

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**DEVELOPMENT OF A FIRE FOLLOWING EARTHQUAKE FUNCTION FOR
HAZTURK SOFTWARE**

Ph.D. THESIS

Selim Serhan YILDIZ

Department of Geomatics Engineering

Geomatics Engineering Programme

Thesis Advisor: Assist. Prof. Dr. Himmet KARAMAN

FEBRUARY 2013

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**HAZTURK YAZILIMI İÇİN BİR DEPREM SONRASI YANGIN FONKSİYONU
GELİŞTİRİLMESİ**

DOKTORA TEZİ

**Selim Serhan YILDIZ
(501082601)**

Geomatik Mühendisliği Anabilim Dalı

Geomatik Mühendisliği Programı

Tez Danışmanı: Yrd. Doç. Dr. Himmet KARAMAN

ŞUBAT 2013

Selim Serhan YILDIZ, a Ph.D. student of ITU Graduate School of Science, Engineering and Technology student ID 501082601, successfully defended the dissertation entitled “DEVELOPMENT OF A FIRE FOLLOWING EARTHQUAKE FUNCTION FOR HAZTURK SOFTWARE”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assist. Prof. Dr. Himmet KARAMAN**
Istanbul Technical University

Jury Members : **Prof. Dr. Muhammed ŞAHİN**
Istanbul Technical University

Prof. Dr. Turgut UZEL
Istanbul Kültür University

Prof. Dr. Derin URAL
Istanbul Technical University

Prof. Dr. Fatmagül KILIÇ
Yıldız Technical University

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To my spouse and daughter,

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(Geomatics Engineer)

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ABBREVIATIONS

ASCII	: American Standard Code for Information Interchange
AWSS	: Auxiliary Water Supply System
CBECS	: Commercial Buildings Energy Consumption Survey
CRM	: Consequence-based Risk Management
CSV	: Comma Separated Value
EBMUD	: East Bay Municipal Utility District
EPA	: Environmental Protection Agency
EPANET	: EPA's Water Distribution Modeling Software
ESRI	: Environmental Systems Research Institute
IBC	: International Building Code
FFE	: Fire Following Earthquake
FFNRE	: Fire Following the NorthRidge Earthquake
GIS	: Geographical Information System
HAZUS	: Hazards U.S.
HAZTURK	: Hazards Turkey
HRR	: Heat Release Rate
LAFD	: Los Angeles Fire Department
MAE	: Mid-America Earthquake
MAEViz	: Mid-America Earthquake Visualization
MMI	: Modified Mercalli Intensity
MMSF	: 1000000 square feet of building floor area
MTB	: Memphis Test Bed
M_w	: Moment Magnitude
MWSS	: Municipality Water Supply System
NCSA	: National Center for Supercomputing Applications
NMSZ	: New Madrid Seismic Zone
PGA	: Peak Ground Acceleration
PGV	: Peak Ground Velocity
PWSS	: Portable Water Supply System
RECS	: Residential Energy Consumption Survey
S_a	: Spectral Acceleration
SERA	: System Earthquake Risk Assessment
SFED	: Single Family Equivalent Dwelling
SMFD	: Santa Monica Fire Department
TOSHO	: Fire Spread Model of Tokyo Fire Department
URAMP	: Utilities Regional Assessment of Mitigation Priorities
USEIA	: United States Energy Information Administration
USGS	: United States Geological Survey
WGS84	: World Geodetic System 1984
WSR	: Water Supply Reliability
XML	: Extensible Markup Language

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DEVELOPMENT OF A FIRE FOLLOWING EARTHQUAKE FUNCTION FOR HAZTURK SOFTWARE

SUMMARY

Fire following earthquakes (FFE) can cause severe losses. These losses can sometimes outweigh the total losses from the direct damage caused by the earthquake, such as collapse of buildings and disruption of lifelines. Many factors affect the severity of the fires following an earthquake. These effects are ignition sources, types and density of fuel, weather conditions, functionality of water systems, and the ability of fire fighters to suppress the fires (HAZUS, 1999).

Post-earthquake urban fires are generally caused by strong ground shakings. Strong shakings damage the structures and infrastructures. As a consequence of earthquake, many ignitions can occur due to gas systems, electrical systems, overturning of electrical appliances, heating equipments or flammable materials in structures. In addition to interior structure ignitions, damaged infrastructure elements such as gas mains and pipelines and damaged electric transmission lines can also cause ignitions. Some of these ignitions are put out by occupants and they don't induce much more damages. Some of them spread due to amount of fuel load (combustible materials), construction material, direction and speed of wind etc. in environment and they can turn into large urban conflagrations.

Furthermore, fire-fighting activities are also a significant factor, which directly affects the spread of fire. The more fire department's response is delayed, the more fire spreads. Fire departments usually have difficulties about reaching fireplace and respond to fire due to narrow streets, closed roads because of collapsed buildings, damages to fire stations and injuries in fire fighters etc.

In fire fighting facilities, fire fighters need high-pressure water and chemical materials to extinguish the fire. Strong earthquakes damage water main and pipelines. Water systems generally sustain many breaks and these breaks results in decreasing in water pressure that complicates the fire response.

Strong earthquakes also damage the communication systems in affected area. Communication systems have an important role in fire reponse. Dispatching fire fighters to different fires from a central fire department prevents fire fighters to respond the same fire and provides time saving.

The most common FFEs are caused by restoration of electricity in red-tagged buildings that are unsafe and nobody is not allowed to enter inside. If there is a gas leakage in building, it will be ignited by restoration of electricity.

There were many earthquakes resulted in FFEs that caused significant damages in history such as the 1906 San Francisco, the 1923 Kanto (Tokyo), 1931 Napier, 1948 Fukui, 1964 Niigata, 1968 Tokachi-oki, 1978 Miyagiken-oki, 1983 Nihonkai-chubu,

1989 Loma Prieta, 1993 Hokkaido Nansei-oki, 1994 Northridge, 1995 Hyogo-ken Nambu (Kobe), 1999 Marmara, 2003 Tokachi-oki and 2011 Tohoku earthquakes.

The 1906 San Francisco and the 1923 Kanto Earthquakes were the biggest ones of them because they both resulted in large urban conflagrations. Most of the fires following the 1906 San Francisco earthquake occurred due to several ruptures in gas mains and pipelines. Scawthorn et al. (2006) state that, post-earthquake ignitions returned to large urban conflagrations because of highly flammable construction, inadequate fire protection and inadequate water supply in the 1906 San Francisco earthquake. In the 1923 Kanto earthquake, 277 fires occurred because of small charcoal braziers, which were widely used for cooking in lunchtime (Scawthorn et al., 2005). According to Kobayashi (1984), 37 fires caused by kitchen range, 15 fires caused by clay charcoal cooking stoves, 8 fires caused by braziers, 9 fires caused by gas failure, 1 fire caused by candle, 1 fire caused by electricity problems and 17 fires caused by chemicals following the 1923 Kanto Earthquake. In the 1999 Marmara earthquake, at least 17 tanks were reported as burned totally and a 90-meter high reinforced concrete heater stack collapsed in fire. In the 2011 Tohoku (Japan) Earthquake, 385 fires were reported. 357 of these fires directly occurred after the mainshock and 28 of them occurred following the aftershocks.

Many scientists made researches to estimate the number of post-earthquake intra-structure ignitions and they developed different models. Most of these models depend on ground motions. There were some researches about multi-parameter ignition model in the last couple of years.

In this study, a GIS-based model was developed to calculate the post-earthquake ignition probability of a building considering damaged building interior gas and electrical distribution system and overturning of appliances. Developed model was implemented to HAZTURK (MAEViz) earthquake loss assessment software developed by Mid-America Earthquake Center with the help of Istanbul Technical University. Existing post-earthquake spread models are also explained and methodology of a physical spread model is suggested. This model includes development of fire in a building and fire spread between buildings.

The post-earthquake ignition model consists of three main components named (a) utility systems, (b) hazardous appliances and contents and (c) less hazardous appliances and contents containing the different sources of post-earthquake ignitions. Ignitions caused by damage to utility systems include damage to interior gas and electrical distribution systems. Ignition probability caused by damaged utility system is calculated due to building damage from a specific ground motion. For hazardous and less hazardous appliances and contents, ignitions are caused by overturning of the appliances and falling of flammable materials from shelves according to exposed acceleration. Overturned appliances and fallen contents including flammable material and appliances with live electricity current or bare flames can produce ignitions. Overturning probabilities of appliances can be estimated by modeling the motion of appliance due to acceleration.

Assuming all the appliances and contents are existed in all occupancy types of buildings is not a realistic approach. In order to make our model more reliable and realistic, a weighting factor is used to define the chance of existence of each appliance or content in the given occupancy.

A questionnaire was prepared to weight the components of post-earthquake ignitions using Analytical Hierarchy Process (AHP). Seven scientists having experiences

about earthquake engineering and post earthquake fires evaluated questionnaire. Results were evaluated to calculate weights (significance) of all main components and subcomponents.

Past earthquake records are important for this study to determine the location of ignited buildings. In order to determine the number and location of ignited buildings from ignition probabilities of buildings, producing a threshold ignition probability is required. PGA values, number of storeys, occupancy type, building age and structure type are necessary to obtain ignition probabilities of ignited buildings in past earthquakes. Ignition records of the 1994 Northridge Earthquake were derived from the report prepared by Scawthorn, Cowell and Borden .

According to ignition probabilities of burned buildings in the 1994 Northridge Earthquake, average threshold values and their standard deviations for different MAEViz structure types were calculated. Because of limited historical earthquake data, it was decided to determine three different thresholds for each structure type. Lower bound of threshold was calculated by subtracting one standard deviation from average threshold value and upper bound of threshold was calculated by adding one standard deviation to average threshold value.

In order to make use of the developed post-earthquake ignition model effective, model was implemented to HAZTURK, which is a free and open source software. HAZTURK was developed by modifying the MAEViz software in accordance with Turkish data structure. HAZTURK was developed with java coding language. So, code of the developed ignition model was written by using Eclipse platform for Java. Specialists from Natural Center for Supercomputing Applications (NCSA) edited this code to make it compatible with HAZTURK source code. Then, edited code was implemented into HAZTURK as a plug-in.

Developed post-earthquake ignition tool was applied to Memphis, Tennessee in the United States and Küçükçekmece, Istanbul in Turkey. Number and location of probable ignited buildings were obtained both for lower bound, average and upper bound thresholds.

Results were evaluated according to structure types, occupancy types, number of storeys, building code and districts. Evaluated results support that post-earthquake ignition probability is inversely proportional to the number of storeys and construction year depending on the building code. Results of analyses for both two cities show that wooden buildings are so vulnerable to both ignition and spread.

HAZTURK YAZILIMI İÇİN BİR DEPREM SONRASI YANGIN FONKSİYONU GELİŞTİRİLMESİ

ÖZET

Deprem sonrası yangınlar çok büyük kayıplara yol açabilmektedir. Bu kayıplar zaman zaman bir binanın yıkılması ya da altyapı sistemlerinin parçalanması gibi doğrudan depreme bağlı olarak gerçekleşen kayıpları aşabilmektedir. Deprem sebebiyle oluşan bir yangının şiddetini etkileyen birçok etken vardır. Bu etkenlere örnek olarak tutuşma kaynakları, yakıt tipi ve yoğunluğu, hava koşulları, su sistemlerinin işlevselliği ve itfaiye görevlilerinin yangını bastırma kabiliyetleri verilebilir (HAZUS, 1999).

Deprem sonrası yangınlar genellikle kuvvetli yer sarsıntılarında kaynaklanırlar. Kuvvetli sarsıntılar üst yapılara ve altyapıları hasara uğrattırır. Gerçekleşen bir deprem sonucunda binalardaki doğalgaz ve elektrik sistemlerinin hasar görmesi ve elektrikli cihazların, ısıtma ekipmanlarının ve yanıcı madde içeren saklama donanımlarının devrilmesine bağlı olarak bir çok tutuşma çıkabilmektedir. Bina içi tutuşmaların yanında, hasara uğramış ana doğalgaz hatları ve kolları ve elektrik iletim hatları gibi bileşenler de tutuşmalara yol açabilmektedir. Bu tutuşmaların bir kısmı bölgede yaşayan halk tarafından söndürülebilmektedir ve bu tutuşmalar çok fazla hasara sebep olmamaktadır. Dolayısıyla bu tür tutuşmalar literatürde deprem sonrası yangınlar olarak değerlendirilmemektedir. Bunların dışında kalan tutuşmaların bir kısmı ise yakıt yükünün miktarına, inşaat malzemesine, rüzgarın yön ve hızına bağlı olarak yayılabilmekte ve büyük kentsel yangınlara dönüşebilmektedir.

Ayrıca, yangın söndürme çalışmaları da yangının yayılımını doğrudan etkileyen çok önemli bir etkindir. İtfaiye ekibinin yangına müdahalesi ne kadar gecikirse yangın o kadar yayılmaktadır. İtfaiye ekipleri olası bir depremden sonra dar sokaklar, binaların çökmesi sebebiyle kapanan yollar, itfaiye istasyonlarının hasar görmesi ve itfaiye personellerinin yaralanması gibi aksaklıklardan dolayı yangın yerine ulaşım ve müdahalede zorluklarla karşılaşmaktadır.

İtfaiye ekipleri yangın söndürme faaliyetlerinde yangını kontrol altına alabilmek için yüksek basınçlı suya ve kimyasal maddelere ihtiyaç duymaktadır. Şiddetli depremler şehirlerdeki ana su hatlarına ve onların bağlantı hatlarına hasar vermektedir. Su sistemleri genellikle bir çok yırtılma ve kırılmaya uğramakta ve bu kırılma ve yırtılmalar su basıncını yangın söndürme faaliyetlerini önemli ölçüde aksatacak kadar azaltmaktadır.

Şiddetli depremler etkili olduğu bölgelerdeki iletişim sistemlerini de önemli ölçüde olumsuz olarak etkilemektedir. İletişim sistemlerinin acil durumlardaki önemi küçümsenemeyecek kadar fazladır. Muhtemel bir depremden sonra yangın çıkması halinde itfaiye ekiplerinin tek bir merkezden yangın çıkan adreslere yönlendirilmesi

gereğinden fazla personel ve araç gerecin aynı yangına yönelmelerini engeller ve zaman kaybına da engel olarak etkili bir müdahale gerçekleşmesini sağlar.

Deprem sonrası yangınlar sıklıkla kırmızı etiketli binalar olarak geçen, güvensiz ve kimsenin içerisine girmesine izin verilmediği, binalarda kesilmiş olan elektriğin yeniden aktif hale gelmesinden ortaya çıkmaktadır. Eğer bu binalarda gaz sızıntısı varsa, bu sızıntı yeniden aktif hale gelen elektrik vesilesiyle tutuşabilir.

Tarihte önemli kayıplara neden olmuş deprem sonrası yangınların gerçekleştiği bir çok deprem bulunmaktadır. Bu depremler sırasıyla 1906 San Francisco (Amerika Birleşik Devletleri), 1923 Kanto (Tokyo-Japonya), 1931 Napier (Yeni Zelanda), 1948 Fukui (Japonya), 1964 Niigata (Japonya), 1968 Tokachi-oki (Japonya), 1978 Miyagiken-oki (Japonya), 1993 Hokkaido Nansei-oki (Japonya), 1994 Northridge (Amerika Birleşik Devletleri), 1995 Hyogo-ken Nambu (Kobe-Japonya), 1999 Marmara, 2003 Tokachi-oki (Japonya) ve 2011 Tohoku (Japonya) depremleridir.

1906 San Francisco ve 1923 Kanto depremleri dünya tarihinde yangınlarla sonuçlanmış olan en büyük depremlerdendir. İki depremde çok büyük kentsel yangınlar yüzünden büyük kayıplara uğramışlardır. 1906 San Francisco depreminden sonra çıkan yangınların çoğu doğalgaz ana hatları ve kollarında gerçekleşen çok sayıda yırtılmadan dolayı gerçekleşmiştir. Scawthorn ve diğ. (2006), 1906 San Francisco depreminden sonra oluşan tutuşmaların yüksek derecede yanıcı yapılar, yetersiz yangın güvenliği ve yetersiz su kaynakları yüzünden geniş çaplı kentsel yangınlara dönüştüğünü belirtmişlerdir. 1923 Kanto depreminde, öğle yemeği saatlerinde yemek pişirmek için yaygın olarak kullanılan küçük kömürlü ızgaralardan kaynaklanan 277 adet yangın çıkmıştır (Scawthorn et al., 2005). Kobayashi (1984)'ye göre 1923 Kanto depreminden sonra mutfak ocaklarından kaynaklanan 37, kilden imal edilmiş kömür ile çalışan ocaklardan kaynaklanan 15, mangallardan kaynaklanan 8, doğalgaz arızalarından kaynaklanan 9, mumlardan kaynaklanan 1, elektrik problemlerinden kaynaklanan 1 ve kimyasallardan kaynaklanan 17 adet yangın çıkmıştır. 1999 Marmara depreminde, en az 17 adet tank tamamıyla yanmış ve 90 metre yüksekliğe sahip güçlendirilmiş betonarme ısıtma bacası yangın sebebiyle yıkılmıştır. Günümüzde sonrasında yangınlara neden olmuş olan en son deprem 2011 Tohoku depremidir. Bu deprem sonrasında 385 adet yangın ortaya çıkmıştır. Bu yangınların 357'si doğrudan ana sarsıntıdan hemen sonra gerçekleşmiş, geri kalan 28 yangın ise artçı şoklardan sonra ortaya çıkmıştır.

Bugüne kadar birçok bilim insanı deprem sonrasında binalarda çıkacak olan tutuşma sayılarını belirleyebilmek için çalışmalar yapmışlardır. Bu çalışmalar sonucunda çok sayıda farklı model geliştirilmiştir. Bu modellerin bir çoğu maksimum yer ivmesi, depremin şiddeti ve yıkılmış olan bina sayısı gibi parametrelerden birini kullanarak tutuşma sayısını hesaplamaktadır. Son yıllarda bazı araştırmacılar çok parametrelili tutuşma modelleri de geliştirmişlerdir.

Bu çalışmada, deprem sonrasında binanın dahili doğalgaz ve elektrik dağılım sisteminin uğradığı hasar ve binada bulunan cihazların devrilmeleri göz önünde bulundurularak binaların tutuşma olasılığını hesaplayan CBS tabanlı bir model geliştirilmiştir. Geliştirilen model İstanbul Teknik Üniversitesi'nden araştırmacıların yardımlarıyla Illinois Üniversitesi Orta Amerika Deprem Merkezi tarafından geliştirilmiş olan HAZTURK deprem kayıp tahmin yazılımına entegre edilmiştir. Ayrıca, mevcut deprem sonrası yangın yayılımı modelleri açıklanmış ve fiziksel bir yayılma modeli metodolojisi ifade edilmiştir.

Geliştirilen deprem sonrası tutuşma modeli üç ana bileşenden oluşmaktadır. Bu bileşenler deprem sonrası farklı tutuşma kaynaklarını kapsayan (a) elektrik ve doğalgaz sistemleri, (b) tehlikeli cihaz ve içerikler ve (c) az tehlikeli cihaz ve içeriklerdir. Hasarlı elektrik ve doğalgaz sistemlerinden kaynaklanan tutuşma olasılığı belirli bir tehlike haritası kullanılarak kuvvetli yer hareketlerine göre üretilen bina hasar değerlerinden hesaplanmaktadır. Tehlikeli cihaz ve içerikler ve az tehlikeli cihaz ve içeriklerden kaynaklanan tutuşma olasılıkları ise binanın maruz kaldığı maksimum yer ivmesi değerine göre cihazların devrilme olasılıkları ve raflarda bulunan yanıcı madde içeren unsurların devrilme olasılıkları göz önünde bulundurularak hesaplanmaktadır. Yanıcı madde içeren devrilmiş cihazlar ve unsurların, kıvılcım üretebilecek veya yalın aleve sahip cihazlar ile aynı ortamda bulunması halinde tutuşma olması kaçınılmazdır. Bu cihazların devrilme olasılıkları maruz kalınan maksimum yer ivmesine göre cihazların boyutlar da hesaba katılmasıyla cihazların hareketleri göz önünde bulundurularak elde edilmiştir.

Bütün cihaz ve içeriklerin mevcut bütün bina türlerinde bulunduğunu varsaymak gerçekçi bir yaklaşım değildir. Dolayısıyla, tasarlanan modeli daha gerçekçi ve güvenilir bir hale getirmek için belirli bir bina kullanım türüne göre her bir cihaz veya içeriğin binada bulunma olasılığını ifade eden bir ağırlık faktörü kullanılmıştır. Bu faktör istatistiksel veriler kullanılarak her bina kullanım türüne göre her cihaz ve içerik için hesaplanmıştır.

Ayrıca, tasarlanan modelin bütün bileşenlerinin deprem sonrası tutuşma oluşmasında eşit katkıya sahip olduğunu düşünmek de gerçekten uzak bir yaklaşımdır. Bundan dolayı modelde bulunan her bir bileşenin ağırlıklandırılması gerekmektedir. Bu amaçla analitik hiyerarşi süreci yöntemi kullanılmış ve bu yöntem uygun olarak deprem sonrası tutuşma modeli bileşenlerini ağırlıklandırmak üzere bir anket hazırlanmıştır. Bu anket deprem mühendisliği, deprem sonrası yangınlar ve afet yönetimi konularında deneyimleri bulunan yedi bilim insanı tarafından doldurulmuştur. Doldurulan anketler değerlendirilmiş ve her bir bileşenin ağırlığı hesaplanmıştır.

Tutuşması tahmin edilen binaların konumlarının belirlenebilmesi için geçmiş deprem kayıtları büyük bir öneme sahiptirler. Binaların tutuşma olasılıklarından tutuşma gerçekleşmesi beklenen binaların sayısının ve konumlarının belirlenebilmesi için bir eşik değerin üretilmesi gerekmektedir. Bu hesaplama için geçmiş depremlerden maksimum yer ivmesi değeri, bina kat adedi, kullanım türü, bina yapım yılı and bina yapı türü verilerine ihtiyaç duyulmaktadır. Bu doğrultuda, sınırlı sayıda veriye sahip olsa da 1994 Northridge depreminin kayıtları elde edilebilmiştir.

1994 Northridge depreminde yanmış olan binaların geliştirilen model ile hesaplanan tutuşma olasılıkları kullanılarak her bir MAEViz bina türüne göre eşik değerler ve standart sapmaları hesaplanmıştır. Sınırlı sayıda geçmiş deprem verilerine erişilebilmiş olunmasından dolayı ortalama, alt sını ve üst sınır olmak üzere üç farklı eşik değer tablosunun oluşturulmasına karar verilmiştir. Alt sınır değerleri ortalama eşik değerlerin bir standart sapma eksiği ve üst sınır değerleri de ortalama eşik değerlerin bir standart sapma fazlası olarak belirlenmiştir.

Geliştirilen modelin kullanımını etkin ve aygın hale getirmek amacıyla, model ücretsiz ve açık kaynak kodlu olan HAZTURK yazılıma entegre edilmiştir. HAZTURK yazılımı MAEViz yazılımının Türkiye verilerine uygun olarak düzenlemiş şeklidir. HAZTURK java programlama dili kullanılarak geliştirilmiş bir yazılım olduğundan geliştirilen modelin java kodu Eclipse platformu kullanılarak

yazılmıştır. Yazılan kod HAZTURK yazılımının kaynak koduyla uyumlu hale gelecek şekilde Illinois Üniversitesi Urbana-Champaign kampüsünde bulunan Natural Center for Supercomputing Applications (NCSA) çalışanları tarafından düzenlenmiştir. Düzenlenen kod HAZTURK yazılımına bir analiz aracı olarak eklenmiştir.

Entegrasyonu tamamlanan modelin örnek uygulamaları HAZTURK yazılımı kullanılarak Amerika Birleşik Devletleri'nin Tennessee eyaletinde bulunan Memphis şehri ve İstanbul ili Küçükçekmece ilçesi için gerçekleştirilmiştir. Olası tutuşmaların sayısı ve konumları alt sınır, ortalama ve üst sınır eşik değer tabloları kullanılarak her iki çalışma için de ayrı ayrı elde edilmiştir.

Gerçekleştirilen analizlerin sonuçları yapı tipleri, kullanım türleri, bina kat adedi, yapı yönetmelikleri ve mahalleler için ayrı ayrı değerlendirilmiştir. Değerlendirilen analiz sonuçları, deprem sonrası tutuşma riskinin bina kat adedi ve bina yapım yılı ile ters orantılı olduğunu göstermektedir. Analizlerde bina yapım yılı ait olunan yönetmeliği belirlemede ve bu yönetmeliğine uygun kırılma eğrilerinin kullanılmasına imkan sağlamaktadır. Dolayısıyla, bina ne kadar eski ise deprem sonrası tutuşma riski de o kadar fazla olmaktadır. Ayrıca, Memphis ve Küçükçekmece için gerçekleştirilen uygulamalar ahşap binaların da ciddi bir deprem sonrası tutuşma riski altında olduğunu göstermektedir. Ahşap binalar diğer yapı türlerine göre yangın yayılımında daha hassas olup hızlı yayılabildiği için tutuşma gerçekleşebilecek ahşap binalar ile ilgili olası bir depreme karşı önlemler alınmalıdır.

1. INTRODUCTION

Fire following earthquakes (FFE) can cause severe losses. These losses can sometimes outweigh the total losses from the direct damage caused by the earthquake, such as collapse of buildings and disruption of lifelines. Many factors affect the severity of the fires following an earthquake. These effects are ignition sources, types and density of fuel, weather conditions, functionality of water systems, and the ability of fire fighters to suppress the fires (HAZUS, 1999).

While FFEs were the dominant cause of the single largest earthquake-related losses in the US and Japan in the twentieth century and a factor in more recent events such as the 1995 Kobe earthquake, in other earthquakes few fires have occurred, with minimal damage. This is due in part to FFE only being a significant concern in seismic regions with large wood building inventories, such as western North America, Japan, and New Zealand, but also simply to the large variability inherent in the FFE process(Lee et al., 2008).

Earthquakes not only cause damages by shaking, but secondary disasters like fires following earthquake, tsunami, liquefaction, land slide etc. also cause large-scale losses. In some cases, fires following earthquake and tsunamis result in losses more than shaking do as shown in the 1906 San Francisco earthquake and the 1923 Kanto earthquake. Fire following the 1999 Marmara Earthquake destroyed at least 17 petroleum tanks. Fire following earthquake is the only issue investigated in this study.

The major earthquakes damage lifelines of cities such as water systems, electrical systems and gas systems in addition to the structures. Heavy damage in the electrical and gas systems can result in leakage from these systems and this leakage can cause many simultaneous fire ignitions. These ignitions can turn into large urban conflagrations due to construction material, water capacity, fire fighting capabilities, inadequate number of firebreaks etc. Water capacity and fire fighting capabilities are decelerated because of damages on water mains and pipelines, debris from collapsed

buildings onto the road and interruption in communication systems. All of these effects provoke many destroyed buildings, numerous deaths and injuries and enormous economical losses.

1.1 Problem Identification

1.1.1 How was it manifested

Post-earthquake urban fires are generally caused by strong ground shakings. Strong shakings damage the structures and infrastructures. As a consequence of earthquake, many ignitions can occur due to gas systems, electrical systems, overturning of electrical appliances, heating equipments or flammable materials in structures. In addition to interior structure ignitions, damaged infrastructure elements such as gas mains and pipelines and damaged electric transmission lines can also cause ignitions. Some of these ignitions are put out by occupants and they don't induce much more damages. Some of them spread due to amount of fuel load (combustible materials), construction material, direction and speed of wind etc. in environment and they can turn into large urban conflagrations. As mentioned before, some FFEs can cause much more damage than earthquakes as shown in the 1906 San Francisco and the 1923 Kanto earthquakes.

