analyse and to provide guidelines for the entrance locations of a library building. Participants re-examine their thoughts with the help of the fuzzy reasoning charts and equations to identify differences and conflicts. So, the design reasoning and argumentation process are quantified through fuzzy logic techniques.

The fuzzy approach is used in many design problems related to uncertain boundaries. Koutamanis (2007) proposes fuzzy modelling as a digital equivalent of analogue sketching which allows designers to register and manipulate imprecise and uncertain information. While the crispness of computer-based models can be an obstacle to certain modes of design thinking and interaction, especially in the early design stages, the fuzzification of crisp forms creates more flexible and adaptable shapes by expressing degrees of tolerance, incompleteness and uncertainty. Figure 3.12 shows the fuzziness in sketches and fuzzy shapes described by minimal and maximal values. Bayraktar and Çağdaş (2013) propose a digital architectural design tool named “Fuzzy Layout Planner,” which allows creating sketch-like footprints. The user can create layouts made of bubbles for the spaces needed. The bubbles are moving dynamic parts, which have fuzzy boundaries. The vague definition of the placement of the spaces brings more opportunities in the design process, thus the architect gets the benefits of trial and error in the early design phase.

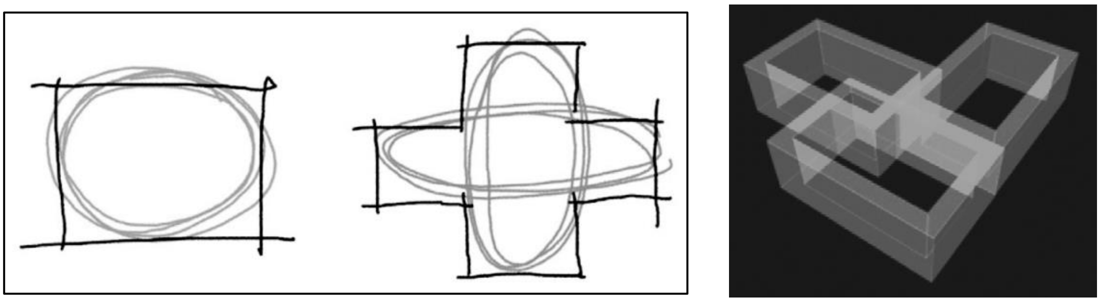


Figure 3.12 : Fuzziness and digital sketching (Koutamanis, 2007).

3.5.2 Design manifest

Fuzzy logic and fuzzy sets are involved in the idea of architectural design as parallel with new developments in mathematics and geometry as well. While mathematics in architecture has historically referenced notions of order, proportion, and ideal form, the discipline of mathematics itself has shifted to encompass uncertainty, incompleteness, relativity, and chaos, moving towards a situation in which truth itself is elusive. Architecture is just beginning to embrace the underlying issues embedded within this contemporary mathematics: uncertainty, unpredictability, chance, recursion, wildness, and informality (Hernandez, 2013).

New interpretations of mass and volume become possible when the conventional distinctions between the components of a building are dissolving. In Figure 3.13, we see five stages of a cube to sphere transformation as a good metaphoric example. The crisp borders disappear and the faces penetrate into each other. The cube and the sphere define two distinct logical formations; Aristo and Fuzzy (Çekmiş, 2014a). In a similar sense, the vertical and horizontal borders (wall and floor), the covering surfaces (roof), accesses (door), holes (window) and other architectural elements become abstract and gain different syntactic and semantic meanings in design. We see a glass wall different from the pattern of a classical window, or a wall stoops and smoothly transforms to a roof. While a wall is bending to a roof, there is a grey zone between them, some roof and some wall. This refers to a membership position in the fuzzy set and a soft transition without hard borders or edges. The architectural design of a stair and a ramp shows it clearly, when we reach from one level to another by having strict borders of sets of each step, or by having a soft climb where the membership of virtual steps change gradually (Figure 3.14).

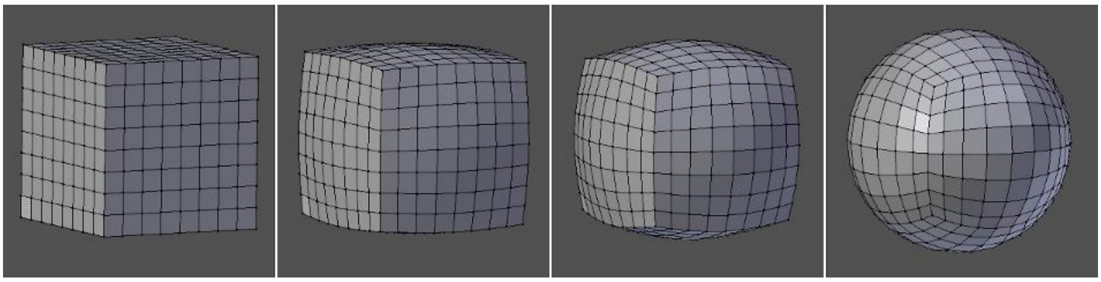


Figure 3.13 : Transformation from cube to sphere (Çekmiş, 2014a).

Figure 3.14 : A photograph from the Machida Railway Station in Tokyo.

Fuzzy logic is used to explain the works of some architects. In her article titled "Study the Works of Peter Eisenman? Why?" Rossi (1999) links the projects of Eisenman with fuzzy logic. Design conveys multiplicities, contradictions and differences into temporary hypotheses. The fluid laws that lie at the base of the planning process inflect solutions that, "if the first projects of Eisenman illustrate the internal virtualities of a rigorously closed, rigid cube, the following plans show the virtualities of the same shape subjected to the internal laws of deformation." The result reflects the mathematical logic lying at the base of the "variable linguistic" or of the "calculation with words" conceived by Zadeh. Talašová (2012) uses fuzzy expert systems to model the vague general principles of Adolf Loos's architectural works. When designing his villas, Adolf Loos applied his Raumplan principle. The principle postulates that no floor plans, no vertical sections and no facades be designed. Also solutions of the exterior and interior of the villas are rather independent.

3.6 Chapter Summary

As discussed in this chapter, many mathematical methods could be used to model uncertainty, among which probability theory was mostly applied in stochastic processes. However, fuzzy logic and the theory of fuzzy sets were introduced as a promising method to deal with uncertainty –by using the computational software: MATLAB. Alternative to Boolean logic and classical sets, fuzzy systems reflect linguistic thinking by replicating the way humans behave against uncertainty. Depending on this property, the fuzzy approach has been applied in the areas of management, urban studies and geography. To express imprecise and vague spatial entities and their relations, the concept of FSOs has been devised in GIS. Fuzzy thinking is also ideal to cope with uncertainty in architectural design, for dissolving boundaries in the conventional expression of form and space both in the design process and in the design manifest.

Overall, this chapter reviewed the literature which constitutes the methodological foundation of the proposed model. The model uses fuzzy logic and fuzzy sets theory as the means for handling uncertainty; for both the representation of ill-defined spatial configurations and for the analytical prediction of how people spatially behave. The fuzzy spatial model is comprehensively explained in the next chapter.

4. MODEL

This chapter describes the fuzzy computing model which predicts and simulates spatial inhabitation in response to higher levels of uncertainty. The first section gives the conceptual base of the model; by interpreting and associating the concepts presented in the previous two chapters. This section also explains the parameters which construct the principles in establishing inhabitation patterns. The second section elaborates both phases of the model: calculation and visualisation; which are operated by the FIS and the image generator in MATLAB. The result of the model is the maps that show the spatial usage in large, ill-defined volumes.

4.1 Conceptual Premise

This section first defines spatial uncertainty which is prevalent in fluid and continuous spaces of open plan designs, and also proposes fuzzy sets to handle ambiguity, vagueness and imperfection in those spaces. Later, a novel conceptual tool: Fuzzy Architectural Spatial Objects (FASOs) is introduced. Additionally, the last part explains the parameters which affect the occupational behaviour; also to which the inputs in the calculation part of the model will refer.

4.1.1 Spatial uncertainty and fuzzy sets in open-plans

This part focuses on the uncertainty in architectural space inherent in the spatial configuration, which we call as spatial uncertainty. This uncertainty is prevalent in fluid and continuous spaces, such as in free and open plan designs where an entire space is occupied in a holistic way, but multi-functionality still plays an important role. Such spaces are common in large exhibition and conference halls, airport foyers and the concourses of train stations. These spaces are not divided into defined rooms by doors or walls, but rather spatial modelling, coupled with material and colour changes, separate various sub-functions and sub-spaces within an overall environment. In terms of usage, a total space is an ensemble of various temporary sub-functions. Each sub-function existing in the overall environment has a spatial entity with an uncertain boundary. Those virtually demarcated spaces are called as sub-spaces. This lack of clear spatial configuration in open-plans also prompts the uncertainty present in inhabitation patterns and it also makes the task of modelling these patterns complex and difficult.

Overall, an open-planned space has many sub-functions and can also be represented as an accumulation of sub-spaces. The theory of fuzzy logic and sets are ideal for expressing this spatial identity. A total space could, hypothetically, be seen as a fuzzy set where each sub-space (and its sub-function) is a fuzzy subset; that is, a membership function. The whole, two-dimensional space is the universe of discourse of the fuzzy set, and the smallest unit of this space -which can accommodate a person- is an element or member. Any member belongs to a sub-space with a membership degree $0 \leq x \leq 1$. So the member can belong to more than one sub-space and a sub-space can be comprised of members with various differing membership degrees. This is a fundamental attribute of spatial uncertainty, where no physical boundaries of sub-spaces exist and people can fulfil multiple functions within different sub-spaces simultaneously. For example, a person could be in a queue to pick up an airline ticket while checking their flight time on a monitor. Such a person is participating in two functional activities while occupying two overlapping sub-spaces of the terminal. This way of thinking about spatial uncertainty is not related to frequency or randomness (statistics or probability) but to the inherent complexity and indeterminacy of human usage of space.

4.1.2 Fuzzy Architectural Spatial Objects (FASOs)

The notion of sub-space is introduced as “Fuzzy Architectural Spatial Objects” (FASOs) in this study, having similar features with FSOs which have been expressed in GIS. The concepts of uncertainty addressed by geographers could be interpreted in the same way as the uncertainties in architectural space. Thus, the geographic notion of an FSO could easily be revised to accommodate architectural space.

A FASO is a fuzzy subset in the total space, which has members (spatial units) with different degrees of belonging. The membership degree is defined by the possibility of a person in that spatial unit; as being present in that sub-space and involved in that sub-function.

4.1.2.1 Data types

FASOs comprise points, lines, regions and complex regions in buildings. A FASO-point may denote a person waiting for a bus at the bus stop, whose position can change. A FASO-line could describe a queue for tickets or the front row at a concert, of which trace and form can change. A FASO-region could describe a group of friends talking in a foyer, and where the space of the conversation shifts to accommodate the people in the group, at any moment in time.

A FASO-region is akin to a FSO-region. All of the spatial units have the membership degree of $x = 1$ in the core, $0 < x < 1$ in the indeterminate boundary and $x = 0$ in the exterior. This describes the possibilities of being wholly or partly involved in the activity, or being totally disengaged from it. These zones of a region are virtually constructed in the space. The borders between them 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, as distinct from "crispy" architectural regions which place strict limits on the definition and usage of space. Thus, any change in the membership degrees of the spatial units makes the FASO-region change, meaning that the core expands or shrinks according to the increase or decrease in membership possibility. Indeed, 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 if the membership grows, and thus a FASO-point may transform into a line and a line into a region. Figure 4.1 shows a hypothetical FASO-region which represents a sub-space in an office, and also illustrates how the membership degrees of spatial units change and the core of the FASO expands if the possibility of presence changes in a certain time period in the office –when many people cluster around one person.

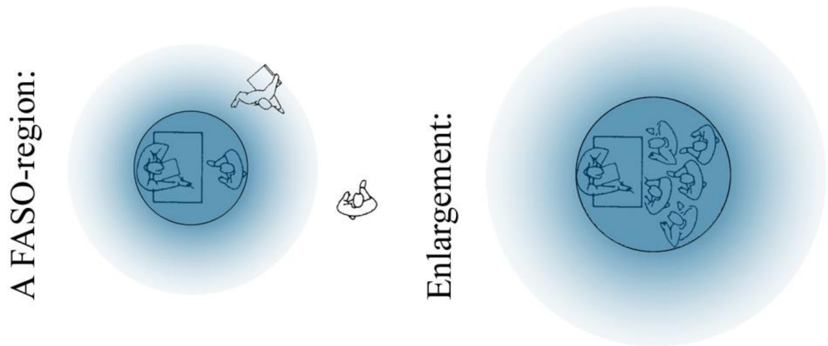


Figure 4.1 : A FASO-region and enlargement.

4.1.2.2 Topological relations

The FASOs also have the same topological relations as those stated for the other spatial objects previously mentioned. The interpretations of these relations gain importance when we make deductions about the use of space. Figure 4.2 shows basic topological relations -disjoint, touch (meet) and overlapping- relevant to the architectural space.

Disjoint means that two objects stand apart with no or a very weak conceptual relation. They probably have different, independent functions which do not require any contact. The distance between them may identify another usage in the space such as a circulation, a redundancy of space, or a deliberate reserve allocated for possible enlargements or other future functions in terms of flexible use. If two objects touch each other, that means they are close but not affiliated. The conditions of disjoint and touch are due to the spatial layout; which the designer would like to express by using proximity: either more privacy or interaction. Overlap implies a more intimate relation between objects. The yellow area in Figure 4.2 shows the zone of minimum and maximum penetration of objects by the overlaying of indeterminate boundaries (from light grey to dark grey). This is both the most connected and cramped condition when compared with the former two relations. But if this invasion extends in a degree to contain the cores, shown as the red area in the same figure, the objects begin to lose their set characteristic. Spatial units get full membership for distinct sub-spaces and sub-functions, which will have a negative impact on usage. This type of overlap brings crowded and uncomfortable spaces into existence which will cause less satisfaction and ill engagement with the activity. Deficiency and unfulfillment occurring in this situation also provide an assessment about the capacity and the performance of the spatial design.

Additional topological relations are also possible: covers, inside, contains, and covered by are examples of involvement, which represent a situation where a region is a part of another bigger one. Lastly, equal represents two or more regions which have the same features, or two or more sub-functions that share the same space.

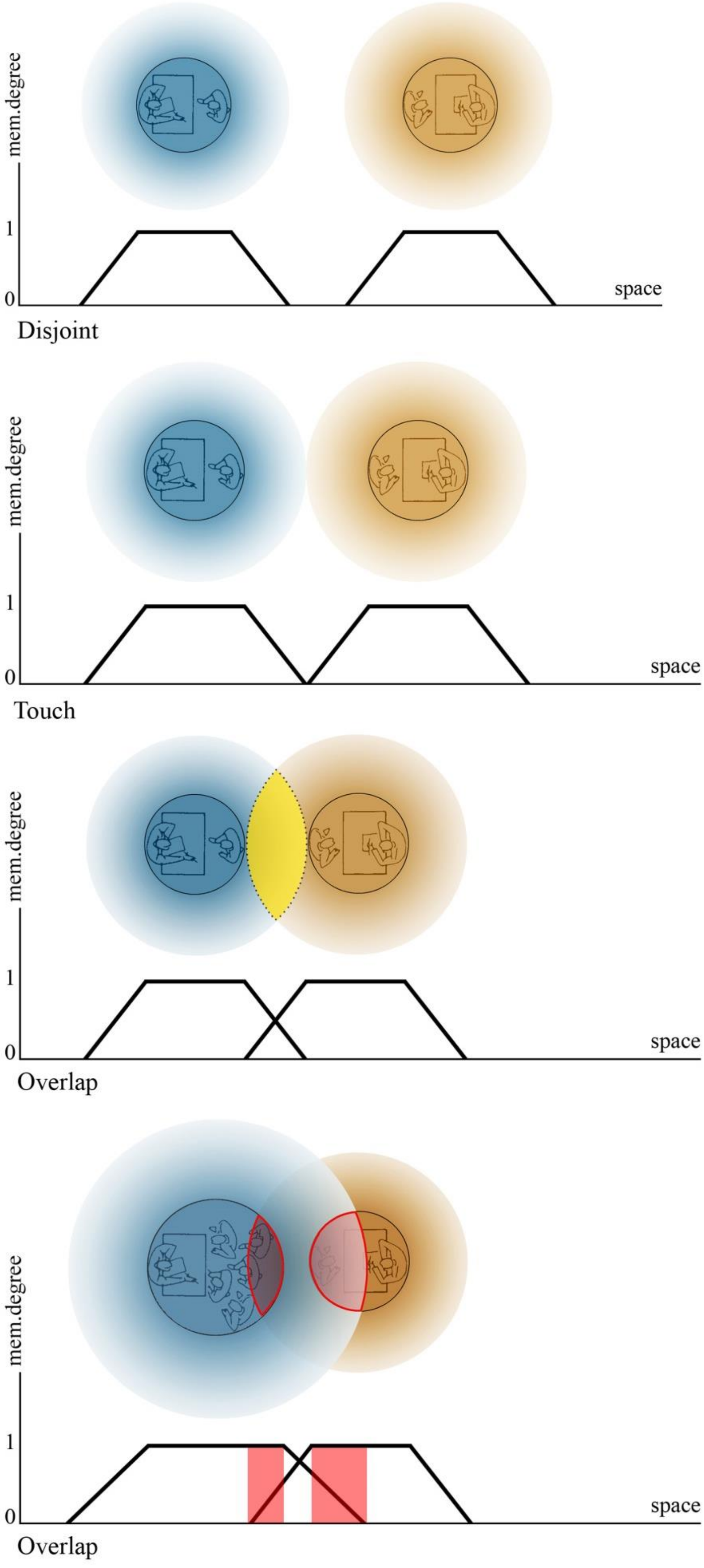


Figure 4.2 : Topological relations between FASOs.

4.1.2.3 FASOs in the model

The practical value of the concept of FASOs in the model is that it provides a spatial response to predictions of the possibility of users being involved in an activity. A FASO corresponds to “a spatial entity” in architecture that is comprised of persons whose possibility of presence changes from 100% (completely present) to 0% (completely absent). This possibility of presence is linked to the membership degree ($0 \leq x \leq 1$) of that spatial unit to a certain spatial entity (FASO). So, spatial usage (inhabitation patterns) could be conceptualised as being about the memberships in a spatial set coupled with the capacity to map the whole space accordingly. On this basis, the aim of the spatial model is to decide the degree of presence and involvement (in terms of partial truth) of each unit in an uncertain environment.

In this context, the model first calculates the possibility of people being involved in a ‘sub-function’ and ‘sub-space’ within a larger volume, and then visualizes the distribution of these possibilities across the whole space in order to show patterns of potential usage. The result maps of the model is a representation of the whole two-dimentional plan as an accumulation of FASOs of various types and sizes.

4.1.3 Parameters

That the main concern of the model is to form and show the FASOs, the factors having influence on the possibilities of presence play a crucial role in the prediction of those possibilities. So, the argument here is the estimation of the possibility of users involved in an activity either in the space fully, partially or not at all; which parameters and to what extent could affect and change that possibility if there are no physical borders around.

The parameters are the elements which could be taken into consideration for the evaluation of the spatial usage. These are the variables that affect the membership degree of a spatial unit by either increasing or decreasing the possibility of a person’s presence there. Conceptually they can be grouped into three areas: space, function and users; as seen in Table 4.1.

Table 4.1 : Parameters.

INPUTS			Examples related to different architectural typologies:		
PARAMETERS:			***Airport Terminal Foyer Area***	***Office Ground Floor***	***Exhibition Space***
SPACE:	**The distance from the sub-function**		The distance from the sub-functions: *check-in, security …*	The distance from the sub-functions: *entrance, elevators …*	The distance from the sub-functions: *exhibits* …
	Space syntax (the relation between the morphology of space and social/behaviour patterns)		Visual integration	Visual integration	Visual integration
FUNCTION:	**Quantitative factors:**	(which affect the *length of time* people spend involved in an activity and their presence in the relevant spatial unit)	Number of the sub-functions: *service units*	Number of the sub-functions: *elevators*	Number of the sub-functions: *exhibits*
	Qualitative factors:		Service Provider (Staff is inexperienced or inefficient)	Relative speed and capacity of the elevators	Popularity of the exhibits
USERS: (people: subject of the model)	**Personal factors**	Different users' profiles encompassing physical, social and behaviour conditions	• Fast or slow movement (with or without baggage) • VIP Passengers: rates of economy, business or first class	• Office workers (card holders) or visitors • Like to linger / meet / wait in the lobby	• Visitor fatigue • Personal interests or expertise • Sense of co-presence
	Density (Population) the number of people in the total space	Density Triggers: (Higher numbers naturally make the FASOs expand to accommodate new participants who become involved in the sub-functions.)	• Delays (caused by e.g. unfavourable weather conditions) • Public Holidays (e.g. Christmas)	• Peak Times (start and end of working hours) • Special days (e.g. meetings, celebrations)	• Group visits • Weekends • Start and end of temporary exhibitions

The distance from the sub-function and space syntax are the two space related parameters. The distance from the sub-function is the fundamental parameter in the occurrence of a FASO. The pre-determined focal point(s) is accepted as the centre of the sub-function. The relative proximity to the focal point raises the possibility of a person being present in the sub-space. As an assumption, a circle of radius r = 50 cm whose centre is the focal point is accepted as the minimum and rigid core of the FASO, where there is always and already 100% possibility of presence attributed to the sub-function. Secondly, the morphology of space has an influence on the formation of the FASOs. Based on the space syntax theorem introduced by Hillier and Hanson (1984), empirical research has revealed a strong connection between syntactic values and the behaviour patterns in the space. For instance, visual integration has an impact on the accessibility and consequently the possibility of presence in certain areas of the space. So, spatial configuration and arrangement has a significant role in the sizes of the FASOs.

The qualitative and quantitative aspects of sub-functions are included in the function related parameters. They affect the length of time people spend for that activity and in their accommodation at the relevant spatial unit. This determines the membership degrees due to the possibility of people involved in the sub-function. As a quantitative factor, the number of the sub-functions, while the other variables are constant, can increase or reduce the possibility of presence. For instance, if the number were less than the actual number of the exhibits in a specific collection, the FASOs of both doing and waiting for the sub-functions would enlarge, and vice versa. On the other hand, the individual popularity of an exhibit in the collection, as a qualitative factor, could make the FASO belonging to that exhibit enlarge and differ from the other FASOs due to being of interest to visitors.

The last category of parameters relates to the people themselves, who are the subject of the predictive model. Personal factors and population are cited under this title. Personal factors describe the variations in the users' profiles encompassing physical, social and behavioural conditions. It has to be noted that the model cannot operate with the individual profile of each user, but can compare two or more conditions when the general profile of all users changes (such as comparing two visit times to an art gallery when at first art school students and later primary school students are the majority, whose behaviour patterns differ totally). Population refers to the number of people in the space, which evenly affects all the dots by changing the possibility degree proportionally. Higher populations naturally make the FASOs expand in a way to supply much space for new participants who become involved in the sub-functions. The number of people is entered into the model as an input variable. If the analysis case is real, the records are helpful to determine the exact population in the space for different conditions. But if the analysis case is hypothetical, the population needs to be projected according to the likely number of people involved in the sub-functions. Such estimation about habitation requires reckoning with all density triggers in the lifespan of the case. For instance, the most visits to an exhibition are generally noted at the weekends, at group visits and at the commencement and cessation dates of the exposition.