Furthermore, fire-fighting activities are also a significant factor, which directly affects the spread of fire. The more fire department's response is delayed, the more fire spreads. Fire departments usually have difficulties about reaching fireplace and respond to fire due to narrow streets, closed roads because of collapsed buildings, damages to fire stations and injuries in fire fighters etc.

In fire fighting activities, fire fighters need high-pressure water and chemical materials to extinguish the fire. Strong earthquakes damage water main and pipelines. Water systems generally sustain many breaks and these breaks result in decreasing in water pressure that complicates the fire response.

Strong earthquakes also damage the communication systems in affected area. Communication systems have an important role in fire response. Dispatching fire fighters to different fires from a central fire department prevents fire fighters to respond the same fire and provides time saving.

The most common FFEs are caused by restoration of electricity in red-tagged buildings which are unsafe and nobody is not allowed to enter inside. If there is a gas leak in building, it will be ignited by restoration of electricity.

According to Mohammadi and Grobbel (1996), FFEs can be caused by gas leaks due to failure of pipes or gas appliances, electrical distribution system problems, flammable material spills and overturning of burning candles, table lamps and gas grills. Actually, equipments like candles and table lamps are not commonly used in present life, so these factors cannot be considered in future studies.

Most of the fires following the 1906 San Francisco earthquake occurred due to several ruptures in gas mains and pipelines (Url-1). Scawthorn et al. (2006) state that, post-earthquake ignitions returned to large urban conflagrations because of highly flammable construction, inadequate fire protection and inadequate water supply in the 1906 San Francisco earthquake.

In the 1923 Kanto earthquake, 277 fires occurred because of small charcoal braziers, which were widely used for cooking in lunchtime (Scawthorn et al., 2005). According to Kobayashi (1984), 37, 15, 8, 9, 1, 1 and 17 fires caused by kitchen range, clay charcoal cooking stoves, braziers, gas failure, candle, electricity problems and chemicals, respectively.

Kobayashi expressed in his study (1984) that, fires following the 1948 Fukui earthquake were caused by kitchen ranges (14), factory furnace (1) and casting fire (1), kitchen fire (1), bath pot (1), brazier (1), chemicals (5) and matches (1). Propane gas bombe caused 1 fire in an ice making shop, frying oil caused 1 fire in a fried food shop, chemicals caused 2 fire in junior high schools and 1 fire in the laboratory of a metal factory, oil tank caused 1 fire, fuel tank caused 1 fire and oil pipe line caused 1 fire in oil factories in the 1964 Niigata earthquake. Overturning of portable oil stoves cause several fires in the 1968 Tokachi-oki earthquake. Portable oil stoves were widely used at the earthquake time because of the cold weather conditions.

With reference to the local fire department's reports, majority of fires were caused by gas and electrical system failure in the 1989 Loma Prieta earthquake. There were also fires ignited by overturned lamps. In the 1994 Northridge earthquake, fires due to gas leaks destroyed approximately 150 mobile homes. Additional fires occurred because of restoration of electrical systems (Mohammadi and Grobbel, 1996).

Causes of fires following the 1995 Hyogo-ken Nambu earthquake were very similar to the 1994 Northridge earthquake. They also occurred due to gas leaks due to shaking and restoration of electrical system after the earthquake (Sekizawa, 1997).

1.1.2 Historical fires following earthquakes

There were many earthquakes resulted in FFEs that caused significant damages in history such as the 1906 San Francisco, the 1923 Kanto (Tokyo), 1931 Napier, 1948 Fukui, 1964 Niigata, 1968 Tokachi-oki, 1978 Miyagiken-oki, 1983 Nihonkai-chubu, 1989 Loma Prieta, 1993 Hokkaido Nansei-oki, 1994 Northridge, 1995 Hyogo-ken Nambu (Kobe), 1999 Marmara, 2003 Tokachi-oki and 2011 Tohoku earthquakes.

The 1906 San Francisco and the 1923 Kanto Earthquakes were the biggest ones of them because they both resulted in large urban conflagrations.

Fire following the 1906 San Francisco earthquake is the most destructive FFE in US history. There were 59 known fires (52 in San Francisco and 7 in other cities) in affected area in the 1906 San Francisco earthquake (Scawthorn and O'Rourke, 1989). 10 fire stations were damaged but engines in these stations were not damaged and they were ready to use (Reed, 1906). There were 300 breaks local city distribution water mains and 23200 breaks in service lines. The fire lasted for 3 days because of the leak of water caused by water main and pipeline damages. Because of highly flammable construction (wooden buildings), inadequate fire protection and inadequate water supply, ignitions turned into large conflagrations (Scawthorn et al., 2006). Figure 1.1 and 1.2 are views from Sacramento Street and Market Street after the 1906 San Francisco earthquake.



Figure 1.1 : A view from Sacramento Street (Url-2).

Finally, the earthquake and fire ended up with approximately 3000 deaths and 28000 destroyed buildings that 80% of them caused by fires following earthquake (Scawthorn et al., 2005). The earthquake and fire resulted in \$524 million (in 1906 dollars) in property loss.



Figure 1.2 : A view from Market Street (Url-3).

The 1923 Kanto fire was the largest urban conflagration in history. According to Nakamura (1925), there were 129 fires in Tokyo City as indicated in a study of Kobayashi (1984). On the other hand, it is specified in the study of Scawthorn et al. (2005), with reference to Okamoto (1984), there were 277 fire outbreaks, about 133 of which spread. 80% of 83600 water services to houses were burned. The conflagration caused approximately 140000 deaths and destroyed approximately 447000 houses (Kanai, 1983; Hamada et al., 1992). Figure 1.3 and 1.4 are photographs taken after conflagration following the 1923 Kanto earthquake.



Figure 1.3 : Destruction of Tokyo due to the quickly spreading fires following the 1923 Great Kanto earthquake (Url-4).



Figure 1.4 : The 1923 Kanto earthquake - enormous damages (Url-5).

The 1931 Napier earthquake damaged water system and main water pipes were broken that caused spread of fire without response. Half of the overall loss was caused by fire following the 1931 Napier earthquake. Spread of fire was limited due to large open grounds, the sea and some relatively wide streets. As a result, the fire caused 256 deaths and destroying of more than 400 buildings covering most of 11 city blocks (Thomas et al., 2006). Figure 1.5 shows the burning buildings at Criterion Corner after the 1931 Napier earthquake.



Figure 1.5 : A view of Criterion Corner in the 1931 Napier earthquake (Url-6).

According to study of Kobayashi (1984), there were 24 fires occurred in the 1948 Fukui earthquake, 9 fires occurred in the 1964 Niigata earthquake, 21 fires occurred in the 1968 Tokachi-oki earthquake, 8 fires occurred in the 1978 Miyagiken-oki earthquake and 2 fires occurred in the 1983 Nihonkai-chubu earthquake. Figure 1.6 is a photograph of unctrolled fires following the 1948 Fukui earthquake.



Figure 1.6 : Uncontrolled fires in the Fukui earthquake (Url-7).

Fires ignited in dwelling houses (7), restaurants (2), delicatessen (1), tofu shop (1), textile factory (1), casting factory (1), store (1), inn (1), bank (1), high school (1), office (1), elementary school (1), technical school (1), agricultural experimental station (1), dyeing materials shop (1), printing shop (1) and matches warehouse (1) (Kobayashi, 1984). 3851 houses were destroyed because of fire in the 1948 Fukui earthquake (Abeki and Maeda, 2004).

9 fires broke out in the 1964 Niigata earthquake and 4 of them were extinguished by citizens. Fires ignited in ice making shop (1), fried food shop (1), junior high schools (2), laboratory of metal factory (1) and oil factories (4). Oil refineries near the River Shinano burned due to oil leakage from tanks, which characterizes the Niigata earthquake. This leakage turned into fire because of vibration effect. Four oil tanks burned in total. Many of them lasted more than a week and one of them lasted 15 days. Figure 1.7 is a photograph of an oil refinery after the 1964 Niigata earthquake.



Figure 1.7 : Oil refinery fire after the 1964 Niigata earthquake (Url-8).

21 fires broke out in the 1968 Tokachi-oki earthquake that affected Aomori, Hachinohe, Towada and Misawa cities. Most of the fires were caused by falls of portable oil stoves used at earthquake time because of cold weather conditions (9°C). Fires ignited in dwelling houses (12), laundry (1), seafood processing factory (1), paint shop (1), office (1), hospital (1), high schools (2) and drugstores (2).

8 fires broke out in the 1978 Miyagiken-oki earthquake where 4 of them were extinguished before spread by occupants. Fires ignited in dwelling houses (1), die casting factory (1), sanitary engineering company (1), universities (3) and gas making plant (1).

2 fires broke out in the 1983 Nihonkai-chubu earthquake that affected Akita city. One occurred in a dwelling house and was extinguished by occupants and the other fire occurred in an oil tank of a thermoelectric power plant and was extinguished by fire brigades (Kobayashi, 1984).

In the 1989 Loma Prieta Earthquake, the Municipal Water Supply System (MWSS) immediately sustained 123 main and service line breaks within the Marina District and 35 other breaks outside the district (O'Rourke et al., 1990). The Auxiliary Water Supply System (AWSS) sustained one main break, one hydrant-branch break and five hydrant-elbow breaks, which made AWSS ineffective in the Marina District (Scawthorn et al., 1992).



Figure 1.8 : Marina District Fire in the 1989 Loma Prieta earthquake (Url-9).

The 1989 Loma Prieta earthquake caused 58 (26 in San Francisco) fires. The most significant fire occurred in the Marina District that had tendency to expand (Scawthorn et al., 2005). Figure 1.8 and 1.9 are photographs of this fire. The MWSS and AWSS were unavailable due to low pressure because of the damage on the mains and service lines. Fortunately, the fire was extinguished by fire department before becoming a major conflagration with the help of The Portable Water Supply System (PWSS) and Phoenix fireboat.



Figure 1.9 : Fire in the Marina district following the 1989 Loma Prieta Earthquake (Url-10).

According to an online report of Yanev, the 1993 Hokkaido Nansei-oki earthquake was an example of triple hazards of earthquake, tsunami and fire. After the main shock of the earthquake, the first tsunami wave reached the island of Okushiri in 5 minutes. Tsunami triggered the fire in Aonae region of Okushiri because of fuel spills, residential and business kerosene tanks (for heating), propane tanks, and the fuel from many boats deposited ashore by the tsunami (Url-11). The fire lasted 11 hours. 340 homes were destroyed due to fire in Aonae area that was approximately half of the homes in Aonae community (Mohammadi and Grabbel, 1996). Figure 1.10 is a photograph of Aonae area after the 1993 Hokkaido Nansei-oki earthquake.



Figure 1.10 : Aonae area of the island Okushiri after the 1993 Hokkaido Nansei-oki earthquake (Url-12).

161 fires were ignited following the 1994 Northridge earthquake and 77 of these fires were in Los Angeles Fire Department service area. The most significant fire occurred in North Balboa Blvd. in the Granada Hills area of the San Fernando Valley. A gas line failed due to liquefaction and escaping gas was ignited by sparks from the ignition system of a pickup truck (Figure 1.11). The resulting gas flare ignited neighboring buildings (Scawthorn et al., 1998). As a result of fire, 5 houses destroyed and 4 houses suffered less damage (Scawthorn et al., 2005). Figure 1.12 is a photograph from this fire.



Figure 1.11 : Gas main burned on Balboa Blvd. in the 1994 Northridge earthquake (Url-13).

The 1994 Northridge earthquake also affected the water system in San Fernando Valley. At least 6 breaks in trunk lines were caused because of the earthquake (Scawthorn et al., 1998).



Figure 1.12 : Structural fire in the building block on Balboa Boulevard(Url-14).

In the 1995 Hyogo-ken Nambu earthquake, water systems and gas systems were damaged heavily because of ground failure. Buried water pipelines were exposed to 2000 breaks and buried gas distribution system was exposed to 1400 breaks. 142 fires were reported on first day of earthquake in Kobe City with respect to Scawthorn and Yanev (1995). The authors claim that, this earthquake caused the largest economic loss about \$130 billion in history. According to Scawthorn et al. (2005), 237 fires occurred in total in the 1995 Hyogo-ken Nambu earthquake. 138 of them occurred in Kobe City and 99 occurred in other cities in the affected area. 108 fires were reported in Kobe City on first day. With reference to Sekizawa (1997), there were 231 fires occurred in the earthquake. 132 of them occurred in Kobe City. 109, 14 and 15 of these fires occurred in first, second and third day, respectively. Figure 1.13 is an aerial photograph Kobe City in the 1995 Hyogo-ken Nambu earthquake.



Figure 1.13 : Aerial photograph of Kobe City in the 1995 Hyogo-ken Nambu earthquake (Url-15).

This shows that the most affected city of this earthquake was Kobe City. 504 deaths were listed as fire related, although many of the victims may have been crushed or suffocated before they were burned (Nakamori et al., 1997). The total burned area was 1 million m² and 650999 m² according to Scawthorn and Yanev (1995) and Sekizawa (1997), respectively. 6900 buildings in 0.66 km² area were damaged and 500 people were killed because of fires following the Hyogo-ken Nambu earthquake (Chung et al., 1996).

The 1999 Marmara earthquake was a catastrophic event claiming over 17000 lives. It did not cause any conflagrations due to non-combustible concrete or masonry building material. It resulted in a major fire at a petroleum refinery, which lasted 5 days. At least 17 tanks were reported as burned totally and a 90-meter high reinforced concrete heater stack collapsed in fire (Scawthorn et al., 2005). Figure 1.14 shows the size of the fire.



Figure 1.14 : Fire in tanks following the 1999 Marmara earthquake (Url-16).

With reference to a report prepared by ABS Consulting (2004), the 2003 Tokachi-oki earthquake caused 2 fires. As a result a crude oil tank (32,778kl) and a naphtha tank (26,000kl) were burned. Figure 1.15 shows the burning oil tank after the 2003 Tokachi-oki earthquake.



Figure 1.15 : Fire in oil tanks after the 2003 Tokachi-oki earthquake (Url-17).

In the 2011 Tohoku earthquake, 385 fires were reported after the earthquake and tsunami occurred. 357 of these fires occurred directly after the main shock and 28 of them occurred after the aftershocks. It was not certain that how many of these fires were triggered by earthquake shaking and how many of these fires were triggered by tsunamis. One of the most destructive fires occurred in the town of Kesenumma in Miyagi Prefecture where fire turned into large conflagrations (Figure 1.16). Ignition of fire depended on tsunami related fishing ship crashes. So this incident is not taken into consideration in future modeling studies.



Figure 1.16 : Fires burn in a harbour following an earthquake and tsunami in Natori City, Miyagi Prefecture (Url-18).

There were multiple large fires were reported at oil refineries (Fukushima, Miyagi and Chiba prefectures), petroleum complexes (Miyagi, Chiba and Kaganawa prefectures), a Japan Coast Guard building (Tokyo Prefecture), city centers (Iwate

Prefecture) and residential areas (Chiba, Saitama, Ibaraki, Tokyo, Fukushima, Miyagi and Iwate prefectures). Figure 1.17 is a photograph of an oil refinery in Chiba city, Chiba prefecture after the 2011 Tohoku earthquake.



Figure 1.17 : An oil refinery is on fire following the Tohoku earthquake in Chiba city, Chiba prefecture (Url-19).

“Following the large aftershocks (magnitudes 7.1 and 6.6) on April 7th and the 11th, there were many fires that were spawned solely by ground shaking. According to NHK, there were 21 separate reports of fires and gas leaks in Miyagi Prefecture (including 18 in the city of Sendai alone). Three additional fires each broke out in Iwate and Ibaraki prefectures, which led to the evacuation of 500 homes” (Impact Forecasting, 2011).

As indicated in a report of Vervaeck and Daniell (2011), there were 3559 damaged roads because of the 2011 Tohoku earthquake. Direct economic loss of the earthquake was \$280 billion and estimated indirect losses according to business interruption were \$110 billion for 2-year period and \$220 billion for 5-year period. 15815 people were died and 3966 people were missing until the study was carried out. 148 people who were 1,1% of deaths were killed by several fires following earthquake.

1.1.3 How to prevent and counter FFE

In order to counter FFEs, causes should be examined in detail. Causes of FFEs are explained in previous section that consist of intra-structure factors, infrastructure factors, construction material, weather conditions, functionality of water systems, fire

fighting capabilities and communication problems. Weather conditions cannot be taken under control because it is a natural event. However, the other factors can be improved for mitigation efforts.

Intra-structure elements include gas and electrical systems, electrical appliances, heating equipments and flammable materials. Damaged gas systems can cause gas leaks and these gas leaks can turn into ignitions because of damaged electrical systems, electrical appliances and heating equipments. Flammable materials can also cause spread of fire rapidly. Automatic seismic shut-off valves for gas and electrical systems should be used and heating equipments should be fixed to decrease the ignition probability.

Strong earthquakes can heavily damage gas mains and pipelines and electrical transmission lines as seen in historical earthquakes. Shaking causes several breaks in gas mains and service lines and contributing factors as collapsed electrical transmission lines, ignition system of a truck or sparks due to any friction can initially cause ignitions. Spread of these types of ignitions is generally faster than intra-structure ignitions. They can turn into large urban conflagrations due to fuel load, construction materials of neighboring structures, wind speed and direction. Gas and electrical networks should be reinforced against a possible earthquake.

A robust and sustainable water supply system has a vital importance in fire fighting. Strong earthquakes also damage water supplies and distribution systems. Several breaks in water mains and pipelines decrease the water pressure and this makes hard to take adequate water from hydrants. In addition to water supply, fire-fighting capabilities have an important role in suppression facilities. Inadequate personnel, vehicle and equipment can cause spread of fire easily. Water networks should be reinforced against a possible earthquake and fire-fighting personnel should be available with a dynamic manner with the help of frequent FFE practices.

Communication systems are also very important in a disaster. Duration of reporting a fire and dispatching fire fighters to the incident have an important role in fire fighting activities. The more time to reach fire, the more fire spread. Advanced communication systems like radios, cell phones or other phones in houses and offices can be out of order due to severe damages after strong earthquakes. In this situation, the most effective methods to detect fires are reconnaissance in affected area and

direct report from people. In order to make people reports more effective, people should be trained about fire fighting activities against fires.

As mentioned before, most fires are caused by restoration of electricity in red tagged buildings. Lack of communication between disaster or emergency managers and power companies results in this type of fires. Power companies should keep in contact with emergency managers before any restoration operation.

There are some factors in stopping fire as large open grounds, wide streets (firebreaks) or railways, a sea, a lake, a river or a large fire resistive structure after the ignitions spread and tend to become an urban conflagration. According to Sekizawa (1997), roads and railways had a 40%, open spaces had a 23%, fire resistive buildings and walls had a 23% and suppression had a 14% effect on stopping a fire as considered in their own in the 1995 Hyogo-ken Nambu earthquake.

Amount of reinforcement of water, gas and electrical systems is a significant factor for cost-benefit analysis. If the reinforcement cost is very higher than expected damage, it is obvious that reinforcement is not an effective way. Expected damage can be obtained from the FFE analysis. FFE has been studied from many years and there are significant substantial ignition, spread and suppression models developed by the respectable scientists.

1.2 Research Objective

Main objective of this study is developing a probabilistic post-earthquake ignition model depending on the real sources. Most of the existing ignition models calculate the number of ignitions in a particular area according to only one parameter such as Peak Ground Acceleration, Modified Mercalli Intensity and building collapse ratio. Estimating the location of an ignition has a vital importance in emergency management. Dispatching fire fighters to the ignited buildings directly avoids the time consuming and makes emergency management effective. Location of ignition is estimated by using threshold values produced from past fire following earthquake records. On the other hand, study makes recommendations for methodology of a spread model. Spread methodology considers the development of fire in a building and fire spread between buildings.

2. LITERATURE REVIEW

2.1 History of Post Earthquake Fire Modeling

Researches on urban fire spread started at 1950s because of large urban conflagrations caused by urban fire bombing during the World War II (Martin, 2004). Hamada expressed the importance of FFE after the 1948 Fukui earthquake and subsequent major conflagrations (U.S. Army, 1949). The first model was developed by Hamada, which consists of a set of equations that estimate urban fire spread using fuel load, wind speed and other factors as input parameters (Hamada, 1951). After this model was developed, some Japanese scientists kept studying this topic in the 1970s (Horiuchi et al., 1974; Mizuno and Horiuchi, 1976; Mizuno, 1978).

On the other hand, there were no studies about FFE in the US until Steinbrugge (1968) mentioned about FFE problem in the San Francisco Bay Area and collected data (Steinbrugge, 1971). There were also no FFE models, but just several researchers collected data and started defining FFE problem (Oppenheim, 1984). Scawthorn developed the first integrated FFE model that includes post-earthquake ignitions, spread and fire department response in the late 1970s and early 1980s. This model was firstly applied in Japan (Scawthorn et al., 1981) and applied in California (Scawthorn, 1986) after Japan. This model was a basis for insurance industry and other modeling approaches for a long time.

The effective and fully deployed FFE model should contain ignition modeling, spread modeling and suppression modeling. The model should be able to estimate number and location of ignitions, spread potential of ignitions due to suppression activities. Performed study only includes estimating number and location of potential post-earthquake ignitions and describing the methodology of a physics-based spread model.

2.2 Post-Earthquake Ignition Models

An ignition can be defined as a fire occurred after earthquake that need fire department response. Fires that are extinguished by occupants are not considered as ignitions in FFE problem. The first step of FFE modeling is modeling the ignitions that means estimating number and location of ignitions. Ignition term can be expressed by different names like fire or fire outbreak in several sources. Occurrence of post-earthquake ignitions can be considered in two different ways. One of them is intra-structure ignitions caused by damage to buildings and the other one is the infrastructure ignitions caused by damage to lifeline systems.

According to structural damage after an earthquake, ignitions can appear because of utility systems of building, heating equipments, cooking equipments and other inflammable or electrical appliances depending on the magnitude of the earthquake. Many scientists made researches to estimate the number of post-earthquake intra-structure ignitions and they developed different models. Most of these models depend on ground motions. There were some researches about multi-parameter ignition model in the last couple of years.

Kawasumi developed an equation (2.1) by using logarithmic regression analysis (Kawasumi, 1961; Kobayashi, 1984; Aoki, 1990; Scawthorn et al., 2005; Zhao et al., 2006). He used only data from the 1923 Kanto earthquake. There is a positive correlation between the rate of ignitions (ϕ) and the the rate of collapsed wooden buildings (θ).

$$\ln \phi = 0.684 \ln \theta - 5.807 \quad (2.1)$$

Mizuno developed an equation to estimate post-earthquake ignitions (Mizuno, 1978; Kobayashi, 1984; Aoki, 1990; Zhao et al., 2006) by improving a logarithmic regression relation between the rate of ignitions (ϕ) per household and the rate of totally collapsed households (θ) (2.2).

$$\ln(-\ln(1 - \phi)) = 0.606 \ln(-\ln(1 - \theta)) - 6.149 \quad (2.2)$$

Equations (2.3) and (2.4) were developed by Kobayashi in order to estimate possible number of ignitions per 10000 m² (y) due to building collapse ratio (x) (Lee et al., 2008).

$$y = 0.00356x + 0.00031 \quad (2.3)$$

$$y = 0.00056 \ln x + 0.00275 \quad (2.4)$$

A logarithmic equation that gives ignition frequency ($\emptyset$) due to the ratio of destroyed building (θ) in a specific region was developed by Chaloner and Duncan (Oppenheim, 1984).

Ignition model developed by Li et al. (2001) is estimating possible ignitions in a specific zone for a certain exceed probability. The model assumes that post-earthquake ignitions are in a Poisson distribution in time and place. The model calculates the incidence of ignitions according to the area of buildings with moderate damage and above (2.5). Duration of post-earthquake ignitions was considered as 3 days (72 hours).

$$\lambda_f = \frac{\rho}{\rho_c} \cdot \mu_m A_m + \rho \cdot A \quad (2.5)$$

λ_f is the incidence of post-earthquake fire, ρ_c is the average incidence of civil fires in a city, ρ is the average incidence of civil fires in the predicted zone of the city, μ_m is the density of fire (the ratio of n to A_m , where n is the number of post-earthquake fires), A_m is the area with moderate damage and above of buildings caused by earthquakes and A is the area of all the buildings in the zone (Li et al., 2001).

Trifunac and Todorovska (1998) developed a linear regression equation by using historical data only from the 1994 Northridge earthquake (2.6). The equation below gives the number of ignitions per 25 km² (m_I) due to MMI (I_{MM}).

$$m_I = -37.94 + 5.37 I_{MM} \quad , I_{MM} \geq 7.07 \quad (2.6)$$

A second order equation was developed by modifying the ignition model developed by Scawthorn (1987) in order to use in HAZUS software (2.7). The new data points representing the ignitions from the 1989 Loma Prieta earthquake were taken into account, the ignition per single family equivalent dwelling (SFED) unit was changed to ignitions per 1000000 square feet of structure inventory and the MMI scale was converted to PGA scale (HAZUS, 1999).

$$Ignitions = -0.025 + (0.592 PGA) - (0.289 PGA^2) \quad (2.7)$$

Scawthorn updated this equation by taking seven earthquakes (1971 San Fernando, 1983 Coalinga, 1984 Morgan Hill, 1986 N. Palm Springs, 1987 Whittier Narrows, 1989 Loma Prieta, 1994 Northridge) into consideration. 238 data points were used in regression equation. Number of ignitions per 1000000 square ft total floor area due to PGA is calculated by using equation (2.8) (Scawthorn, 2009).

$$Ignitions = (0.581895 PGA^2) - (0.029444 PGA) \quad (2.8)$$

$$MMI \geq VI ; population density \geq 3000 \text{ per km}^2$$

The URAMP software (Utilities Regional Assessment of Mitigation Priorities) estimates post-earthquake ignition rate according to PGA or MMI for different types of building occupancy (residential, commercial and industrial) separately (Scawthorn et al., 2005). Ignition locations are determined randomly (Seligson et al., 2003).

Table 2.1 : Number of ignitions according to MMI and PGA in URAMP (Seligson, 2003).

MMI (PGA, in g)	Number of Ignitions per million ft ²		
	Residential	Commercial	Industrial
VI (0.09-0.18)	0.024	0.007	0.002
VII (0.18-0.34)	0.071	0.019	0.005
VIII (0.34-0.65)	0.177	0.047	0.012
IX (0.65-1.24)	0.397	0.106	0.026
X (>1.24)	0.819	0.218	0.055

Cousins and Smith (2004) assumed that there is an linear relation between the mean number of ignitions per millions of m² of floor area (N) and the shaking intensity (MMI). They developed a simple equation below (2.9).

$$N = MMI - 8.5 \quad (2.9)$$

They supposed that if MMI is smaller than 8, it will not cause an ignition (Cousins and Smith, 2004).

Ignition equation of HAZUS was modified by taking post-earthquake fires occurred in the US, Japan and China between 1900-1996 into account. Ren and Xie (2004) produced a new second-order relation (2.10).

$$y = -0.11749 + 1.34534x - 0.8476x^2 \quad (2.10)$$

y is the number of fire sites per 100000 square meters, and x is the PGA.

The ignition probability of a building for a specific PGA can be calculated with equation (2.11) and (2.12):

$$P(R_{ji}) = P(M) \times P(F_K/M) \times P(D_J) \times P(G) \quad (2.11)$$

P(M): the probability that a building contains or is constructed of flammable materials.

P(F_K/M): the probability that each type of combustible material will be found in a building.