In sum, the parameters are the main factors shaping the FASOs. They are the inputs, and predicates on which the logical postulates in the calculation part of the model are based. This given list of parameters is not fixed and the inputs are chosen according to any specific spatio-temporal condition of analysis.

In addition, some basic behaviour patterns that are likely to occur, and will probably generate new FASOs, are typically included in the base model. These allow for activities such as queuing, wandering and waiting. These patterns can be included in the category of “intermediate activities” which is different from the typologically defined “skeleton activities”. Tabak and de Vries (2010) describe skeleton activities as the activities that depend on the role of a person in an organization and are usually defined in his/her functional description (e.g. chair meeting, give lesson, etc.). However, intermediate activities depend on a person’s role to a lesser degree but have a strong relationship with the psychological and physical needs (e.g. get a drink). For instance, in an art gallery, besides the sub-functions of viewing the exhibits, the activity of probable queuing for a popular exhibit should also be taken as a sub-function -which has its own sub-space. Thus, the distance from this sub-function will also become an input in the model.

4.2 Process

The computational stages of the model serves to calculate and visualise the memberships in spatial sets thereby revealing the FASOs in an architectural plan.

4.2.1 Calculation

This part of the model determines the membership degrees of spatial units ($0 \leq x \leq 1$) according to pre-set parameters and logical postulates.

Given that the smallest spatial unit is one which can be inhabited by a person, the architectural plan being analysed is first divided using a 50 by 50 cm grid. This grid, and its associated coordinate system, replicates the concepts of personal space and intimate distance (Hall, 1959). The geometric centre-point of each cell in the grid is its centroid. In fuzzy set theory, which is not usually associated with geometry, the method used to derive the result in a set is called 'centroid logic' (Rojas, 1996). While these two uses of the term centroid are notionally different (one denotes a numeric value and the other a geometric location), in this research the two are directly connected, with the result for each fuzzy set linked to the centre of a geometric cell. So, each spatial unit is defined as a centroid, which is given a particular ID number in the model. The identification is automatically managed by using ArcMap software; by first attending an XY coordinate to the plan, and then sorting the centroinds according to the value selecting from point_X and point_Y.

The calculation part of the model is undertaken using a fuzzy inference engine, including an 'input data file,' and a 'fuzzy inference system structure' which is constructed in the "FIS Editor".

4.2.1.1 Input data file

The input data file is the whole list of parameter variables of all the spatial units (centroids) in the plan. Parameter variables for centroids are obtained by using additional methods including observations, experiments and analytical calculations according to the type of parameter.

Some parameter variables vary with each centroid, and thus need to be indicated one by one. All space related parameters are like that. Also, some parameters required to be considered spatially fall into this category, such as the qualitative factors related to the sub-functions. For instance, popularity of a single exhibit in a collection is defined spatially in the model, and the centroids which are assumed to belong to this sub-function get higher input values than those which belong to less popular exhibits. Conversely, some of the parameters' variables are taken as the same for every centroid in a specific condition –which means that the parameter affects all of the centroids evenly, and the variable changes proportionally when the condition changes. All users related parameters are like that. Also, quantitative factors related to the sub-functions can be involved in this category.

4.2.1.2 Fuzzy Inference System (FIS)

The FIS takes input data which it processes using fuzzy reasoning and set theory through a series of rules to calculate output data (a measure of the potential inhabitants in, or location of, a FASO).

That the Sugeno-type inference system is seen as a more compact and computationally efficient representation than a Mamdani system (MathWorks, 2013a), the model in this thesis is constructed by using Sugeno system. The steps of the FIS; fuzzification, rules, inference and aggregation are operated as has been explained in detail in the previous chapter.

For model applications, memberhship functions of inputs can be chosen as either triangular or trapezoidal in the fuzzification process. The universe of discourse; x-axis (the input space) is delimited by the minimum and maximum parameter value when the variables can be measured (including the distance from the sub-function, space syntax values, the quantitative factors of sub-functions and the number of users: population). If the variables cannot be measured, the input space is defined as an interval between 0-100 expressing the percentage of satisfaction of the input set (including the qualitative factors of sub-functions and users' profiles). In this way each member is assigned a variable relative to the other members for that parameter. Additionally, since the Sugeno type of FIS is implemented in the present model, the output MFs are listed between 0 and 1.

To obtain the output in FIS, inputs are processed using a set of control rules. The rules are modelled according to the logical relation between the inputs and the output. For example, "if the distance from the sub-function is far, then the membership degree in the FASO is low". The inference process determines an output by evaluating each rule, and the final output of the FIS is the weighted average of all rule outputs. So, in the end, each given centroid has a crisp single-valued quantity: $0 \leq x \leq 1$, expressing the membership degree in the set of a certain FASO. The output value MF = 1 means the dot is in the core, value MF = 0 means it is in the exterior, and any value between 0 and 1 represents gradual membership which is in the zone of the indeterminate boundary.

When the overall calculation process is completed, a list of outputs, sorted in ascending order of the ID of centroids, is produced as a precursor to visualisation.

4.2.2 Visualisation

This part of the model makes the FASOs appear on the architectural plan, by representing their core, exterior and intermediate values by means of colouring the centroids according to their membership degrees calculated in the previous stage. An image process built in MATLAB manages the visualization. However, there are two fundamental steps first, which creates a grid matrix of the two-dimensional plan and assigns an interpolation scale to the plan –both are also run in MATLAB.

4.2.2.1 Grid matrix and interpolation

Firstly, the listed outputs of centroids are mapped to a matrix that corresponds to the grid cells on the architectural plan. The aim here is to create the fuzzy subsets (the FASO sets) spatially in a numeric form. The matrix will represent the FASOs in the space with each centroid having its own output value (membership degree). Matrix in the model is managed by entering the specific column number (or raw number) of the grid, where the membership degree and the certain location of each centroid (identified by ID) are matched up. This operation is done by using `vec2mat` built-in MATLAB function. `mat = vec2mat(vec,matcol)` which converts the vector vec into a matrix with matcol columns, creating one row at a time. If the length of vec is not a multiple of matcol, then extra zeros are placed in the last row of mat (MathWorks, 2013b). An example is given below:

```
vec = [1 2 3 4 5];
```

```
mat = vec2mat(vec,2)

mat = 1    2

      3    4

      5    0
```

```
mat = vec2mat(vec,3)

mat = 1    2    3

      4    5    0
```

```
mat = vec2mat(vec,4)

mat = 1    2    3    4

      5    0    0    0
```

Secondly, the model asks the variable (n); for n times interpolation in order to provide a robust visualisation in terms of sensitive colour gradients and higher image resolution. Interpolation is a way of estimating values of a function between those given by some set of data points (Hanselman and Littlefield, 1997). Grid-based interpolation provides an efficient way to approximate the value at any location between the grid points. Figure 4.3 illustrates the process of interpolation. MATLAB `interp` family of functions (`interp1`, `interp2`, `interp3`, and `intern`), also `griddedInterpolant` class supports grid-based interpolation (MathWorks, 2013c). The function `interp1` performs one-dimensional interpolation. The `interp2` and `interp3` functions perform two and three-dimensional interpolation respectively, and they interpolate grids in the `meshgrid` format. The function `interpn` performs n-dimensional interpolation on grids that are in the `ndgrid` format. Two-dimentional interpolation is applied in the model, since we analyse two-dimentional architectural plans. So, given that only the central mathematical value is known for each cell (centroid), intermediate values are interpolated between cells.

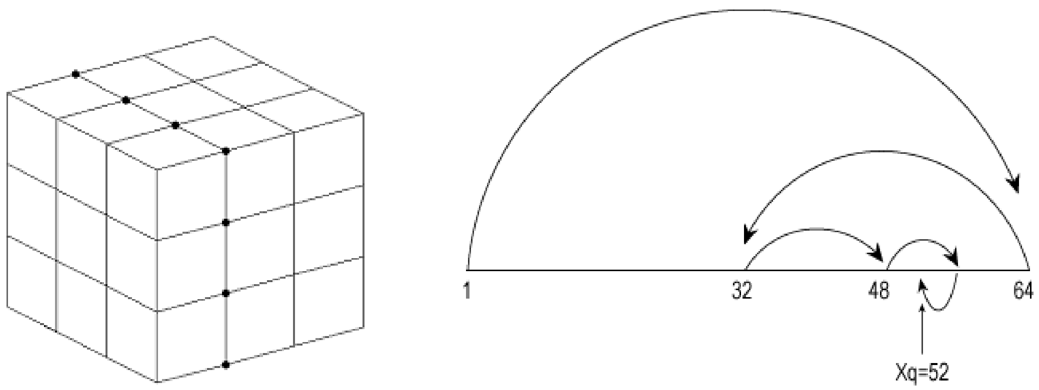


Figure 4.3 : Interpolation (MathWorks, 2013c).

4.2.2.2 Image process

Once the interpolation is complete, the image process aims to code the complete set of values by using colour gradients to produce a heat-map for the architectural plan. So, the fuzzy subsets (the FASO sets), produced by grid matrix will transform into sub-spaces (the FASO region) in the total space.

MATLAB has an image processing toolbox for image analysis, visualization and algorithm development, by which could be performed image enhancement, image deblurring, feature detection, noise reduction, image segmentation, geometric transformations, and image registration. However, visualizing data can also be managed easily by using MATLAB graphics features. MATLAB provides a set of high-level graphing routines. These routines implement commonly used techniques for displaying data, such as line plots in rectangular and polar coordinates, bar and histogram graphs, contour plots, mesh and surface plots, and animation (MathWorks, 2013d).

In the model, MATLAB > Graphics > Images > Image File Operations: `imagesc` is used. There are two fundamental functions in "Image File Operations:" `image` and `imagesc`. The command `image` displays an image in a figure window. The command `imagesc` works like `image`, except that it rescales the values in a two-dimensional array so that the highest number corresponds to the higher numbered color in the current colormap and the lowest number corresponds to the lowest numbered color. With the default colormap in effect, hot regions will be colored red and cold regions will be colored blue, with other colors representing intermediate temperatures (Hunt et al., 2010). To display the colormap next to the image, `colorbar` is typed on the command line.

In this process, the aim is to imply the membership degree of each centroid in the FASO set (the belonging degree of each spatial unit to the sub-space and sub-function). So the certain place of each centroid in the FASO is displayed according to the zone it belongs to; either in the core, indeterminate boundary or exterior. In the result map, dark blue cells are in the exterior (MF = 0) of the FASO whereas dark red are the FASO core (MF = 1). Green represents the half membership (MF = 0.5) whereas ochre and turquoise represent less or more partial membership in the indeterminate boundary. In practical terms the colours describe the likelihood of people being present in a space. Figure 4.4 shows a hypothetical FASO-region of the model with its mathematical representation as a fuzzy subset (membership function). It is seen that an output (centroid in the region) identifies a membership degree in the FASO set and signifies a colour accordingly. The core, dark red, area of the FASO is most likely to be populated with people.

When the visualisation process terminates, total space is illustrated as an accumulation of the FASOs with different sizes and shapes (describing the probability of inhabitation) according to the parameter variables of each spatial unit, which are submitted to the FIS as input variables.

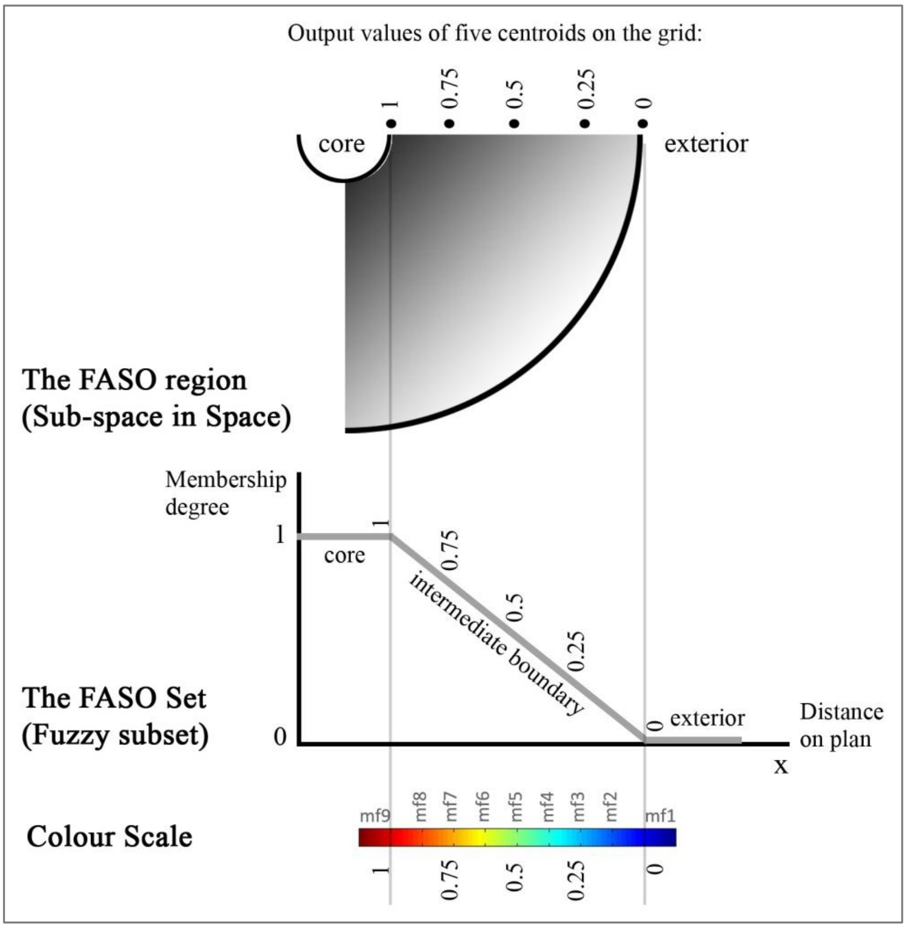


Figure 4.4 : A hypothetical FASO-region.

4.2.3 Result

The result map of the model is also regarded as the map of spatial usage, since the zones of the FASOs (core, indeterminate boundary and exterior) which are shown by colours represent the possibility of people being present in that zone. For instance, the core -the dark red area- of a region, tells that in all likelihood there will be a person or persons in this area (with 1 or almost 1 possibility). The cores of every FASO vary in size and shape according to the differences between sub-functions (such as the popularity level and syntactic property) and also would expand or shrink due to the conditions (such as an increase in the number of people in the space). If the number of people in the space (density variable) changes e.g. multiplies by two, the core -the dark red area- is expected to expand due to the inevitable increase in the possibility value. So, any change in the input variables -the parameter variables related to the space, function and users- will make the FASOs change. And the model will create new maps each time, which represents new spatial usages of the new conditions. This allows us to evaluate the space in many aspects incuding the capacity and the quality of inhabitation.

4.3 Chapter Summary

Spatial uncertainty is an attribute of open-plans, since functions are not spatially demarcated. Inhabitation patterns becomes complex and difficult due to that uncertainty. The model explained in this chapter intended to simulate spatial usage; by predicting occupancy behaviour according to some pre-set parameters specific to a given condition. The computational model used 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.

The model is designed as an autonomous and adaptive rule based expert system. Although it has to operate with a vague and limited data set, it nevertheless provides a senario which replicates the actual behaviour. This model is seen as an analysis framework for architecture, as it is open to the addition of new rules or parameters to suit specific conditions. Thus, the model is capable of mapping every space-function-user combination, which means numerous usage maps. The analysis fundamentally depends on the comparison of these maps according to what is intended to be evaluated.

For a better realisation of the model, the next chapter presents an application. The exhibition space is chosen among the typological variations of open-plans, and also relevant space, function and user parameters for exhibition spaces are consulted. The case study is aimed at mapping the spatial usage in a total space of an exhibition hall during a specific display.

5. CASE STUDY

This chapter demonstrates an application of the FASO model. Tophane-i Amire Main Exhibition Hall in Istanbul was analysed when the Salvador Dali Exhibition was on display. The model was run several times to see the inhabitation patterns during different population densities.

The first section introduces the exhibition hall and the exhibition chosen for this particular case study. The whole operation of the model and results are presented afterwards. Different usage maps are discussed by interpreting the FASO and their typological relations. Predicted inhabitation patterns are also compared with actual behaviour in order to prove the accuracy of the model. Finally, further studies related to this case are addressed.

5.1 Selected Space and Layout: Tophane-i Amire and Dali Exhibition

"Tophane-i Amire" ("Ottoman Royal Cannon Foundry" in Turkish) is a renovated and transformed historical group of military buildings in Istanbul. It is located on the European side in Tophane neighbourhood which is bordered by the Bosphorus (Figure 5.1). Tophane-i Amire is on the arterial road between Besiktas and Karaköy; also close to the city centre; Taksim. Hence, it is easily accessible by both public and private transport. Tophane-i Amire was built in the 15th century, by Mehmed II after the Conqueror, as the biggest casting centre of the day (Aydüz, 2009). Tophane-i Amire complex was a big centre of military industry containing a foundry (dökümhane), barracks, magazines, carpentery workshops and a training centre (talimhane). Throughout the years the complex has undergone various arrangements; some parts were destroyed, rebuilt or renovated. It also became unable to maintain its industrial function. In the beginning of the 1900s it was used as an education centre, and after 1958 it was used as a military museum (Eralp, 1996). Since 1992, the buildings have been operated by Mimar Sinan Fine Arts University as a multipurpose gallery, and renamed as "Mimar Sinan Güzel Sanatlar Üniversitesi (MSGSÜ) Tophane-i Amire Kültür ve Sanat Merkezi".

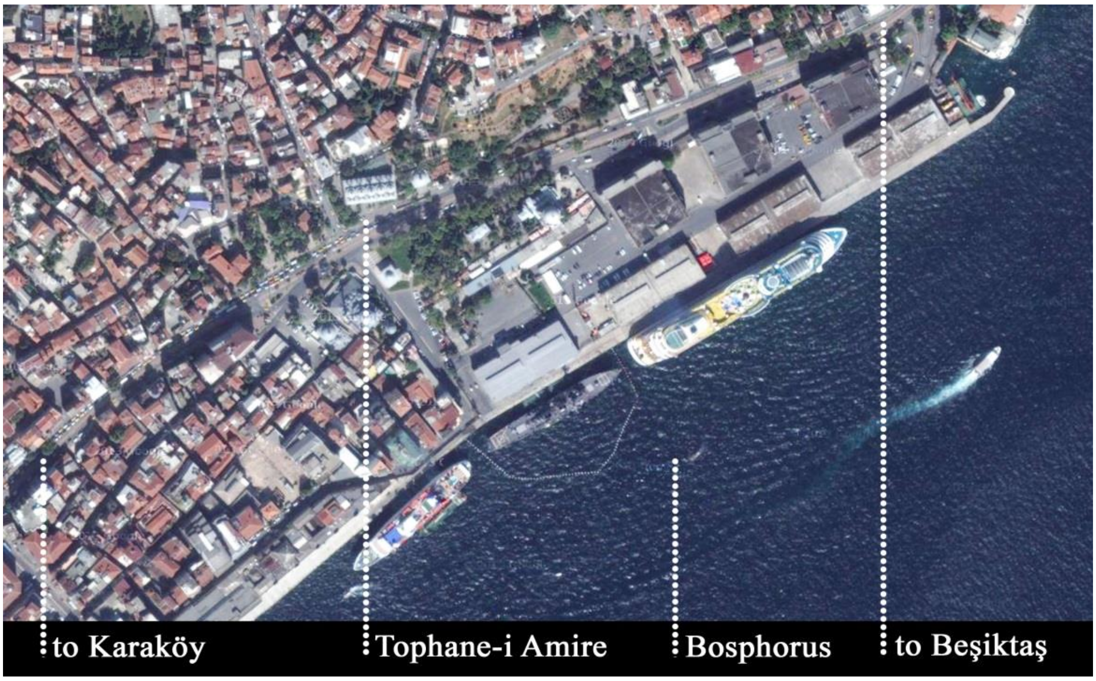


Figure 5.1 : Tophane (adapted from Google maps, January, 2014).

Tophane-i Amire comprises three exhibition halls of different sizes housed in old buildings; “Tophane-i Amire Beş Kubbe,” “Tophane-i Amire Tek Kubbe” and “Tophane-i Amire Sarnıçlar”. Tophane-i Amire Beş Kubbe, the biggest hall of 1150 m² (Figure 5.2), is the case study area. This main exhibition hall is a masonry structure with eight pillars. The massive structure constructed on a stone base is quite prominent in the cityscape due to its monumental effect and overwhelming scale in its environment. The hall has a rectangular symmetrical plan which, despite its eight pillars, can be regarded as an open plan (Figure 5.3).

Tophane-i Amire main exhibition hall houses various major local and international collections. Some of them have been: “Mimar Sinan Meets Palladio in Istanbul” (29 November - 31 December 2010) which introduced the figures and work of Andrea Palladio by displaying 17 large wooden models of his buildings; “Dali” (23 December 2011 - 26 February 2012), which covered 121 pieces of art by the surrealist artist Salvador Dali; “The Great Masters Leonardo, Michelangelo, Raphael” (1 June - 27 August 2012) which included architecture, technology and other scientific subjects presented by various mediums such as drawings, paintings, sculptures, models, and reproductions of works; and “Piri Reis and 1513 World Map: 500 years in Mystery” (15 March - 31 May 2013) which featured 90 large maps by Piri Reis including the oldest map of the world, and nearly 30 ceramic artworks.