P(D_J): The influence of a building's damages on the probability of a conflagration occurring.

$$P(D_J) = \sum [P(D_J/I_i) \times P(C_J/D_J) \times P(S_J/D_J)] \quad (2.12)$$

P(D_J/I_i): the probability of each different building's degree of damage in a specific PGA.

P(C_J/D_J): the probability of the leakage and diffusion of ignitable materials in a specific building's degree of damage.

P(S_J/D_J): the probability that earthquake-induced ignition will cause a specific degree of damage.

P(G): the index of other factors such as weather, season, and environment.

Scawthorn et al. (2005) developed two equations according to seismic intensity and building density. Equation (2.13) calculates the number of ignitions per thousand SFED (1 SFED=1500 sq ft) due to MMI scale and equation (2.14) calculates the number of ignitions per 1000000 square feet of building floor area (MMSF) due to PGA scale.

$$IGN \text{ per } 1000 \text{ SFED} = 0.015(MMI)^2 - 0.185(MMI) + 0.61 \quad (2.13)$$

$$IGN \text{ per } MMSF = 0.028 \exp(4.16PGA) \quad (2.14)$$

In the study of Zhao et al. (2005), post-earthquake ignition risk, fire-spread risk and integrated risk were calculated by using Analytic Hierarchy Process (AHP). Ignition risk assessment considered three main factors: Potential ignition sources, seismic damages and shaking time.

Potential ignition sources consisted of daily cooking appliances (stove, gas pipeline, gas switches and gas bottles, etc.), chemical products, gas-stored places, oil-stored places and underground gas pipelines. Seismic damages consisted of seismic damage to buildings and seismic damage to underground gas pipelines. Shaking time consisted of season and time of day. Figure 18 shows the AHP event tree for ignition probability.

Study area was divided into 100m x 100m grids. All of the input parameters were obtained for each grid and then model calculated the ignition probability for each grid.

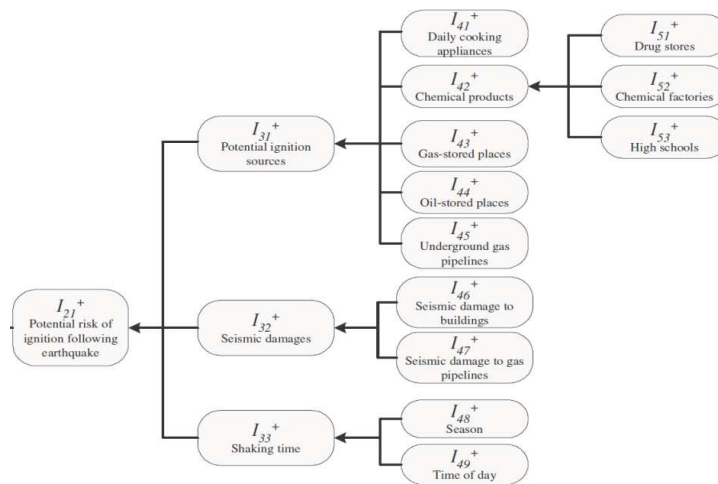


Figure 2.1 : AHP event tree for ignition probability (Zhao et al., 2005).

Fires occurred after the 1995 Hyogo-ken Nanbu earthquake were analyzed in detail and spatial and temporal characteristics of FFEs were determined by Zhao et al (2006). They detected that significant number of ignitions occurred just after the main shock simultaneously. These ignitions depended on the shaking directly and the other ignitions occurred due to restoration of electrical system and recovery activities.

Authors suppose this situation of ignitions as a general statement and a linear regression equation was developed by taking historical FFEs in the US, Japan and China in the 20th century into account (2.15).

$$\lambda = 0.0042 + 0.5985PGA \quad (2.15)$$

λ is the number of ignitions per 100000m² building floor area.

Model also estimates the time of ignitions by using the Weibull distribution function and creates a timetable for all ignitions.

Kanamori et al. (2007) developed a PGA depended regression equation for determining post-earthquake ignition based on the investigation data of the 1994 Northridge and 1995 Hyogo-ken Nambu earthquakes (2.16). Equation was developed to be used in “an evacuation plan from a fire following earthquake” study.

$$y = 0.6078\ln(x) + 1.887 \quad (2.16)$$

y is the number of ignitions per 100 hector (ha) and x is the PGA.

Davidson (2009) developed two different models for two different datasets to estimate the number of ignitions per census tract by using negative binomial regression models. Two datasets were developed to explore the possible effect of missing ignition data. Both two models use multiple variables. Instrumental intensity (x_{ii}), percentage of land area that is commercial, industrial, or transportation (x_{CIT}), total building area in m² (x_{tbldg}), percentage of building area that is URM ($x_{\%URM}$) and people per km² (x_{dens}) were used in the first model (2.17). Instrumental intensity, high-intensity residential area (m²), percentage of land area that is commercial, industrial, or transportation, median year built over all housing units, percentage of building area that is URM and people per (km²) were used in the second model (Scawthorn, 2009).

$$\begin{aligned} & \ln (\text{Mean Ign. Rate}) \\ &= -15.42 + 1.13x_{ii} - 32.48x_{CIT} + 0.85 \ln(x_{tbldg}) \\ &+ 27.70x_{\%URM} + 0.0000453x_{dens} \end{aligned} \quad (2.17)$$

Zolfaghari et al. (2009) estimated the ignition probability of a building with analytical approach. Three ignition sources are considered depending on ground

motion and structural damage. Building utility damage, damaged braced non-structural equipments and overturning of braced equipments or contents are three main components of model.

2.2.1 Comparison of basic post-earthquake ignition models

Firstly, PGA depended, MMI depended and building collapse ratio depended models were compared separately. Unit area of models were different from each other (1000 SFED, 1.000.000 ft², 1.000.000 m², 100.000 m², 100 ha). Therefore, unit area was normalized to 100.000 m² for all PGA and MMI depended models. Then, models were compared by using MS Excel program. Figure 2.2, 2.3 and 2.4 show comparisons of PGA depended, MMI depended and building collapse ratio depended models, respectively. Linear mean trendline of PGA depended and polynomial mean trendline MMI depended models were also plotted and equations were written.

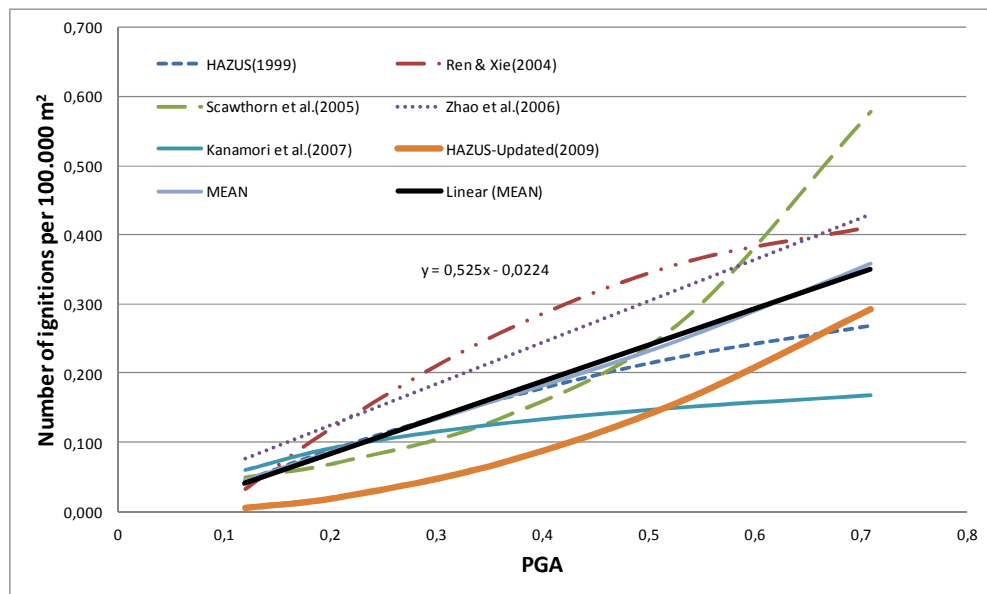


Figure 2.2 : Comparison of PGA depended models.

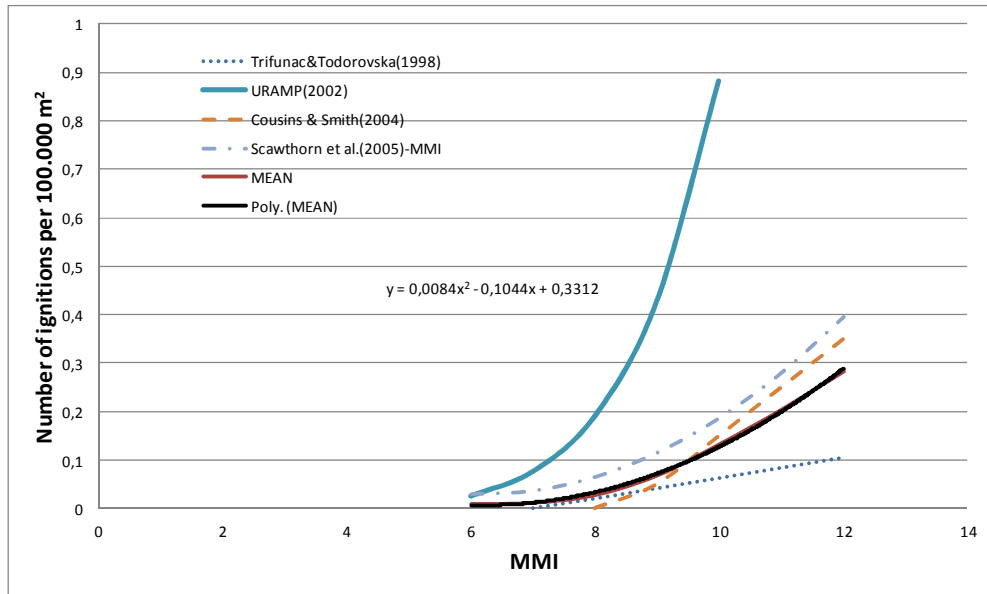


Figure 2.3 : Comparison of MMI depended models.

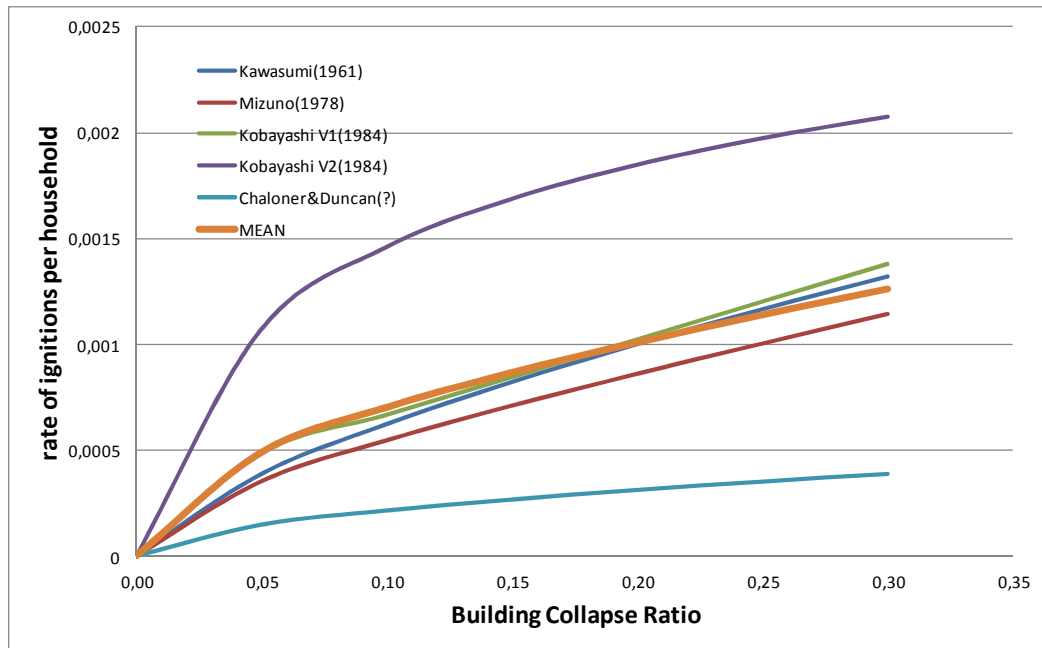


Figure 2.4 : Comparison of building collapse ratio depended models.

In order to compare all PGA and MMI depended models, MMI values were converted to PGA values by using HAZUS conversion table showed in table 2 (HAZUS, 1999).

Table 2.2 : MMI to PGA conversion table (HAZUS, 1999).

MMI	VI	VII	VIII	IX	X
PGA	0.12	0.21	0.36	0.53	0.71

Figure 2.5 shows the overall comparison of PGA and MMI dependent models, the trendline and equation of mean model.

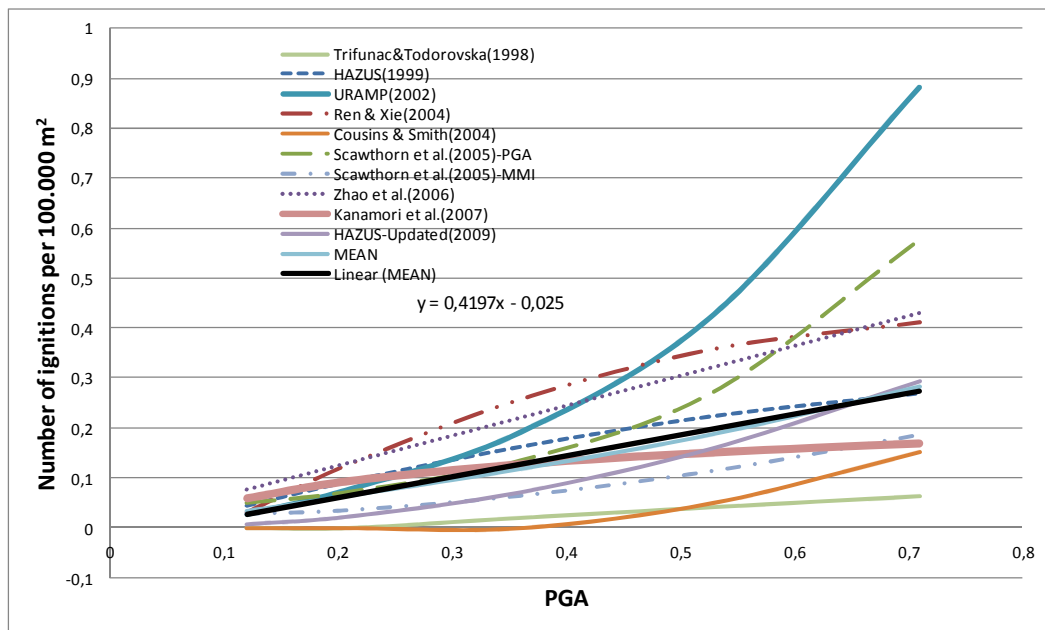


Figure 2.5 : Overall comparison of PGA and MMI dependent models.

2.3 Post-Earthquake Spread Models

Post-earthquake fire spread causes significant damage in countries that have a great number of wooden structures such as United States, Japan and New Zealand. Some of the post-earthquake ignitions can turn into large urban conflagrations because of spread of these ignitions depending on amount of fuel load (combustible materials), construction material, weather conditions, number of firebreaks, fire fighting capability and communication problems. Most of the existing spread models are empirical and depend on the weather conditions (speed and direction of wind).

Hamada created the first post-earthquake fire spread model in 1951. Equations of Hamada spread model are based on Japanese experience in twentieth century conflagrations both in peacetime and in wartime. Model assumes that an urban area consists of equal blocks of structures and structures have equal dimensions. Spaces between structures in a block are also equal. Average plan dimension of a structure is calculated by using percentages of different sized structures for a block. Dimensions of streets and sidewalks and firebreaks are not taken into account in the model. Growth of the fire is elliptical due to uniformly distributed fuel load, constant wind speed and wind direction (Figure 2.6).

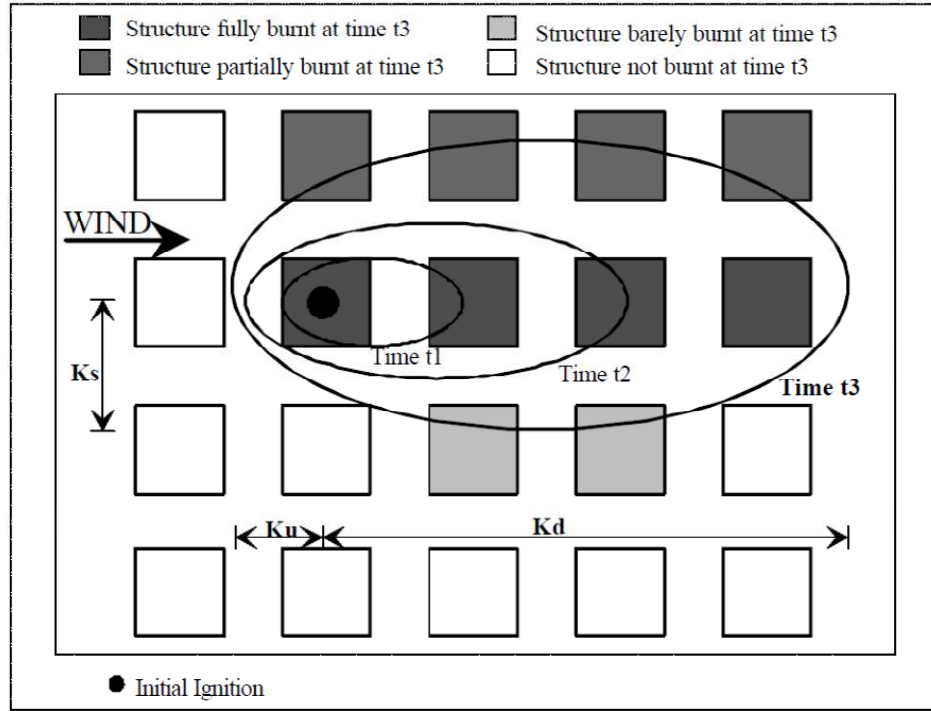


Figure 2.6 : Fire spread process of Hamada model (HAZUS, 1999).

Number of low-rise buildings destroyed by fire spread per ignition ($N(x_t, V)$) is calculated as a function of time, wind speed, average building plan dimension (a_0), length of fire in downwind (K_d), upwind (K_u) and sidewind (K_s) directions and space between buildings (2.18). Wooden buildings are also considered in the model by using built-upness (δ) which is ratio of area of wooden buildings to total area except water area.

$$N(x_t, V) = \left[\frac{1.5\delta}{a_0^2} \right] K_s (K_d + K_u) \quad (2.18)$$

A model for determination of post-earthquake fire hazard in urban regions is formulated by Scawthorn et al. (1981), which considers building density and properties, wind velocity, fire fighting response and deterioration of this response with increasing seismic intensity. The model for determining expected losses due to post-earthquake fire spreading among low-rise wooden buildings is shown schematically in Figure 2.7.

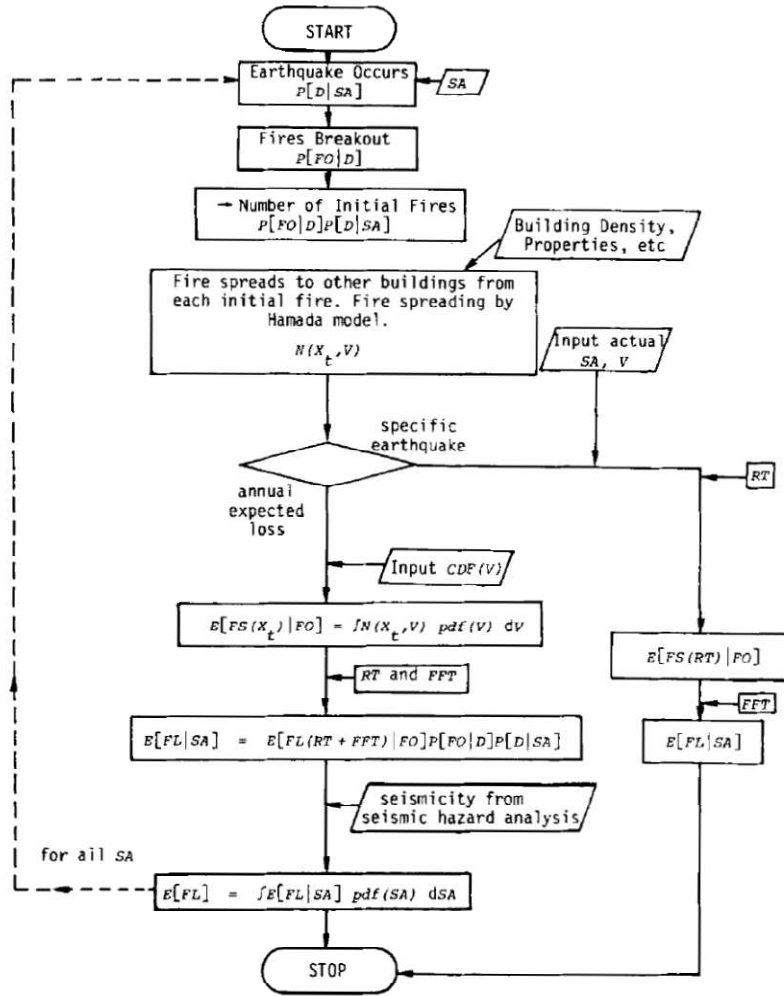


Figure 2.7 : Schematic diagram of methodology (Scawthorn et al., 1981).

Fire spread and damage to mid-rise buildings, compared with low-rise buildings, is assumed as negligible, based on the usually much higher expected damage to low-rise buildings. The formulation begins with the occurrence of an earthquake, which can either be postulated probabilistically, based on a seismic hazard analysis, or specifically. Due to ground shaking, many buildings suffer damage and/or collapse.

There are seven calculation steps for determining total number of houses destroyed by fire spread:

- $P[D|SA]$: probability of collapse per building given SA
- $P[FO|D]$: probability of fire occurrence per building given SA
- RT: post-earthquake response time of fire fighting teams
- $N(x_t, V)$ or $N(RT, V)$: number of low-rise buildings destroyed by fire spread per fire outbreak. $N(RT, V)$ is used for actual historical earthquakes.

- FFT: fire fighting time
- $N(x_t, V)$: total number of houses destroyed by fire spread per fire outbreak
- Number of fire outbreaks $\times N(x_t, V)$: total number of houses destroyed by fire spread

The formulation is general, it relies on region-specific empirical relationships to model fire incidence and spreading, so that application to urban regions with very different building properties must use modified empirical relationships. The methodology indicates that, on average, post-earthquake fire spreading is less of a problem than direct structural damage due to shaking, but that there exist situations where this may be reversed. The formulation clarifies the relationship of the various factors involved in post-earthquake fire spreading, from which it is seen that deteriorating fire fighting capability is an important factor.

System Earthquake Risk Assessment (SERA) is a GIS-based simulation model for lifeline systems. It is applied for water and transit systems. The model contains seismic fragility of the water systems in order to estimate situation of water systems every minute for 24 hours after the earthquake. SERA analyses were applied to East Bay Municipal Utility District's (EBMUD) water system. According to Scawthorn et al. (2005), it was run to EBMUD service area for five scenario earthquakes, under five possible conditions of the water system (as-is, \$13 million seismic upgrade, \$16 million seismic upgrade, \$84 million seismic upgrade and \$202 million seismic upgrade). Five different earthquake scenarios were Hayward $M=7.0$, Hayward $M=6.0$, Calaveras $M=6.75$, Concord $M=6.5$ and Loma Prieta $M=7.0$). Analyses were run due to three different wind speeds (calm=0 m/s, light=3 m/s, high=12 m/s).

HAZUS model is based on the Hamada model. Because the Hamada model results in different fire spreading rates in the downwind, crosswind and upwind directions even for zero wind speed, a linear interpolation function is used in order to correct this problem when wind speed is less than 10m/sec that results in equal fire spreading rate for all directions. Model estimates the total burned area and the population and building exposure affected by the fire. Suppression activities are also considered in the model (HAZUS, 1999).

TOSHO model was developed by Tokyo Fire Department and estimates the fire spread in four directions (upwind, downwind and 2 sidewinds). As in the Hamada

model, a city consists of structure blocks having average block dimension and block separation. Each block includes equally sized structures and equal spaces between structures. Fire spread is elliptical due to uniform distribution of fuel load, but wind speed is updated in each time step. The firebreaks are not considered in the model.

TOSHO model is very similar to Hamada model, but it differs from Hamada model by using data from recent fires (1975 Sakata conflagration and 1995 Hyogo-ken Nanbu earthquake). The spreading speeds are generally lower than the Hamada model and this is accepted as more realistic according to Scawthorn et al. (2005).

Dynamic and static post earthquake spread models were developed by Cousins et al. (2002). Dynamic model uses a set of physics-based fire rules that are modified by historical data. Wind, radiation, sparking, branding, building separations and building claddings are taken into account in these fire rules (Table 2.3).

Table 2.3 : Basic fire spread rules based on fire physics (Cousins et al., 2002).

Rule No	Rule	Wind Strength
1	1 or more burning cells within 3.0m causes spontaneous ignition of a target cell	Calm
2	2 or more burning cells within 6.0m causes spontaneous ignition	
3	1 or more burning cells within 6.0m can cause spark (piloted) ignition	
4	5 or more burning cells within 9.0m causes spontaneous ignition	
5	2 or more burning cells within 9.0m can cause spark ignition	Moderate Breeze
6	no spontaneous ignition at 12.0m	
7	3 or more burning cells within 12.0m can cause spark ignition	Fresh Breeze
8	no spontaneous ignition at 15.0m	
9	5 or more burning cells within 15.0m can cause spark ignition	Near Gale
10	no spontaneous ignition at 18.0m	
11	8 or more burning cells within 18.0m can cause spark ignition	
12	no spontaneous ignition at 21.0m	
13	13 or more burning cells within 21.0m can cause spark ignition	
14	no spontaneous ignition at 24.0m	
15	25 or more burning cells within 24.0m can cause spark ignition	
16	no spontaneous ignition at 27.0m	
17	no spark ignition at 27.0m	

Model considers fire spread by radiation, spontaneous ignition, piloted ignition, branding. Cladding materials of neighboring buildings are also taken into account.

Table 2.4 : Spread distances for sparking according to wind speed (Cousins et al., 2002).

Wind strength (and approximate speed)	Calm	Moderate Breeze (20km/h)	Fresh Breeze (30km/h)	Near Gale (50 km/h)
Spread distance downwind (m)	12	15	21	45
Spread distance cross and upwind (m)	12	12	12	12

Cellular automaton technique is used in model in which the study area consists of 3mx3m equal-sized grid cells. Each cell is assigned a set of states and properties. Fire spread is determined depending on the state of burning cell and the ignition probability of neighboring cells according to intensity of combustion, distances from burning cells and wind. The required duration for a cell to change the state from ignition to full intensity of burning is 7.5 minutes, full intensity burning duration is 15 minutes and burn-down duration is 12.5 minutes.

Static model only considers the critical separation which is the maximum distance that a fire can spread from one building to another and the claddings of buildings as combustible or not. Speed and direction of wind is not considered in the model. Model generates the burn-zones according to critical separation and all of the buildings in a burn-zone are assumed as burned completely. Model is useful for determining overall significance of post-earthquake fires and assessment of general mitigation efforts.

Utilities Regional Assessment of Mitigation Priorities (URAMP) software was developed to estimate losses caused by earthquakes in order to determine mitigation priorities for water networks. The software was integrated with EPANET which is a hydraulic modeling software package distributed by the US Environmental Protection Agency (EPA). It is based on a benefit-cost framework to determine most effective seismic risk reduction program for a water utility. FFE module of URAMP was developed by Scawthorn. Brush zone areas consist of wild vegetation were taken into account in spread model. A water supply reliability (WSR) factor, between 0 and 1, depended FFE spread estimation was carried out due to high, medium and low density residential, commercial and industrial occupancies (Scawthorn et al., 2005).

The unit geographical area is the census tract in the model. PGA was used as the input ground motion except pipelines. PGV was used for pipelines. The input data required by model includes:

- local building inventory (exposed building area, construction material and occupancy),
- fire-fighting resources (number and location of fire engines and crews),
- meteorological conditions (wind speed and direction),
- estimated earthquake ground motions (PGA and PGV).

Mean burnt area is acquired as a function of PGA, building density (total building area per square mile for low, medium and high-density residential, commercial and industrial construction) and water supply availability (from EPANET) with respect to Seligson et al. (2003).

Model developed by Iwami et al. (2004) uses the physics of fire spread as a basis and defines fire spread in four stages. They are progress of fire in each unit, heat release from a burning unit, heat transmission from one unit to another neighboring unit and temperature rise and ignition of ignitable area. Direction and speed of wind are also considered in model. Model assumes that situation of fire changes from MODE1 (flame rising from only opening) to MODE2 (flame rising from opening and roof) in 20 minutes and from MODE2 to MODE3 (completely burned) in 30 minutes (Figure 2.8). Spread of fire from one unit to another neighboring unit depends on flame touch, radiation and convection. Effect of flame touch is determined with shape of the flame which is a cylinder with a diameter D . Heat transfer according to radiation and convection are calculated and sum of them are considered as heat flux. A neighboring unit is assumed as ignited if there is a direct flame touch on it or its temperature becomes higher than 593°K depending on the received heat flux.

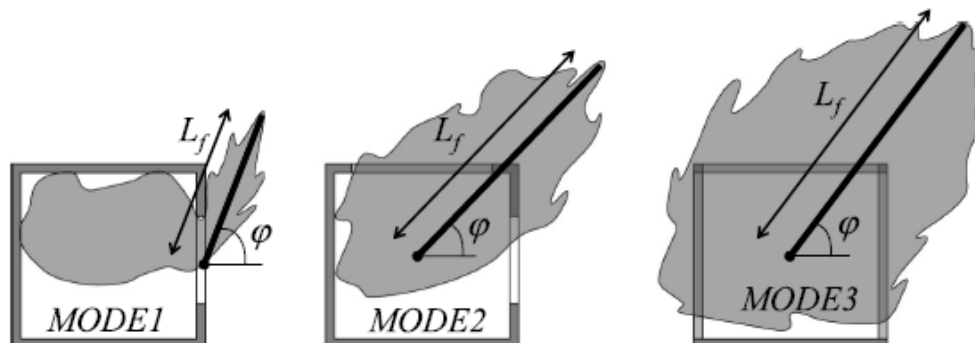


Figure 2.8 : Flame shape of each unit for different modes (Iwami et al., 2004).

The ResQ Fire simulator uses physical laws to obtain fire spread according to different modes of fire spread separately. Model calculates the fire spread for three modes (direct heat transport, radiation and convection) similar to the Iwami et al. (2004). Model considers direction and speed of wind by using air cells in simulation. Each air cell has particular temperature and these cells represent the effects of wind (Nüssle et al., 2004).

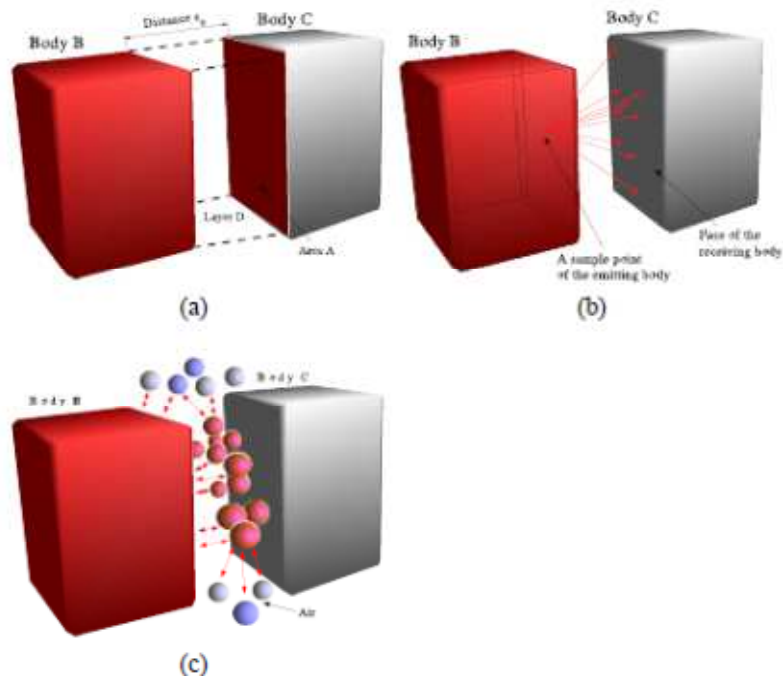


Figure 2.9 : Three ways of heat transportation: direct heat transport (a), radiation (b) and convection (c) (Nüssle et al., 2004).

Model developed by Ren and Xie (2004) calculates the fire prone area according to fire stopping distances of buildings with respect to distance between buildings. Fire spread distances and fire-stopping distance are determined depending on the type and height of the buildings, wind speed and wind direction (Table 2.5 and 2.6).

Table 2.5 : Fire spread distances in crosswind direction according to structure types and height of buildings (Ren and Xie, 2004).

Wind Velocity (m/s)	Building Type								
	Single-floor Average Sized Buildings			Two-floors Average Sized Buildings, Single-floor Large Buildings			Two-floors Large Buildings		
	Wooden	Wooden	House with Plaster	Wooden	Wooden	House with Plaster	Wooden	Wooden	House with Plaster
	to Wooden	to House with Plaster	to House with Plaster	to Wooden	to House with Plaster	to House with Plaster	to Wooden	to House with Plaster	to House with Plaster
0-3	6	3	1	8	4	2	10	5	2
3-5	6	3	1	9	4	2	11	5	2
5-7	7	4	2	9	5	2	11	6	3
7-8	8	4	2	10	5	2	13	7	3
10-15	9	4	2	12	6	3	15	8	3
15-20	10	5	2	14	7	7	17	9	4

Table 2.6 : Fire stopping distances according to different structure types (Ren and Xie, 2004).

Building Type	Fireproofing	Fire Stop Distance (m)
Brick and wooden building	Yes	6
Brick and wooden building	No	20
Mixed structure building	Yes	2
Mixed structure building	No	3
Reinforced concrete building	Yes	2
Reinforced concrete building	No	2
Other structure building	Yes	5
Other structure building	No	15

Model provides the following results:

- The fire spread area over time.
- Total number of people and buildings exposed to a fire over time.
- The amount of water required to extinguish a fire.
- The number and type of fire engines that should be allocated.

A dynamic fire spread model was also developed based on Huygen's principle. The fire spread shapes were assumed as elliptical under uniform condition as in Hamada model.

Model developed by Tsujihara et al. (2004) calculates fire spread by using the shortest route approach of Dijkstra algorithm. Models uses fire spread velocity for

wooden (52.1 m/h), wooden fire-preventive (42.8 m/h), quasi-fire-resistive and fire-resistive buildings proposed by Tokyo Fire Department. Fire spread velocity of quasi-fire-resistive and fire-resistive buildings are calculated by a function of building damage due to seismic intensity and wind speed. A building is simply represented by four nodes and six links (Figure 2.10). Each link includes spread time depending on distance and wind speed.

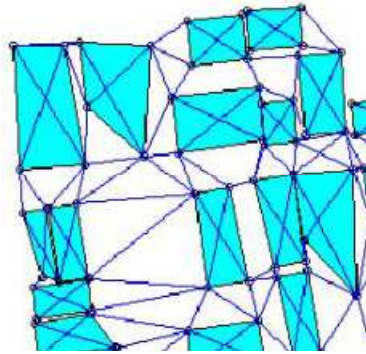


Figure 2.10 : Modeling of buildings by Tsujihara (2004).

Kato et al. (2006) developed a spread model that calculates the fire destruction probability of each building according to their fire breakout probability. Fire breakout probability is obtained by using equations that estimate the number of fire breakout (ignitions) for a particular area for given ground motion parameters (PGA or MMI). Then, spread of fire is determined depending on these fire destruction probabilities. Methodology uses a deterministic model, which includes fire spread limit distance (d) between neighboring buildings. Fire breakout probabilities of buildings in a particular cluster (Figure 2.11) are calculated from equation of ignition models.

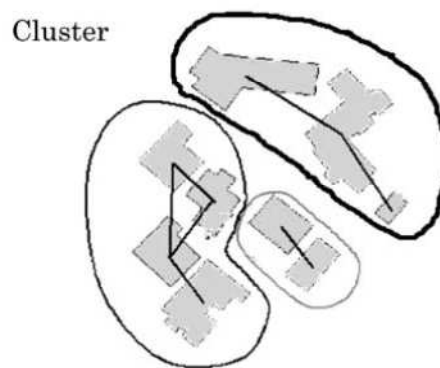


Figure 2.11 : Sample clusters used in model (Neighboring buildings located within the fire spread limit distance belong to the same cluster) (Kato et al., 2006).

Fire destruction probability is obtained for clusters and building's fire destruction probabilities are calculated by dividing them by the number of buildings in a cluster. Final burnt area is determined by multiplying fire destruction probability of each building by the total floor area.

Model developed by Ohgai et al. (2007) uses cellular automata to calculate fire spread. Interested area is divided into 3m x 3m grid cells (Figure 2.12) and fire risk status of each cell (Unburnable, not burning yet, catching fire, burning and extinguished) is determined with model. Building condition (building material, floor area and height), weather condition (direction and speed of wind) and characteristics of built-up area (vacant land, pitch of buildings and roads) are used as attributes for each cell in fire spread modeling. Fire spreading probability is used to determine whether or not the neighboring cell one state to another state.

A fire suppression sub-model is also used to estimate the fire spread under firefighting operations. Suppression model uses capacity of water utilization for firefighting (m^3), volume of water that a nozzle consumes per minute (m^3/min), the range of a nozzle (number of cells) and time required to extinguish a cell.

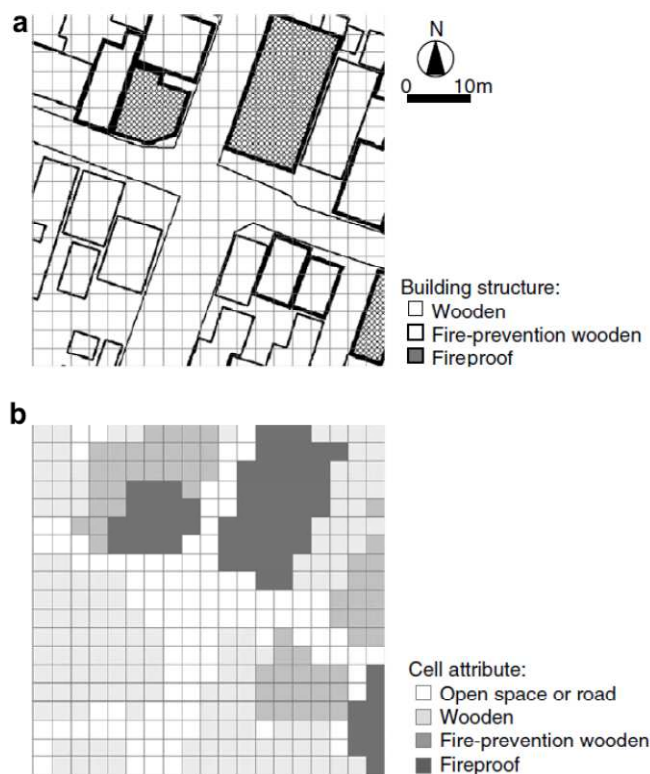


Figure 2.12 : Defining a built-up area in the form of cells. (a) Cells overlaid on a map of a built-up area. (b) Result of expressing the built-up area in the form of cells (Ohgai et al., 2007).

In the model of Zhong et al. (2008), fire spread is defined by two processes. First one is progress of fire in a burning building and the other one is development of fire between burning and neighboring buildings. Fire spread time between buildings is calculated depending on distance and combustion speed for different structure types (tall building, reinforced concrete building, multi-stories brick masonry building, single-storey civil house, wooden house and the other categories). Critical spread distances are used for these structure types in order to determine whether fire spread to neighboring building or not.

In the model of Himoto and Tanaka (2008), urban fire is interpreted as an ensemble of multiple building fires; that is, the fire spread is simulated by predicting behaviors of individual building fires under the thermal influence of neighboring building fires.

Governing equations of mass, energy, and chemical species in component rooms are solved simultaneously, for the development of temperature, concentrations of chemical species, and other properties.

The model consists of two major submodels: one that describes fire behaviors inside buildings; and another that describes building-to-building fire spread.

As to the building fire model, each room of a building is considered as a control volume with uniform physical properties, and transient development of internal fire behaviors are calculated by solving the governing equations for the properties of control volumes simultaneously. This uniformity assumption is appropriate as vigorous phase of fire occupies a large portion of compartment fires, and building-to-building fire spread takes place mostly within this particular phase.

As to the building-to-building fire spread, following mechanisms are considered as contributing factors:

- thermal radiation from fire-involved buildings
- temperature rise due to wind-blown fire plumes
- firebrand spotting

Occurrence of fire spread is determined when one of the following conditions is met:

- incident heat flux through opening exceeds a critical value
- surface temperature of exterior wooden wall exceeds a critical value

- firebrands at high energy states are fallen upon combustibles

Two processes are considered in fire spread model of Zhao (2010). These are fire development in a single building and fire spread among buildings. Fire development in a single building includes five stages: ignition, flashover, full-development, collapse and extinguishment (Figure 2.13). Time intervals are also used to calculate duration of the stages (Table 2.7).

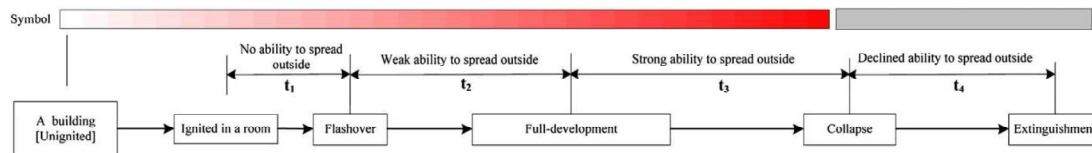


Figure 2.13 : Stages of fire development in a single building (Zhao, 2010).

Table 2.7 : Time intervals of fire development for different structure types.

Fire Stages	Time interval (min)	Structural type		
		Wooden	Fire-proof	Fire-resisting
Ignition - Flashover	t_1	[5,10]	[5,10]	[5,10]
Flashover - Full development	t_2	[20,30]	[30,50]	[50,60]
Full development - Collapse	t_3	[50,60]	[80,100]	[120,180]
Collapse - Extinguishment	t_4	[240,300]	[30,40]	[20,30]

Spread of fire is calculated depending on thermal radiation and thermal plumb heating (Figure 2.14). Weather factors like temperature, humidity, rain and wind are considered in model.

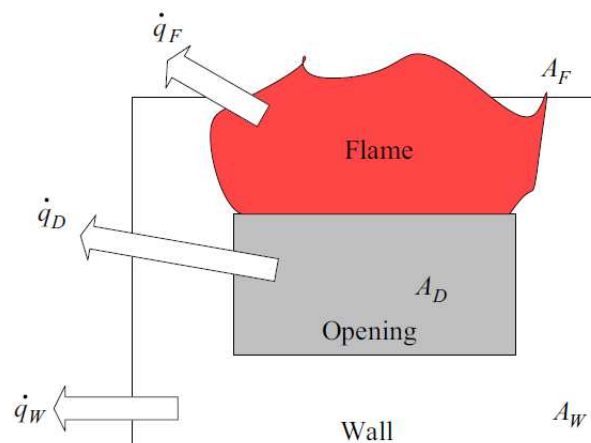


Figure 2.14 : Radiation heat flux from the external wall of fire building (Zhao, 2010).

Simulation of fire spread is carried out in five steps:

- Setting the weather conditions for each hour for the total simulation time.
- Temperature and heat release rate (HRR) are calculated and the fire stage of building is determined according to elapsed time.
- If the building is in full-development stage, received heat flux of neighboring buildings is calculated by using fire spread model.
- Ignited neighboring buildings are determined.
- Previous four steps are performed for newly ignited buildings.

Suppression model includes five firefighting steps: fire discovery, fire report, fire response, arrival of fire brigade and fire control. Duration of each step is determined according to HAZUS standards. Normal procedure of fire spread is used until arrival of firefighters. After the arrival of firefighters, fire spread is calculated by considering suppression activities. Figure 2.15 shows the simulation flow of the model.

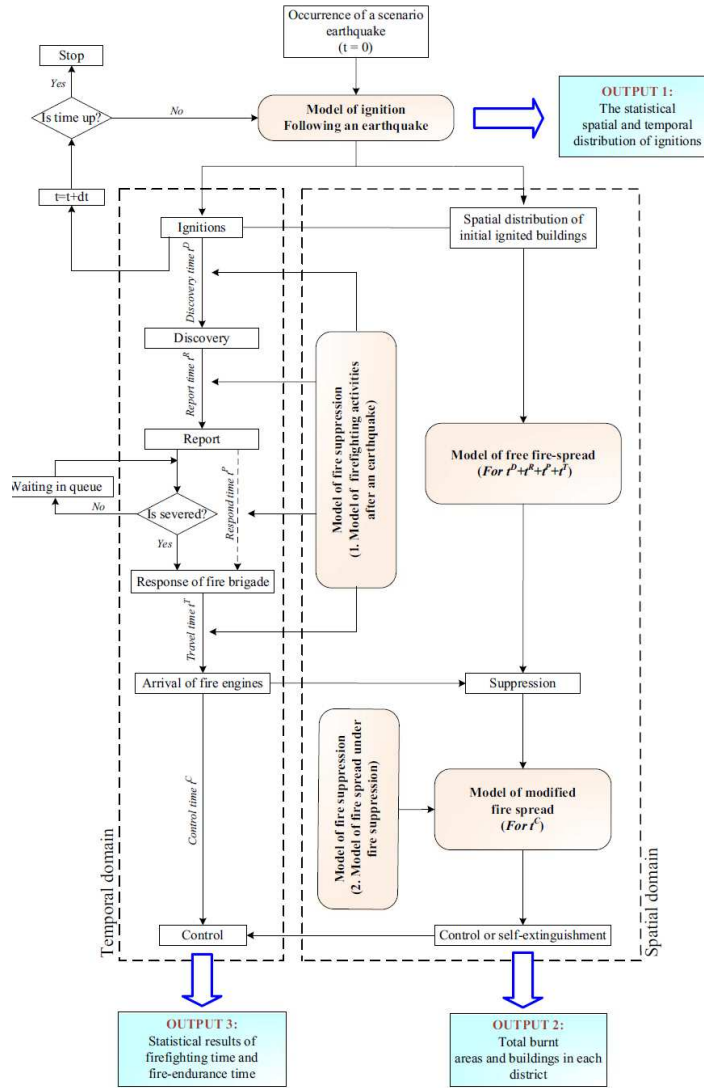


Figure 2.15 : The simulation flow of Zhao (2010).

Lee (2009) developed a post-earthquake fire spread model by adapting and integrating compartment fire models. This model is able to obtain (1) the evolution of fire within a room or roof, (2) room-to-room spread within a building through doorways, by burning through walls and ceilings, and by leapfrogging between windows and (3) building-to-building spread by window flame impingement; radiation from window flames, room gas, and roof flames; and branding (Lee and Davidson, 2010).

3. METHODOLOGY

3.1 Post-Earthquake Ignition

3.1.1 Sources of post-earthquake ignition

Post-earthquake ignitions occur as a result of building damage caused by strong earthquakes. Interior gas piping system and electrical distribution system suffer damage because of strong shaking and this can be resulted in leakage in gas system and sparking from electrical distribution system. Appliances containing fuel source, electrical mechanism or bare flames in dwellings can also cause ignitions. Leakage from interior gas system or spilling of flammable materials from overturning of appliances can be ignited by overturned electrical appliances, wiring failures in electrical distribution system or bare flames. Shelves containing flammable materials, parked automobiles under buildings and structures containing chemical materials like universities are also ignition sources.

Each of these sources has an influence on ignition occurrence. These sources should be modeled to estimate potential post-earthquake ignitions. In this study, a post-earthquake ignition is estimated by considering damage to building interior gas system and electrical distribution system and overturning of appliances.

Scawthorn (2010) expressed in his study that although electric power often fails during the earthquake shaking in high intensity areas, electrically caused ignitions still occur, due to either arcing before power fails, stored energy in electrical appliances and/or when power is restored.

Strong shakings result in high values of ground accelerations and displacements lead to damage to building utility systems such as gas and electrical distribution systems. Damage to gas systems can cause leakage from pipelines and this leakage can be ignited by a spark source caused by wiring failure.

Interior gas systems of buildings suffer from strong earthquakes resulted in gas leakage from breaks or joints. If there is a sparking source or bare flame in the environment, gas leakage is ignited when it reaches an ignitable level. The source of

ignition may be due to wiring failures caused by damage to the electrical distribution systems of buildings result in sparking in a damaged building.

According to Mohammadi et al. (1992), occurrence of post-earthquake ignition is realized in five steps:

- Overstress in the gas piping system components.
- Emergence of gas leak.
- Gas is accumulated in an enclosed area.
- Gas intensity in the air reaches an ignitable level.
- An ignition source is activated.

A consultant report of California Energy Commission (2000) indicates that post-earthquake ignitions occur when (a) a gas pipe in a building is broken, and an electric spark from damaged electrical wiring is present near the released gas to cause ignition or (b) a gas pipe in a building is broken due to building structural damage, and the delayed ignition of the released gas occurs when an ignitable mixture of gas and air is reached in the presence of a source of ignition.

Inadequately fixed appliances can slide or overturn because of an earthquake. Piping or electrical connections to this appliance can be damaged if adequate flexibility has not been provided. Fittings and joints on pipes can be separated due to excessive bending, rotation or movement. Excessive swinging of the pipe can damage hangers, resulting in loss of vertical support for the pipe, and often leading to failure. Gas leakage, spilling of flammable materials and sparking can appear depending on the failure of appliances. The most common appliances that can cause ignition following an earthquake are water heater, cooking stove, portable heater, refrigerator, TV, lighting fixtures, PC and microwave. Water heater and cooking stove are more hazardous than the appliances. Reports of historical earthquakes show that the most of the ignitions were gas and electrical related and water heaters had an great effect in these ignitions.

When a water heater is overturned by the earthquake, fittings and joints of gas piping may be ruptured and released gas can be ignited by a flame or spark. Water heaters are mostly used in the US, but they are not common in Turkey.

Overturning of cooking stoves can cause gas leakage and/or sparking according to the type of cooking stove. If a cooking stove uses gas as fuel source, overturning of this cooking stove can cause both fuel and bare flame.

When an earthquake occurs, electrical service to a structure is interrupted. If an electrical appliance is displaced or damaged by the earthquake and encounters a quantity of fuel that is in a flammable state, and when the electric power is restored to the building, this appliance causes the ignition of the flammable fuel. An example of such a scenario might be a high-intensity light falling onto a polyurethane or couch (California Energy Commission, 2000).

Flammable materials contained in shelves can be spilled during an earthquake. Bottles or open cans of flammable liquids can be thrown to the floor, and an open bare flame or an electric spark can ignite them.

Buildings in Turkey generally have two types of heating systems. These are central heating systems working with natural gas, fuel oil or charcoal, which supplies heating and hot water to all dwellings and central heating systems that supply heating and hot water for each individual dwelling, separately. Systems working with gas or fuel oil can cause ignitions due to gas leakage or fuel spill and sparking. Systems using charcoal as fuel source have bare flames in heating compartments and these flames can cause ignitions because of overturning.

In addition to these systems there are also some buildings using coal, wood or gas stoves for heating. These stoves contain bare flames when they are in use. Overturning of these stoves can directly cause an ignition when they reach a combustible material.

Parked automobiles under buildings can cause ignition if the building collapses. Automobiles contain fuel tank and this fuel can be spilled because of debris from collapsed building. If there is a spark source near the spilled fuel, ignition will occur due to reaction between fuel and spark.

Structures containing chemical materials such as laboratories of the universities, factories and pharmacies are potential ignition sources depending on the chemical reaction. There were many examples of ignitions occurred in drug stores and universities in historical earthquakes.

3.1.2 A probabilistic approach to realistic post-earthquake ignition modeling

The model consists of three main components named (a) utility systems, (b) hazardous appliances and contents and (c) less hazardous appliances and contents containing the different sources of post-earthquake ignitions.

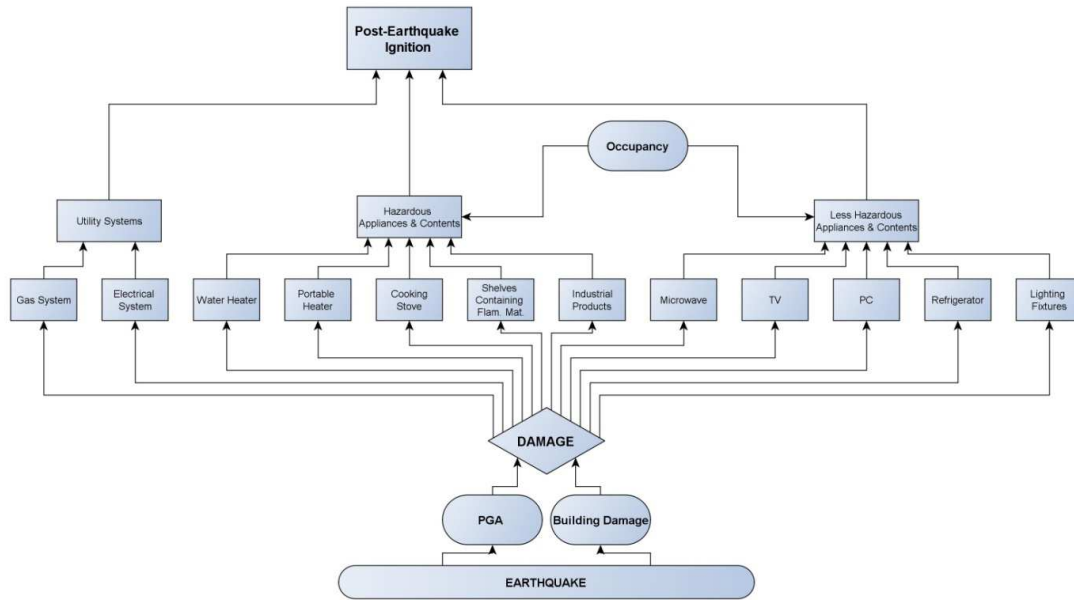


Figure 3.1 : Structure of ignition model.

3.1.2.1 Utility related post-earthquake ignition probability

An ignition caused by damage to utility systems includes damage to interior gas and electrical distribution systems. Ignition probability caused by damaged utility system is calculated due to building damage from a specific ground motion. Approach of Peyghaleh (2006) was adopted to calculate utility related ignition probability in the model. Building damages are produced by using HAZTURK (MAEViz) software for a particular scenario earthquake. Utility related ignition probability is calculated with four different damage states (insigfinicant, moderate, heavy and complete) obtained from building damage analysis executed with HAZTURK (MAEViz). Building damage file produced by different software can also be used with importing this file into HAZTURK (MAEViz). A mapping operation is necessary to link the attributes of input file with the required attributes for the model. Occurrence of ignition was defined by using an event tree (Figure 3.2).