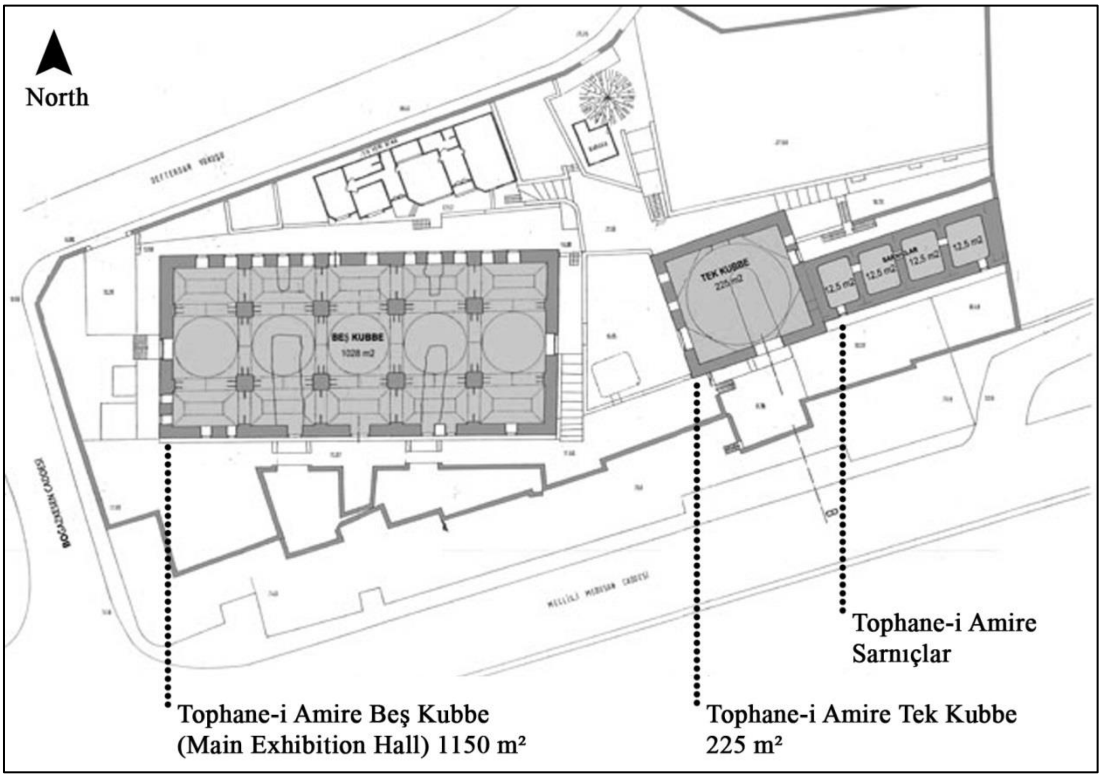


Figure 5.2 : Tophane-i Amire; photograph (from Author's album) and site plan (adapted from the web site of MSGSU.edu.tr).

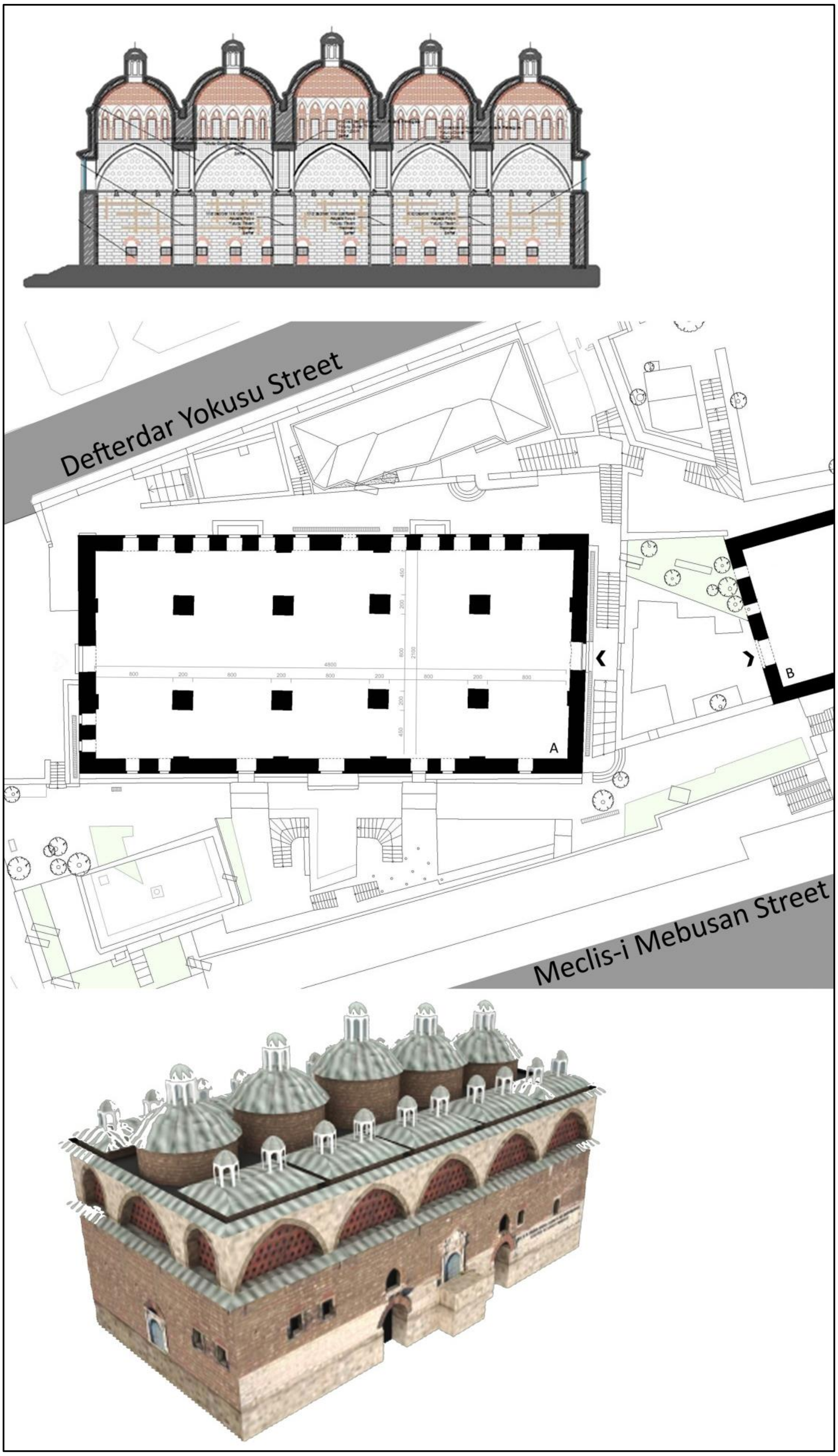


Figure 5.3 : Tophane-i Amire main exhibition hall; plan in the middle (adapted from the web site of MSGSU.edu.tr), section at the top (from Erke Tasarım) and 3D view at the bottom (Google Sketchup, by Burçin Cem Arabacıoğlu, January, 2014).

The Dali Exhibition was chosen for this analysis in order to conduct a comprehensible but uncomplicated application of the model. The exhibition included only one type of display material, which clearly defined the sub-functions. Spatial arrangement was not complex or tiresome, also the viewing route was easy to follow. Additionally, when “Dali” was on display between 23 December 2011 and 26 February 2012, it was a popular and attractive event in the city, visited by hundreds of people each day. Hence, it would be realistic and effective to analyse spatial usage during different population densities.

“Dali” was a travelling exhibition and in Istanbul it was hosted by Mimar Sinan Fine Arts University in collaboration with “Kült Art” for exhibition management and organization. The exhibition explored the works of the 20th century Spanish artist Salvador Dali under three themes; “Dinner with Gala” (12 prints), “Traces of Surrealism” (9 prints) and “Divine Comedy,” which was divided into three canticles: “Hell” (34 prints in red signature), “Purgatory” (33 prints in violet signature) and “Paradise” (33 prints in blue signature) –which were representative of Dante’s imaginary journeys. So, the exhibition contained 121 pieces; 100 water color paintings of Divine Comedy and 21 colored lithographs of Dinner with Gala and Traces of Surrealism. The sizes of the canvas differed across each theme: 40 x 50cm for Divine Comedy, 90 x 70 for Dinner with Gala, 70 x 90 for Traces of Surrealism.

The interior space was arranged using separator walls in order to create a new symmetrical-linear plan and partition for each thematic section. In the first axis niches, there were seats for visitors on the right of the entrance; a small souvenior desk and a video show on the left. Two pillars remaining inside the new spatial configuration were disguised by big boxes and reshaped as a part of the exhibition. Also a similar box, facing the entrance, was placed on the second axis. Six of the separator façades were imprinted by the selected drawings from the themes. Figure 5.4, 5.5 and 5.6 show the installation on the plan, 3D model and related pictures.

During the period of exposition, the hall was surveyed to draw the plan showing the spatial arrangement and display layout. The hall was also photographed rigorously at various times, additional to the surveillance video records. This data in regard to the reality of spatial usage was expected to verify the model. Additionally an interview was conducted with the curator Onursal Şark, from Kült Art, to get more information about the exhibition, also to obtain expert opinion for the model.

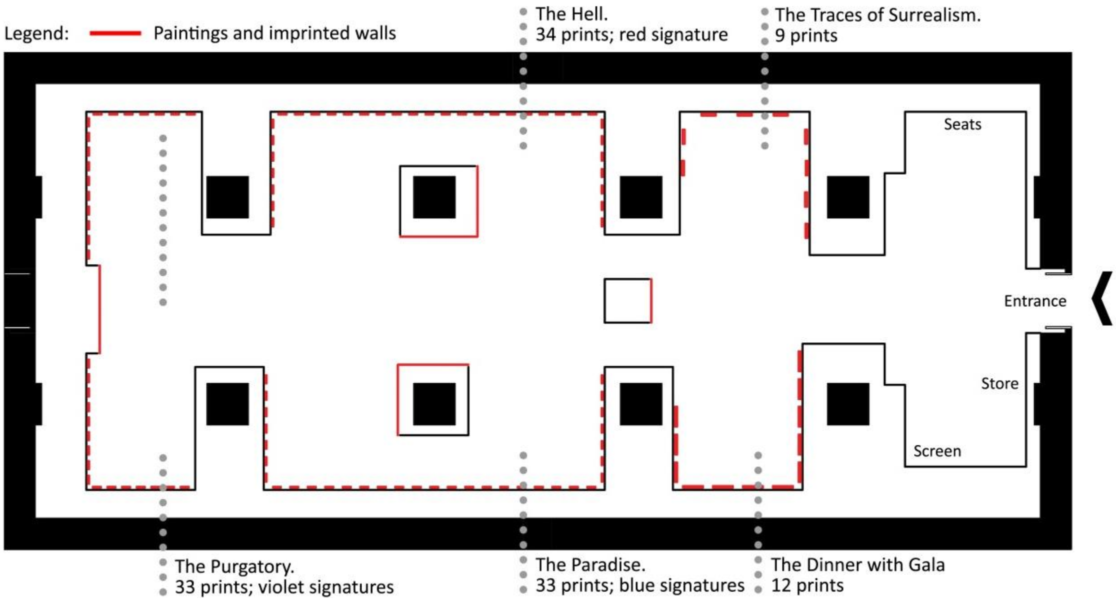
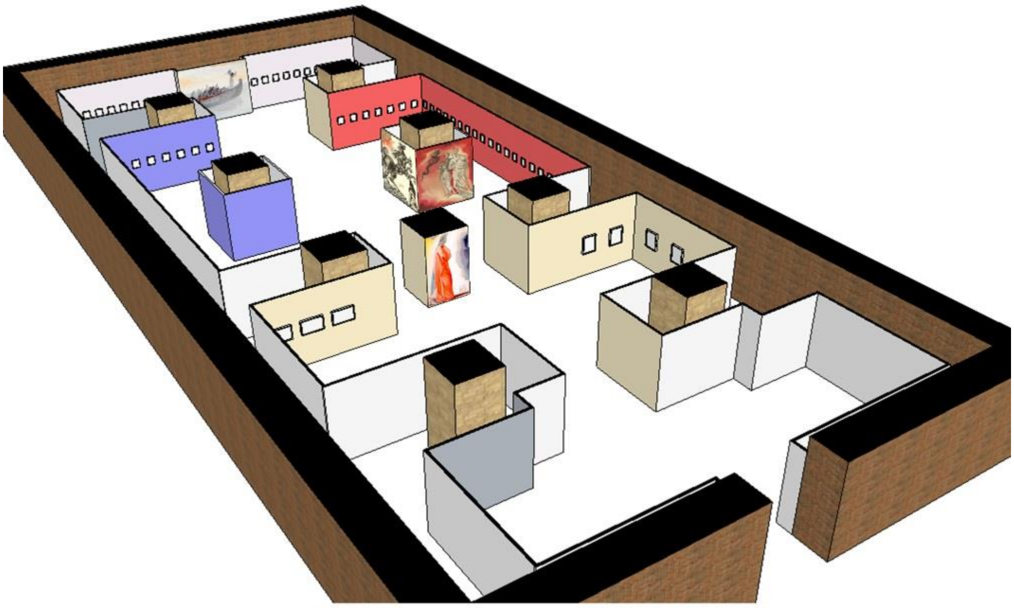


Figure 5.4 : Dali Exhibition; plan.



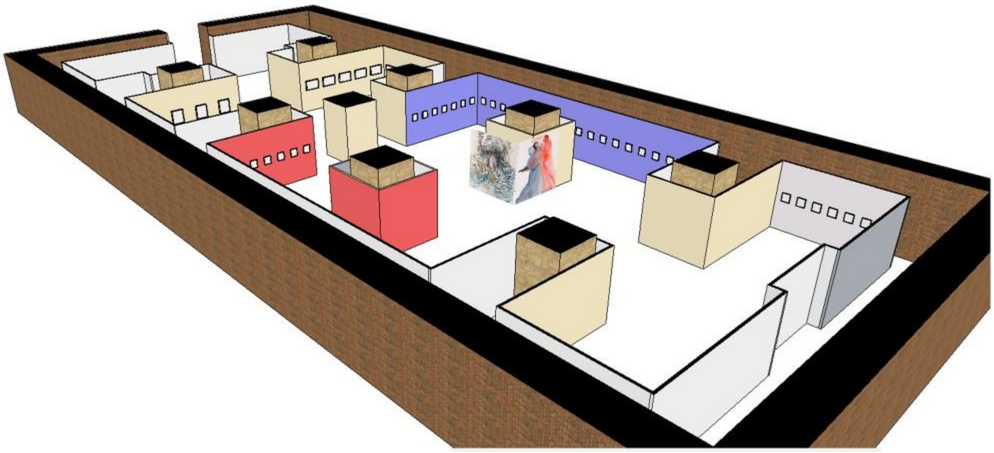


Figure 5.5 : Dali Exhibition; views from 3D model.

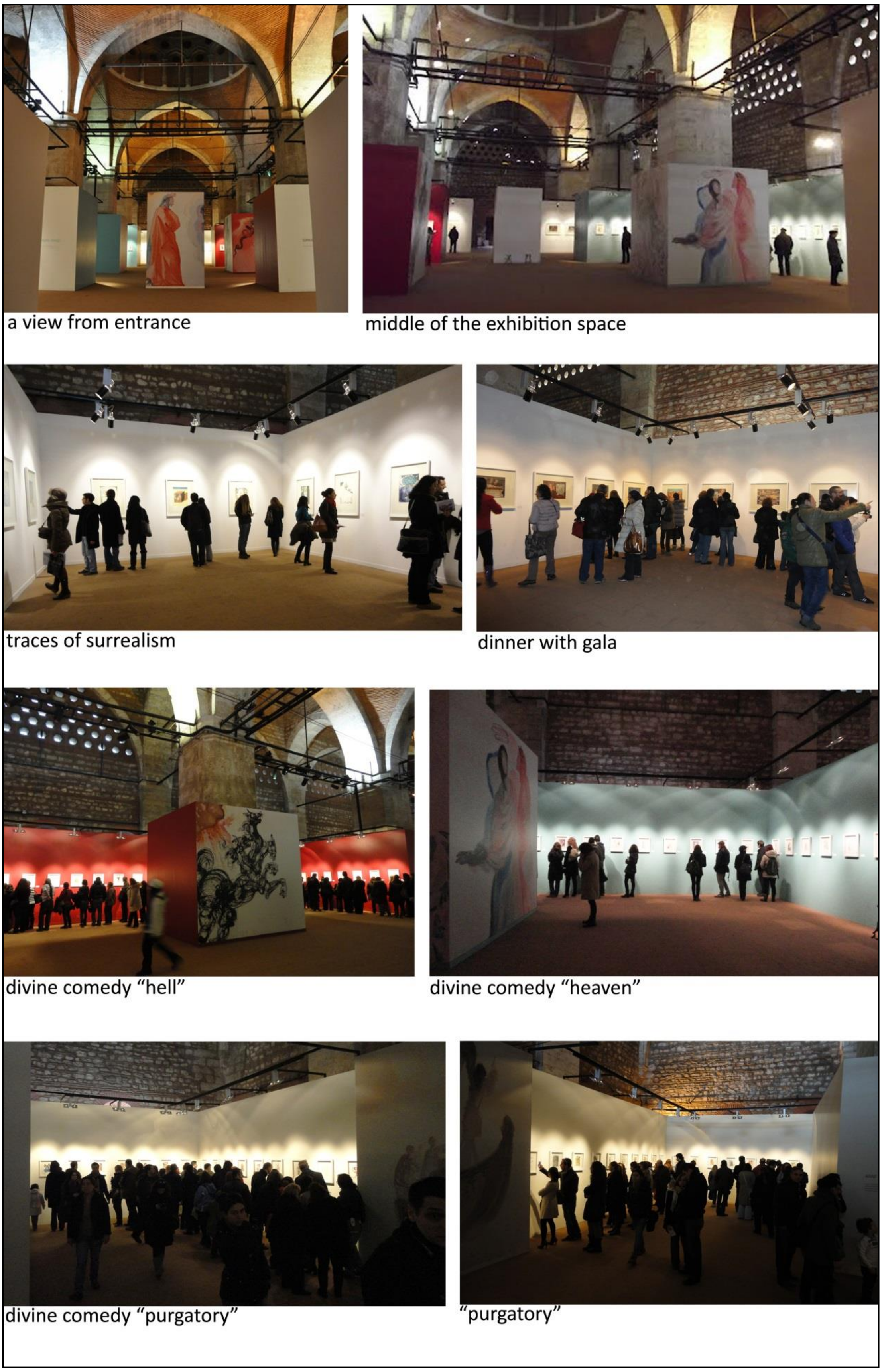


Figure 5.6 : Dali Exhibition; pictures.

5.2 Model Operation

The model was aimed at predicting and simulating spatial inhabitation patterns in Tophane-i Amire main exhibition hall during the Dali Exhibition. Firtsly, the parameters were given, which would determine the possibility distribution of spatial occupancy. Later, the model was computationally operated through calculation and visualisation steps by following the aformentioned guidelines. MATLAB software for this application of the model was downloaded from the web site of Istanbul Technical University, Center of Information Technology, which provides license for students and academics.

5.2.1 Parameters

As listed before, the parameters were mainly grouped into three areas: function, space and users. For this case, there was a certain skeleton activity (engagement with art objects) and an intermediate activity (queuing and gathering), which signified the sub-functions. The sub-spaces of those functions (the FASOs) would not be solely defined by the parameters containing sub-functions such as ‘the distance from the sub-function’. For instance, spatial configuration and the number of visitors would become important factors in determining the size and shape of each FASO.

Four key parameters were selected for this application of the model as the fundamental variables affecting the possible occupational behaviour, thereby the formation of the FASOs. But before describing them, several others were deliberately not chosen. For example, the number of exhibits was fixed for the duration of the exhibition meaning that functions were largely invariable. Secondly, in terms of popularity, all the pieces of art in the Dali collection were prominent and on a par with each other. This meant that there were no striking inequalities in the usage of space like those found around the Mona Lisa at the Musée du Louvre. The fact that people chose to attend the exhibit was also taken as a basis to ignore personal preference parameters. Therefore, the four main parameters chosen for the model are as follows.

1. “The Distance from the Viewing Point” (dVP) is a space-related parameter using the distance from sub-function rule in the FIS. The viewing point (VP) refers to the best place to engage with an object (artwork) depending on the distance and angle between the exhibit and visitor. The VP is the focal point, accepted as the centre of

the core of the FASO-region for each exhibit (skeleton activity). The relative proximity to the focal point raises the possibility of a person being present in the sub-space. This parameter is related to the spatial installation of an exhibit with respect to the intended experience by the artist or curator. So, the VP differs for each object according to its size and shape, also the space it is displayed in.

The VPs were marked on the plan (independently from the model grid) as a VP was on the right angle and 75cm away from a painting of The Traces of Surrealism and The Dinner with Gala; but 50cm away from a painting of The Divine Comedy, which was smaller in size than the other two groups. These points were validated in a further comparison with expert knowledge by receiving the curator’s opinion (Şark, 2012). Figure 5.7 shows the VPs as the red points in front of every painting, which are strung on the order line.

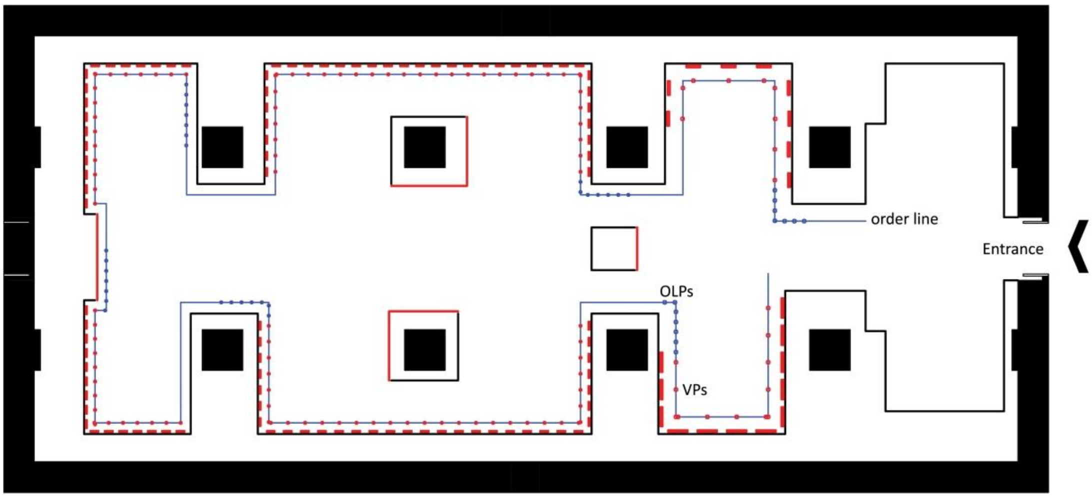


Figure 5.7 : VPs and OLPs on the plan.

2. “The Distance from the Order Line Point” (dOLP) is a space-related parameter using the distance from sub-function rule in the FIS. The Order line refers to the proposed itinerary of the visit in the exhibition space. It is assumed that when a higher number of visitors are in the hall at the same time, they start to gather and queue up to see the first object of a theme or series for the sake of the narrative continuity. The order line points (OLPs) then represent the prospective nodes of queuing and gathering along the order line. The OLP is also the focal point, accepted as the centre of the core of the FASO-region or -line for the intermediate activities: queuing and gathering emerged at a higher visitor population. The relative proximity to the focal point raises the possibility of a person being present in the sub-space.

The OLPs, independently from the model grid, were the successive seven points placed on the route at every 50 cm by starting before the VP of the first exhibit of each theme or series (such as the first print of The "Hell"). These points were validated in a further comparison with expert knowledge by receiving the curator's opinion (Şark, 2012) as well as the visual data showing the gathering and queues in the space. Figure 5.7 shows the proposed itinerary as the blue order line; and the OLPs as the blue points at the beginning of each theme and series.

3. "Visual Integration" (VI) is another space-related parameter, which is related to the syntactic property of the space. Based on the space syntax theorem, much research on galleries and museums; such as Choi, 1999, Peponis et al., 2004, Tzortzi, 2007 and Rohloff et al., 2009, have explored that the morphological values are influential on the patterns of visitors in terms of the encounter and exploration in an exhibition space. In this application visual integration was taken as the parameter reflecting the impact of the spatial configuration and arrangement. The pattern of integration shows how much a person can see from certain points, those where movement is more exploratory and desirable. Thus, the FASOs (of both skelaton and intermediate activities) residing in highly integrated zones of the space would be much larger in order to support a higher possibility of presence.