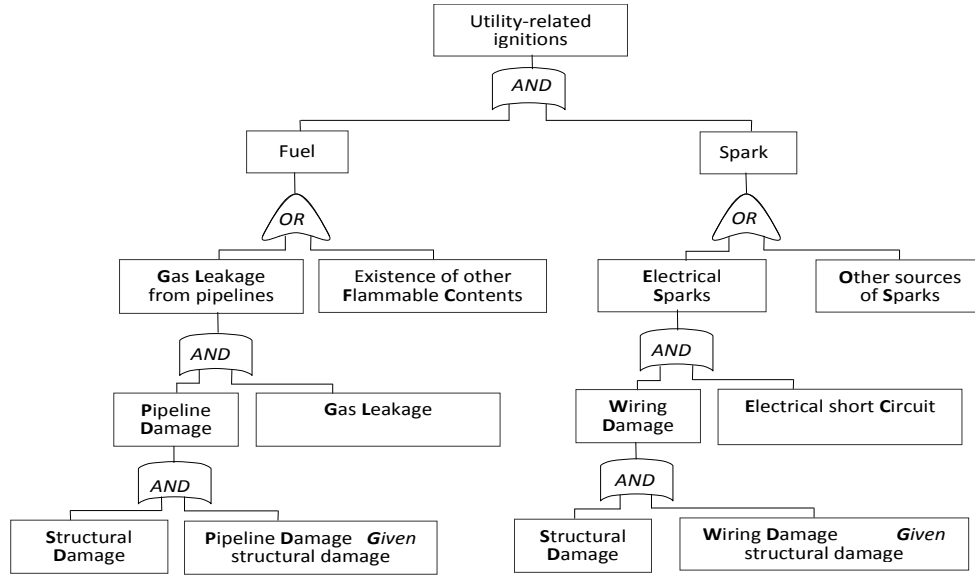


Figure 3.2 : Event tree of ignition probability caused by damaged utility systems (Peyghaleh, 2006).

Structural damage triggers pipeline and wiring damage. These pipeline and wiring damages result in gas leakage and electrical sparks. Finally, an ignition is caused by combination of these gas leakage and electrical sparks. Ignition probability is calculated by using equation (3.1) (Zolfaghari et al., 2009).

$$\begin{aligned}
 &P(Ig) \\
 &= (P(OS) + P(ECG) \times P(SD) \times P(WDG)) \times (P(GLG) \times P(SD) \times P(PDG) \\
 &+ P(FC))
 \end{aligned} \tag{3.1}$$

3.1.2.2 Appliances and contents related post-earthquake ignition probability

For hazardous and less hazardous appliances and contents, ignitions are caused by overturning of the appliances and falling of flammable materials from shelves according to exposed acceleration. Overturned appliances and fallen contents including flammable material and appliances with live electricity current or bare flames can produce ignitions. Overturning probabilities of appliances can be estimated by modeling the motion of appliance due to acceleration. Mohammadi et al. (1992) used a series of simulation analyses to investigate the overturning probability of a typical water heater by considering the geometry of heater, its weight, attachment to gas and water pipes and whether or not it is secured to the wall

via straps. They obtained the probabilities (Table 3.1) by using the 1989 Loma Prieta Earthquake records.

Table 3.1 : Overturning probabilities for a typical water heater.

Acceleration (g)	W/O Strap	With Strap
0,10	0,081	0,000
0,20	0,949	0,001
0,30	0,999	0,004
0,40	1,000	0,009
0,50	1,000	0,020

Ignition probabilities of appliances and contents are obtained by using the methodology of Prof. Dr. Luis Esteva and his team from the Institute of Engineering at the National University of Mexico. According to Reinoso et al. (2010), overturning of content is occurred when the horizontal acceleration exceeds the critical acceleration level defined for each content based on its size and shape. Recorded ground motions from 21 different earthquakes were used to obtain the minimum PGA value to produce overturning for each object. After a value of the failure intensity is obtained for each ground motion time history, adequately scaled, a sample will be available, and a function $F_{YF}(y)$ may be fitted to it, representing the probability distribution function of the minimum value of the intensity required to produce overturning.

Overturning probability of each content is calculated by using lognormal functions depending on exposed PGA value for a particular building (3.2). Overturning probabilities were calculated according to mean and standard deviation of experimental results with respect to the exposed PGA value.

$$F_{YF}(y) = \Phi \left[\frac{1}{\sigma_{\ln YF}} \ln \left(\frac{y}{\tilde{m}_{YF}} \right) \right] \quad (3.2)$$

y is PGA value, Φ is the cumulative standard normal distribution of the logarithm of the sample of random values of YF, the minimum intensity required to produce overturning failure, σ is the standard deviation of the natural logarithm, and m is the median value.

Existence of an appliance depends on the occupancy of dwellings in a building. A weighting factor (P_{occ}) is used to define the chance of existence of each appliance or content in the given occupancy (3.3).

$$P(\text{Overturning, Occupancy}) = P_{\text{overturning}} \times P_{\text{occ}} \quad (3.3)$$

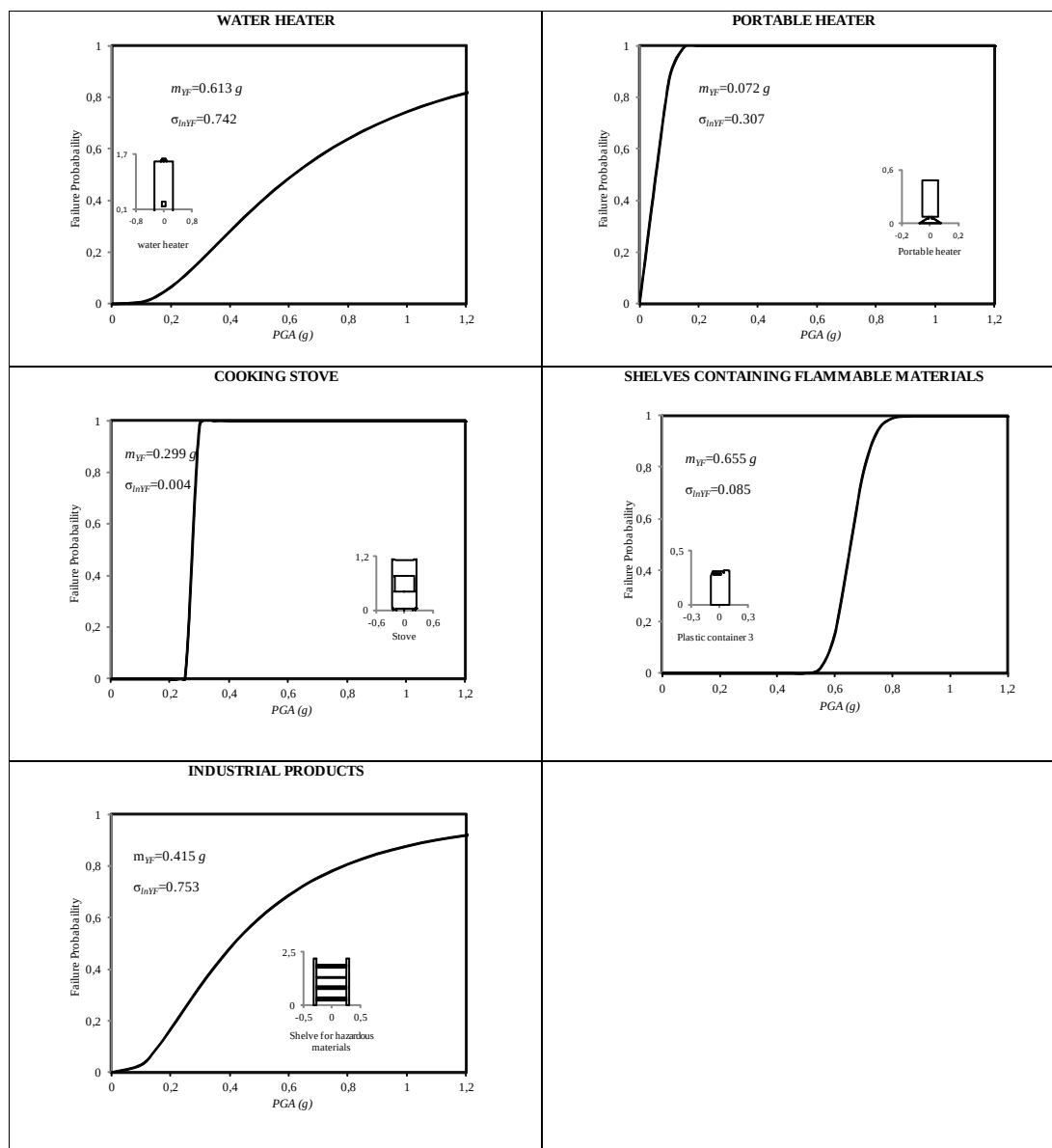


Figure 3.3 : Overturning probability for hazardous appliances & contents.

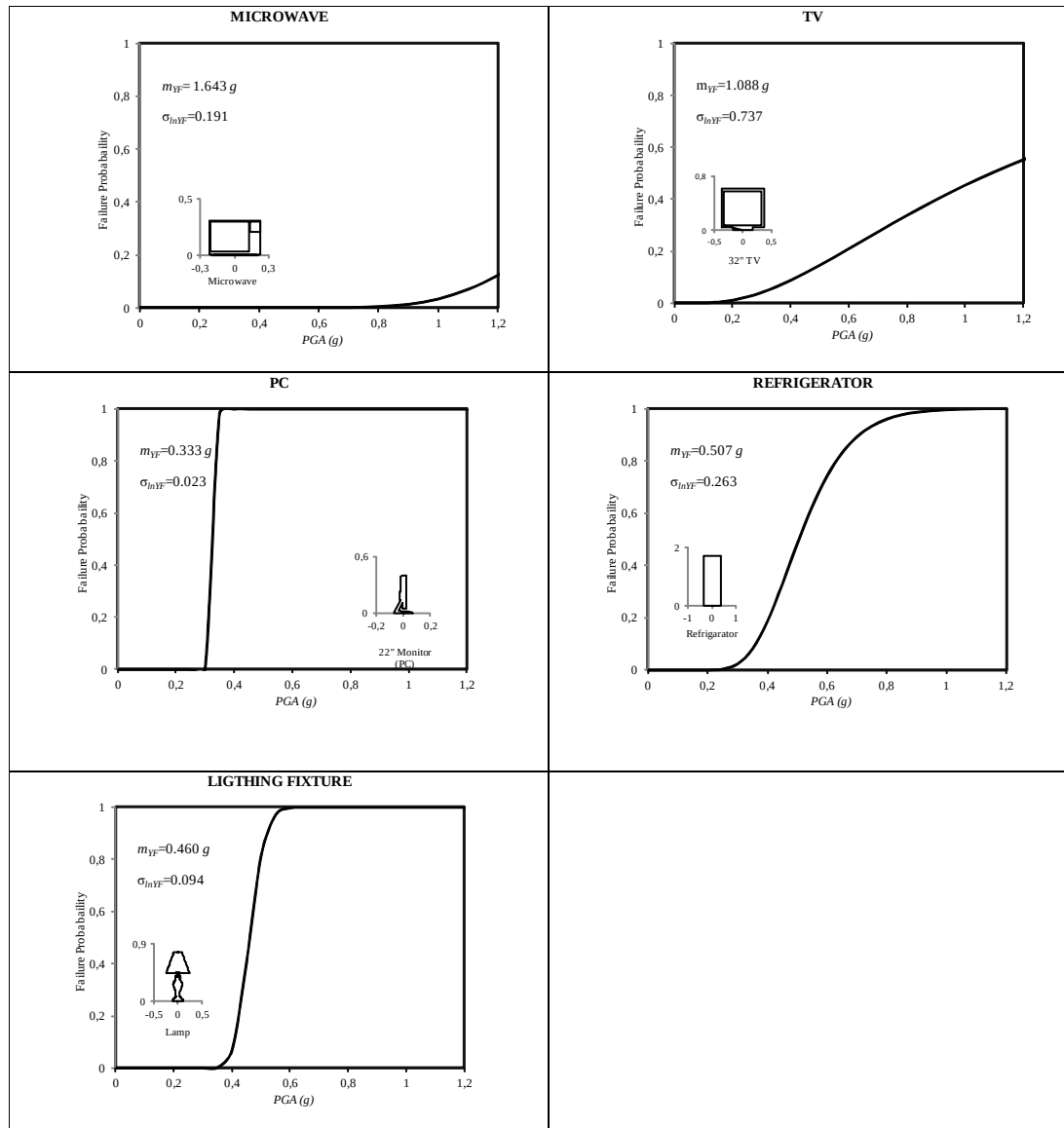


Figure 3.4 : Overturning probability for less hazardous appliances & contents.

Table 3.2 : Mean, standard deviation and sample overturning probabilities for appliances & contents used in the model.

	Water Heater	Portable Heater	Cooking Stove	SCFM	Industrial Products	Microwave	32" TV	PC	Refrigerator	Lighting Fixture
$m_{YF}(g)$	0,613	0,071	0,298	0,655	0,415	1,643	1,088	0,333	0,506	0,460
σ_{lnYF}	0,742	0,306	0,003	0,085	0,753	0,270	0,737	0,023	0,263	0,094
PGA (g)	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$	$F_{YF}(y)$
0,00	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
0,10	0,0073	0,8685	0,0000	0,0000	0,0294	0,0000	0,0006	0,0000	0,0000	0,0000
0,15	0,0289	0,9927	0,0000	0,0000	0,0883	0,0000	0,0036	0,0000	0,0000	0,0000
0,20	0,0656	0,9996	0,0000	0,0000	0,1662	0,0000	0,0108	0,0000	0,0002	0,0000
0,25	0,1134	1,0000	0,0000	0,0000	0,2505	0,0000	0,0230	0,0000	0,0037	0,0000
0,30	0,1678	1,0000	0,9871	0,0000	0,3333	0,0000	0,0402	0,0000	0,0234	0,0000
0,35	0,2250	1,0000	1,0000	0,0000	0,4105	0,0000	0,0619	0,9848	0,0805	0,0018
0,40	0,2825	1,0000	1,0000	0,0000	0,4805	0,0000	0,0873	1,0000	0,1857	0,0685
0,45	0,3385	1,0000	1,0000	0,0000	0,5428	0,0000	0,1155	1,0000	0,3278	0,4076
0,50	0,3918	1,0000	1,0000	0,0007	0,5977	0,0000	0,1457	1,0000	0,4819	0,8125
0,55	0,4419	1,0000	1,0000	0,0199	0,6458	0,0000	0,1773	1,0000	0,6244	0,9713
0,60	0,4885	1,0000	1,0000	0,1511	0,6878	0,0001	0,2097	1,0000	0,7415	0,9976
0,65	0,5315	1,0000	1,0000	0,4641	0,7244	0,0003	0,2423	1,0000	0,8295	0,9999
0,70	0,5710	1,0000	1,0000	0,7828	0,7563	0,0008	0,2748	1,0000	0,8914	1,0000
0,75	0,6071	1,0000	1,0000	0,9445	0,7840	0,0018	0,3069	1,0000	0,9327	1,0000
0,80	0,6401	1,0000	1,0000	0,9907	0,8083	0,0038	0,3383	1,0000	0,9592	1,0000
0,85	0,6702	1,0000	1,0000	0,9989	0,8295	0,0073	0,3688	1,0000	0,9757	1,0000
0,90	0,6976	1,0000	1,0000	0,9999	0,8480	0,0129	0,3984	1,0000	0,9857	1,0000
0,95	0,7225	1,0000	1,0000	1,0000	0,8643	0,0212	0,4270	1,0000	0,9917	1,0000
1,00	0,7452	1,0000	1,0000	1,0000	0,8786	0,0330	0,4544	1,0000	0,9952	1,0000

3.1.2.3 Weighting components with analytical hierarchy process

Analytical Hierarchy Process (AHP) is a method of prioritizing different components in decision making. The method based on pairwise comparison of components. Importances of components are determined by creating a pairwise comparison matrix. Pairwise comparisons should be performed by experts of the subject. The comparisons are made using a scale of absolute judgements that represents how much more one element dominates another with respect to a given attribute.

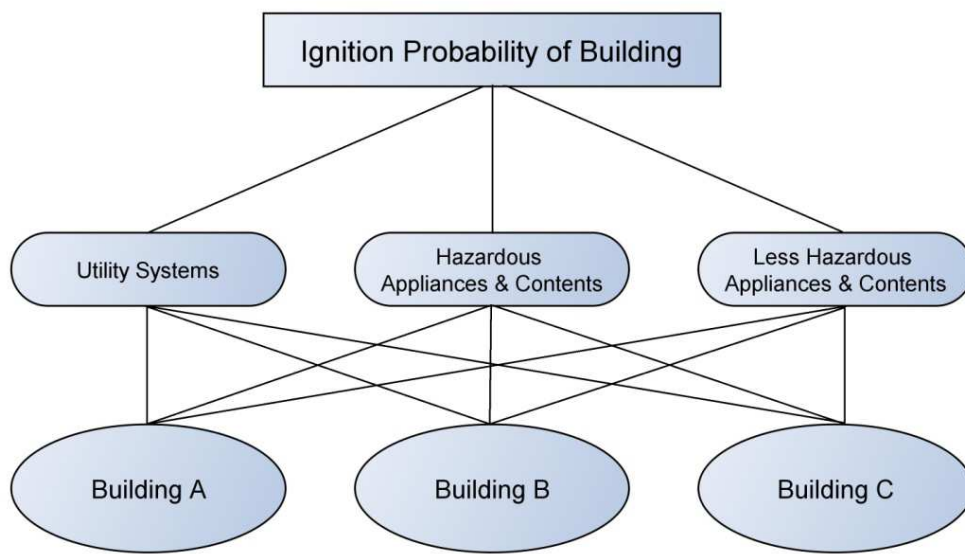


Figure 3.5 : Structure of AHP for post-earthquake ignition.

In a pairwise comparison matrix, the number (a_{ij}) in the i_{th} row and j_{th} column gives the relative importance of C_i as compared with O_j . a_{ji} is equal to $1/a_{ij}$. This means reciprocal of a comparison is transpose of it.

Table 3.3 : The fundamental scale of absolute numbers in AHP (Saaty, 2008).

Intensity of Importance	Definition
1	Equal Importance
2	Slight importance
3	Moderate importance
4	Moderate plus importance
5	Strong importance
6	Strong plus importance
7	Very strong or demonstrated importance
8	Very, very strong importance
9	Extreme importance

A questionnaire was prepared to weight the components of post-earthquake ignitions. Questionnaire includes pairwise comparison of

- water heater, portable heater, cooking stove, shelves containing flammable material and industrial products
- microwave, TV, PC, refrigerator and lighting fixture
- three main components (utility systems, hazardous and less hazardous appliances).

Figure 3.6 shows an example of pairwise comparison. For given example, Utility systems component has moderate importance (3) with respect to Hazardous Appliances & Contents.

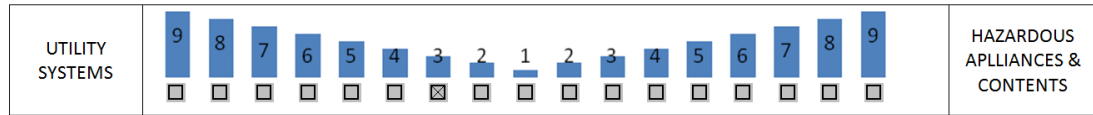


Figure 3.6 : Example of a pairwise comparison from questionnaire.

Questionnaire was evaluated by seven scientists having experiences about earthquake engineering and post earthquake fires. Results were evaluated to calculate weights (significance) of all main components and subcomponents.

Pairwise comparison of water heater, cooking stove, shelves containing flammable materials and portable heater were performed to prioritize components of hazardous appliances and contents and determine the weights of them (Table 3.4).

Table 3.4 : Pairwise comparison matrix and weights of hazardous appliances and contents.

	Water Heater	Portable Heater	Cooking Stove	Shelves Con. Flam. Mat.	Industrial Products	Weights
Water Heater	1,000	1,088	0,781	1,694	1,448	0,22088
Portable Heater	0,919	1,000	1,472	2,380	2,280	0,28324
Cooking Stove	1,280	0,679	1,000	1,811	2,188	0,24263
Shelves Con. Flam. Mat.	0,590	0,420	0,552	1,000	1,076	0,12795
Industrial Products	0,691	0,439	0,457	0,930	1,000	0,12529

Post-earthquake ignition probability caused by hazardous appliances and contents can be calculated by using the equation (3.4).

$$P_{HA} = 0.22088 \times P_{WH} + 0.28324 \times P_{PH} + 0.24263 \times P_{CS} + 0.12795 \times P_{SCFM} + 0.12529 \times P_{IP} \quad (3.4)$$

The same process was performed to components of less hazardous appliances and contents (Table 3.5).

Table 3.5 : Pairwise comparison matrix and weights of less hazardous appliances and contents.

	Microwave	TV	PC	Refrigerator	Lighting Fixture	Weights
Microwave	1,000	1,170	2,034	2,567	0,635	0,23602
TV	0,855	1,000	1,534	2,583	0,615	0,20793
PC	0,492	0,652	1,000	1,458	0,436	0,13098
Refrigerator	0,390	0,387	0,686	1,000	0,247	0,08623
Lighting Fixture	1,575	1,626	2,296	4,054	1,000	0,33885

Post-earthquake ignition probability caused by less hazardous appliances and contents can be calculated by using the equation (3.5).

$$P_{LHA} = 0.23602 \times P_{MW} + 0.20793 \times P_{TV} + 0.13098 \times P_{PC} + 0.08623 \times P_R + 0.33885 \times P_{LF} \quad (3.5)$$

In order to prioritize main components and obtain overall weighting of them, utility system, hazardous appliances and less hazardous appliances were compared in pairs (Table 3.6).

Table 3.6 : Pairwise comparison matrix and weights of main components.

	Utility System	Hazardous Appliances	Less Hazardous Appliances	Weights
Utility System	1,000	1,170	2,034	0,23602
Hazardous Appliances	0,390	0,387	0,686	0,08623
Less Hazardous Appliances	1,575	1,626	2,296	0,33885

According to these pairwise comparisons, utility system is the most important component in post-earthquake ignition occurrence. The overall equation of post-

earthquake ignition was obtained by using AHP. Post-earthquake ignition probability of a building can be calculated by using equation (3.6).

$$P_{(ig)} = 0.51588 \times P_{US} + 0.38378 \times P_{HA} + 0.10034 \times P_{LHA} \quad (3.6)$$

3.1.2.4 Determination of existence probabilities of appliances and contents according to occupancy

Assuming all the appliances and contents are existed in all occupancy types of buildings is not a realistic approach. In order to make our model more reliable and realistic, an existence probability is used for each appliance or content for each type of occupancy class.

Residential Energy Consumption Survey (RECS) and Commercial Buildings Energy Consumption Survey (CBECS) data from United States Energy Information Administration (USEIA) was used to produce existence probabilities of appliances. RECS data was produced in 2009 and CBECS data was produced in 2003. RECS and CBECS contain the number of buildings that include particular appliances and total number of buildings for particular occupancy types.

Since occupancy types in CBECS are different from MAEViz occupancy types (Table 3.7), a matching process was carried out to determine existence probabilities for MAEViz occupancy types (Table 3.8).

Table 3.7 : MAEViz occupancy types.

Label	Occupancy Class	Example Descriptions
Residential		
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Instutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
Commercial		
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	

Table 3.7 (cont.): MAEViz occupancy types.

Label	Occupancy Class	Example Descriptions
	Commercial	
COM8	Entertainment/Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
	Industrial	
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory
IND5	High Technology	Factory
IND6	Construction	Office
	Agriculture	
AGR1	Agriculture	
	Religion/Non-Profit	
REL1	Church/Non-Profit	
	Government	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
	Education	
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

Table 3.8 : Matching of USEIA and MAEViz occupancy types.

Occupancy (USEIA)	Occupancy (MAEviz)
Education	EDU1, EDU2
Food Sales	COM8
Food Service	COM8
Health Care (Inpatient)	COM6
Health Care (Outpatient)	COM7
Lodging	RES4, RES5
Retail (Other Than Mall)	COM1
Office	COM4, COM5
Public Assembly	GOV1
Public Order and Safety	GOV2
Religious Worship	REL1
Service	COM3
Warehouse and Storage	COM2, AGR1

According to RECS data, existence probabilities of water heater, cooking stove, microwave, portable heater, refrigerator, TV and PC for residential occupancies were produced (Table 3.9).

Table 3.9 : Existence probabilities of appliances for residential buildings.

Total Number of Buildings: 113.600.000		
	Number	Percentage
Water Heater	110.800.000	0,975
Cooking Stove	102.300.000	0,901
Microwave	109.000.000	0,960
Portable Heater	4.900.000	0,043
Refrigerator	113.400.000	0,998
TV	112.200.000	0,988
PC	86.300.000	0,760

Existence probabilities of water heater, cooking stove, lighting fixtures, portable heater and refrigerator for commercial buildings were produced by using data from CBECS (Table 3.10).

Existence probabilities of appliances and contents for MAEViz occupancy types were determined according to produced probabilities from USEIA surveys (Table 3.11). HAZTURK (MAEViz) software is able to use this file in CSV format.

Table 3.10 : Existence probabilities of appliances for commercial buildings (* million).

Occupancy	All Buildings*	Water Heater		Cooking Stove		Lighting Fixtures		Portable Heater		Refrigerator	
		Number*	Probability	Number*	Probability	Number*	Probability	Number*	Probability	Number*	Probability
Education	386	298	0,772	125	0,324	384	0,995	178	0,461	254	0,658
Food Sales	226	186	0,823	84	0,372	221	0,978			212	0,938
Food Service	297	297	1,000	284	0,956	296	0,997	153	0,515	296	0,997
Health Care	129	127	0,984	12	0,093	129	1,000	82	0,636	116	0,899
Inpatient	8	8	1,000	7	0,875	8	1,000			8	1,000
Outpatient	121	119	0,983			121	1,000	77	0,636	108	0,893
Lodging	142	142	1,000	47	0,331	142	1,000	88	0,620	126	0,887
Retail	443	314	0,709	14	0,032	442	0,998	302	0,682	319	0,720
Office	824	733	0,890	23	0,028	824	1,000	519	0,630	643	0,780
Public Assembly	277	227	0,819	73	0,264	264	0,953	166	0,599	210	0,758
Public Order and Safety	71	70	0,986	14	0,197	68	0,958			67	0,944
Religious Worship	370	315	0,851	108	0,292	370	1,000	264	0,714	271	0,732
Service	622	418	0,672			582	0,936	419	0,674	362	0,582
Warehouse and Storage	597	243	0,407			414	0,693	254	0,425	225	0,377

Table 3.11 : Appliance existence probabilities.

	WH	PH	CS	SCFM	IP	MW	TV	PC	RE	LF
RES1	0,975	0,224	0,901	1	0	0,96	0,988	0,76	0,998	1
RES2	0,975	0,224	0,901	1	0	0,96	0,988	0,76	0,998	1
RES3	0,975	0,224	0,901	1	0	0,96	0,988	0,76	0,998	1
RES4	1	0,62	0,331	1	0	1	1	0,1	0,887	1
RES5	1	0,62	0,331	1	0	0,2	1	1	0,887	1
RES6	0,975	0,224	0,901	1	0	0,96	0,988	0,76	0,998	1
COM1	0,709	0,682	0,032	0,2	0,2	0,2	0,5	1	0,72	0,998
COM2	0,407	0,425	0	1	1	0,2	0,2	0,2	0,377	0,693
COM3	0,672	0,674	0	1	0,2	0,2	0,5	1	0,582	0,936
COM4	0,89	0,63	0,028	0,2	0,2	0,2	1	1	0,78	1
COM5	0,89	0,63	0,028	0,2	0	0,2	1	1	0,78	1
COM6	1	0,5	0,875	1	1	0,2	1	1	1	1
COM7	0,983	0,636	0,2	1	1	0,2	0,2	1	0,893	1
COM8	0,924	0,293	0,704	1	0	0,2	0,5	1	0,971	0,989
COM9	1	0,5	0,05	0	0	0,2	0,5	1	0,2	1
COM10	0	0	0	0	0	0	0,2	1	0	1
IND1	1	0,2	1	1	1	0,2	0,2	1	0,2	1
IND2	1	0,2	1	1	1	0,2	0,2	1	0,2	1
IND3	1	0,2	1	1	1	0,2	0,2	1	0,2	1
IND4	1	0,2	1	1	1	0,2	0,2	1	0,2	1
IND5	1	0,2	1	1	1	0,2	0,2	1	0,2	1
IND6	0	0	0	0	1	0	0	0	0	0
AGR1	0,407	0,425	0	0,5	0,2	0,2	0,5	0,5	0,377	0,693
REL1	0,851	0,714	0,292	0,2	0	0,2	0,2	1	0,732	1
GOV1	0,819	0,599	0,264	0,2	0,2	0,2	1	1	0,758	0,953
GOV2	0,986	0,2	0,197	0,2	1	0,2	0,2	1	0,944	0,958
EDU1	0,772	0,461	0,324	1	1	0,2	1	1	0,658	0,995
EDU2	0,772	0,461	0,324	1	1	0,2	1	1	0,658	0,995

3.1.2.5 Using past earthquake records and producing threshold values

Past earthquake records are important for this study to determine the location of ignited buildings. In order to determine the number and location of ignited buildings from ignition probabilities of buildings, producing a threshold ignition probability is required. PGA values, number of storeys, occupancy type, building age and structure type are necessary to obtain ignition probabilities of ignited buildings in past earthquakes.

Ignition records of the 1994 Northridge Earthquake were derived from the report prepared by Scawthorn, Cowell and Borden. The report was prepared for US National Institute of Standards and Technology.

Scawthorn et al. (1998) collected ignition records from Los Angeles Fire Department (LAFD) and Santa Monica Fire Department (SMFD) field incident reports logged on January 17, 1994, from 4:31AM to 11:59PM. These records were retained in a database termed Fire Following the Northridge Earthquake (FFNRE). FFNRE database contains various type of data related to each ignition (Table 3.12 and 3.13). Address, number of storeys, occupancy type and construction type data were used as attributes for our study.

Table 3.12 : LAFD incident reports, January 17, 1994 (earthquake-related fires only) (Scawthorn et al., 1998).

IKEY	AT	SCNE_TIME	TYPE_INC	LOCATION	CEN_TRACT	USE_GEN	AGT_APT_T	KNK_DWN_T	AREA_ORIG	FORM_IGN	IGN_FACT	CONTRIB_1
9401170101	04.36.38	04.42.00	11	1118 W 3rd St	3202000	41	444	630	26	36	82	399
9401178100	04.53.10	04.53.00	12	15455 N Glenoaks Blvd	1064020	41			71	21	82	804
9401178138	04.58.50	05.10.00	11	11742 Luanda St	1043000	41			0	0	82	
9401178045	05.08.02	05.10.00	11	21601 San Jose St	1132130	41	444	449	47	30	82	
9401178172	05.12.36	05.35.56	11	19443 W Ventura Blvd	1394000	0	441	520	0	0	82	804
9401170154	05.19.20	05.32.43	11	365 W 47th Pl	2319000	41	455	515	24	14	82	804
9401170180	05.26.08	05.28.37	11	10949 N McVine Ave	1031000	41	515	525	47	14	82	480
9401178040	05.27.10	05.27.00	11	15445 Cobalt St	1064020	41	505	0	62	14	82	720
9401170227	05.27.30	05.33.00	11	2741 S Palm Grove Ave	2196000	41			71	14	82	720
9401170245	05.46.06	05.50.00	11	7655 N Delia Ave	1222000	41			0	0	82	
9401178273	05.59.54	06.04.00	12	8801 N Eton Ave	1132030	41	535	600	25	14	82	206
9401170275	06.13.00	06.30.00	11	8901 N Eton Ave	1132030	41			0	0	82	
9401170310	14.27.00	14.31.10	11	5842 W Harold Way	1910000	41	535	555	21	21	82	804
9401170315	15.01.22	15.02.22	17	11700 N Balboa Blvd	1111000	96	500	700	99	36	82	804
9401170317	15.40.24	15.44.00	11	2324 S Chariton St	2703000	41	534	544	14	14	82	804
9401178059	16.12.42	16.20.00	11	20033 N Gypsy Ln	1375040	41	532	540	47	14	82	804
9401178027	16.40.24	16.47.00	11	3845 N Bobstone Dr	1417000	41	538	630	21	36	82	
9401170389	17.22.40	17.27.02	11	7820 W De Longpre Ave	1944000	41	552	512	14	81	54	804
9401170436	18.26.56	18.36.18	11	1622 N Serrano Ave	1904000	42	610	615	75	33	82	804
9401178009	18.26.04	18.28.00	12	215005 Lassen St	1132130	41	604	700	0	0	82	804
9401170480	18.37.10	18.47.00	17	634 W Omelveny Ave	1095000	96	635	800	92	48	82	804
9401177004	19.00.00	08.00.00	11	2400 S Beverly Dr	2695000	41	632	640	62	15	82	804
9401175006	19.17.48	19.23.10	11	10763 N Forbes Ave	1111020	41	630	645	47	14	82	804
9401176013	19.23.06	19.31.50	11	3024 S Livonia Ave	2697000	42			21	46	82	
9401176022	19.42.26	19.48.52	11	42082 S 10th Ave	2343000	41			21	34	82	
9401175035	20.21.44	20.37.36	11	10630 N Louise Ave	1113010	41			0	0	82	804

Table 3.12 (cont.):LAFD incident reports, January 17, 1994 (earthquake-related fires only) (Scawthorn et al., 1998).

IKEY	AT	SCNE_TIME	TYPE_INC	LOCATION	CEN_TRACT	USE_GEN	AGT_APT_T	KNK_DWN_T	AREA_ORIG	FORM_IGN	IGN_FACT	CONTRIB_1
9401176059	21.49.16	21.57.58	11	4230 S 11th Ave	2343000	96			73	0	82	
9401178207	22.11.24	22.23.36	11	9250 Owensmouth Ave	1132020	89			41	0	82	
9401176096	22.19.04	22.24.20	11	18111 W Nordhoff St	1151020	21	820	845	31	72	82	480
9401178243	22.22.44	22.26.00	11	Nordhoff/Vanalden	1151020	41			41	43	82	
9401178110	22.32.38	22.42.26	11	18111 W Nordhoff St	1151020	21	915	930	31	72	82	480
9401177080	22.52.34	22.57.22	11	7138 W Greeley St	1012000	42			24	46	82	
9401178091	22.55.34	23.00.00	11	1818 S Stoner Ave	2672000	42			21	32	82	
9401176129	23.14.52	23.21.44	11	10157 Wisner Ave	1096020	41			24	14	82	
9401176134	23.27.06	23.41.48	11	2517 W 54th St	2346000	42			14	15	54	804
9401175085	17.32.00	17.37.00	11	9108 W 25th St	2697000	41			75	0	82	
9401177098	06.27.00	06.28.00	11	6132 W De Longpre Ave	1908000	42	944	100	62	81	82	804
9401177103	06.52.00	07.41.00	11	2421 N Creston Way	1896000	41	101	103	21	36	53	804
9401176172	09.18.00	09.25.00	17	18100 W Strathern St	1314000	61	100	102	92	17	82	804
9401176181	10.45.00	10.45.00	11	2134 W 54th St	2325000	41			24	34	82	
9401176200	12.59.00	13.28.00	11	17609 W Ventura Blvd	1395000	59			62	81	82	804
9401175131	06.31.00	06.35.00	11	4500 N Woodman Ave	1246000	42	104	105	24	14	82	804
9401176218	06.37.00	06.45.00	11	14225 W Ventura Blvd	1412000	59			51	0	82	
9401176226	06.43.00	06.45.00	17	4618 N Sylmar Ave	1412000	92			94	35	58	804
9401176235	07.09.00	07.12.00	11	12036 W Ventura Blvd	1436020	16			25	34	82	
9401176250	08.02.00	08.05.00	11	14569 W Benefit St	1413010	42			24	46	82	
9401177175	08.56.00	09.01.00	11	10885 N Jamie Ave	1041020	88			47	0	82	
9401176257	08.59.00	09.07.00	11	7237 N Anatola Ave	1319000	41	120	120	21	34	82	804
9401177053	09.57.00	10.00.00	11	17515 W Enadia Way	1319000	41	123	125	47	34	82	804

Table 3.13 : SMFD incident reports, January 17, 1994 (earthquake-related fires only) (Scawthorn et al., 1998).

FDID1	PROYEAR	INCNUM	INCEXP	CORREC	INCDATE	DISTIME	ARVTIME	ENDTIME	FOUND1	AIDTYPE	ALARMTH	INCADDR	INCROOM	INCZIP	GENERAL	SPECIES	OCCUPCY	STRUCTP	STRUCT
19180	94	9400000311	0	1	940117	236	239	400	11	8	7	1255 20th St		90404	92	929	R10	1	5
19180	94	9400000317	1	1	940117	451	455	1030	11	8	7	914 14th St		90403	42	424	R10	1	2
19180	94	9400000317	2	1	940117	451	455	1030	11	8	7	1324 Idaho Ave		90403	42	422	R10	1	2
19180	94	9400000317	3	1	940117	451	455	1030	11	8	7	909 Euclid St		90403	42	422	R10	1	2
19180	94	9400000317	0	1	940117	451	455	1030	11	8	7	908 14th St		90403	42	424	R10	1	2
19180	94	9400000319	0	1	940117	511	512	636	11	8	7	1446 7th St		90401	42	422	R10	1	2
19180	94	9400000361	0	1	940117	801	806	849	11	8	7	838 9th St		90403	42	422	R10	5	2
19180	94	9400000479	0	1	940117	1433	1437	1630	11	8	7	908 14th St		90403	42	423	R10	1	2
19180	94	9400000492	0	1	940117	1545	1546	1550	11	8	7	457 Lincoln Blvd		90402	41	411	R30	1	2
19180	94	9400000514	0	1	940117	1844	1848	1935	11	8	7	829 Pacific St	2	90405	41	410	R10	1	2
19180	94	9400000518	0	1	940117	1913	1918	2000	11	8	7	1339 3rd St		90401	59	591	B20	1	2
19180	94	9400000519	0	1	940117	1955	1958	2041	11	8	7	3400 Pico Blvd		90405	96	962			
19180	94	9400001500	0	1	940117	330	331	345	11	8	6	2030 Wilshire Blvd		90403	16	163	B20	1	1
19180	94	9400001118	0	1	940117	1200	1230	1230	11	8	7	3232 Broadway		90404	42	424	R10	1	2

As we use PGA as input in our model, we need to obtain PGA values for each building that ignition occurred in the 1994 Northridge earthquake. PGA and 1.0 sec Spectral Acceleration (Sa) maps were downloaded from the United States Geological Survey (USGS) website in *.shp format compatible with geographical information system (GIS) software (Figure 3.7).

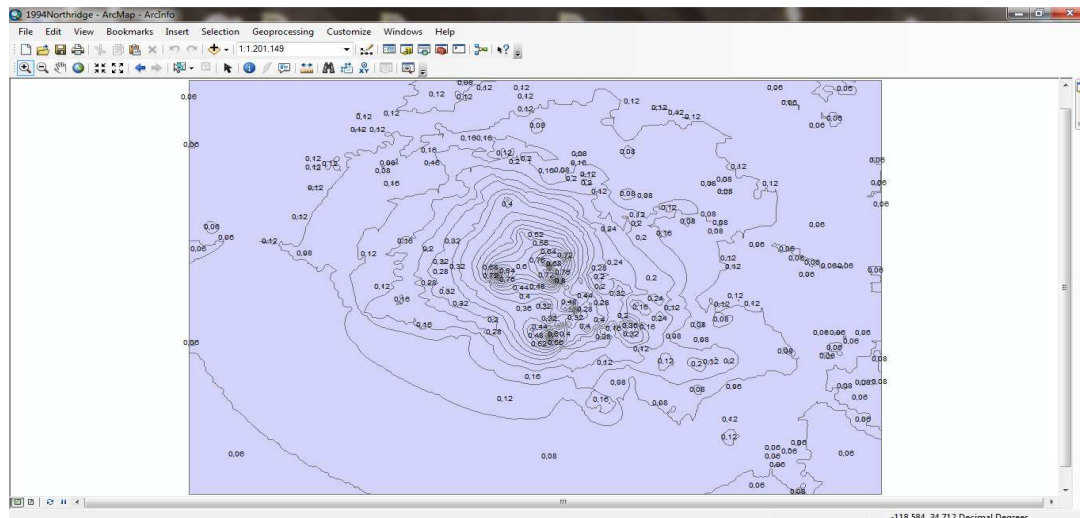


Figure 3.7 : USGS ShakeMap (PGA) of the 1994 Northridge earthquake.

FFNRE database contains location of ignitions in the form of building number and street address. In order to match location of ignitions with appropriate PGA values, addresses were converted to locations with geographical coordinates by using geocoding method (Figure 3.8 and 3.9). Geocoding is the process of converting addresses (like “1118 West 3rd Street, Los Angeles, CA”) into geographic coordinates (like latitude 34.057 and longitude -118.257). Google Maps application was used to do this operation.

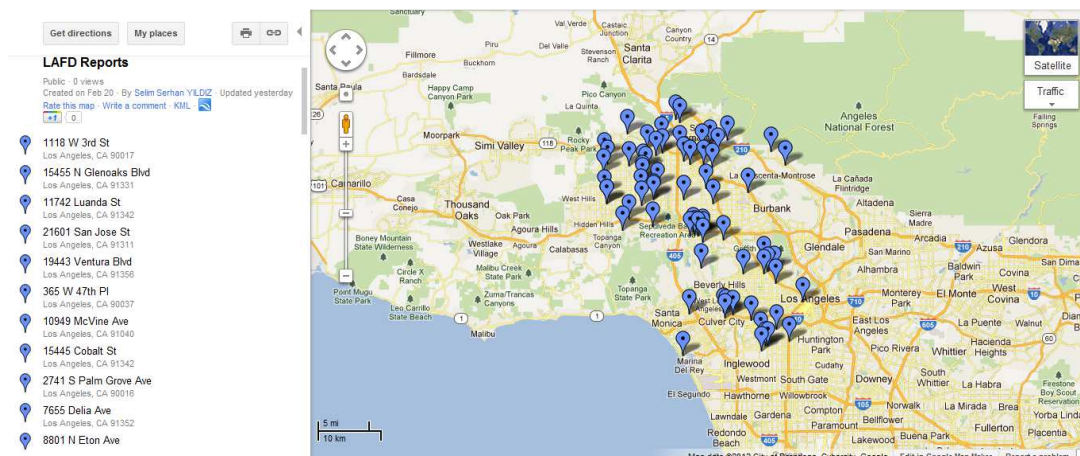


Figure 3.8 : Ignitions obtained from LAFD reports on Google Maps.

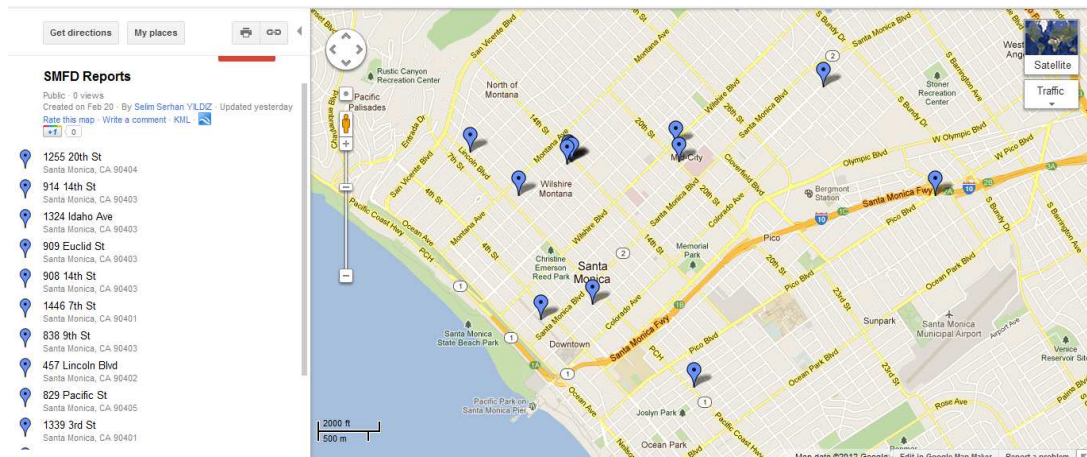


Figure 3.9 : Ignitions obtained from SMFD reports on Google Maps.

All addresses were determined on Google Map and saved as KML files for LAFD and SMFD records, separately. These KML files were converted to shape files by using ArcGIS software. Then, PGA values were matched with each ignition record. PGA value, number of storeys, occupancy type and construction type were added for each building in an attribute table (Figure 3.10).

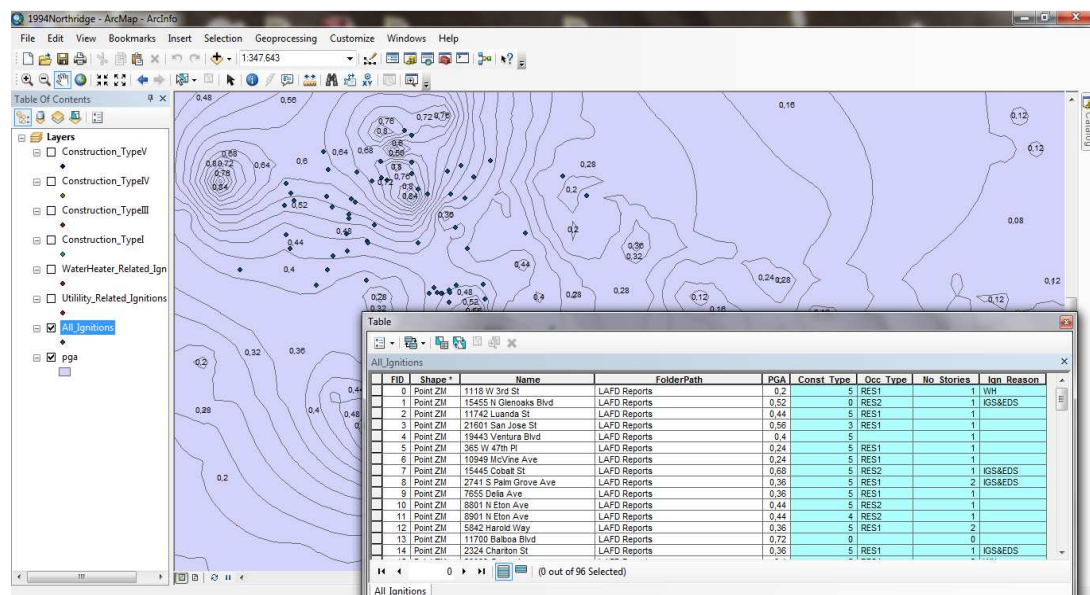


Figure 3.10 : Ignitions with PGA value, number of storeys, occupancy type and construction type.

Because FFNRE database does not contain structure types of buildings, structure types were obtained by matching construction types with structure types used in MAEViz software (Table 3.14). There are five construction types identified in FFNRE database (Table 3.15).

Table 3.14 : Structure types used in MAEViz.

No	Label	Description	Height			
			Range		Typical	
			Name	Storeys	Storeys	Feet
1	W1	Wood, Light Frame (£5,000 sq. ft.)		1-2	1	14
2	W2	Wood, Commercial and Industrial (>5,000 sq. ft.)		All	2	24
3	S1L	Steel Moment Frame	Low-Rise	1-3	2	24
4	S1M		Mid-Rise	4-7	5	60
5	S1H		High-Rise	8+	13	156
6	S2L	Steel Braced Frame	Low-Rise	1-3	2	24
7	S2M		Mid-Rise	4-7	5	60
8	S2H		High-Rise	8+	13	156
9	S3	Steel Light Frame		All	1	15
10	S4L	Steel Frame with Cast- in-Place Concrete	Low-Rise	1-3	2	24
11	S4M		Mid-Rise	4-7	5	60
12	S4H		High-Rise	8+	13	156
13	S5L	Steel Frame with Unreinforced Masonry	Low-Rise	1-3	2	24
14	S5M		Mid-Rise	4-7	5	60
15	S5H		High-Rise	8+	13	156
16	C1L	Concrete Moment Frame	Low-Rise	1-3	2	20
17	C1M		Mid-Rise	4-7	5	50
18	C1H		High-Rise	8+	12	120
19	C2L	Concrete Shear Walls	Low-Rise	1-3	2	20
20	C2M		Mid-Rise	4-7	5	50
21	C2H		High-Rise	8+	12	120
22	C3L	Concrete Frame with Unreinforced Masonry	Low-Rise	1-3	2	20
23	C3M		Mid-Rise	4-7	5	50
24	C3H		High-Rise	8+	12	120
25	PC1	Precast Concrete Tilt- Up Walls		All	1	15
26	PC2L	Precast Concrete Frames with Concrete	Low-Rise	1-3	2	20
27	PC2M		Mid-Rise	4-7	5	50
28	PC2H		High-Rise	8+	12	120
29	RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	20
30	RM1M		Mid-Rise	4+	5	50
31	RM2L		Low-Rise	1-3	2	20
32	RM2M	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Mid-Rise	4-7	5	50
33	RM2H		High-Rise	8+	12	120
34	URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	1	15
35	URMM		Mid-Rise	3+	3	35
36	MH	Mobile Homes		All	1	10

Table 3.15 : Construction types in FFNRE database.

TYPE I	Noncombustible highrise
TYPE II	Smaller noncombustible
TYPE III	Noncombustible walls, Combustible roof, floor
TYPE IV	Noncombustible light metal or Concrete parking structure
TYPE V	Combustible, Wood or Stucco

Matching of MAEViz structure types and FFNRE construction types was made with the help of a scientist who is experienced in MAEViz. As a result, matching table was obtained (Table 3.16).

Table 3.16 : Matching of MAEViz structure types and FFNRE construction types.

	FFNRE CONSTRUCTION TYPES				
	1	2	3	4	5
MAEViz STRUCTURE TYPES	S1M	S1L	C3L	S3	W1
	S1H	S2L	C3M	Park. Str.	W2
	S2M	S4L	C3H		MH
	S2H	S5L	RM1L		
	S4M	C1L	RM1M		
	S4H	C2L	URML		
	S5M	PC2L	URMM		
	S5H	RM2L			
	C1M				
	C1H				
	C2M				
	C2H				
	PC1				
	PC2M				
	PC2H				
	RM2M				
	RM2H				

According to this matching table, structure types of buildings, which were ignited in the 1994 Northridge Earthquake, were determined. A building was identified with different structure types, when matching addressed more than one structure type. For example, structure type of a university building at 18111 Nordhoff Street, Los Angeles was described as S1L, C1L, C2L, PC1 and PC2L, separately (Figure 3.11).

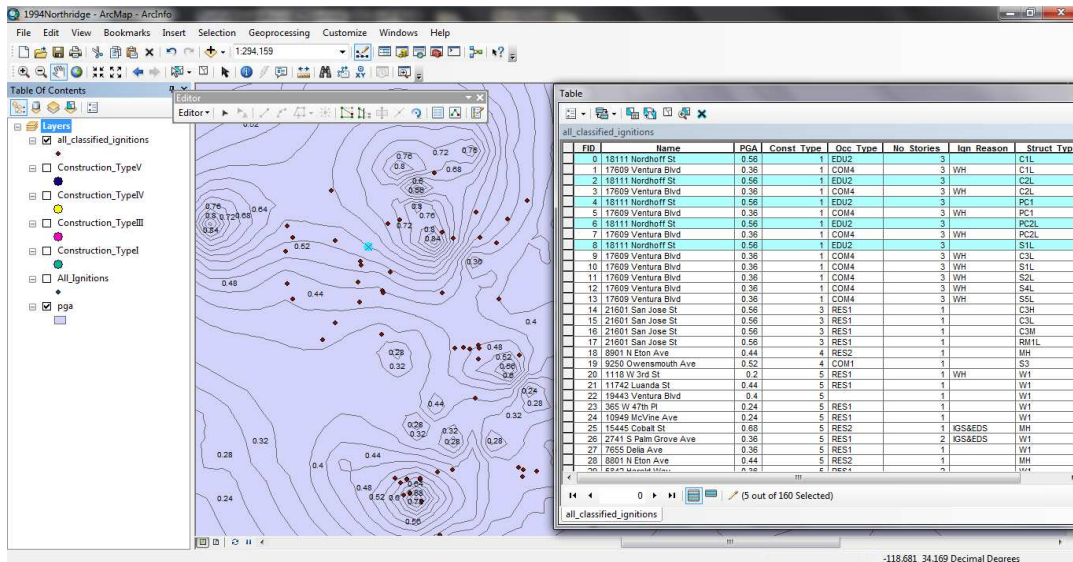


Figure 3.11 : Representing buildings with different structure types depending on construction type matching.

After determining the structure types of buildings, building damage analyses were performed to determine the damage probabilities of buildings according to occupancy type, number of storeys and structure type by using MAEViz software. 1.0 Sa map was used as hazard map for these analyses. Construction type of ignited buildings at 17609 Ventura Blvd and 18111 Nordhoff St were recorded as Type I-Noncombustible highrise but they had both 3 storeys. They were considered as low-rise building because of this reason and their structure types were designated as S1L, C1L, C2L, PC1 and PC2L, separately.

Building damage analyses were carried out for ignited buildings for all structure types according to matching table. Shape files were imported to MAEViz as building inventory v5.0 (Figure 3.12).

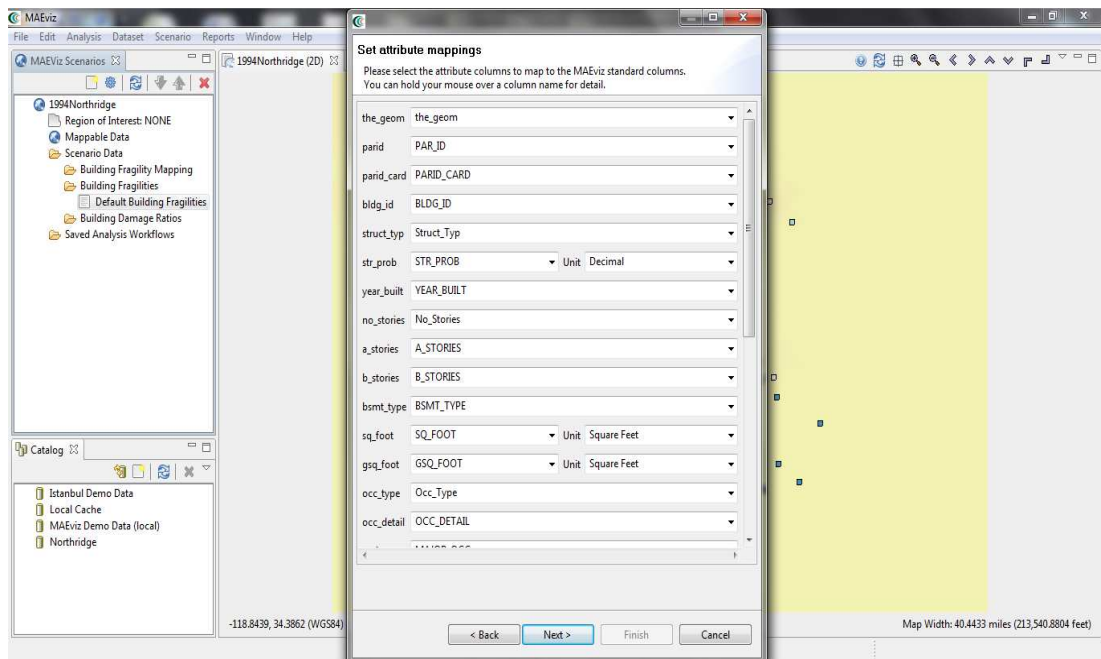


Figure 3.12 : Importing shape files of ignited buildings in the 1994 northridge earthquake.