4. "Density" (D) is the fourth parameter, from the user related set. The population in an exhibition space has an influence on the fulfilment of the sub-functions in terms of the engagement with the art object. Higher populations make the skeleton FASOs expand in a way to supply more places for new participants who are inclined to be involved in the sub-functions. Also new intermediate activites: queuing and gathering threaten the performance of the exhibition, and rearticulate spatial usage.

The most densely visited times during the display were recorded on weekend afternoons, especially on the last days of the exhibition. Some group visits and guided tours also created temporary clusters in the space. On the contrary, the least densely visited times were weekday midday hours, when there were fewer visitors than the number of total exhibits.

Overall, the inputs in the calculation part of the model were decided as: the distance from the viewing point; the distance from the order line point; visual integration and density.

5.2.2 Calculation

The FASOs would be formed according to the membership degrees of the spatial units as the results of FIS process. The spatial units (centroids) were illustrated by placing a 50 by 50 cm grid coordinate system on the plan of the Tophane-i Amire main exhibition hall (Figure 5.8). The 37x77 grid generated 2849 centroids in total due to each intersection. The partition contained both habitable spatial units (2196 centroids) which were within the exhibition area and also some units which were not habitable (between the structural walls and separator walls; 653 centroids). Each centroid was assigned an ID by using the ArcMap software. This ID system would help to generate the grid matrix in the visualisation part.

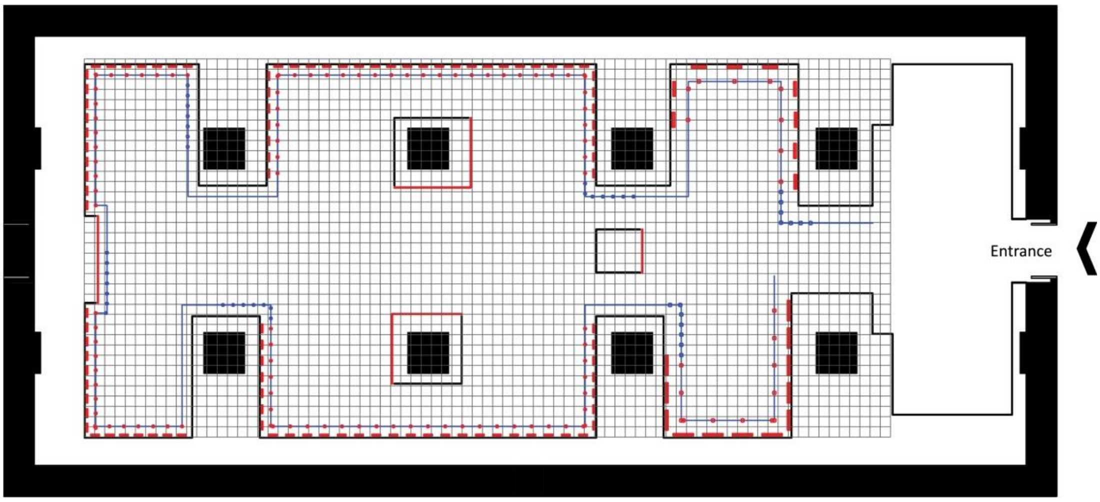


Figure 5.8 : The grid on the plan.

As mentioned, the calculation part needed the input data file: the whole list of the parameter variables of all the centroids, and fuzzy inference system structure, which would be constructed in FIS Editor in MATLAB.

5.2.2.1 Input data file

The input data file was comprised of the parameter variables of all 2849 centroids on the grid. The centroids outside the exhibition area were treated as having all input variables as “0,” since they had been excluded by the spatial arrangement.

Parameter variables for the habitable centroids were obtained by using additional methods; proximity measurements in ArcMap software for the first two parameters: dVP and dOLP; visibility graph analysis in Depthmap software for the parameter: VI and; observation, visual data and people counting for the last parameter: D.

For each centroid, the distance from the VP was identified as the measurement of the shortest distance from the nearest VP on the plan. The numeric variables for 2196 centroids were calculated by using ArcMap software and taken as an ordered list. The list was exported into the input data file as the variables of INPUT-1.

In the same way, for each centroid, the distance from the OLP was identified as the measurement of the shortest distance from the nearest OLP on the plan. Similar to the calculation of the distances from the VPs, the numeric variables for 2196 centroids were calculated by using ArcMap software and taken as an ordered list. The list was exported into the input data file as the variables of INPUT-2.

To obtain visual integration values Visibility Graph Analysis (VGA) was run in the UCL Depthmap application (Turner, 2001), the space syntax software which performs visibility analysis of architectural and urban systems. VGA both gave the list of all numeric VI values for every centroid and created a heat-map showing the integration in the whole space (Figure 5.9). For this spatial arrangement of the Dali Exhibition in Tophane-i Amire the horizontal axis of the space had a higher visual integration, especially where the two series of The Divine Comedy: The Hell and The Heaven started and ended, which would result in this area having a higher possibility of occupancy. The list of all numeric VI values was exported into the input data file as the variables of INPUT-3.

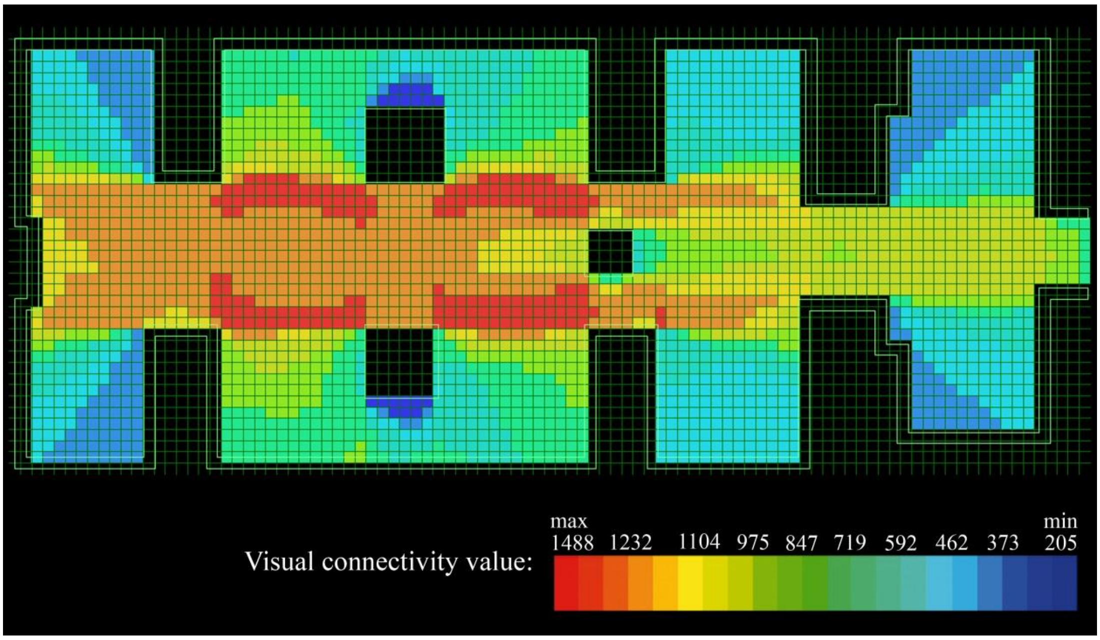


Figure 5.9 : The VGA map.

Density value was taken as a certain number of visitors, which would be the same for every centroid in the analytical grid. Since this was a real case, the frequency of visits in the exhibition hall had been observed during the period when the exhibits were on display. According to the data collected through systematic counting of visitors (recorded at entry), three typical population levels were identified. The low density (d1) equated to roughly one person for each drawing; the medium density (d2) represented two persons per drawing, while the high density (d3) represented three persons, which meant 121, 242 and 363 people in total, respectively. So, D = 121; = 242 and = 363 were taken as the parameter variable for all of the centroids in the exhibition space. The list of all 2196 centroids was exported into the input data file as the variables of INPUT-4.

5.2.2.2 Fuzzy Inference System (FIS)

The Sugeno-type fuzzy inference system was built in MATLAB as a four-input, one-output, and forty five-rule analysis problem. It transformed the crisp inputs to fuzzified inputs (fuzzification: input to inputmf) then to outputs (evaluation of the fuzzy control rules: inputmf to outputmf), and finally to the single crisp output (aggregation: ouputmf to output) as seen in Figure 5.10.

In the fuzzification process, the inputs were defined as fuzzy sets. The universe of discourse and the MFs of each input: dVP, dOLP, VI and D were designed as follows;

1. INPUT-1: dVP. The input space was accepted as 0 – 1000 cm in the space where the minimum distance from any VP for any dot was 2.98 cm while the maximum distance was 838.54 cm. The MF *in*, *near* and *far* for the input dVP was organized as (Figure 5.11a):

[0 0 0 100, 0 100 300, 100 300 400 1000]

2. INPUT-2: dOLP. The input space was accepted as 0 – 1000 cm in the space where the minimum distance from any OLP for any dot was 9.47 cm while the maximum distance was 996.73 cm. The MF *in*, *near* and *far* for the input dOLP was organized as (Figure 5.11b):

[0 0 0 50, 0 50 150, 50 150 200 1000]

3. INPUT-3: VI. According to the VGA map, the minimum and maximum integration variable in the space where the grid covers was 205 and 1488, which also delimitated the universe of discourse. The average attribute 946 was regarded as the midpoint of the input variable scale. So, the MF *min*, *average* and *max* for the input VI was organized as (Figure 5.11c):

[205 205 946, 205 946 1488, 946 1488 1488]

4. INPUT-4: D. The number of the visitors in the exhibition hall at the peak and off-peak times determined the universe of discourse, which was 0 - 363. And, according to the population levels, the full membership in the *low*, *medium* and *high* density was assigned as 121, 242 and 363 proportionally to the number of pieces in the collection. The MF *d1*, *d2* and *d3* for the input D was organized as (Figure 5.11d):

[0 0 121 242, 121 242 363, 242 363 484 484]

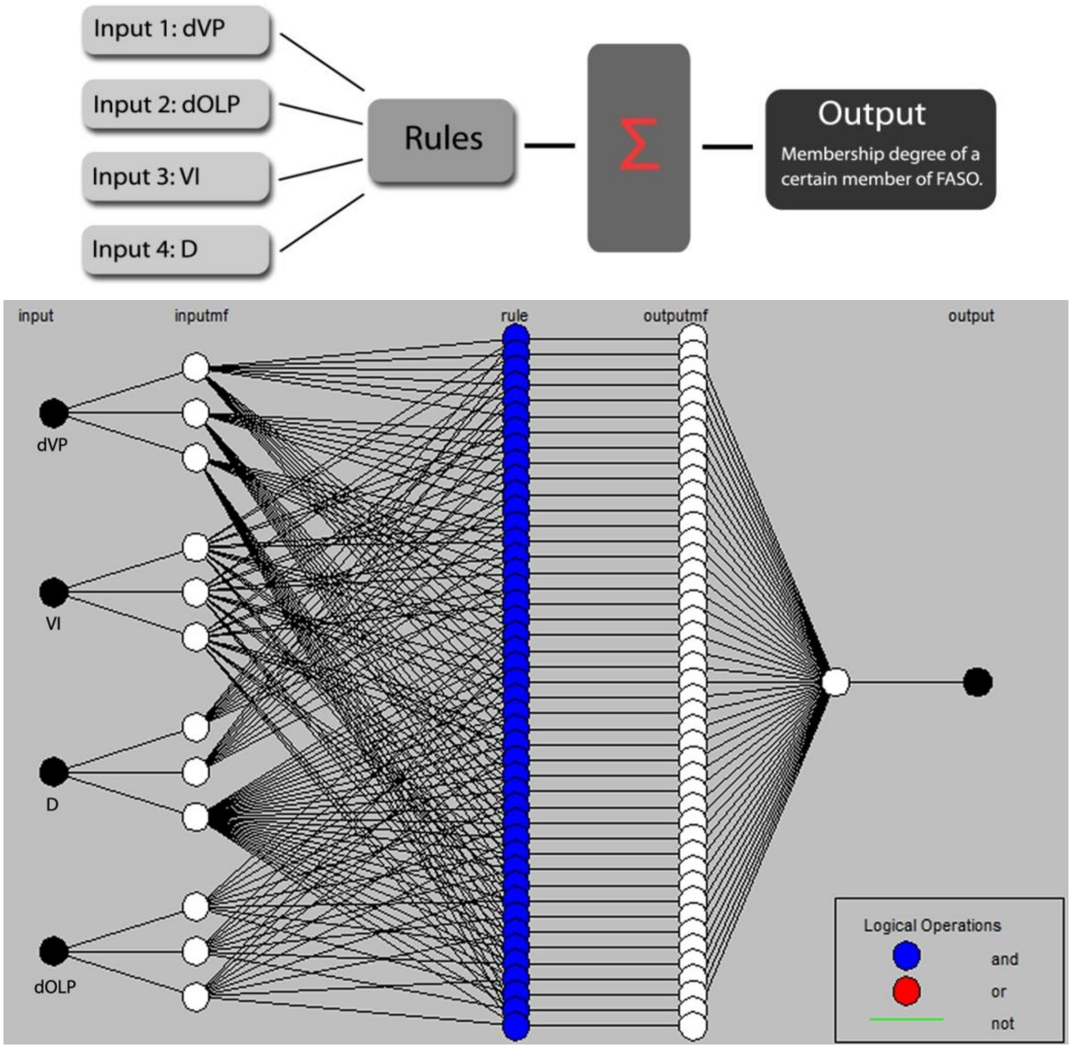
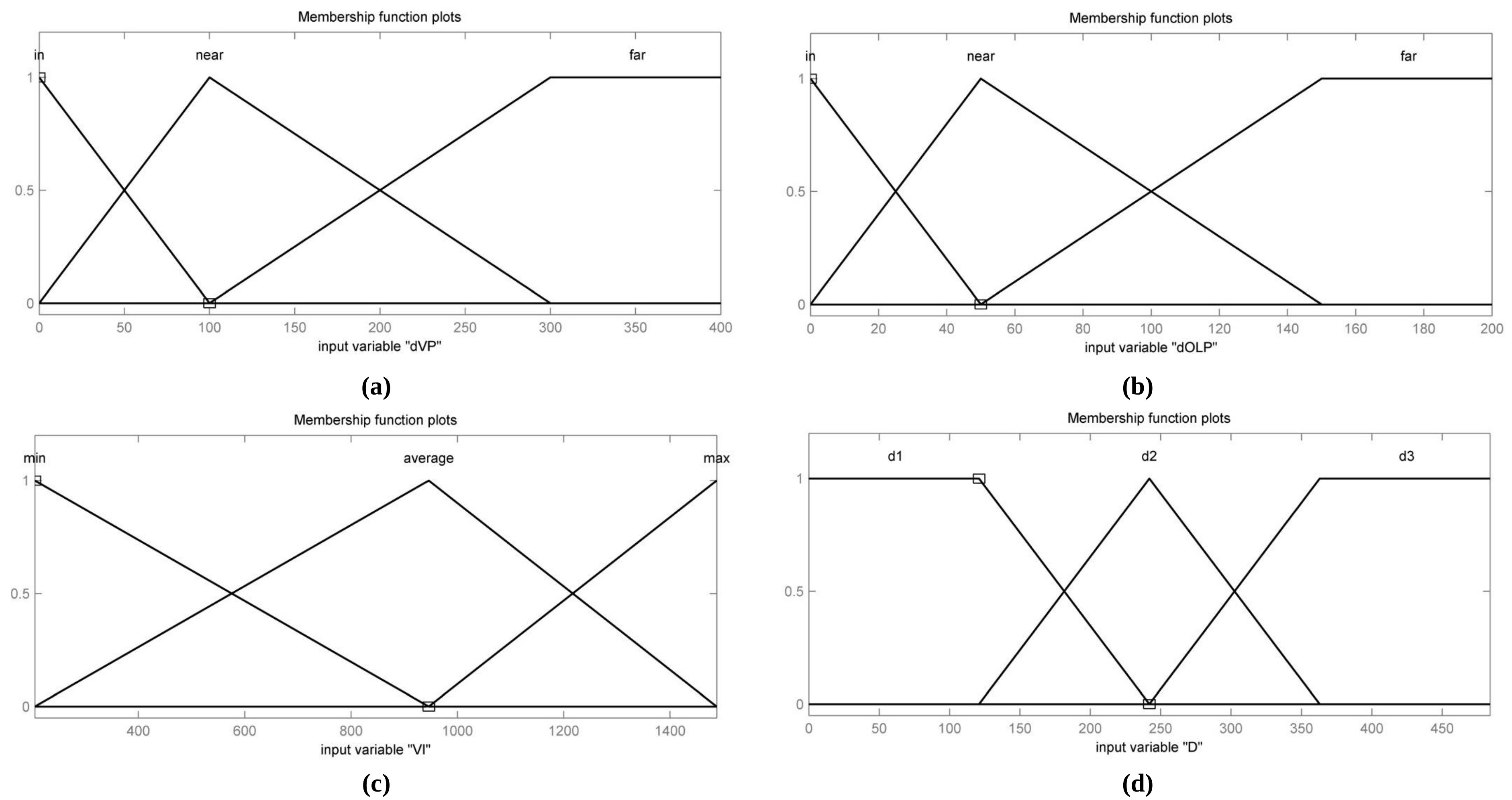


Figure 5.10 : Fuzzy inference system structure.



(a) **(b)** **(c)** **(d)**

Figure 5.11 : Membership Functions (MFs).

After the fuzzification of the inputs, the output was also translated into the MFs from the lowest membership to the highest membership as follows:

mf 1 :	0
mf 2 :	0.125
mf 3 :	0.25
mf 4 :	0.375
mf 5 :	0.5
mf 6 :	0,625
mf 7 :	0.75
mf 8 :	0.875
mf 9 :	1

According to the membership degrees, mf9 represented the 100% possibility of presence attributed to the sub-function, whereas mf1 denoted total disengagement from it. These values of outputs created the fuzzy sub-sets and the FASOs by existing either in the core, indeterminate boundary or in the exterior.

After the fuzzification process, fuzzy control rules were generated according to the logical postulates (relations) between each input and output. The basic arguments are stated as follows:

- "If the distance from the VP is far then the membership degree of the centroid is low."
- "If the distance from the OLP is far then the membership degree of the centroid is low."
- "If the visual integration value is max then the membership degree of the centroid is high."
- "If density is high (d3) then the membership degree of the centroid is high."

In the mechanical representation 81 rules were created when all the MFs of all the rules were combined. However, some of them were eliminated according to the assumption explained below.

The rules which premised dVP and dOLP MF: *in*, ended with the output: mf9. These rules (21 rules in total) identified the minimum and rigid core of the FASO, where there was nearly 100% possibility of presence attributed to the sub-function.

The rules which premised dVP and dOLP MF: *near* and MF: *far* concluded in different MFs of output from mf1 to mf9 according to the variables of VI and D inputs. Through the *min*, *average* and *max* of VI, and the *d1*, *d2* and *d3* of D the result mf increased respectively, which meant that the centroids being rather far from the VP and the OLP were gradually included in the FASO with higher membership degrees. As an example, while a centroid fitting the rule [14] "If (dVP is far) and (VI is min) and (D is d1) then (mem.degree is mf1) (1)" was in the exterior of the FASO, the same centroid became a member of the FASO when only the number of people increased in the space (from d1 to d3) due to the rule [39] "If (dVP is far) and (VI is min) and (D is d3) and (dOLP is far) then (mem.degree is mf3) (1)". Another centroid, for instance, with the same attributes but a higher VI value only was not in the exterior anymore due to its favourable place in the spatial arrangement, as the rule said; [17] "If (dVP is far) and (VI is max) and (D is d1) then (mem.degree is mf3) (1)".

The rules including D MF: *d1* and MF: *d2* in the antecedent did not contain the input dOLP, and the inference system operated with only three sets of input: dVP, VI and D. Because the parameter: distance from the OLP was only valid when a huge density occured in the space, this prompted people to gather and queue up to see the first paintings of each theme or series. Only at a higher population, new FASOs appeared in the plan, which were the new sub-spaces of the sub-function: 'waiting for the x exhibit' emerging on and around the OLPs of x. There were 26 rules which premised D MF: *d3* and these rules were comprised of all four inputs as including dOLP.

At the end, 45 rules in total between all inputs and output were formulated in this application by connecting individual relations between antecedent and consequent (App. A). The rules were in the same weight: 1, since all of them were accepted as having the same degree of influence on the inhabitation patterns.

After the fuzzification and rules process, the subsequent two steps of FIS; the inference and aggregation (not defuzzification because of the Sugeno-type FIS) were operated for all of the centroids. The inference process determined an output for each centroid in model application by evaluating the rules. All the outputs of all the rules were grouped together in the aggregation process in order to obtain one crisp output for that certain centroid. Figure 5.12 shows a sample: the "Rule Viewer" (MATLAB, FIS Editor) for the centroid ID 11, whose input variables were dVP = 32.08, dOLP = 122, VI = 894 and D = 121. The rules were evaluated according to the membership functions of the input variables, and all the outputs were aggregated in the result; mf = 0.877. Like this centroid, each centroid on the habitable part of the analytical grid got a single-valued output variable: $0 \leq x \leq 1$. This quantity denoted the membership degree in the set of a certain FASO. The centroids outside the display area had output mf = 0 since all the input variables are 0, which did not refer to any membership in a FASO.