Sa map was converted from shape file to raster file in ASCII format and imported to MAE Viz as a deterministic hazard (Figure 3.13 and 3.14).

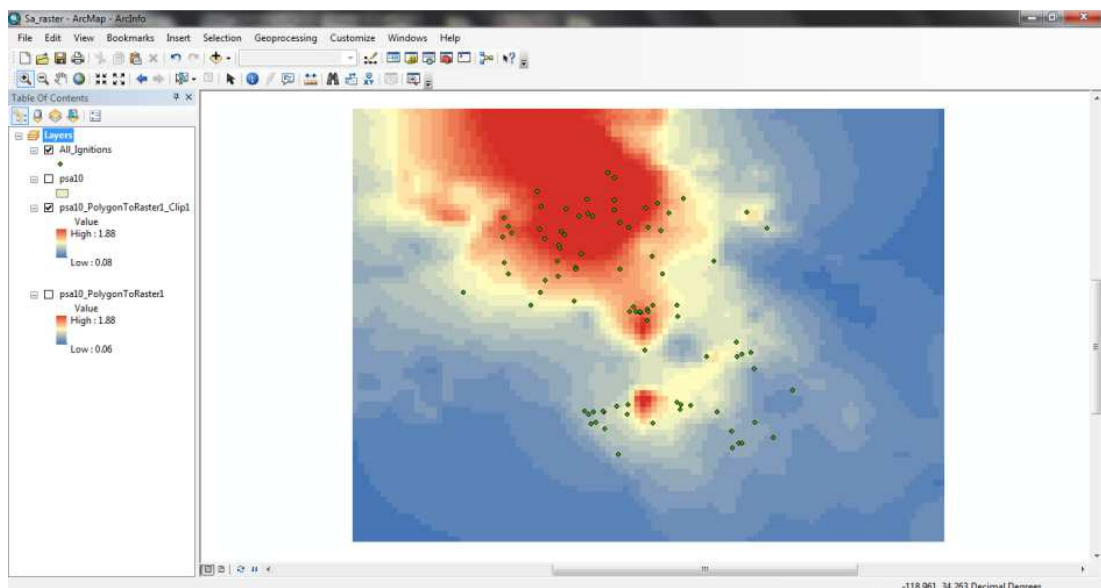


Figure 3.13 : 1.0 sec Sa map in raster format for the 1994 Northridge earthquake.

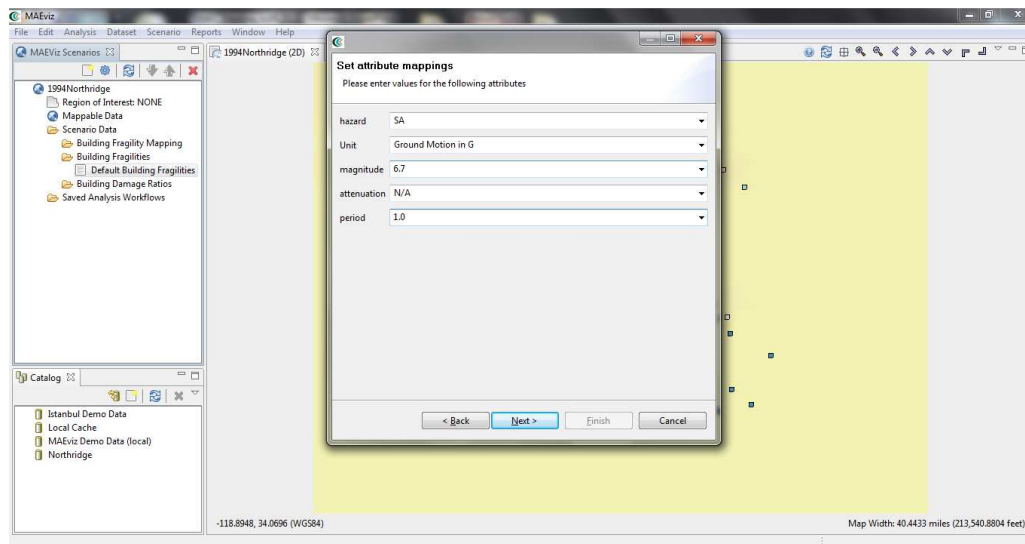


Figure 3.14 : Importing 1.0 sec Sa map for the 1994 Northridge earthquake.

Building damage probabilities were obtained from structural analysis (Figure 3.15). Building inventory, 1.0 sec Sa map, fragilities and fragility mapping for Western US and building damage ratios v1.1 were used in these analysis. MAEViz default fragility mapping file is using 0.2 sec Sa map as hazard map and this map is not available for the 1994 Northridge Earthquake. Fragility mapping file was modified to use 1.0 sec Sa map as hazard map. All of the ignited buildings were analyzed and building damages were obtained for them (Figure 3.16).

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Sa</td><td>1.04</td></tr><tr><td>0.33</td><td>0.40</td><td>0.20</td><td>0.07</td><td>0.24</td><td>0.27</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec Sa</td><td>0.20</td></tr><tr><td>0.27</td><td>0.40</td><td>0.23</td><td>0.10</td><td>0.28</td><td>0.29</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec Sa</td><td>0.28</td></tr><tr><td>0.22</td><td>0.40</td><td>0.26</td><td>0.12</td><td>0.32</td><td>0.30</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec Sa</td><td>0.36</td></tr><tr><td>0.13</td><td>0.35</td><td>0.31</td><td>0.22</td><td>0.42</td><td>0.33</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec Sa</td><td>0.72</td></tr><tr><td>0.07</td><td>0.27</td><td>0.33</td><td>0.33</td><td>0.52</td><td>0.33</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec Sa</td><td>0.92</td></tr><tr><td>0.10</td><td>0.32</td><td>0.32</td><td>0.26</td><td>0.46</td><td>0.33</td><td>Pre-Code</td><td>Pre-Code</td><td>1.0 sec 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Sa	0.72	0.12	0.34	0.31	0.22	0.43	0.33	Pre-Code	Pre-Code	1.0 sec Sa	0.76	0.21	0.39	0.26	0.14	0.33	0.31	Pre-Code	Pre-Code	1.0 sec Sa	0.40	0.14	0.35	0.30	0.21	0.41	0.32	Pre-Code	Pre-Code	1.0 sec Sa	0.68	0.18	0.38	0.28	0.16	0.36	0.32	Pre-Code	Pre-Code	1.0 sec Sa	0.48	0.33	0.40	0.20	0.07	0.24	0.27	Pre-Code	Pre-Code	1.0 sec Sa	0.20	0.29	0.41	0.22	0.09	0.26	0.28	Pre-Code	Pre-Code	1.0 sec Sa	0.24	0.29	0.41	0.22	0.09	0.26	0.28	Pre-Code	Pre-Code	1.0 sec Sa	0.24	0.08	0.20	0.37	0.36	0.56	0.32	Pre-Code	Pre-Code	1.0 sec Sa	0.48	0.17	0.38	0.29	0.17	0.37	0.32	Pre-Code	Pre-Code	1.0 sec Sa	0.52	0.29	0.41	0.22	0.09	0.26	0.28	Pre-Code	Pre-Code	1.0 sec Sa	0.24	0.10	0.32	0.32	0.26	0.46	0.33	Pre-Code	Pre-Code	1.0 sec Sa	0.92	0.24	0.40	0.24	0.11	0.30	0.30	Pre-Code	Pre-Code	1.0 sec Sa	0.32	0.12	0.34	0.31	0.22	0.43	0.33	Pre-Code	Pre-Code	1.0 sec Sa	0.76	0.12	0.34	0.31	0.22	0.43	0.33	Pre-Code	Pre-Code	1.0 sec Sa	0.76	0.02	0.10	0.27	0.60	0.71	0.28	Pre-Code	Pre-Code	1.0 sec 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Figure 3.15 : Building damage probabilities of ignited buildings in the 1994 Northridge earthquake.

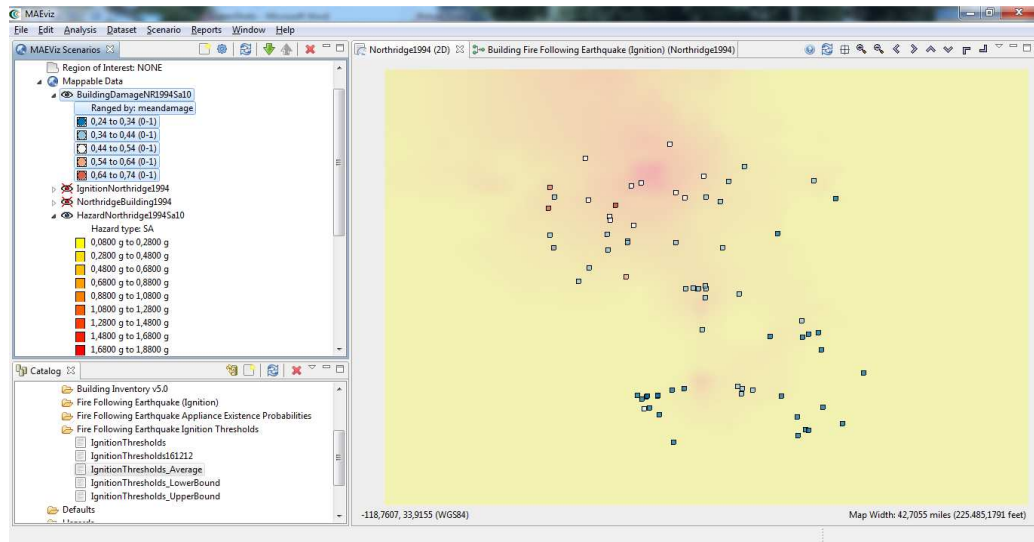


Figure 3.16 : Building damage analysis of ignited buildings in the 1994 Northridge earthquake.

Ignition probabilities of ignited buildings caused by utility systems, hazardous and less hazardous appliances&contents were calculated and overall ignition probability of these buildings were calculated to produce threshold values. Ignition probabilities of ignited buildings are given in Appendix A.

According to ignition probabilities of these burned buildings in the 1994 Northridge Earthquake, average threshold values and their standard deviations for different MAEViz structure types were calculated. Because of limited historical earthquake data, it was decided to determine three different thresholds for each structure type. Lower bound of threshold was calculated by subtracting one standard deviation from average threshold value and upper bound of threshold was calculated by adding one standard deviation to average threshold value. These average, lower and upper bound threshold values are given in Table 3.17. These threshold values could be improved depending on the new past earthquake ignition records.

Since the structure type of the ignited buildings is not known, each building was analyzed with all structure types according to construction type in the building damage analysis. For example, if construction type of a 4-storey building is 1, it is considered as nine different buildings with structure type of S1M, S2M, S4M, S5M, C1M, C2M, PC1, PC2M and RM2M. Although it is seen that there is only one data point for construction type 1 and 3, there are nine buildings for construction type 1 and three buildings for construction type 3 analyzed in the building damage analysis.

Table 3.17 : Ignition threshold values for different structure types.

	CONSTRUCTION TYPES				
	1	2	3	4	5
STRUCTURE TYPES	S1M	S1L	C3L	S3	W1
	S1H	S2L	C3M		W2
	S2M	S4L	C3H		MH
	S2H	S5L	RM1L		
	S4M	C1L	RM1M		
	S4H	C2L	URML		
	S5M	PC2L	URMM		
	S5H	RM2L			
	C1M				
	C1H				
	C2M				
	C2H				
	PC1				
	PC2M				
	PC2H				
	RM2M				
	RM2H				
Data Points	1(9)	0	1(3)	2	62
THRESHOLDS	0,45720	0,45720	0,43057	0,43877	0,26386
St. Dev.	0,02252	0,02252	0,02557	0,03380	0,07665
Lower Bound	0,43468	0,43468	0,40500	0,40497	0,18721
Upper Bound	0,47972	0,47972	0,45614	0,47257	0,34051

Most of the buildings that are seen not ignited after post-earthquake ignition analysis with average thresholds had ignitions caused by short circuit, heat radiation from normal equipment operation or fire spread from the neighboring buildings following the 1994 Northridge earthquake. It was also expected for some of the buildings in FFNRE inventory not to be ignited because the average thresholds were produced from the ignition probability of these buildings. The inventory constituted only from the burned buildings where, the reason of the fire was both ignition and spread. For example, ignition occurred in the building located at 2421 Creston Way was caused by heat radiation from normal equipment operation. Another example of ignition at 1622 N. Serrano Avenue was caused by short circuit. The last example for FFNRE inventory is ignition at 2517 W. 54th Street was caused by fire spread from the neighboring buildings.

3.2 Post-Earthquake Spread

Depending on the physics of structural fires, it was decided to consider two different phases of fire spread in intended model. These fire spread phases are development of fire in a building and fire spread between buildings.

3.2.1 Development of fire in a building

Approach of Zhao (2010) is selected as a reference for intended model. Development of fire in a building is defined with time intervals for four different fire phases depending on the structure type of building (Table 3.18).

Table 3.18 : Time intervals for different fire phases (Zhao, 2010).

Fire Stages	Time interval (min)	Structural type		
		Wooden	Fire-proof	Fire-resisting
Ignition - Flashover	t_1	[5,10]	[5,10]	[5,10]
Flashover - Full development	t_2	[20,30]	[30,50]	[50,60]
Full development - Collapse	t_3	[50,60]	[80,100]	[120,180]
Collapse - Extinguishment	t_4	[240,300]	[30,40]	[20,30]

Temperature and heat release rates for structural fires are considered in determining these time intervals (Figure 3.17).

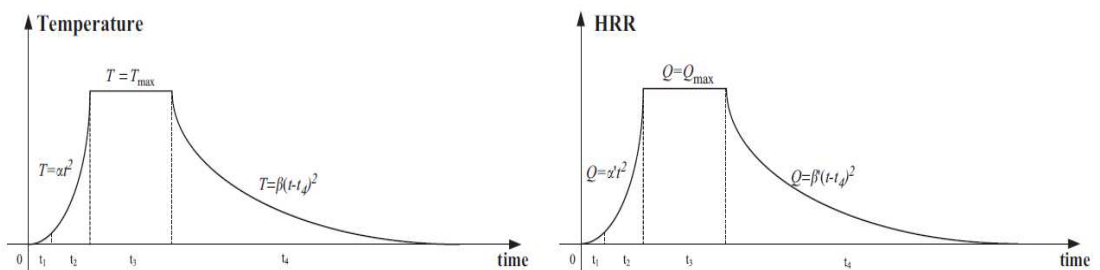


Figure 3.17 : Temperature and heat release rate curves for structural fires (Zhao, 2010).

Because structure types used in Zhao's model are different from MAEViz structure types, it is required to carry out a matching between these two structure types. Firstly, structure types in Zhao's model was matched with construction types in international building code (IBC) because both two approaches were done based on

the fire literature and there is already a matching table between IBC construction and MAEViz structure types (Table 3.19).

Table 3.19 : Matching between structure types in Zhao’s model and IBC construction types.

Structure Type	IBC Construction Type
Wooden	V
Fire-proof	III & IV
Fire-resisting	I & II

After this matching, time intervals of different fire phases for MAEViz structure types were determined (Table 3.20).

Table 3.20 : Development of fire - time intervals for MAEViz structure types (in minutes).

	Ignition ↓ Flashover	Flashover ↓ Full Development	Full Development ↓ Collapse	Collapse ↓ Extinguishment		Ignition ↓ Flashover	Flashover ↓ Full Development	Full Development ↓ Collapse	Collapse ↓ Extinguishment
W1	10	30	60	300	C2L	10	50	120	20
W2	10	30	60	300	C2M	10	60	180	30
S1L	10	50	120	20	C2H	10	60	180	30
S1M	10	60	180	30	C3L	10	40	90	35
S1H	10	60	180	30	C3M	10	40	90	35
S2L	10	50	120	20	C3H	10	40	90	35
S2M	10	60	180	30	PC1	10	60	180	30
S2H	10	60	180	30	PC2L	10	50	120	20
S3	10	40	90	35	PC2M	10	60	180	30
S4L	10	50	120	20	PC2H	10	60	180	30
S4M	10	60	180	30	RM1L	10	40	90	35
S4H	10	60	180	30	RM1M	10	40	90	35
S5L	10	50	120	20	RM2L	10	50	120	20
S5M	10	60	180	30	RM2M	10	60	180	30
S5H	10	60	180	30	RM2H	10	60	180	30
C1L	10	50	120	20	URML	10	40	90	35
C1M	10	60	180	30	URMM	10	40	90	35
C1H	10	60	180	30	MH	10	30	60	300

3.2.2 Fire spread between buildings

Since post-earthquake fire spread is considered with its physical sources, approach of Lee (2009) is adopted to estimate fire spread between buildings. Intended fire spread model consists of two components (Figure 3.18):

- Direct Flame Contact (Flame impingement or Flame touch)
- Radiations from flame through openings and radiation from room gas

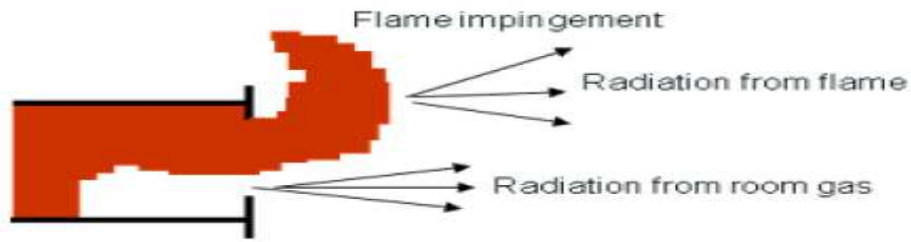


Figure 3.18 : Flame impingement and radiation from a window (Lee, 2009).

Ejecting flame geometry will be determined depending on window size and wind. If the neighboring building is in the range of flame, it is assumed as immediately ignited.

Flame geometry is represented by 3 parameters (Figure 3.19) and calculated by using equations (3.7) and (3.8).

- Width of the flame (w) = width of the window
- Height of the flame tip above the top of the window (z)

$$z = (23.9 - 0.43 \times R \times A_w - 0.5) - h \quad (3.7)$$

R : rate of burning, A_w : Window area

- Horizontal outward projection of the flame from the exterior wall (x)

$$x = 0.605 \times \left(\frac{u^2}{h} \right) \times 0.22 \times (z + h) \quad (3.8)$$

u : wind speed

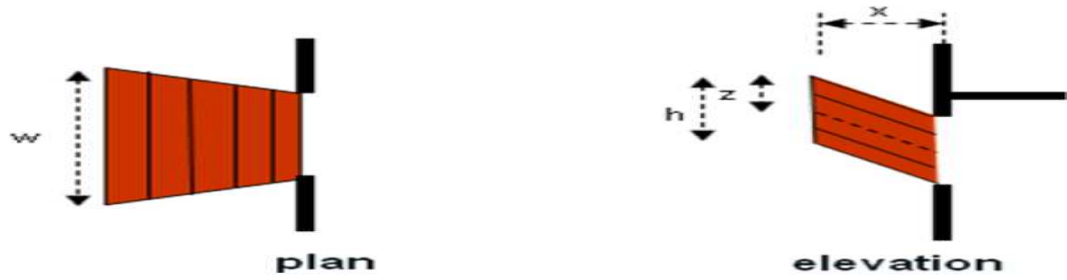


Figure 3.19 : Flame geometry for through draft condition (Lee, 2009).

Radiation from flame through openings and radiation from room gas are calculated with the equations (3.9) and (3.10).

$$I_z = \emptyset \varepsilon_z \sigma (T_z^4 - T_\alpha^4) \quad (3.9)$$

$$I_f = \emptyset \varepsilon_f \sigma (T_f^4 - T_\alpha^4) \quad (3.10)$$

I_z, I_f : radiations transferred from the window flame radiator to each receiver

$\emptyset$: Configuration factor

$\varepsilon_z, \varepsilon_f$: Emissivity of the flame and room gas

σ : Stefan-Boltzmann constant

T_z, T_f, T_α : Temperature of the flame, room gas and ambient

Configuration factor:

"The configuration factor represents the fraction of radiation emitted from the radiator (source) that is received by the receiver (target). The receivers are assumed to be the centroids of the windows in the facing wall that are on the same floor as the radiator. The receiver is the point on the facing wall that is closest to the burning room window (Figure 3.20). The configuration factor depends on the size of the radiator, and the distance between and relative orientation of the radiator and receiver"(Lee, 2009).

Because the buildings are described as points, radiator and receiving windows are assumed as parallel. So, configuration factor between radiator and receiver is calculated from the equations (3.11) and (3.12).

$$\phi = \frac{1}{2\pi} \left[\left(\frac{a}{(1+a^2)^{1/2}} \right) \tan^{-1} \left(\frac{b}{(1+a^2)^{1/2}} \right) + \left(\frac{b}{(1+b^2)^{1/2}} \right) \tan^{-1} \left(\frac{a}{(1+b^2)^{1/2}} \right) \right] \quad (3.11)$$

$$a = \frac{h'}{S'} \quad ; \quad b = \frac{w'}{S'} \quad (3.12)$$

h: Height of the window ; w: Width of the window

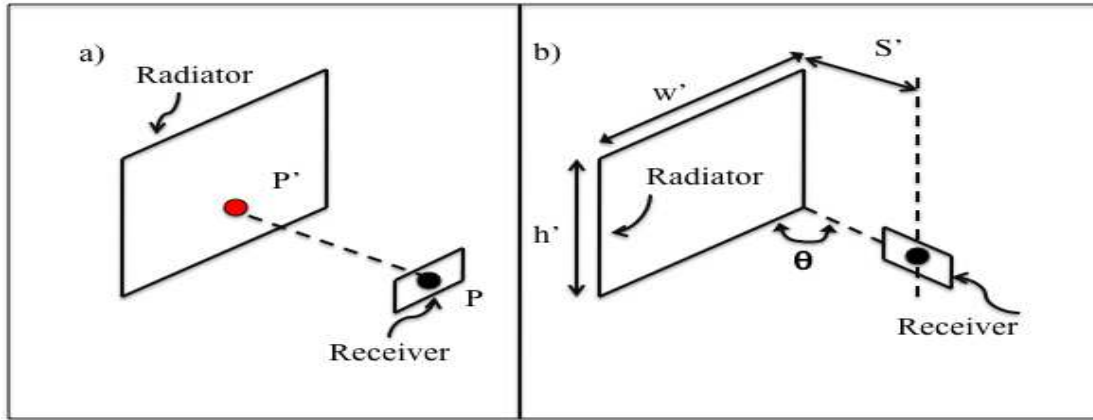


Figure 3.20 : Configuration factor scenario (radiator and receiver are parallel) (Lee and Davidson, 2010).

Emissivity:

The efficiency of the radiator as compared to a blackbody is called its emissivity. A blackbody has an emissivity of 1.

Emissivity of the flame is calculated with the equation (3.13).

$$\varepsilon_z = 1 - e^{-0.3\lambda} \quad (3.13)$$

λ is the thickness of the flame at the top of the window and it is equal to horizontal outward projection of the flame from the exterior wall (x) for through draft condition.

Emissivity of the room gas is considered as 1 because it is assumed that the gas from the window radiates from the entire window area (3.14).

$$\varepsilon_f = 1 \quad (3.14)$$

Temperature:

Temperature of the flame for through draft condition is calculated with equations (3.15).

$$\begin{aligned}
 T_z &= (T_w - T_0) \left[1 - 0.3325 (L_x \sqrt{w_t} / Q) \right] + T_0 ; \\
 T_w &= \frac{520}{1 - 0.3325 \left(\frac{L_x \sqrt{w_t}}{Q} \right)} + T_0 \\
 L_f &= \sqrt{L_L^2 + L_H^2} \quad ; \quad L_L = \left(1.366 \left(\frac{1}{u} \right)^{0.43} \frac{Q}{\sqrt{A_v}} \right) - h_{eq} \\
 L_H &= 0.605 \left(\frac{u^2}{h_{eq}} \right)^{0.22} (L_L + h_{eq})
 \end{aligned} \tag{3.15}$$

Temperature of the room gas for through draft condition is calculated with equations (3.16).

$$T_f = T_a + 1200(1 - e^{-0.04\psi}) \quad ; \quad \psi = L / \sqrt{A_w A_T} \quad ; \quad L = A_F q \tag{3.16}$$

L : total room fire load (kg)

A_w : window area (m²)

A_T : total area of floor, ceiling, and walls minus total window area (m²)

A_F : floor area (m²)

q : occupancy-dependent fire load density (kg/m²)

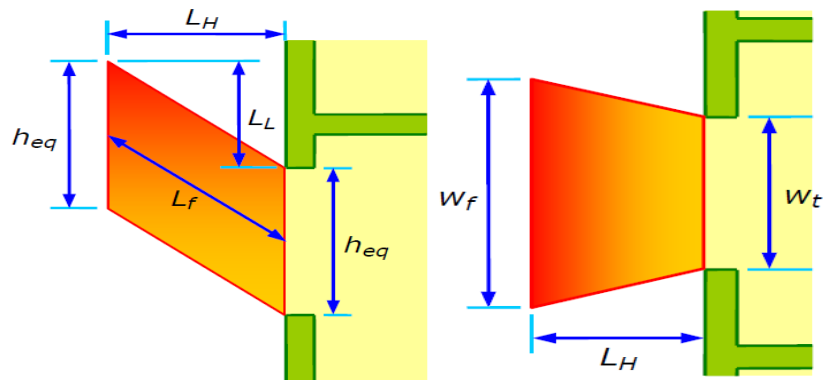


Figure 3.21 : Parameters of flame geometry used in temperature calculation.

4. COMPUTER IMPLEMENTATION

4.1 MAEViz and HAZTURK

The Mid-America Earthquake Center Visualization (MAEViz) software is a seismic loss assessment software developed by Mid-America Earthquake (MAE) Center in collaboration with the Natural Center for Supercomputing Applications (NSCA) located on the University of Illinois, Urbana-Champaign campus. It is an open-source project that gives an opportunity to researchers, practitioners, and decision makers to integrate their latest research findings, new methodologies and up to date data in to a single software product. MAEViz is developed using industry-standard open source tools. Users can integrate their new methodologies and research findings via a plug-in system. Developed post-earthquake ignition model was implemented to MAEViz in this way.

MAEViz adopts the Consequence-based Risk Management (CRM) methodology. It constitutes damage estimates from scientific and engineering principles and data, planning the appropriate mitigation strategies using a visually based and user-friendly menu system.

MAEViz includes more than 48 analyses. These analyses vary from direct seismic impact assessment to the socio-economic estimations. Software is able to show mappable source and result data in 2D and 3D forms. User-friendly analysis interface simplifies the relation between inputs and outputs. Users can see table, chart, graphs and printable reports for result data (Url-20).

MAEViz was modified for Turkey that is compatible with Turkish data structure and HAZards TURKey (HAZTURK) software was developed (Karaman, 2008). HAZTURK consists of hazard, fragility and inventory components, which are fundamentals of earthquake loss assessment studies (Figure 4.1).