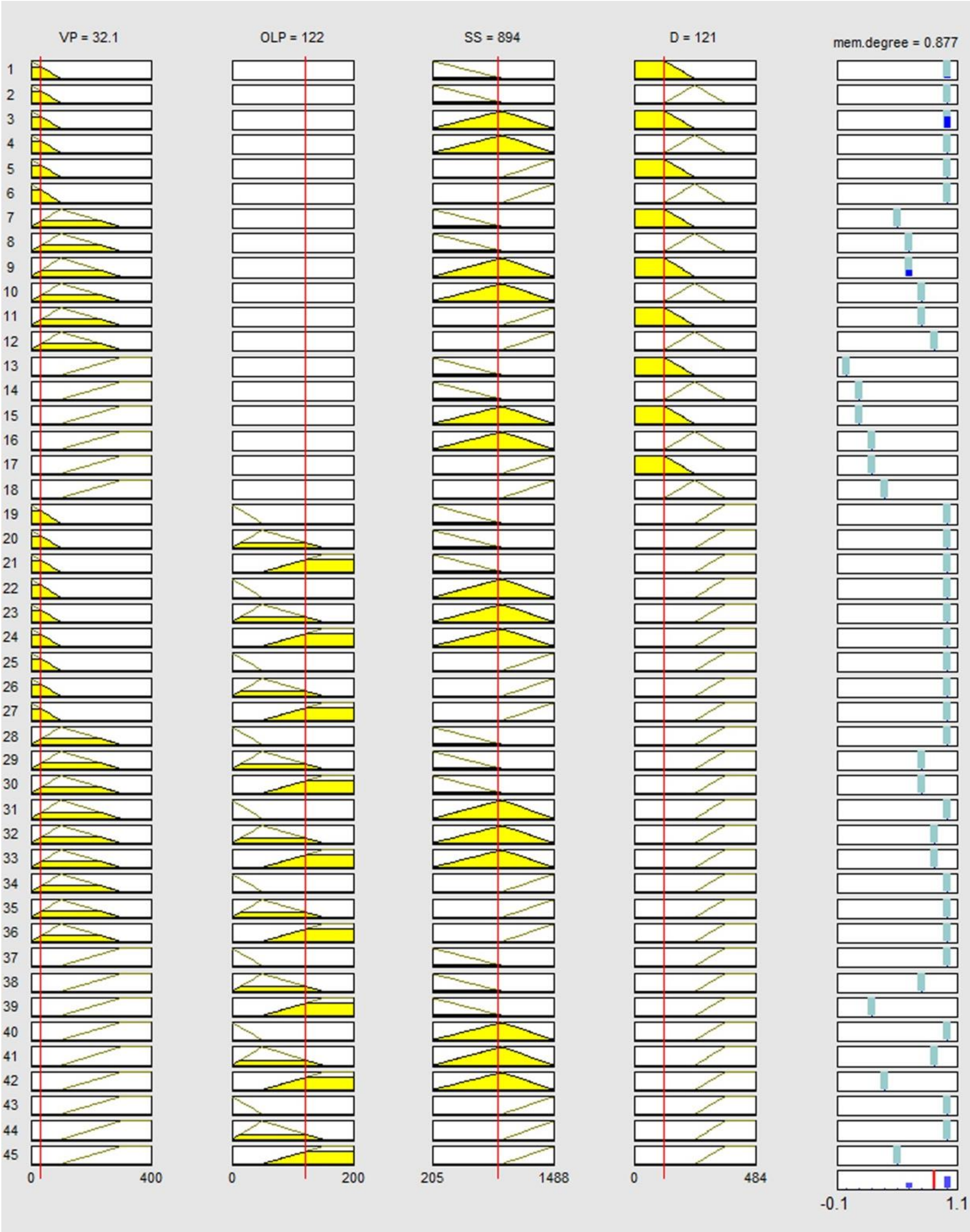


Figure 5.12 : The inference and aggregation process for the centroid ID 11.

The calculation process terminated when the list of 2849 outputs -sorted in ascending order of the ID of dots- proceeded to visualization.

5.2.3 Visualisation

The visualisation part of the model was operated according to the guideline issued in the previous chapter.

5.2.3.1 Grid matrix and interpolation

In order to transpose the vertical range of 2849 separate outputs as a matrix that would match up with the spatial grid (37x77), the coloum number = 77 was given to the model. So the model created the matrix by arraying the outputs of the centroids according to the IDs they belonged to.

In the interpolation step of this application `interp2` = 6 was used, which managed a rapid and efficient operation without an error in the programme. By running two-dimensional interpolation, the model resulted in a new 2305 x 4865 matrix, which meant 65 additional calculations between two specific centroids.

5.2.3.2 Image process

The image process coded the complete set of values (1.1213.825 values in the matrix) by using colour gradients to produce a heat-map for the Tophane-i Amire main exhibition hall. `imagesc` operation displayed higher numbers as hot colours, which the dark red was mf9, and lower numbers as cold colours, which the dark blue was mf1. When all the variables on the matrix were transformed into the corresponding colours a map of total space occured which was comprised of more than one hundred different sized and shaped FASOs.

5.2.4 Results

The application process was repeated three times for the three visitor population density values: D = 121, = 242 and = 363 (as changed in the input data file) which would substantially trigger the rules containing *d1*, *d2* or *d3* respectively and fully satisfy the relevant subset of the input. For this case, the only input subject to change was "D;" the user related parameter: population. The other inputs (dVP, dOLP and VI) were constant, since the spatial arrangement and display layout did not change.

So, this analysis would allow us to understand how the spatial usage changed at different visitor populations by creating three different maps for comparison.

In Figure 5.13 a small part of the maps is examined in detail to show the input variables of the centroids and three outputs with corresponding colouring on the maps of low (d1), middle (d2) and high (d3) density. Also a typical FASO set for each density level is seen, where the centroids are on the x-axis at 50, 100 … 350 cm away from the viewing point of a certain exhibit. When the population tripled the membership degrees of the centroids increased and their places (in the core, the indeterminate boundary or the exterior) changed accordingly as reflected by appropriate colouring.

Figure 5.14 presents the whole maps of the spatial usage as the results of the fuzzy computational model for three different visitor populations in the Tophane-i Amire main exhibition hall during the Dali Exhibition. The first map (d1) displayed the result when the density variable (D) was 121, and showed the pattern of inhabitation when a maximum 121 visitors were in the exhibition area. In this map every sub-function had its own sub-space represented by the FASOs, where up to r = 50 from the VP was the core (MF = 1), r = 175 circle was the 0.5-cut boundary –implying that up to this level were higher membership degrees in the intermediate boundary– and the r = 325 circle was the outside edge (MF = 0), implying that beyond this limit was exterior (mf1). Visually, a large amount of the space in the hall was coloured in a blue scale for this population, which signified a very low membership degree, a remote possibility of people in those parts of the space. The FASO of each painting of the Traces of Surrealism and the Dinner with Gala series were clearly noticeable, whereas the FASOs belonging to The Divine Comedy were more indistinct since their intermediate zones disappeared at both sides due to their close proximity to each other. The overlap that existed outside the core was the outcome of a design decision which aimed at keeping a sub-function in a more spatial and visual contact with the other sub-functions nearby by enabling a quick and non-stop passing from one painting to another. These positions and topological relations of the FASOs were the results of the display layout of the exhibits. Notably, the FASOs located in those areas where the visual connectivity was very high (around the horizontal axis) were larger than those located on the less integrated parts of the space. This directly arose from the spatial arrangement of the exhibition.

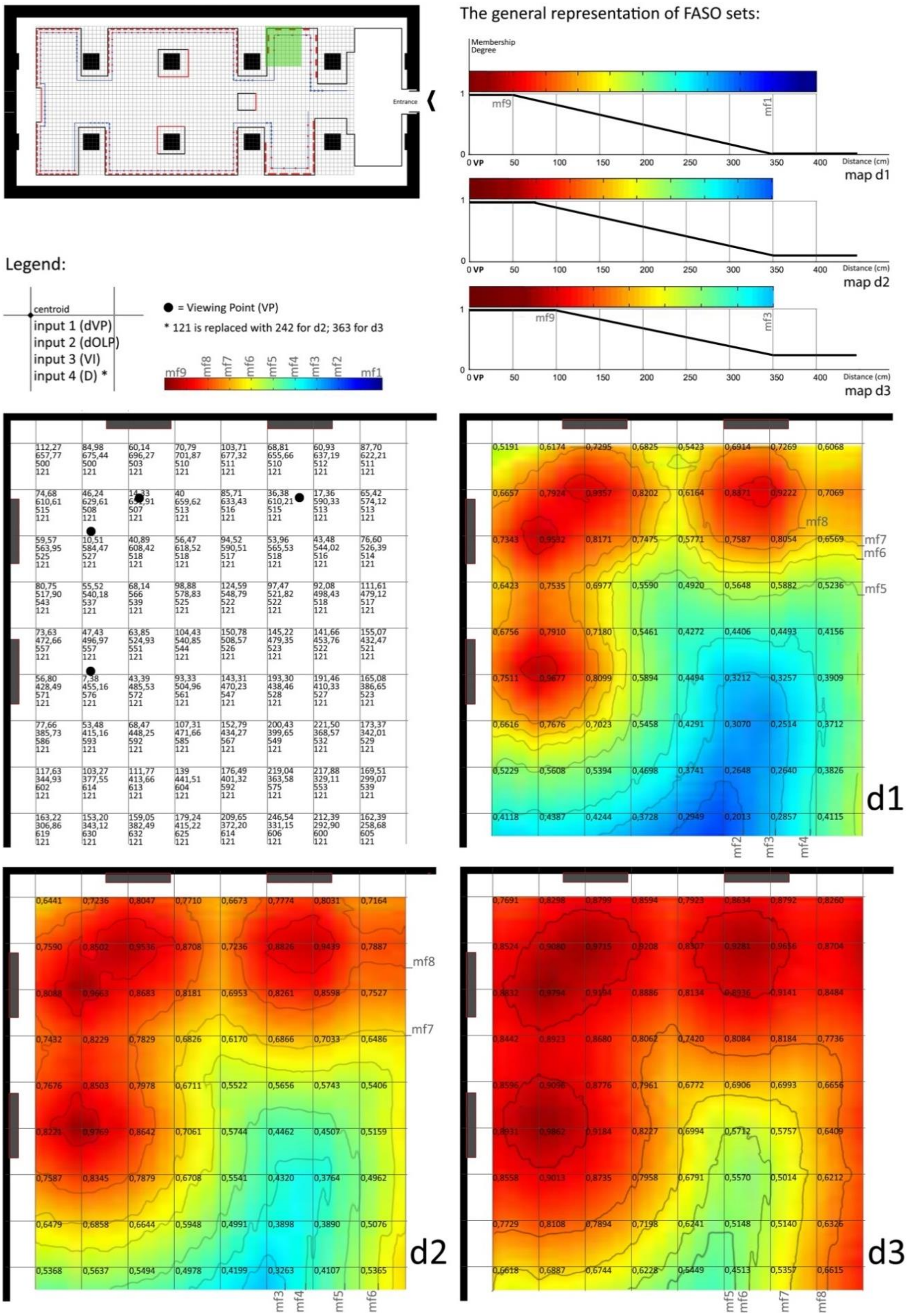


Figure 5.13 : The plan detail.

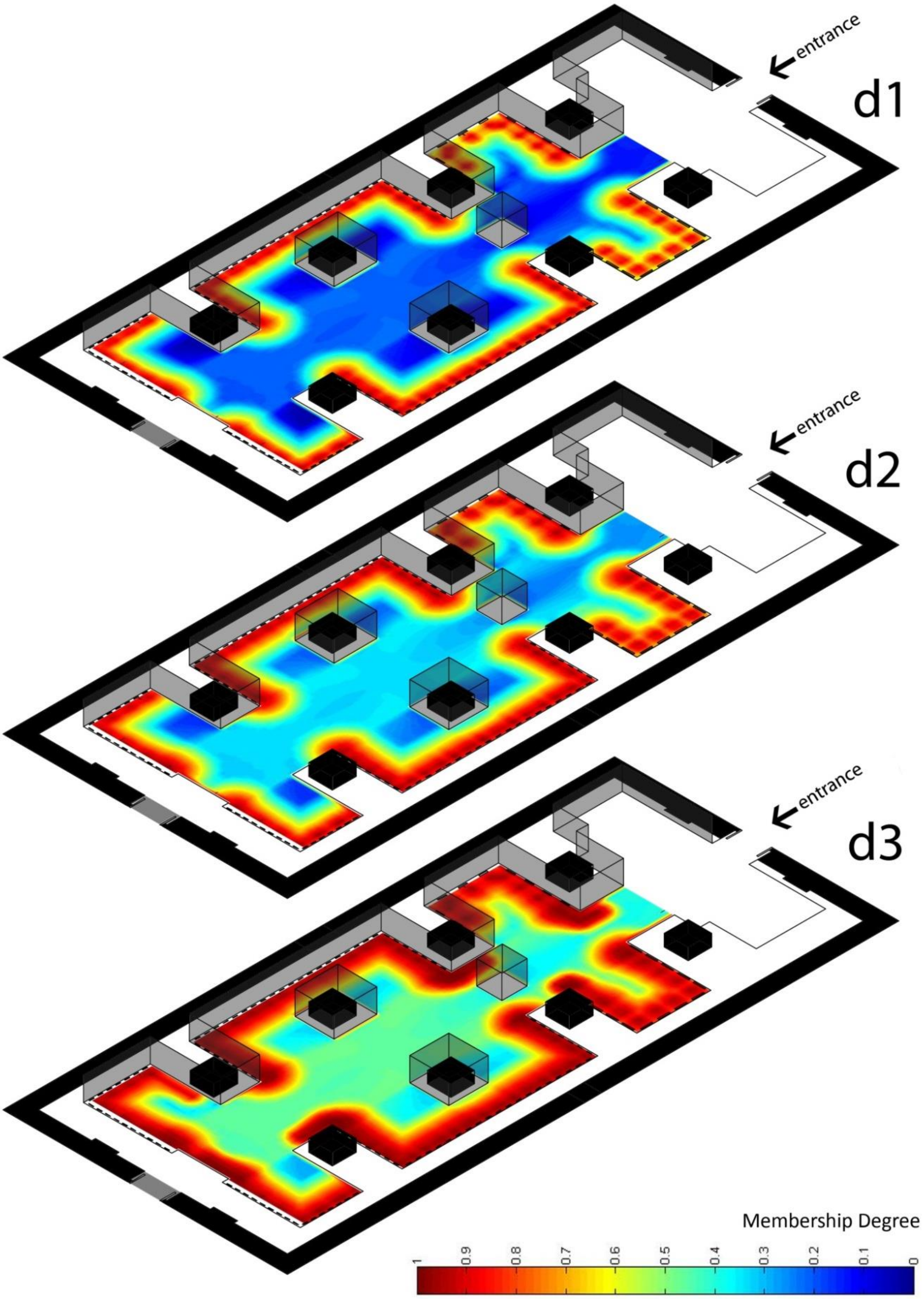


Figure 5.14 : The spatial usage maps.

The second map (d2) showed the spatial usage when nearly 242 people (two persons per drawing) were visiting the exhibition; the number which fully satisfied the medium density without taking part in the d1 and d3 subsets. This map did not represent a substantial difference from the first, excluding the merging of some FASOs in response to the increase in population. Also, the FASOs around the horizontal axis became more congested in the bottleneck of the hall where it narrowed around columns. However, if there were 360 visitors or more in the hall (d3) the difference in the result was more dramatic. The FASOs changed as, up to r = 100 from the VP was core (mf9), r = 250 circle was the 0.5-cut boundary, and r = 325 circle was the border of mf3, pushing the limit two steps forward from the place in the first map. As a result, the red-coloured cores expanded enormously obliterating the yellow intermediate zones at the immediate points of the sub-functions, whereas the exterior (mf1) and the blue area of the low membership degrees in the intermediate boundary totally vanished. In many areas in the space especially around the corners, the FASOs were overlapped to an extent that the two sub-functions became topologically equal. Moreover new FASOs appeared on the route before the first paintings of the themes, which represented the queues gathering at the beginning of each narrative series.

Table 5.1 : Statistical results of three analyses.

(a)			
The membership degree of FASO	d1	d2	d3
The smallest value:	0.0305	0.1555	0.2805
The highest value:	0.9877	0.9914	1.0000

(b)								
Membership functions	Membership degrees					Total number of centroids		
						d1	d2	d3
mf8 - mf9	0.875	≤	x			134	256	623
mf7 - mf8	0.75	≤	x	<	0.875	297	346	317
mf6 - mf7	0.625	≤	x	<	0.75	190	244	214
mf5 - mf6	0.5	≤	x	<	0.625	225	216	220
mf4 - mf5	0.375	≤	x	<	0.5	216	235	*682*
mf3 - mf4	0.25	≤	x	<	0.375	235	*740*	140
mf2 - mf3	0.125	≤	x	<	0.25	*740*	159	0
mf1 - mf2			x	<	0.125	159	0	0
					Σ	2196	2196	2196

Table 5.1a and 5.1b presents the statistical results belonging to all three maps. Seen in Table 5.1a, every point in the total space had at least more than 0.25 of 1 (25%) possibility of occupation at the highest density (d3), where the smallest output in the system increased from 0.0305 to 0.2805. In Table 5.1b, the highest numbers of centroids in all density levels were mostly the centroids at where any art object was not displayed including middle horizontal axis which covered a wide area relatively in the exhibition space. The possibility value of these centroids rose from mf2 to mf5 due to the increase in population.

5.3 Verification and Discussion

In this part the efficacy of the model against observed behaviour was examined. The verification was performed through the Dali application; by comparing the model results with obtained visual data from the exhibition. The spatial inhabitation, as predicted by the model and proved by the actual patterns of occupation, were architecturally discussed.

For the validation of the model, three sample time frames, which represented the typical properties of d1, d2 and d3, were chosen (Figure 5.15). By using photographs and video recordings the current locations of visitors at each time frame were indicated on the plan in order to display actual spatial occupancy. These maps were superimposed with the output maps of the model (Figure 5.16). A visual comparison of the maps verified that visitors mostly gathered on the spatial units which were expected to accommodate increased numbers of people.

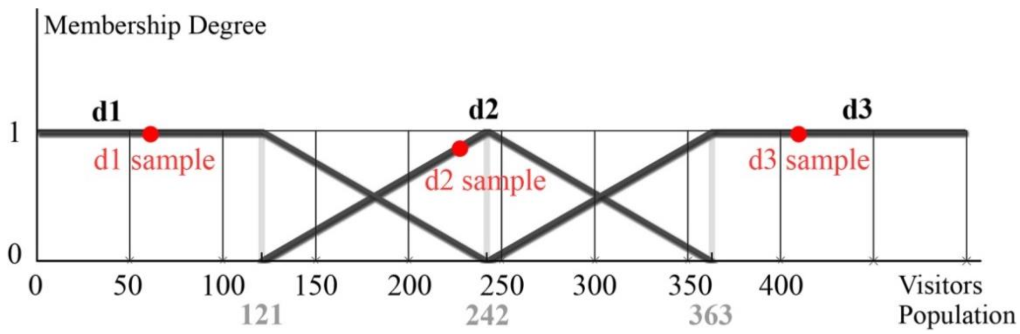
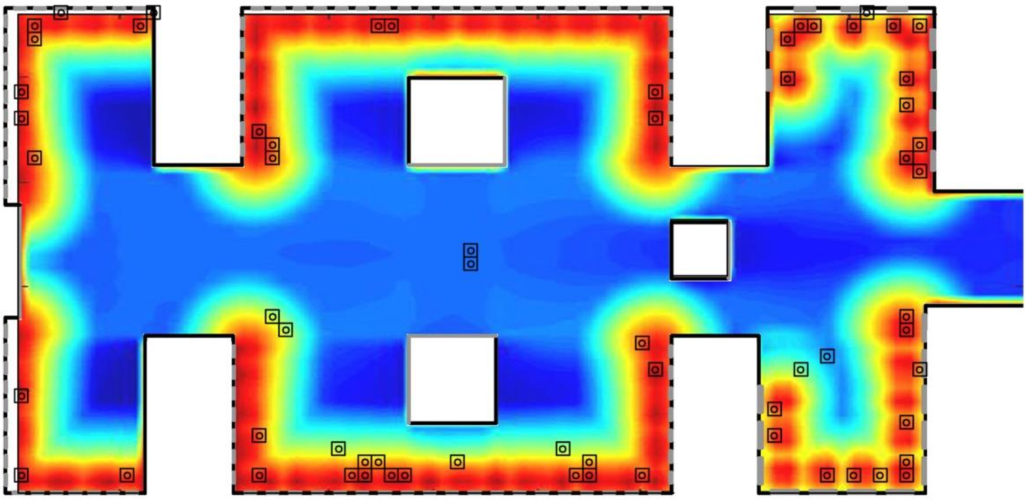
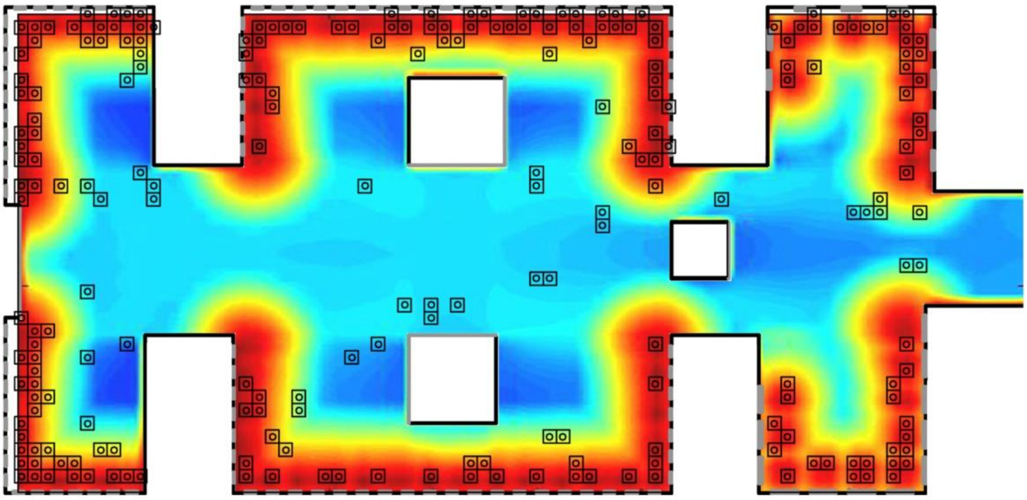


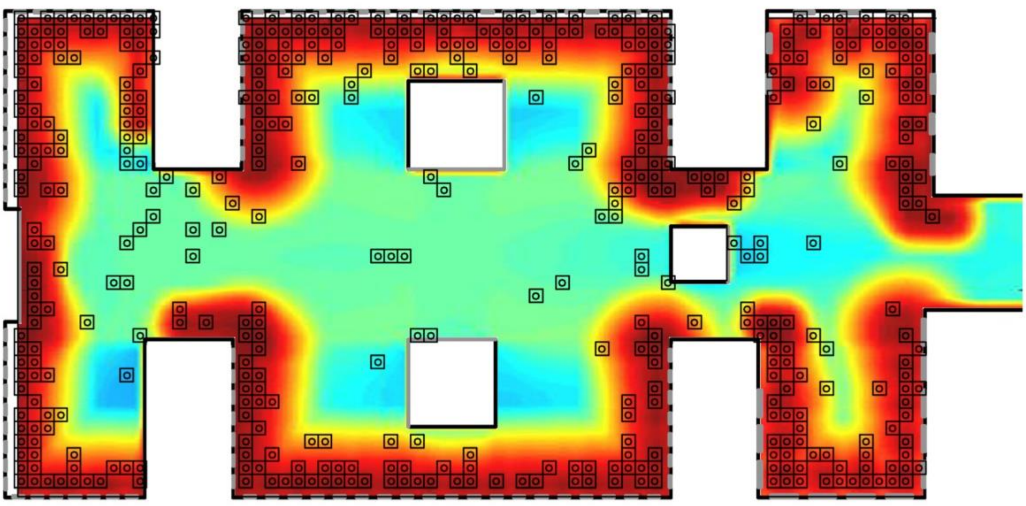
Figure 5.15 : Samples on membership function.



d1 sample 08.02.2012 / Wednesday / 13:10:00 (65 visitors)



d2 sample 11.02.2012 / Saturday / 11:05:00 (230 visitors)



d3 sample 12.02.2012 / Sunday / 16:50:00 (467 visitors)

Figure 5.16 : Validation of three samples.

Likewise, the statistical data in Table 5.2 showed that 80% of the occupied centroids in each density level coincided with the centroids which had already taken the membership degree: $x \geq 0.75$ (mf7) from the predictive model.

Table 5.2 : Statistical results of three samples.

Samples:	**(d1)**		**(d2)**		**(d3)**	
Membership functions	NCO*	%	NCO*	%	NCO*	%
mf8 - mf9	24	37%	124	54%	315	67%
mf7 - mf8	29	45%	57	25%	72	15%
mf6 - mf7	3	5%	11	5%	25	5%
mf5 - mf6	6	9%	7	3%	16	3%
mf4 - mf5	0	0%	8	3%	31	7%
mf3 - mf4	1	2%	22	10%	8	2%
mf2 - mf3	2	3%	1	0%		
mf1 - mf2	0	0%				
Σ	65	100%	230	100%	467	100%
* NCO: Number of centroids occupied						

While the validation above depends on only one frame, it is clear that the frames will change every few minutes since the people are in motion. Nevertheless, we may state that the new maps for each frame show the permutations of the set of the units with high membership degrees within the predictive pattern of spatial usage. To follow this notion, a sequence of frames was examined as another way of validating the model result. A small part of the exhibition hall, where No.2 corporate camera (Figure 5.17) had been in operation was chosen, and 30 frames of video were taken every two minutes to cover an hour period at the medium density (d2). Frames were from 11.02.2012 Saturday and time period: 14:40:00 – 15:40:00, given in App. B. Figure 5.18 represents an analysed data by the accumulation of all the frames superimposed as a single map. The lightest grey indicates that occupation occurred only once over the entire time while the units of dark grey illustrate a higher level of occupation throughout those 30 different combinations of usage. The density map of layers can be interpreted as the representation of the actual possibility values of inhabitation although it relies on a small data set. When compared with the d2 map of the model, it can be seen that the two maps mirror each other with the actual possibility values correlating to the FASOs' predicted values.

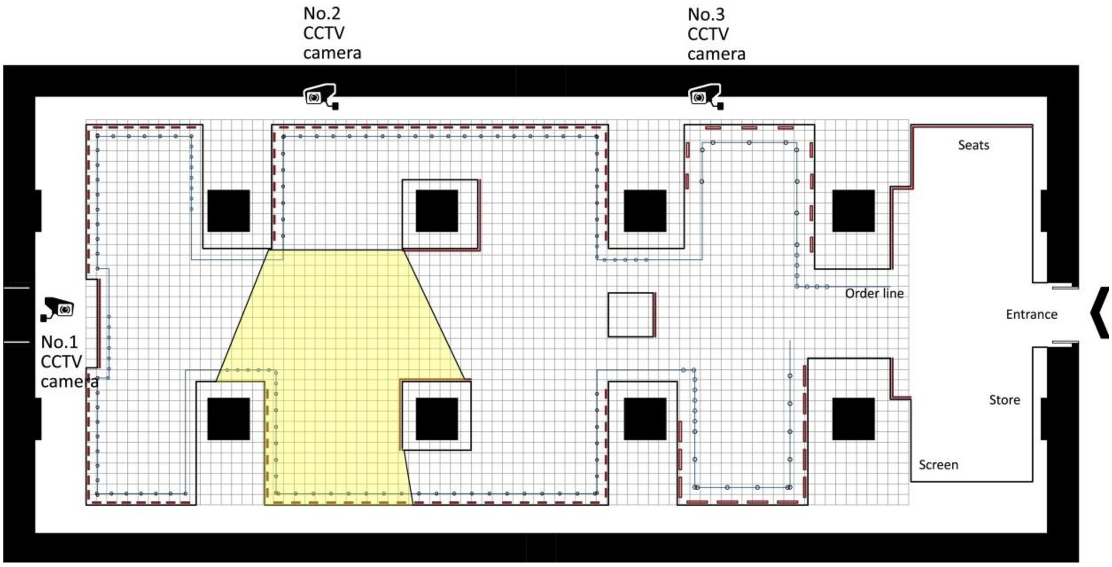


Figure 5.17 : The view path of the No.2 CCTV camera.

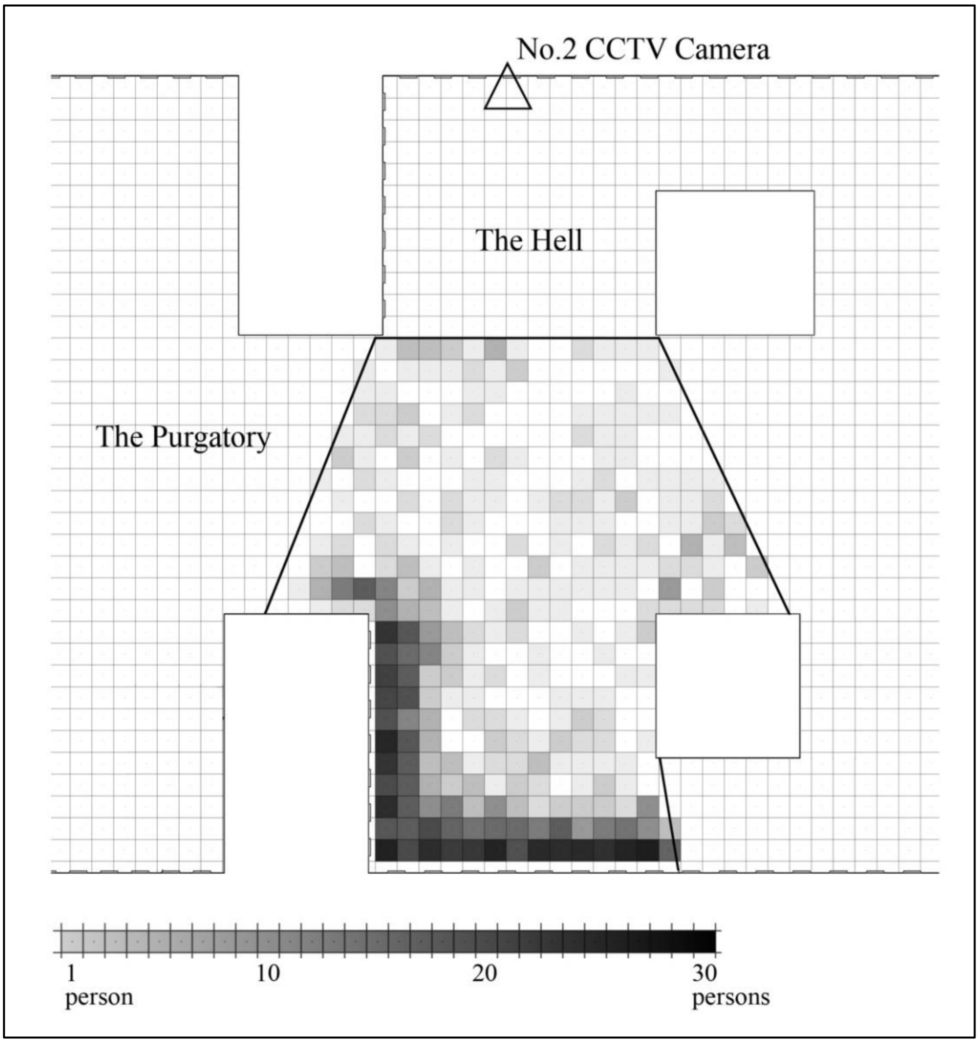


Figure 5.18 : Validation of video frame sequence.

According to this verification, the model appears to capture what is happening in the real space. From an architectural perspective, the predictive maps which broadly replicates the observed usage of space shows that the arrangement and display layout of the Dali Exhibition in Tophane-i Amire is efficient and effective for a lower population density, but it is less so for much higher densities.

The problems are highlighted through the visual data which belongs to the d3 level of population, seen in Figure 5.20 (a, b, c, d, e, f, g, h, j and k). The points that photos were taken are indicated in the legend shown in the Figure 5.19. This data shows actual occupancy behaviour and matches up properly with the occupancy behaviour prediction of the model in terms of spatial usage.

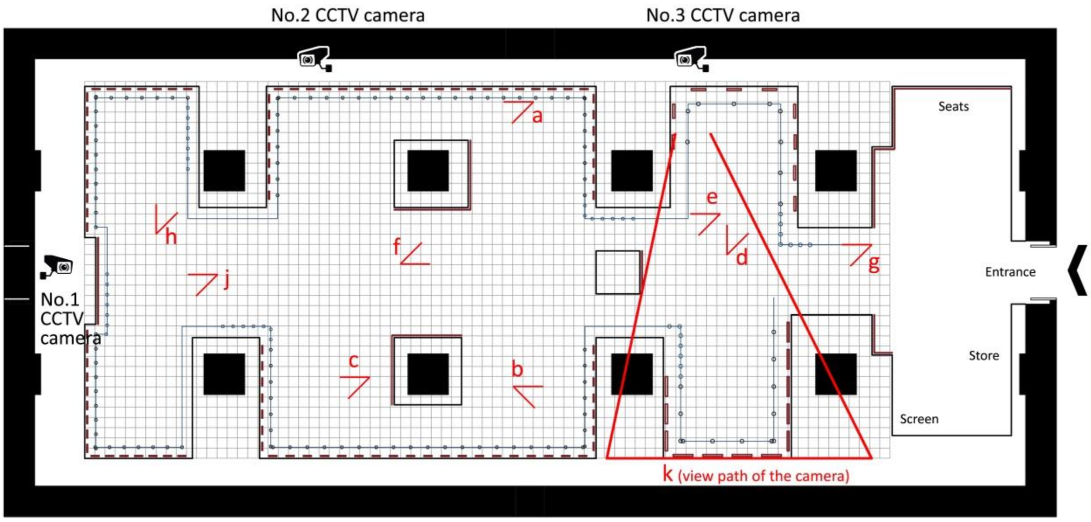


Figure 5.19 : The legend map.

The photographs cited as Figure 5.20 a, b, c and d show that the crowd begins to undermine the spatial function (engagement with an art object) as three or more people are involved in the same activity in the same space at the same time. In the result d3 map of the model, this behaviour is represented as the continuous thick dark red blush, like in front of the group of The Divine Comedy –The Hell as validated in Figure 5.20 a. The reason being is that the expansion of the FASOs causes a penetration of the cores and the higher membership zones of the indeterminate boundary. Also, gathering exists on the corners of the space, where in the model the cores of the objects at the edges are overlapped such as representing only one function –which means that two sub-functions become equal topologically. This cluster can be seen in Figure 5.20 b, where the corners are more crowded than the other display walls.

Additionally, as seen in Figure 5.20 e, f and g the queuing zones block the view when they form around display walls, interrupting visitor flow on the main circulation paths. These queues are also predicted in the result d3 map of the model and appear as new FASOs with the involvement of the input dOLP. Notably, the two queues at the beginning of the two divided parts of The Purgatory show variation. The first queue in Figure 5.20 h is formed along with a spare space in where a display has not been proposed. This can be appreciated as a design quality; an approach that references to the topological relation of disjoint. But, the other queue for the second part of The Purgatory in Figure 5.20 j covers the image imprinted on the separator wall behind which is facing the middle axis. Although it is on the most prestigious point of the space, it is not perceived in this density and loses its intended emphasis in design.

Figure 5.20 k represents two video frames of a dense and very dense time in order to express the negative effects of overcrowding. Especially in the third video frame, there is a cramped sense of space, where the clusters of people are standing in front of the exhibits. It seems very difficult for visitors to have a comfortable and efficient exhibition experience. Additionally we see the queue at the beginging of the “Dinner with Gala,” which blocks the circulation path at the adjacent side of the box in the middle axis. Also, we can easily say that in those densely populated times the perception of space and also the cognitive mapping deteriorate in a way not to be commended by designer and curator.

To a certain extent these results (both the predicted and the actual) do correspond to those that might be logically intuited for this particular space. In part, this is because the model has a fixed spatial function (viewing art in a controlled sequence) and only two complex variables, population density and spatial opportunity (where to stand or what paths to follow to allow the viewing of art). However, even with only a limited parameter set, the model not only predicts where overcrowding will occur for different population densities, but also where that overflow will spill. These factors add a critical functional dimension to the purely geometric ones present in the majority of spatial analysis approaches, which, by virtue of its foundation in fuzzy logic, is ideally suited to larger, open-planned and complex spaces.

Figure 5.20 : Visual data in higher population.

g

h

j

No.3 CCTV camera
(recording view of The Dinner with Gala)

Date: 12.02.2012 / Sunday
Times: from top to bottom
- 09:42:10 (before opening hour)
- 17:01:36
- 17:12:22

k

Figure 5.20 (continued) : Visual data in higher population.

5.4 Future Work on the Case Study

According to the findings about spatial usage of the Dali Exhibition in Tophane-i Amire main exhibition hall, the spatial arrangement and layout is efficient in a lower visitor density in terms of the fulfilment of function and the quality of display, but insufficient to adapt to higher densities. The occupancy behaviour and pattern of inhabitation pertaining to higher population levels could be foreseen (and potentially avoided) by modelling the FASOs and evaluating their topological relations. The disadvantages caused by the increased number of visitors 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. However, the model is basically intended to be used in the preliminary design process in order to minimize the problems during the occupation. Thus, alternative layouts could also be modelled and evaluated before the installation. As hypothetically, new spatial arrangements and display layouts could be devised, that would initially change the parameters such as VI. New proposals could be different patterns of subdivision (more cell-like or more free-plan) or different patterns of circulation (as a sequence which is more deterministic or as a network of connections which is more probabilistic).

Figure 5.21 shows some other possible installations of the Dali Exhibition. The a and b plans impose a linear path of itinerary that are more deterministic, also their designs depend on a cell-like partition in the total space. The spatial arrangement of c is a combination of cell-like and free-plan, where the visit would be less deterministic. The d plan presents a circular route for viewing where the three thematic layers are displayed in a semi-concentric pattern in the building. Even though it is not a very cell-like nor a deterministic system, the planning does not still provide an itinerary which is perceptually easy to follow by bloking the view from the entrance. The last alternatives e and f are the most free planned designs, also manifesting unsettled patterns of visit. Those six different layouts could be modelled and compared with the current installation of the Dali Exhibition as to whether any of them were a more promising option according to the evaluation criteria listed below:

- The fullfilment of function; the engagement with art objects (the aspect of accommodating high density better than existing design).
- The perception of space from an architectural point of view.
- The expression of collection from an artistic point of view.

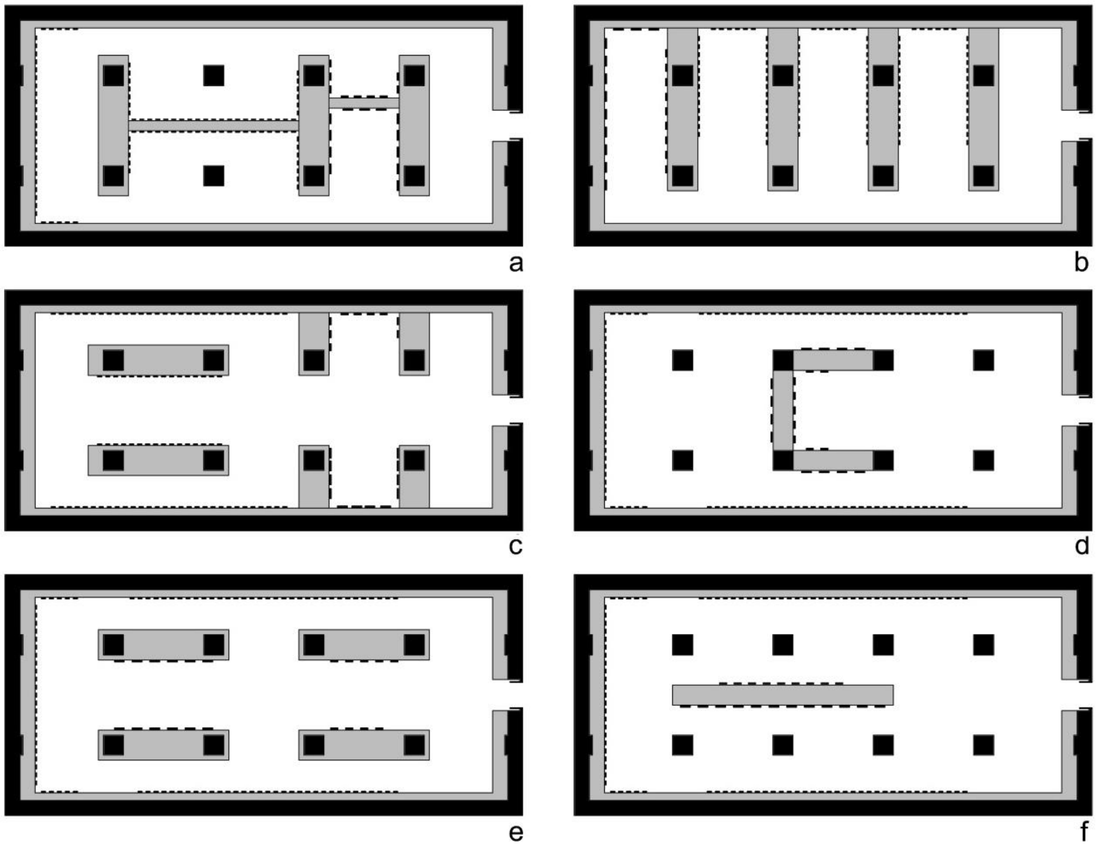


Figure 5.21 : Layout alternatives for the Dali Exhibition

So, the case study here together with the proposed alternative installations will allow us to see the flexibility of the exhibition hall particularly for the Dali Exhibition in different conditions by a change in the parameters which affect the spatial usage. Furthermore, we can make an extensive assessment of the flexibility of the exhibition hall, by not analysing a single exhibition but many exhibitions that have taken place, where each of them will define new parameters and rules. As Tophane-i Amire main exhibition hall is an open-plan total space, it is expected to be adaptable to change for different types of accommodations in terms of flexibility. The same analysis process of the Dali Exhibition with all its aspects can be applied to other temporary exhibitions in the hall –especially to those which will allow distinct spatial usages, e.g. a sculpture exhibition. By this, the architect or creator will decide which conditions are unfavourable in terms of space-function-user relation. These steps of future work are illustrated in Figure 5.22.

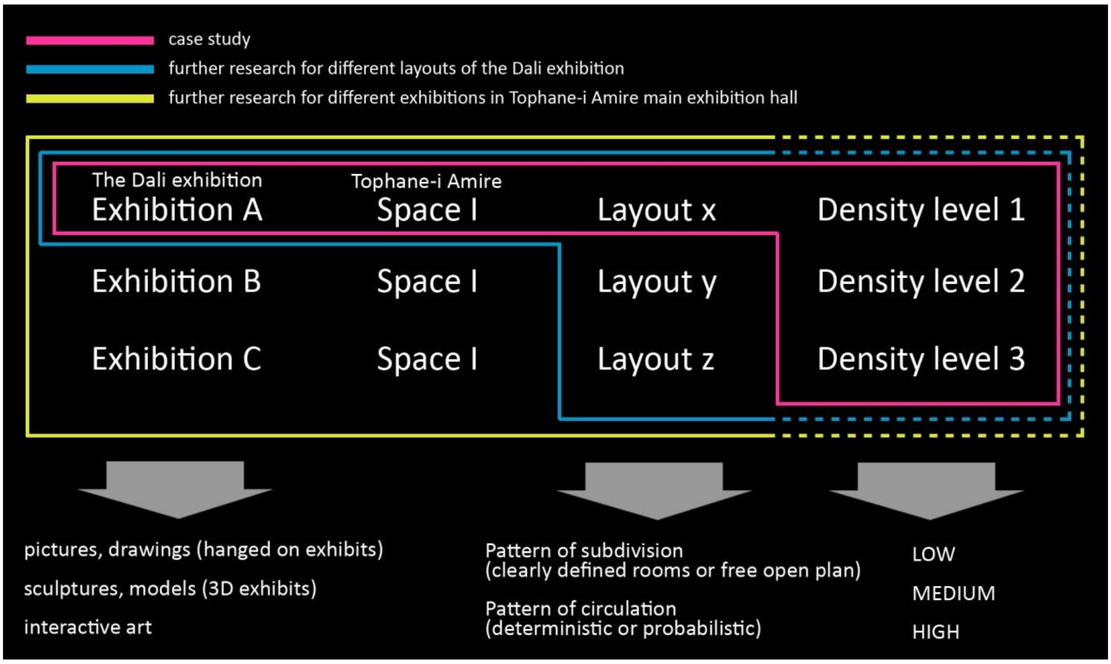


Figure 5.22 : Future work

In addition, we can analyse different exhibition spaces for a single exhibition –e.g. for the Dali Exhibition, which is a travelling exhibition located at different venues all around the world. While, the quantities related to the sub-functions such as VP and all the qualitative and quantitative parameters related to the function are constant, the syntactic features and proposed itinerary will change due to the different spatial arrangements and layouts for each case. It is clear that this difference in installation mainly depend on the distinct spatial configuration of each exhibition hall. And, this research will enable us to see the effect of architectural design on the certain function. The cases can be broadened towards a more comprehensive research which will provide general principles about exhibition spaces (typology) and displays, as a contribution to the relevant literature.

6. CONCLUSION

This final chapter first reviews the major findings of the study. Later, limitations of the model are discussed along with ideas and proposals for further research. The chapter and the whole thesis are finalized with the important contributions this work makes to professional practice, scientific research and relevant literature.

6.1 Results

This thesis introduced a computational model for analyzing patterns of usage, which is capable of dealing with uncertainty in ill-defined spaces. Firstly, the work gave a detailed discussion of the theoretical and methodological base of the proposed model. The basic arguments are highlighted here as follows:

- Uncertainty reflects a lack of sureness, clarity and precision.
- Uncertainty may arise from the unknown results of events, and from the ambiguity embedded in facts.
- Uncertainty exists in almost every real world problem, also in architecture; as in the designing process and as the objective of the design.
- The idea of indeterminacy is materialized in a building and space by offering flexibility and adaptability to change.
- The design of open-plans is an architectural response to uncertainty, where the total space could accommodate various arrangements, functions and populations.
- Since open-plans are not designed as spatially fixed but left free, predicting usage becomes difficult, needing special treatment to handle uncertainty.
- Among many techniques measuring uncertainty, fuzzy logic and sets theory is proposed as the most suitable method to be used in the model.
- Spatial uncertainty and prediction of usage are not related to frequency or randomness but to the inherent complexity and indeterminacy in occupational behaviour. Thus, fuzzy thinking is ideal for expressing this spatial identity and the patterns of usage.

- Fuzzy logic is based on the notion of partial or relative truth which fluctuates between completely true and completely false.
- Fuzziness is mathematically expressed by fuzzy sets, which do not put a sharp distinction between members and non-members; thereby containing elements that have varying degrees of membership.
- The fuzzy logic and sets capabilities can be exercised by using Fuzzy Inference System (FIS) in MATLAB software.
- The fuzzy approach can be used in many design problems related to uncertain boundaries.
- "Fuzzy Spatial Objects" (FSOs) are specifically suggested by geographers to solve the problems in defining the entities with imprecise or vague spatial attributes.

Based on these concepts, a computational model was developed to predict and simulate the patterns of spatial inhabitation in open planned spaces, where the configuration of space does not define strict patterns of usage.

Depending on the purpose of the research, the model measured the possibility distributions of spatial occupancy by using fuzzy inference system; a function of the features, objects and people within the space. This distribution was visualised as the accumulation of the "fuzzy architectural spatial objects" (FASOs); which represented the virtual sub-spaces of sub-functions, comprising of the zones: core, indeterminate boundary and exterior. The result of the model was a map of spatial usage pertaining to a specific spatio-temporal condition, which could be evaluated by interpreting the different sizes and shapes of the FASOs, also their topological relations.

As to the result, the model properly handled uncertainty by applying fuzzy thinking to spatial settings. To see the operation process and test the efficiency of the model, a case study was exercised which investigated the patterns of inhabitation during the Dali Exhibition in Tophane-i Amire exhibition hall. Within the contextual limits and logical relations of the probable usage, the model mapped the patterns of inhabitation during different visitor populations. In the end, a high degree of similarity was demonstrated between the model's prediction and observed behaviour. This case study can be regarded as a pilot implementation for future applications and outcomes of the model.

6.2 Restrictions and Further Research

Within the case study, proposals for future work were indicated which would examine different display layouts of the Dali Exhibition. Also, Tophane-i Amire exhibition hall as an open-plan was expressed as the subject of an architectural analysis which would evaluate the flexibility of the space for various other art installations.

Besides this example and in general terms for exhibitions and exhibition spaces like museums and art galleries, new applications are also possible for different functions and typologies. The model can be used to predict spatial usage in airport foyers and the concourses of train stations, where there is a constant flow of people throughout the day. Also, occupancy behaviour can be simulated on the ground floors, foyers and lobbies of big scale buildings such as high-rise offices, conference halls and hotels. For example, the entrance of a headquarters can be mapped by using the model. So, the inhabitation patterns, especially at peak times when working hours start and end will be acquired –like the clusters that form in front of elavators and information desks. However, it must be acknowledged that the proposed model is not effective for the analysis of divided cell-like spaces or fixed furnished settings (such as a prison or a theatre). So, the model cannot be applied for the spatial configuration where uncertainty is eliminated by strictly imposed usages of space.

In addition to applications in architectural scale and for open planned interior environments, the model can also be utilised for cases of urban studies, like the usage of public squares and parks by assigning relevant parameters and rules.

The model is further advanced as a layout planner in the preliminary design process by underlining the capacity of the FASOs as generative-syntactic components (Çekmiş, 2014b). Architectural plans presented as the scatter of the FASOs can be arranged for more feasible and rational design solutions. Thus, the model is developed towards a design decision tool to assist layout planning in uncertain and ill-defined spaces. 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 the idea that the FASOs are delimited by the walls of a building, the idea arises that the structural form can transform according to the designed FASOs. So a reverse process is initiated; from FASOs housed in open plans to kinetic and adaptable spaces and buildings shaped by the FASOs.

The thesis stresses the importance of future work towards the extension of this research and also the development of the FASO model. It is clear that the model needs a much larger set of examples to be tested before its flexibility can be determined. A more detailed correlation analysis will also need to be undertaken between prediction and behaviour to define the model's limits. Furthermore, some improvements in new versions of the model are required for managing a faster, computationally more practical and user-friendly system, especially in terms of the individual measurements of the input variables and their integration into the inference engine.

6.3 Contributions

The significance of the model is found in the way it deals with spatial uncertainty and the challenges in determining the inhabitation patterns in those ill-defined spaces. Accordingly, the model can predict occupancy behaviour by using a vague and limited data set. The prediction results from the cooperation of many different factors effecting human usage of space; like the morphological features, functional requirements and user related issues. Those all replicate the human subjective reasoning and decision making system; and consequently offer seemingly valuable simulations which overlap with the reality.

The model was designed to provide an analytical framework for architecture, as it is open to the addition of new rules and parameters as required. This flexible property allows the model to be capable of mapping a specific condition of spatial arrangement, function and user set, and remapping any change in usage. In this way it is possible to compare different predictive maps and to evaluate them for various altered conditions (e.g. different population densities).

The model is mainly appreciated as a design decision tool in the preliminary design stage, like the given layout planner example in the previous section. It can also be utilized at further stages of concept projects. By showing the prospective usage, the result predictions give immediate feedback and the opportunity of assessing various design criteria like flexibility and population capacity. So it is possible to make changes, also take the necessary precautions. At this level, the model will be helpful for designers and architects as well as students and educators. Additionally, by being able to operate in the very early stages of an idea, when the space is yet to be defined with clear-cut boundaries, the model allows the design process to retain creativity and productivity.

Besides, the model is still a proper tool after the project is built. At this time the model will be helpful for managers, operators, users and occupants. The predictions for future un/foreseen and un/expected spatio-temporal senarios during the life of the building will enable people to make pragmatic adjustments and arrangements such as re-designing the exits during an extreme evacuation.

On the other hand, the results of the model at any stage of design and occupation will provide appropriate data for a wide range of research in different disciplines and of various scopes; including performance assessments, feasibility studies, perception and cognition mapping, post occupancy evaluations and user satisfaction analyses.

In conclusion, the thesis is expected to have an important place in the literature and practice of architectural computing and simulation of spatial usage. While further evidence is needed, along with refinement of the model, to confirm its applications, it offers a rare way of approaching the analysis of uncertain spaces; a way to test the total space and whether it is adaptable to change by measuring its capacity under differing space, function and user related conditions.

REFERENCES

Alcalá, R., Alcalá-Fdez, J., Gacto, M. J., & Herrera, F. (2009). Improving fuzzy logic controllers obtained by experts: a case study in HVAC systems. *Applied Intelligence, 31*(1), 15-30.

Arabacıoğlu, B. C. (2010). Using fuzzy inference system for architectural space analysis. *Applied Soft Computing, 10*(3), 926-937.

Aydüz, S. (2009). *The Ottoman Royal Cannon Foundry: "Tophane-i Amire"*. Paper presented at the XXIII International Congress of History of Science and Technology, Budapest, Hungary.

Ayyub, B. M., & Klir, G. J. (2006). *Uncertainty Modeling and Analysis in Engineering and the Sciences*. USA: Chapman and Hall/CRC.

Batty, M. (2007). *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*. USA: The MIT Press.

Batty, M., Gray, S., Hudson-Smith, A., Milton, R., O'Brien, O., & Roumpani, F. (2013). *Visualising Spatial and Social Media*. CASA Working Papers Series, UCL (Paper 190). London.

Bayraktar, M. E., & Çağdaş, G. (2013). Fuzzy Layout Planner: A simple layout planning tool for early stages of design. In R. Stouffs, (Ed.), *Computation and Performance - Proceedings of the 31st eCAADe Conference*, (pp. 375-382). Delft, The Netherlands : Faculty of Architecture, Delft University of Technology, September 18-20.

Bhatia, S., Chalup, S. K., & Ostwald, M. J. (2012). *Analyzing architectural space: Identifying salient regions by computing 3d isovists*. Paper presented at the Building on Knowledge: Theory and Practice, 46th Annual Conference of the Australian and New Zealand Architectural Science Association, Southport, Queensland.

Bhavani, R. G., & Khan, M. A. (2009). An intelligent simulation model for blind position control in daylighting schemes in buildings. *Building Simulation, 2*(4), 253-262.

Bordogna, G., & Chiesa, S. (2003). A Fuzzy Object-Based Data Model for Imperfect Spatial Information Integrating Exact Objects and Fields. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 11*(1), 23-41.

Bordogna, G., Chiesa, S., & Geneletti, D. (2006). Linguistic modelling of imperfect spatial information as a basis for simplifying spatial analysis. *Information Sciences, 176*, 366-389.

Brubaker, W. C. (1998). *Planning and Designing Schools*. New York: McGraw-Hill.

Byrne, D. (1998). *Complexity Theory and the Social Sciences: An Introduction*. New York: Routledge.

Camerer, C., & Weber, M. (1992). Recent developments in modeling preferences: Uncertainty and ambiguity. *Journal of Risk and Uncertainty, 5*(4), 325-370.

Campari, I. (1996). Uncertain Boundaries in Urban Space. In P. A. Burrough & A. U. Frank (Eds.), *Geographic Objects with Indeterminate Boundaries* (pp. 57-71). London: Taylor&Francis.

Cao, Q., & Protzen, J.-P. (1999). Managing design information: Issue-Based Information Systems and Fuzzy Reasoning System. *Design Studies, 20*, 343-362.

Cardinall, D., & Day, J. C. (1998). Embracing value and uncertainty in environmental management and planning: a heuristic model. *Environments, 25*(2/3), 110-125.

Cassidy, D. C. (2009). *Beyond Uncertainty: Heisenberg, Quantum Physics, and the Bomb*. New York: Bellevue Literary Press.

Chaitin, G. J. (2007). *Thinking about Gödel and Turing Essays on Complexity 1970-2007*. Singapore: World Scientific.

Chan, A. P. C., Chan, D. W. M., & Yeung, J. F. Y. (2009). Overview of the Application of “Fuzzy Techniques” in Construction Management Research. *Journal of Construction Engineering and Management, 135*(11), 1241-1252.

Chao, R.-J., & Ayyub, B. M. (1998). Reliability Analysis with Fuzziness and Randomness. In B. M. Ayyub & M. M. Gupta (Eds.), *Uncertainty Analysis in Engineering and Sciences: Fuzzy Logic, Statistics* (pp. 69-80). USA: Kluwer.

Chapman, C., & Ward, S. (2011). *How to Manage Project Opportunity and Risk: Why Uncertainty Management Can be a Much Better Approach Than Risk Management*. UK: John Wiley & Sons.

Cheshire, J., & O’Brien, O. (2013). *Revealing and Informing Transport Behaviour from Bicycle Sharing Systems*. Paper presented at the GISRUK 2013, Liverpool.

Choi, Y. K. (1999). The morphology of exploration and encounter in museum layouts. *Environment and Planning B: Planning and Design, 26*(2), 241-250.

Cohen, J.-L. (1996). *Mies Van Der Rohe*. UK: Chapman&Hall.

Cook, P. (1999). *Archigram*. New York: Princeton.

Cornelissen, A. M. G., Berg, J. v. d., Koops, W. J., Grossman, M., & Udo, H. M. J. (2001). Assessment of the contribution of sustainability indicators to sustainable development: a novel approach using fuzzy set theory. *Agriculture, Ecosystems & Environment, 86*(2), 173-185.

Couclelis, H. (1996). Towards an Operational Typology of Geographic Entities with Ill-defined Boundaries. In P. A. Burrough & A. U. Frank (Eds.), *Geographic Objects with Indeterminate Boundaries* (pp. 45-57). London: Taylor&Francis.

Cupers, K., & Miessen, M. (2002). *Spaces of Uncertainty*. Germany: Verlag Müller + Busmann.

Çekmiş, A. (2012). A model to assess flexibility of uncertain spaces: a case for exhibitions. The Bartlett / Centre for Advanced Spatial Analysis Seminars. http://www.bartlett.ucl.ac.uk/casa/events/2012-09-28-asli-cekmis-gorgulu

Çekmiş, A. (2014a). Uncertain Boundaries and Fuzzy Sets Approach in Architecture. In N. Çatak & E. Duyan (Eds.), *Contemporary Discussions and Design Methodologies in Architecture - ARCHDESIGN'14 / Architectural Design Conference* (pp. 65-78). MSGSÜ, Istanbul, Turkey: DAKAM.

Çekmiş, A. (2014b). Fuzzy computing for layout design in ill-defined, uncertain spaces. In E. M. Thompson (Ed.), *Fusion - Proceedings of the 32nd eCAADe Conference* (Vol. 1, pp. 277-286). Newcastle upon Tyne, England, UK: Department of Architecture and Built Environment, Faculty of Engineering and Environment, September 10-12.

Çekmiş, A., & Hacıhasanoğlu, I. (2011). An Alternative Approach to Architectural Design Studio: A Conceptual Study. In C. D'Amato (Ed.), *Proceedings of the 1st International Congress of ReteVitruvio: Architectural Design between Teaching and Research* (Vol. 3, pp. 1557-1564). Bari, Italy: Politecnico di Bari, May 2-6.

Çekmiş, A., Hacıhasanoğlu, I., & Ostwald, M. J. (2014). A computational model for accommodating spatial uncertainty: Predicting inhabitation patterns in open-planned spaces. *Building and Environment, 73*, 115-126.

Çelikyılmaz, F. A. (2008). *Modeling Uncertainty with Evolutionary Improved "Fuzzy Functions".* (Doctoral), University of Toronto, Canada.

Dai, J., Li, X., & Liu, L. (2013). Simulation of pedestrian counter flow through bottlenecks by using an agent-based model. *Physica A, 392*(9), 2202-2211.

Degelman, L. O. (1999). A Model for Simulation of Daylighting and Occupancy Sensors as an Energy Control Strategy for Office Buildings. In N. Nakahara, H. Yoshida, M. Udagawa & J.L.M. Hensen (Eds.), *Proceedings of Building simulation '99 : sixth international IBPSA conference* (pp. 571-578). Kyoto, Japan: IBPSA, September 13-15.

Deshpande, N. P., & Gupta, R. (2010). Crowd management using fuzzy logic and G.I.S. In C. A. Brebbia (Ed.), *Risk Analysis VII and Brownfields V* (pp. 325-337). UK: WIT Press.

Dluhosch, E. J. (1973). *Flexibility/Variability in Prefabricated Housing.* (Doctoral), University of California, Berkeley, USA.

Dubois, D., Ostasiewicz, W., & Prade, H. (2000). Fuzzy Sets: History and Basic Notions. In D. Dubois & H. Prade (Eds.), *Fundamentals of Fuzzy Sets* (pp. 21-124) . USA: Kluwer.

Egenhofer, M., Clementini, E., & Felice, P. d. (1994). Topological Relations between Regions with Holes. *International Journal of Geographical Information Systems, 8*(2), 129-144.

Epstein, L. G. (1999). A Definition of Uncertainty Aversion. *Review of Economic Studies, 66*(3), 579-608.

Eralp, T. N. (1996). *Tophane-i Amire, XV. Yüzyıldan Günümüze Tarihi Oluşumu, İşlevleri ve İlk Restorasyon Çalışmaları*.

Erkaya, G. (2008). *From Scriptual to Spatial: "Labeling" As a Metaphor to Understand Museum Space.* (Masters), Middle East Technical University, Ankara.

Evans, R. (1997). *Translations from Drawing to Building and Other Essays*. London: Architectural Association.

Fang, Z., Li, Q., Li, Q., Han, L. D., & Wang, D. (2011). A proposed pedestrian waiting-time model for improving space-time use efficiency in stadium evacuation scenarios. *Building and Environment, 46*(9), 1774-1784.

Forty, A. (2000). *Words and Building: A Vocabulary of Modern Architecture*. London: Thames and Hudson.

Fujii, H., & Tanimoto, J. (2004). Integration of building simulation and agent simulation for exploration to environmentally symbiotic architecture. *Building and Environment, 39*(8), 885-893.

Gleick, J. (1987). *Chaos: Making a New Science*. New York: Penguin.

Glimcher, P. W. (2004). *Decisions, Uncertainty, and the Brain: The Science of Neuroeconomics*. USA: The MIT Press.

Gong, Y., & Mackett, R. (2011). Visualizing Children's Walking Behavior Using Portable Global Positioning (GPS) Units and Activity Monitors. In H. Lin & M. Batty (Eds.), *Virtual Geographic Environments* (pp. 295-311). Beijing: Science Press.

Granger, K. (2000). Hazards and Risk Concepts-Confidence, uncertainty and probability. In K. Granger & M. Hayne (Eds.), *Natural hazards and the risks they pose to South-East Queensland*. Australian Geological Survey Organisation in conjunction with Bureau of Meteorology.

Grinstead, C. M., & Snell, J. L. (1997). *Introduction to Probability*. USA: American Mathematical Society.

Güçlü, R., & Yazıcı, H. (2007). Fuzzy Logic Control of a Non-linear Structural System against Earthquake Induced Vibration. *Journal of Vibration and Control, 13*(11), 1535-1551.

Habib, F., & Shokoohi, A. (2009). Classification and resolving urban problems by means of fuzzy approach. *World Academy of Science, Engineering and Technology, 60*, 894-901.

Habraken, N. J. (1976). *Variations : the systematic design of supports*. USA: The MIT Press.

Hall, E. T. (1959). *The Silent Language*. New York: NY Anchor.

Hanselman, D. C., & Littlefield, B. R. (1997). *Mastering MATLAB 5: A Comprehensive Tutorial and Reference*. USA: Prentice Hall.

Harris, Y. (2002). *Architecture and Motion: Ideas on Fluidity in Sound, Image and Space.* Paper presented at the Proceedings of Symposium on Systems Research in the Arts, Baden, Germany.

Hernandez, D. (2013). The Cornell Journal of Architecture 9: Mathematics. Retrieved 1 Apr 2014, from <http://www.archdaily.com/?p=383534>

Hill, J. (2003). *Actions of Architecture: Architects and Creative Users*. London: Routledge.

Hillier, B., & Hanson, J. (1984). *The Social Logic of Space*. UK: Cambridge University Press.

Hines, J. W. (1997). *MATLAB Supplement to Fuzzy and Neural Approaches in Engieering*. USA: John Wiley&Sons.

Hughes, J. (2000). The indeterminate building. In J. Hughes & S. Sadler (Eds.), *Non-Plan: essays on fredom participation and change in modern architecture and urbanism* (pp. 90-103). USA: Massachusetts: Architectural Press.

Hunt, B. R., Lipsman, R. L., Rosenberg, J. M., Coombes, K. R., Osborn, J. E., & Stuck, G. J. (2010). *A Guide to MATLAB: For Beginners and Experienced Users*. UK: Cambridge University Press.

Iris, A. (2008). *On Un/Certainty as a Method in Architectural Digital Design.* (Masters), Technion Israel Institute of Technology, Israel

Jordaan, I. (2005). *Decisions under Uncertainty: Probabilistic Analysis for Engineering Decisions*. UK: Cambridge University Press.

Kaynar, I. (2009). *Museum gallery layouts and their interactions with exhibition narratives and space use patterns: An investigation of the YCBA, the MoMA and the HMA galleries.* (Doctoral), University of Michigan, Ann Arbor.

Kecman, V. (2001). *Learning and Soft Computing. Support Vector Machines, Neural Networks, and Fuzzy Logic Models*. Massachusetts: The MIT Press.

Klir, G. J., & Wierman, M. (1999). *Uncertainty-Based Information: Elements of Generalized Information Theory*. Germany: Physica-Verlag.

Klir, G. J., & Yuan, B. (1995). *Fuzzy Sets and Fuzzy Logic: Theory and Aplications*. New Jersey: Prentice Hall.

Knight, F. H. (2009). *Risk, Uncertainty and Profit*. USA: Signalman.

Kolokotsa, D. (2007). Artificial Intelligence in Buildings: A Review of the Application of Fuzzy Logic. *Advances in Building Energy Research, 1*(1), 29-54.

Koolhaas, R., & Mau, B. (1995). *S, M, L, XL*. USA: Monacelli Press.

Kosko, B. (1993). *Fuzzy Thinking: The New Science of Fuzzy Logic* New York: Hyperion.

Koutamanis, A. (2006). Building and Affordances. In J. S. Gero (Ed.), *Design Computing and Cognition '06* (pp. 345-364). The Netherlands: Springer.

Koutamanis, A. (2007). Fuzzy Modelling for Early Architectural Design. *International Journal of Architectural Computing (IJAC), 5*(4), 589-610.

Kronenburg, R. (2007). *Flexible: Architecture that Responds to Change* London: Laurence King Publishers.

Laplace, P. S. (1902). *A philosophical Essay on Probabilities*. London: John Wiley&Sons.

Lester, R. K., & Piore, M. J. (2004). *Innovation - The Missing Dimension*. USA: Harvard University Press.

Leung, Y. (1983). Fuzzy sets approach to spatial analysis and planning — a nontechnical evaluation. *Geografiska Annaler, 65B*(2), 65-75.

Li, D., & Du, Y. (2007). *Artificial Intelligence with Uncertainty*. USA: Chapman and Hall/CRC.

Lo, A. W., & Mueller, M. T. (2010). *WARNING: Physics Envy May Be Hazardous To Your Wealth!* Working Paper Series, MIT. USA.

Lootsma, F. A. (1997). *Fuzzy Logic for Planning and Decision Making*. The Netherlands: Kluwer.

Lovell, B. E. (1995). *A Taxonomy of Types of Uncertainty.* (Doctoral), Portland State University, USA.

Lu, X., Clements-Croome, D., & Viljanen, M. (2010). Integration of chaos theory and mathematical models in building simulation Part I: Literature review. *Automation in Construction*, *19*(4), 447-451.

Maccreanor, G. (1998). Adaptability. *A+T Magazine,* 40-45.

Maier, J. R. A., Fadel, G. M., & Battisto, D. G. (2009). An affordance-based approach to architectural theory, design, and practice. *Design Studies, 30*(4), 393-414.

Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies, 7*(1), 1-13.

Mandelbrot, B. B. (1983). *The Fractal Geometry Of Nature*. New York: W.H. Freeman.

Marusic, B. G. (2011). Analysis of patterns of spatial occupancy in urban open space using behaviour maps and GIS. *URBAN DESIGN International, 16*(1), 36-50.

MathWorks. (2013a). Fuzzy Logic Toolbox.

MathWorks. (2013b). Communications System Toolbox.

MathWorks. (2013c). MATLAB: Mathematics.

MathWorks. (2013d). MATLAB: Graphics.

Moharram, L. A. (1980). *A method for evaluating the flexibility of floor plans in multi-story housing.* (Doctoral), University of Pennsylvania, USA.

Moles, A. (2004). *Les sciences de l'imprécis* (N. Bilgin, Trans. E. Rohmer-Moles Ed.). İstanbul: Yapı Kredi Yayınları.

Molnár, D. H. a. P. (1995). Social force model for pedestrian dynamics. *Physical Review E, 51*(5), 4282-4286.

Monahan, T. (2002). Flexible Space & Built Pedagogy: Emerging IT Embodiments. *Inventio, 4*(1), 1-19.

Nguyen, H. T., & Walker, E. A. (2006). *A First Course in Fuzzy Logic*. USA: Chapman&Hall/CRC.

Novak, M. (1991). Liquid Architectures in Cyberspace. In M. Benedikt (Ed.), *Cyberspace: First Steps* (pp. 225-254). USA: The MIT Press.

Oberkampf, W. L., Helton, J. C., Joslyn, C. A., Wojtkiewicz, S. F., & Ferson, S. (2004). Challenge problems: uncertainty in system response given uncertain parameters. *Reliability Engineering & System Safety, 85*(1-3), 11-19.

Ostwald, M. J. (2011). The Mathematics of Spatial Configuration: Revisiting, Revising and Critiquing Justified Plan Graph Theory. *Nexus Network Journal, 13*(2), 445-470.

Özkar, M. (2004). *Uncertainties of Reason: Pragmatist Plurality In Basic Design Education.* (Doctoral), Massachusetts Institute of Technology, USA.

Palabıyık, S., & Çolakoğlu, B. (2012). Mimari Tasarım Sürecinde Son Ürünün Değerlendirilmesi: Bir Bulanık Karar Verme Modeli. *Megaron, 7*(3), 191-206.

Pawlak, Z. (1991). *Rough Sets: Theoretical Aspects of Reasoning about Data*. The Netherlands: Kluwer

Peat, F. D. (2002). *From Certainty to Uncertainty: The Story of Science and Ideas in the Twentieth Century*. Washington: Joseph Henry Press.

Penn, A. (2003). Space Syntax And Spatial Cognition : Or Why the Axial Line? *Environment and Behavior, 35*(1), 30-65.

Peponis, J., Dalton, R. C., Wineman, J., & Dalton, N. (2004). Measuring the effects of layout upon visitors' spatial behaviors in open plan exhibition settings. *Environment and Planning B: Planning and Design, 31*, 453-473.

Peponis, J., Wineman, J., Rashid, M., Kim, S. H., & Bafna, S. (1997). On the description of shape and spatial configuration inside buildings: three convex partitions and their local properties. *Environment and Planning B: Planning and Design, 24*, 761-781.

Phillips, S. J. (2008). *Elastic Architecture: Frederick Kiesler and His Resarch Practice - A Study of Continuity in the Age of Modern Production.* (Doctoral), Princeton University, USA.

Pipkin, J. S. (1978). Fuzzy Sets and Spatial Choice. *Annals of the Association of American Geographers, 68*(2), 196-204.

Polkinghorne, J. C. (1994). *Science and Christian Belief: Theological Reflections of a Bottom-up Thinker*. London: Sheldon Press.

Price, C. (2003). *The Square Book*. UK: Wiley-Academy.

Pullar, D., & Egenhofer, M. (1988). Toward Formal Definitions of Topological Relations Among Spatial Objects. In D. Marble (Ed.), *Proceedings of the 3rd International Symposium on Spatial Data Handling* (pp. 225-241). Sydney, Australia.

Rabeneck, A., Sheppard, D., & Town, P. (1974). Housing – Flexibility/Adaptability? *Architectural Design, 44*, 76-91.

Raol, J. R. (2010). *Multi-Sensor Data Fusion with MATLAB*. USA: CRC Press.

Rohloff, I. K., Psarra, S., & Wineman, J. (2009). Experiencing Museum Gallery Layouts through Local and Global Visibility Properties in Morphology: an inquiry on the YCBA, the MoMA and the HMA. In D. Koch, L. Marcus & J. Steen (Eds.), *Proceedings of the 7th International Space Syntax Symposium* (pp. 94:1-94:14). Stockholm: KTH.

Rojas, R. (1996). *Neural Networks: A Systematic Introduction*. Berlin: Springer.

Rolston, D. W. (1988). *Principles of Artificial Intelligence and Expert Systems Development*. New York: McGraw-Hill.

Rosenberg, D. (2009). *Designing For Uncertainty Novel Shapes and Behaviors using Scissor-pair Transformable Structures.* (Masters), Massachusetts Institute of Technology, USA.

Rosenman, M. A., & Gero, J. S. (1993). Creativity in design using a design prototype approach. In J. S. Gero & M. L. Maher (Eds.), *Modeling Creativity and Knowledge-Based Creative Design* (pp. 111-139). USA: Lawrence Erlbaum.

Rosenman, M. A., Gero, J. S., & Oxman, R. E. (1991). What’s in a case: the use of case bases, knowledge bases and databases in design. In G. N. Schmitt (Ed.), *CAAD Futures '91* (pp. 285-300). Zürich: ETH.

Rossi, A. (1999). Study the Works of Peter Eisenman? Why?! *Nexus Network Journal, 1*(1-2), 65-74.

Sadler, S. (2005). *Archigram Architecture Without Architecture*. USA: The MIT Press.

Sassen, S. (2010). Cityness. Roaming thoughts about making and experiencing cityness. *ex æquo, 22*, 13-18.

Schneider, M. (1999). Uncertainty Management for Spatial Data in Databases: Fuzzy Spatial Data Types. In Guting R. H., Papadias D. & Lochovsky F. (Eds.), *Advances in Spatial Databases: 6th International Symposium, SSD'99* (pp. 330-351). Hong Kong.

Schneider, T., & Till, J. (2007). *Flexible Housing*. UK: Architectural Press.

Schön, D. A. (1987). *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*. USA: Jossey-Bass.

Sennett, R. (2007). The open city. In R. Burdett & D. Sudjic (Eds.), *The endless city: The urban age project by the London School of Economics and Deutsche Bank's Alfred Herrhausen Society* (pp. 290-297). London: Phaidon.

Shafer, G. (1976). *A Mathematical Theory of Evidence.* New Jersey: Princeton University Press.

Shelhorn, T., O'Sullivan, D., Haklay, M., & Thurstain-Goodwin, M. (1999). *STREETS: an agent-based pedestrian model*. CASA Working Papers Series, UCL (Paper 9). London.

Shpuza, E., & Peponis, J. (2008). The effect of floorplate shape upon office layout integration. *Environment and Planning B: Planning and Design, 35*(2), 318-336.

Silver, N. (1994). *The Making of Beaubourg: A Building Biography of the Centre Pompidou, Paris*. Massachusetts: The MIT Press.

Singh, H. (2006). *Modeling and simulation of multi-agent systems for emergency scenarios.* (Doctoral), Wayne State University, USA.

Sivanandam, S. N., Sumathi, S., & Deepa, S. N. (2007). *Introduction to Fuzzy Logic using MATLAB*. Berlin: Springer-Verlag.

Skiena, S. (2001). *Calculated Bets: Computers, Gambling, and Mathematical Modeling to Win*. UK: Cambridge University Press.

Sözer, A. (2010). *Design and Implementation of Spatiotemporal Databases.* (Doctoral), Middle East Technical University, Ankara.

Sözer, A., Yazıcı, A., Oğuztüzün, H., & Taş, O. (2008). Modeling and querying fuzzy spatiotemporal databases. *Information Sciences, 178*(19), 3665-3682.

Stiny, G. (2008). *Shape: Talking about Seeing and Doing*. USA: The MIT Press.

Sugeno, M. (1985). *Industrial applications of fuzzy control*. UK: Elsevier Science.

Şark, O. (2012). Interview. In A. Çekmiş (Ed.).

Şen, Z. (2009). *Bulanık Mantık İlkeleri ve Modelleme (Mühendislik ve Sosyal Bilimler)*. İstanbul: Su Vakfı.

Şen, Z. (2010). Rapid visual earthquake hazard evaluation of existing buildings by fuzzy logic modeling. *Expert Systems with Applications, 37*(8), 5653-5660.

Tabak, V., & Vries, B. d. (2010). Methods for the prediction of intermediate activities by office occupants. *Building and Environment, 45*(6), 1366-1372.

Tah, J. H. M., & Carr, V. (2000). A proposal for construction project risk assessment using fuzzy logic. *Construction Management and Economics, 18*(4), 491-500.

Talašová, Z. (2012). Fuzzy approach to the analysis of architectural composition: As applied to villa design by Adolf Loos. In H. Achten, J. Pavlicek, J. Hulin & D. Matějovska (Eds.), *Digital Physicality: Proceedings of the 30th eCAADe Conference* (Vol. 1, pp. 425-432). Prague, Czech Republic: Czech Technical University in Prague, Faculty of Architecture, September 12-14.

Talley, D. N. (2008). *Methodology For The Conceptual Design Of A Robust And Opportunistic System-Of-Systems.* (Doctoral), Georgia Institute of Technology, USA.

Tan, Q., Huang, G. H., Wu, C., Cai, Y., & Yan, X. (2009). Development of an Inexact Fuzzy Robust Programming Model for Integrated Evacuation Management under Uncertainty. *Journal of Urban Planning and Development, 135*(1), 39-49.

Tang, X., Fang, Y., & Kainz, W. (2006). Fuzzy Topological Relations Between Fuzzy Spatial Objects. In L. Wang, L. Jiao, G. Shi, X. Lu & J. Liu (Eds.), *Fuzzy Systems and Knowledge Discovery: 3rd International Conference, FSKD 2006* (pp. 324-333). Xi'an, China.

Thill, J.-C., & Sui, D. Z. (1993). Mental Maps and Fuzziness in Space Preferences. *The Professional Geographer, 45*(3), 264-276.

Touw, K. (2006). *Firmitas re-visited: Permanence in Contemporary Architecture.* (Masters), University of Waterloo, Canada.

Tsoukalas, L. H., & Uhrig, R. E. (1997). *Fuzzy and Neural Approaches in Engineering*. USA: John Wiley&Sons.

Turner, A. (2001). Depthmap: A program to perform visibility graph analysis. In J. Peponis, J. Wineman & S. Bafna (Eds.), *Proceedings of the 3rd International Space Syntax Symposium* (pp. 31:1-31:9). Atlanta: A. Alfred Taubman College of Architecture and Urban Planning, University of Michigan.

Turner, A. (2003). Analysing the visual dynamics of spatial morphology. *Environment and Planning B: Planning and Design, 30*(5), 657-676.

Türkşen, I. B. (2006). *An Ontological and Epistemological Perspective of Fuzzy Set Theory*. The Netherlands: Elsevier.

Tzortzi, K. (2007). Museum Building Design and Exhibition Layout: Patterns of Interaction. In A. S. Kubat (Ed.), *Proceedings of the 6th International Space Syntax Symposium* (pp. 072:1-072:16). Istanbul: Istanbul Technical University.

Vakili-Ardebili, A., & Boussabaine, A. H. (2007). Application of fuzzy techniques to develop an assessment framework for building design eco-drivers. *Building and Environment, 42*(11), 3785-3800.

Wang, C., Yan, D., & Jiang, Y. (2011). A novel approach for building occupancy simulation. *Building Simulation, 4*(2), 149-167.

Wong, A. S. W., Chalup, S. K., Bhatia, S., Jalalian, A., Kulk, J., Nicklin, S., & Ostwald, M. J. (2012). Visual Gaze Analysis of Robotic Pedestrians Moving in Urban Space. *Architectural Science Review, 55*(3), 213-223.

Xiaoping, Z., Jiahui, S., & Yuan, C. (2010). Analysis of crowd jam in public buildings based on cusp-catastrophe theory. *Building and Environment, 45*(8), 1755-1761.

Yang, L. Z., Zhao, D. L., Li, J., & Fang, T. Y. (2005). Simulation of the kin behavior in building occupant evacuation based on Cellular Automaton. *Building and Environment, 40*(3), 411-415.

Yao, Y. Y. (1998). A Comparative Study of Fuzzy Sets and Rough Sets. *Information Sciences, 109*(1-4), 227-242.

Zadeh, L. A. (1975). Fuzzy logic and approximate reasoning. *Synthese, 30*(3-4), 407-428.

Zadeh, L. A. (1978). Fuzzy sets as a basis for a theory of possibility. *Fuzzy Sets and Systems, 1*(1), 3-28.

Zadeh, L. A. (1979). A theory of approximate reasoning. In J. Hayes, D. Michie & L.I. Mikulich (Eds.), *Machine Intelligence* (Vol. 9, pp. 149-194). New York: Halstead Press.

Zadeh, L. A. (1996). Fuzzy Logic = Computing with Words. *IEEE Transactions on Fuzzy Systems, 4*(2), 103-111.

Zadeh, L. A. (1997). Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic. *Fuzzy Sets and Systems, 90*(2), 111-127.

Zadeh, L. A. (1998). Foreword. In E. Orlowska (Ed.), *Incomplete Information: Rough Set Analysis (Studies in Fuzziness and Soft Computing)* (pp. v-ix). Germany: Physica-Verlag.

Zadeh, L. A. (2008). Is there a need for fuzzy logic? *Information Sciences, 178,* 2751-2779.

Zhan, F. B., & Lin, H. (2003). Overlay of Two Simple Polygons with Indeterminate Boundaries. *Transactions in GIS, 7*(1), 67-81.

Zhang, J., & Goodchild, M. F. (2002). *Uncertainty in Geographical Information*. UK: Taylor&Francis.

Zhu, B., Liu, T., & Tang, Y. (2008). *Research on pedestrian evacuation simulation based on fuzzy logic.* Paper presented at the 9th International Conference on Computer-Aided Industrial Design and Conceptual Design (CAID/CD 2008). Kunming, China.

Zimmermann, H.-J. (2001). *Fuzzy Set Theory -and Its Applications*. USA: Kluwer.

Zuk, W., & Clark, R. (1970). *Kinetic Architecture*. New York: Van Nostrand Reinhold.

APPENDICES

APPENDIX A: The rules

APPENDIX B: 30 video frames used for validation

APPENDIX A: The rules

1. If (dVP is in) and (VI is min) and (D is d1) then (mem.degree is mf9) (1)
2. If (dVP is in) and (VI is min) and (D is d2) then (mem.degree is mf9) (1)
3. If (dVP is in) and (VI is average) and (D is d1) then (mem.degree is mf9) (1)
4. If (dVP is in) and (VI is average) and (D is d2) then (mem.degree is mf9) (1)
5. If (dVP is in) and (VI is max) and (D is d1) then (mem.degree is mf9) (1)
6. If (dVP is in) and (VI is max) and (D is d2) then (mem.degree is mf9) (1)
7. If (dVP is near) and (VI is min) and (D is d1) then (mem.degree is mf5) (1)
8. If (dVP is near) and (VI is min) and (D is d2) then (mem.degree is mf6) (1)
9. If (dVP is near) and (VI is average) and (D is d1) then (mem.degree is mf6) (1)
10. If (dVP is near) and (VI is average) and (D is d2) then (mem.degree is mf7) (1)
11. If (dVP is near) and (VI is max) and (D is d1) then (mem.degree is mf7) (1)
12. If (dVP is near) and (VI is max) and (D is d2) then (mem.degree is mf8) (1)
13. If (dVP is far) and (VI is min) and (D is d1) then (mem.degree is mf1) (1)
14. If (dVP is far) and (VI is min) and (D is d2) then (mem.degree is mf2) (1)
15. If (dVP is far) and (VI is average) and (D is d1) then (mem.degree is mf2) (1)
16. If (dVP is far) and (VI is average) and (D is d2) then (mem.degree is mf3) (1)
17. If (dVP is far) and (VI is max) and (D is d1) then (mem.degree is mf3) (1)
18. If (dVP is far) and (VI is max) and (D is d2) then (mem.degree is mf4) (1)
19. If (dVP is in) and (VI is min) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
20. If (dVP is in) and (VI is min) and (D is d3) and (dOLP is near) then (mem.degree is mf9) (1)
21. If (dVP is in) and (VI is min) and (D is d3) and (dOLP is far) then (mem.degree is mf9) (1)
22. If (dVP is in) and (VI is average) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
23. If (dVP is in) and (VI is average) and (D is d3) and (dOLP is near) then (mem.degree is mf9) (1)
24. If (dVP is in) and (VI is average) and (D is d3) and (dOLP is far) then (mem.degree is mf9) (1)
25. If (dVP is in) and (VI is max) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
26. If (dVP is in) and (VI is max) and (D is d3) and (dOLP is near) then (mem.degree is mf9) (1)
27. If (dVP is in) and (VI is max) and (D is d3) and (dOLP is far) then (mem.degree is mf9) (1)

28. If (dVP is near) and (VI is min) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
29. If (dVP is near) and (VI is min) and (D is d3) and (dOLP is near) then (mem.degree is mf7) (1)
30. If (dVP is near) and (VI is min) and (D is d3) and (dOLP is far) then (mem.degree is mf7) (1)
31. If (dVP is near) and (VI is average) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
32. If (dVP is near) and (VI is average) and (D is d3) and (dOLP is near) then (mem.degree is mf8) (1)
33. If (dVP is near) and (VI is average) and (D is d3) and (dOLP is far) then (mem.degree is mf8) (1)
34. If (dVP is near) and (VI is max) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
35. If (dVP is near) and (VI is max) and (D is d3) and (dOLP is near) then (mem.degree is mf9) (1)
36. If (dVP is near) and (VI is max) and (D is d3) and (dOLP is far) then (mem.degree is mf9) (1)
37. If (dVP is far) and (VI is min) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
38. If (dVP is far) and (VI is min) and (D is d3) and (dOLP is near) then (mem.degree is mf7) (1)
39. If (dVP is far) and (VI is min) and (D is d3) and (dOLP is far) then (mem.degree is mf3) (1)
40. If (dVP is far) and (VI is average) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
41. If (dVP is far) and (VI is average) and (D is d3) and (dOLP is near) then (mem.degree is mf8) (1)
42. If (dVP is far) and (VI is average) and (D is d3) and (dOLP is far) then (mem.degree is mf4) (1)
43. If (dVP is far) and (VI is max) and (D is d3) and (dOLP is in) then (mem.degree is mf9) (1)
44. If (dVP is far) and (VI is max) and (D is d3) and (dOLP is near) then (mem.degree is mf9) (1)
45. If (dVP is far) and (VI is max) and (D is d3) and (dOLP is far) then (mem.degree is mf5) (1)

APPENDIX B: 30 video frames used for validation

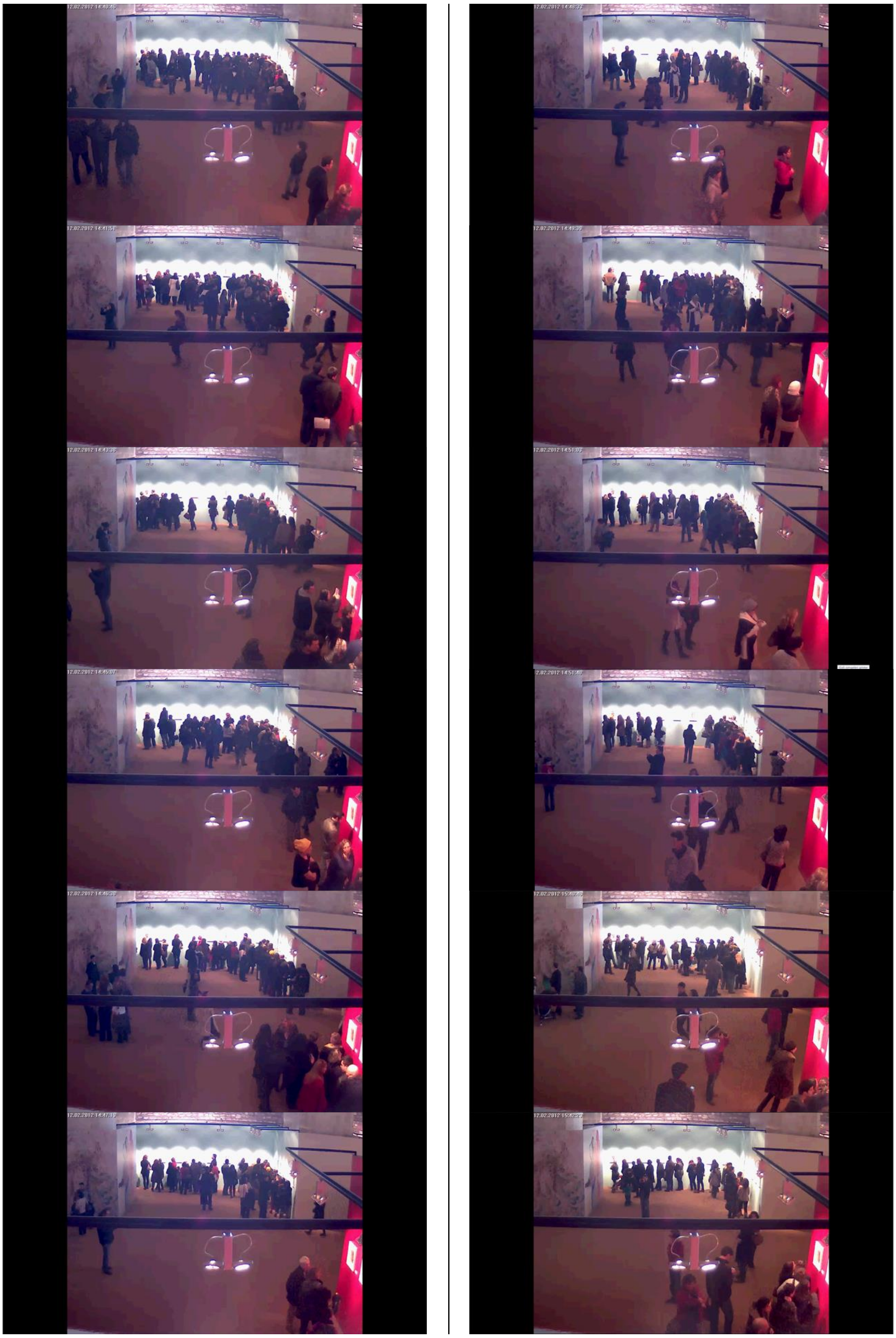


Figure A.1 : 30 frames (11.02.2012; 14:40:38 – 15:40:38)

Figure A.1 (continued) : 30 frames (11.02.2012; 14:40:38 – 15:40:38)

Figure A.1 (continued) : 30 frames (11.02.2012; 14:40:38 – 15:40:38)

CURRICULUM VITAE

Name Surname: Aslı ÇEKMİŞ

Place and Date of Birth: İstanbul, 14/09/1983

Address: ITU, Faculty of Architecture, Department of Architecture

E-Mail: cekmis@itu.edu.tr

Website: http://akademi.itu.edu.tr/cekmis/

B.Sc.: ITU, Architecture

M.Sc.: ITU, Architectural Design

Professional Experience: (2006 -) Research and Teaching Assistant at ITU

PUBLICATIONS/PRESENTATIONS ON THE THESIS

- **Çekmiş, A., Hacıhasanoğlu, I., & Ostwald, M. J.** (2014). A computational model for accommodating spatial uncertainty: Predicting inhabitation patterns in open-planned spaces. *Building and Environment, 73*, 115-126.
- **Çekmiş, A.** (2014). Fuzzy computing for layout design in ill-defined, uncertain spaces. In E. M. Thompson (Ed.), *Fusion - Proceedings of the 32nd eCAADe Conference* (Vol. 1, pp. 277-286). Newcastle upon Tyne, England, UK: Department of Architecture and Built Environment, Faculty of Engineering and Environment, September 10-12.
- **Çekmiş, A.** (2014). Uncertain Boundaries and Fuzzy Sets Approach in Architecture. In N. Çatak & E. Duyan (Eds.), *Contemporary Discussions and Design Methodologies in Architecture - ARCHDESIGN'14 / Architectural Design Conference* (pp. 65-78). MSGSÜ, Istanbul, Turkey: DAKAM.
- **Çekmiş, A.** (2012). A model to assess flexibility of uncertain spaces: a case for exhibitions. The Bartlett / Centre for Advanced Spatial Analysis Seminars. http://www.bartlett.ucl.ac.uk/casa/events/2012-09-28-asli-cekmis-gorgulu