Figure 4.1 : Fundemantal components of earthquake loss assessment studies (Karaman, 2008).

HAZTURK uses inventories and datasets stored in repositories that can be a local repository in a local drive or online repository with remote connection. In data import operation, existing attributes in the imported file must be mapped with required attributes. Data types of attributes in the imported file must compatible with HAZTURK data standards. Figure 4.2 shows the general view of HAZTURK containing four different scenarios, visualization, data catalog and style editor window.

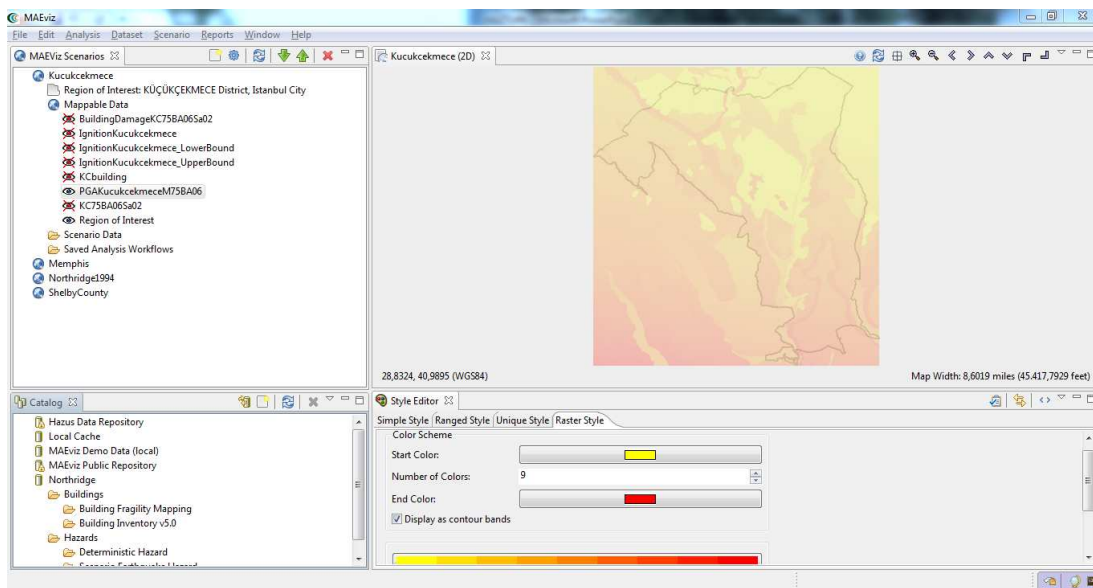


Figure 4.2 : General view of HAZTURK.

4.2 Data Formats

4.2.1 ESRI shapefile

Shapefile is a geospatial data format that contains both geometric location and attribute information of geographic features. This is a vector-based GIS format. The entire vector data used in HAZTURK (MAEViz) is in this format. Geographic features in a shapefile can be represented by points, lines and polygons. An ESRI shapefile consists of three files: A main file (*.shp), an index file (*.shx) and a dBASE table (*.dbf) (ESRI, 1997). All of the shapefiles used in HAZTURK should be defined in WGS84 geographical coordinate system.

4.2.2 ESRI ASCII raster

It is raster-based GIS format. Data is represented by cells and each cell has a specific value. ASCII raster data contains header information and values. Header information consists of the properties of raster such as the cell size, the number of rows and columns, and the coordinates of the origin of the raster. Cell values follow the header information with rows and columns. All of the raster data used in HAZTURK should be defined in WGS84 geographical coordinate system.

4.2.3 Comma separated values (.csv)

It is a common interchange data format between spreadsheets, database applications or software packages supporting tabular data. Each field in the file is separated by a comma. CSV is a common file format because most database systems are able import and export this file format. This feature makes it popular in transferring data.

4.2.4 Extensible markup language (.xml)

Mapping files in HAZTURK (MAEViz) software is in XML format. These files are used to map building inventory with building fragility curves. For example, it defines the unreinforced masonry building higher than 3 storeys.

4.3 Java Coding and Implementation to MAEViz and HAZTURK

In order to make use of the developed post-earthquake ignition model effective, model was implemented to HAZTURK, which is free and open source software. HAZTURK was developed by modifying the MAEViz software in accordance with

Turkish data structure. HAZTURK was developed with java coding language. So, code of the developed ignition model was written by using Eclipse platform for Java. Figure 4.3 is shows screenshot of the written java code.

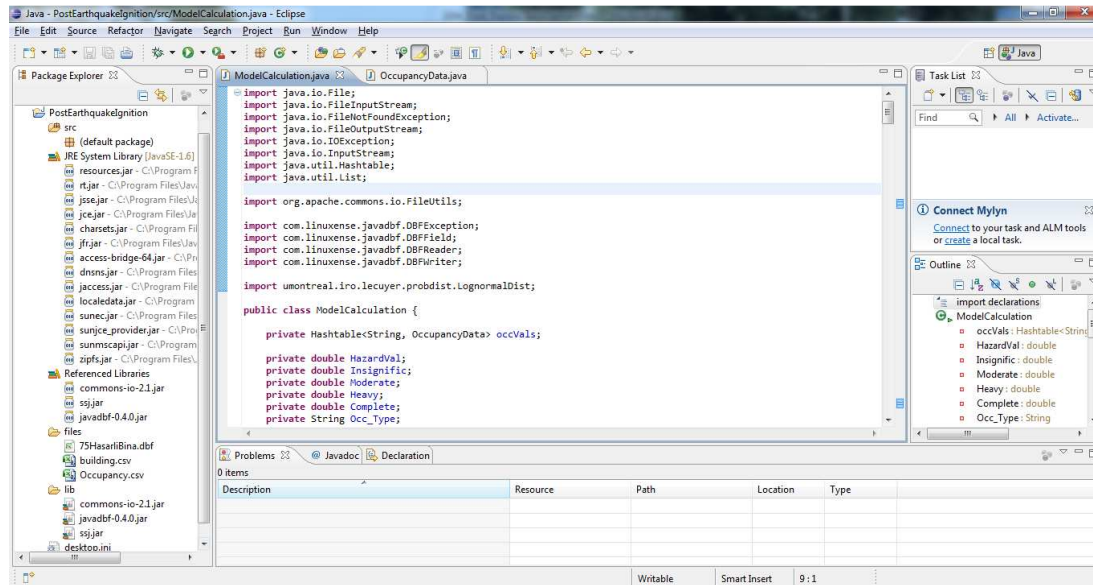


Figure 4.3 : Code of new post-earthquake ignition model in Eclipse platform.

This code was edited to make it compatible with HAZTURK source code by specialists from NCSA. Figure 4.4 shows the edited code in the HAZTURK source code.

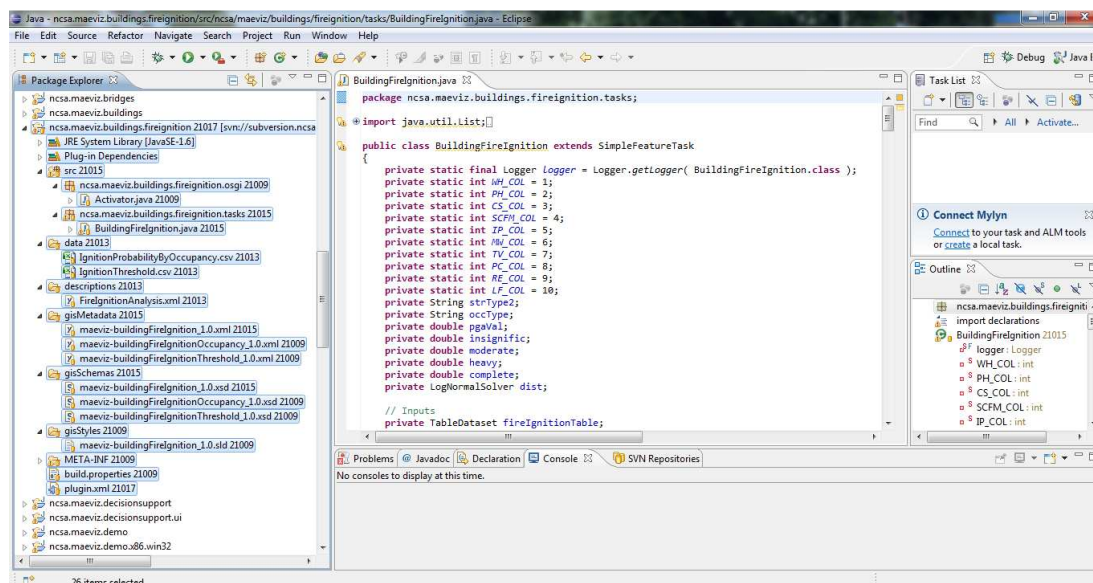


Figure 4.4 : Edited code of new post-earthquake ignition model in HAZTURK source code.

Then, edited code was implemented into HAZTURK as a plug-in. Written and edited codes are given in Appendix B. Figure 4.5 shows the interface of the new post-earthquake ignition analysis.

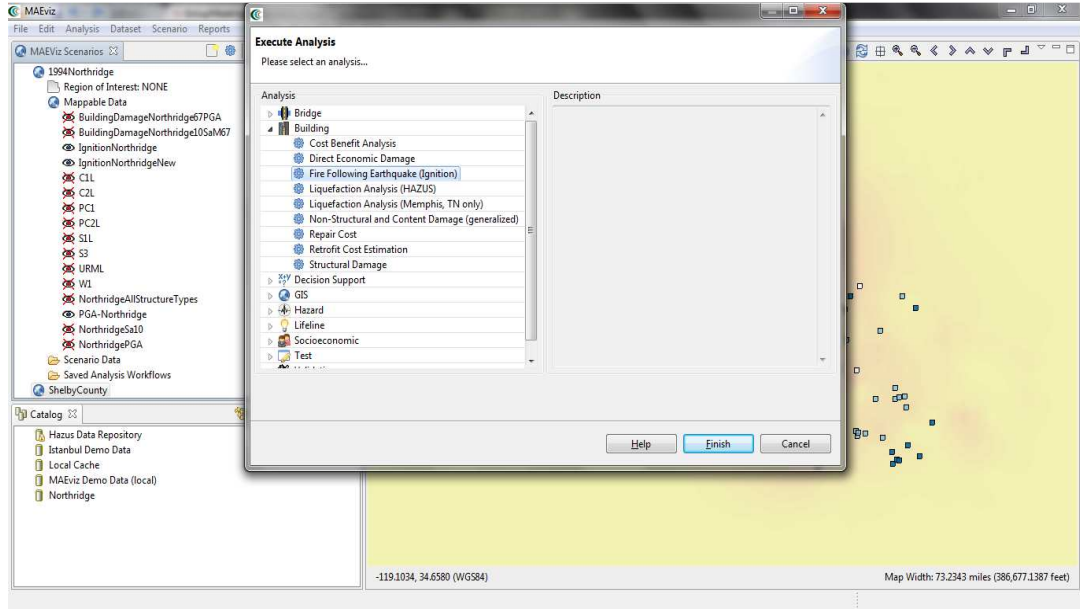


Figure 4.5 : New fire following earthquake (ignition) analysis in HAZTURK.

New post-earthquake ignition model calculates the ignition probability of a building depending on building damage probabilities for four damage states and PGA values that building exposed. Created appliance existence probabilities and ignition probability thresholds are also used in calculation.

Building damage data is obtained from building structural damage analysis. Building damage probabilities are calculated using a hazard map. HAZTURK is able produce hazard maps for spectral acceleration (Sa), peak ground acceleration (PGA) or peak ground velocity (PGV) hazard outputs for a scenario earthquake depending on the attenuation function, epicenter parameters, fault type, slope map and soil geology (Figure 4.6).

Geology, topography and attenuation files are required to produce hazard map. Hazard map, building inventory, building fragility and building fragility mapping files are required to obtain building damage probabilities. Table 4.1 shows the required datasets and their data formats, file extensions and data types.

The figure displays four sequential screenshots of the 'Scenario Earthquake Analysis' software interface, illustrating the steps for hazard map production.

- Step 1: Azalım Fonksiyonu Seçimi (Attenuation Function Selection)**
 - Header: Azalım Fonksiyonu Seçimi
 - Sub-header: Kullanılacak azalım fonksiyonunu ve olay/fay türünü tanımlayın.
 - Form: A dropdown menu for 'Azalım Fonksiyonu:' with options like 'Boore and Atkinson 2006', 'CEUS Source Event', 'Campbell (2002)', 'Campbell and Bozorgnia 2003', 'Campbell and Bozorgnia 2006', and 'Chiou and Youngs 2006'. A checkbox 'Varsayılan Azalım Fonksiyonlarını Kullanırsın mı?' is present.
 - Buttons: Help, < Back, Next >, Finish, Cancel.
- Step 2: Epicenter Parametreleri (Epicenter Parameters)**
 - Header: Epicenter Parametreleri
 - Sub-header: Görel bir olay için parametreleri tanımlayın.
 - Form: Fields for 'Girdi' (Input), 'Sonuç Adı:' (Output Name: 'Deprem Tehlike Haritası 2011'), 'Enlem (deg):' (Latitude: 40.9), 'Boylam (deg):' (Longitude: 28.9), 'Magnitude:' (7.5), 'Derinlik (km):' (Depth: 10.0), 'Zemin Sınıfı:' (Soil Class: 'D'), 'Zemin Sınıfı Haritası:' (Soil Class Map: 'Turkey Soil Types'), 'Grid Aralığı (deg):' (Grid Interval: 0.0005), 'Grid Noktaları:' (Grid Points: 113505), 'Maximum x:', 'Maximum y:', 'Minimum x:', and 'Minimum y:'.
 - Buttons: Help, < Back, Next >, Finish, Cancel.
- Step 3: Gelişmiş Parametreler (Advanced Parameters)**
 - Header: Gelişmiş Parametreler
 - Sub-header: Seçili azalım modeli için gerekli olan gelişmiş parametreleri belirleyin.
 - Form: Fields for 'Girdi' (Input), 'Fay Türü:' (Fault Type: 'Strike-Slip'), 'Jeoloji:' (Geology: 'Normal'), 'Ufuk Açılış Açısı (Dip Angle) (deg):' (Dip Angle: 90.0), 'Azimuth Açısı (deg):' (Azimuth: 100.0), 'Eğim Açısı (Strike Angle) (deg):' (Strike Angle: 176.0), 'Coseismic Rupture Derinliği (km):' (Coseismic Rupture Depth: 0.0), 'Seismogenic Derinlik (km):' (Seismogenic Depth: 3.0), '2.5 km/s Derinlikteki Kesme Dalgası (km):' (2.5 km/s Depth Shear Wave: 2.0), and 'Eğim Haritası:' (Strike Map: 'DEM Slope Map Analysis').
 - Buttons: Help, < Back, Next >, Finish, Cancel.
- Step 4: Afet Çıktı Seçimi (Disaster Output Selection)**
 - Header: Afet Çıktı Seçimi
 - Sub-header: Okun sol taraftaki afet, azalım ilişkisi tarafından hesaplanacaktır, sağ taraftaki ise çıktı olacaktır.
 - Form: A grid of checkboxes for disaster outputs: PGV, PGA, 0.05 Sa, 0.1 Sa, 0.2 Sa, 0.3 Sa, 0.5 Sa, 1.0 Sa, 2.0 Sa, 3.0 Sa, 4.0 Sa, 5.0 Sa. Below the grid are 'Standard Deviation' (Hayır) and 'Dönüşümleri Göster' (Hayır) options.
 - Buttons: Help, < Back, Next >, Finish, Cancel.

Figure 4.6 : Steps of hazard map production.

Table 4.1 : Data classification for post-earthquake ignition analysis.

Dataset	Data Format	File Extension	Data Type
Hazard	ASCII Raster	*.asc, *.txt	ASCII
Building	ESRI Shapefile	*.shp	Point
Geology	ESRI Shapefile	*.shp	Polygon
Topography	ASCII Raster	*.asc, *.txt	ASCII
Boundry	ESRI Shape file	*.shp	Polygon
Attenuation	Table	*.csv	Table
Building Fragility	Table	*.csv	Table
Building Fragility Mapping	XML	*.xml	XML
Building Damage	ESRI Shapefile	*.shp	Point
PGA Map	ASCII Raster	*.asc, *.txt	ASCII
Appliance Existence Probability	Table	*.csv	Table
Ignition Probability Thresholds	Table	*.csv	Table

Required attributes in building damage data are the probabilities of insignificant, moderate, heavy and complete damage states and occupancy type. Required attributes and their data types are given in table 4.2.

Table 4.2 : Required attributes in building damage data.

Attribute	Data Type
Occ_Type	String (Text)
Insignificant	Double
Moderate	Double
Heavy	Double
Complete	Double

PGA Distribution Map is used to calculate the overturning probability of appliances and contents. Ignition probability is produced from this overturning probability by multiplying it with appliance existence probability and coefficient from the results of AHP.

Appliance existence probabilities are explained in chapter 3 and probabilities depending on the occupancy types are tabulated in Table 3.11.

Ignition probability thresholds are used to evaluate the ignition probabilities. Building having an ignition probability higher than the threshold value is considered as ignited. Threshold calculation process is also explained in chapter 3 and thresholds depending on the structure types are tabulated in Table 3.17.

New post-earthquake ignition tool was executed for ignition records from the 1994 Northridge earthquake to test the new tool (Figure 4.7). Ignition probability result values were compared with ignition probabilities calculated with MS Excel before. Therefore, it was determined that it works correctly. Figure 4.8 and Figure 4.9 show the result of analysis in visualized and tabular form.

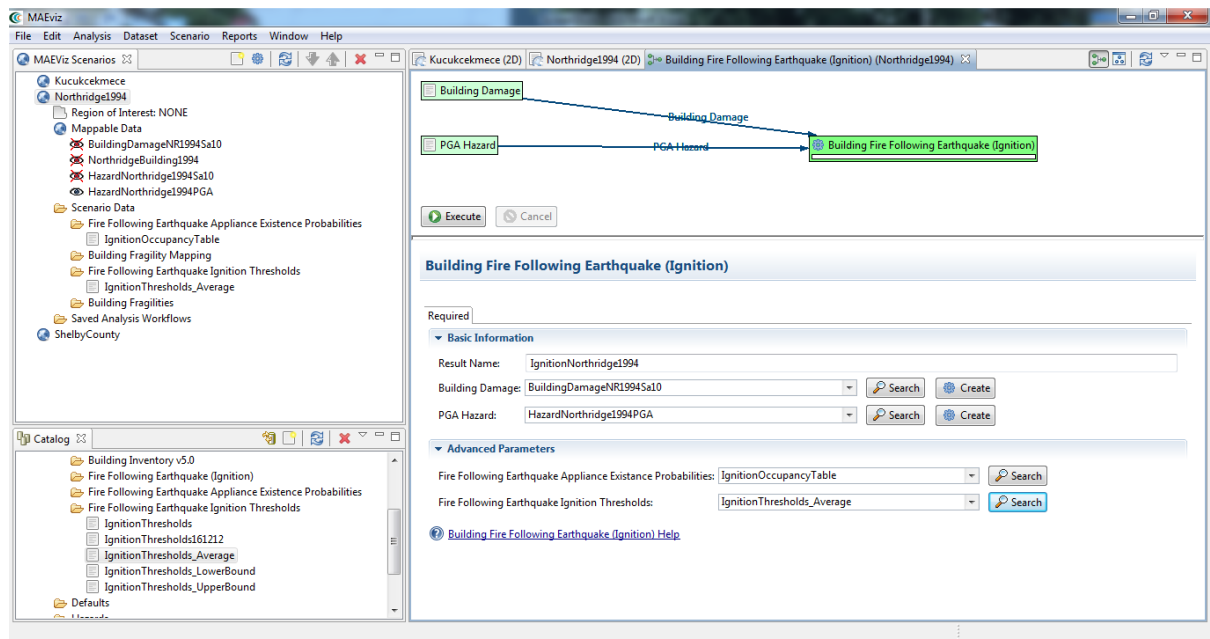


Figure 4.7 : Analysis window of new post-earthquake ignition tool.

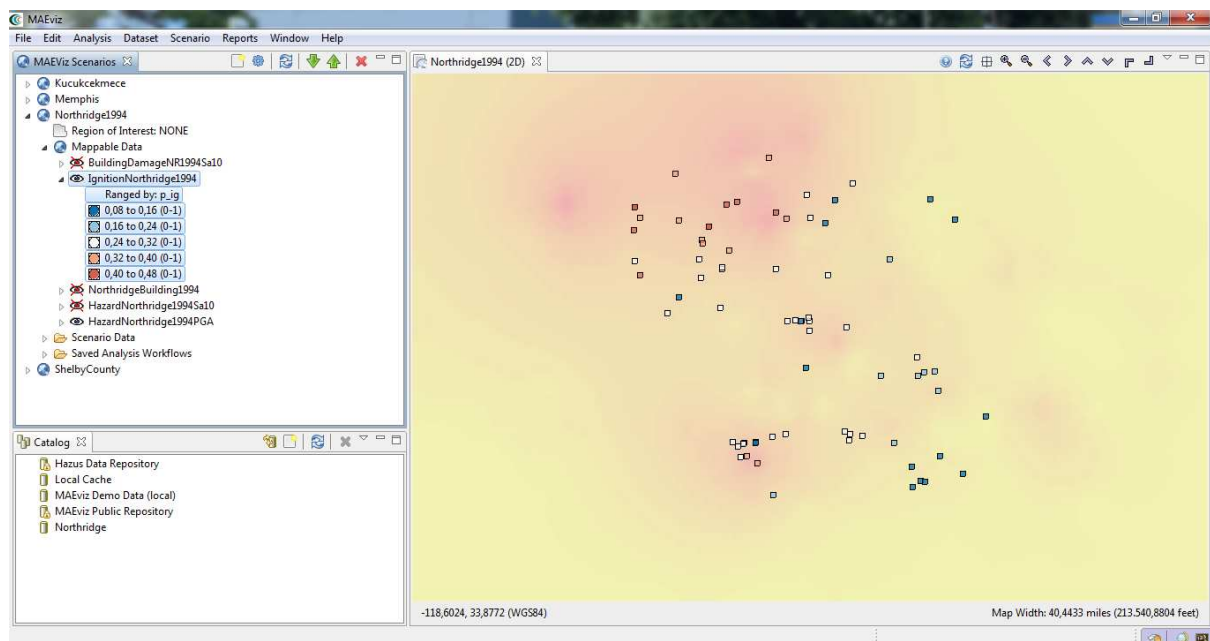


Figure 4.8 : Visualized result of new post-earthquake ignition tool for the 1994 Northridge ignitions.

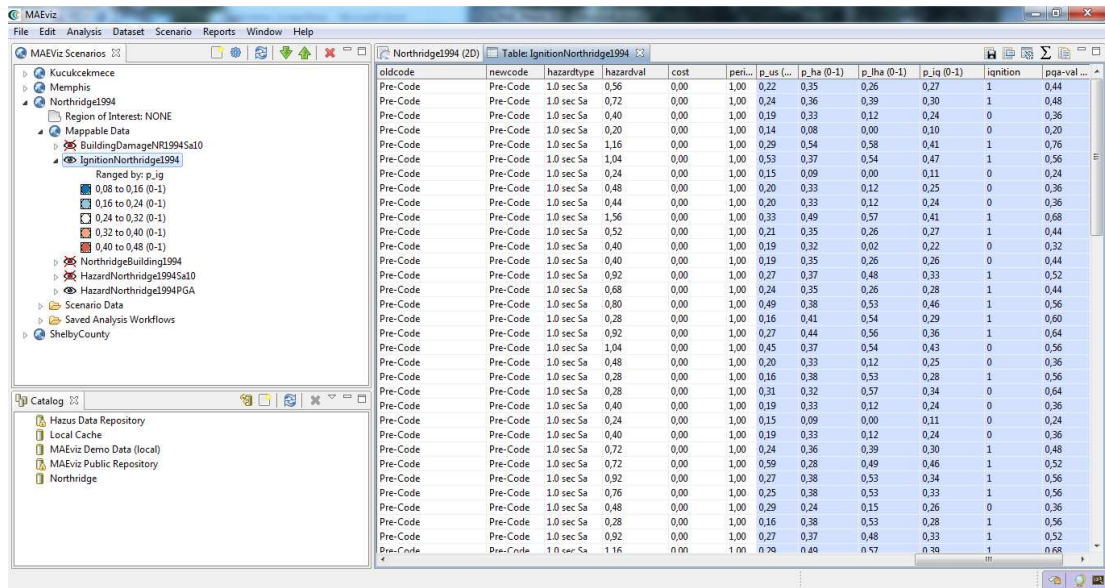


Figure 4.9 : Result of new post-earthquake ignition tool for the 1994 Northridge ignitions in tabular form.

5. APPLICATION

Developed post-earthquake ignition tool was applied to Memphis, Tennessee in the United States and Küçükçekmece, Istanbul in Turkey. Number and location of probable ignited buildings were obtained both for lower bound, average and upper bound thresholds.

5.1 Memphis, Tennessee (United States of America)

Memphis is the largest city in the New Madrid Seismic Zone (NMSZ). It is an important transportation center. Memphis International Airport is the busiest cargo airport in the world (Url-21). There are three fault segments in the NMSZ as shown in Figure 5.1. They are the northeast segment, central segment and the southwest segment. Each segment constitutes a deterministic magnitude 7.7 (M_w 7.7) earthquake caused by a rupture over the entire length of the segment (Elnashai et al., 2008). Three earthquakes occurred in the NMSZ in the period of 1811 and 1812 having magnitudes around 8. Although earthquakes generated some of the strongest shakings in the US history, limited damage occurred depending on the rarely populated area .A potential earthquake similar to 1811 and 1812 earthquake would affect the major urban center of Memphis (Cleveland et al., 2007).

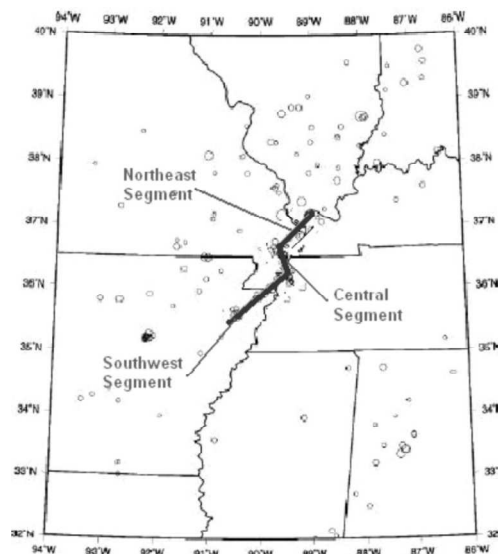


Figure 5.1 : New Madrid Seismic Zone (Elnashai et. al, 2008).

There are 14118 buildings in Memphis Test Bed (MTB) data. Most of these are light frame steel and unreinforced masonry buildings. Number of buildings with respect to the structure types and occupancy types are given in Table 5.1 and 5.2, respectively. Building inventory is also given in visualized form in Figure 5.2.

Table 5.1 : Number and structure types of buildings in Memphis.

Structure Type (Label)	Structure Type (Description)	Number of Buildings
C1	Concrete Moment Frame	290
C2	Concrete Shear Walls	93
PC1	Precast Concrete Tilt-up Walls	974
PC2	Precast Concrete Frames with Concrete Shear Walls	100
RM	Reinforced Masonry	945
S1	Steel Moment Frame	204
S3	Steel Light Frame	5695
URM	Unreinforced Masonry Bearing Walls	4588
W1	Wood, Light Frame	966
W2	Wood, Commercial and Industrial	263

Table 5.2 : Number of buildings according to occupancy type in Memphis.

Occupancy Type	Description	Number of Buildings
COM1	Commercial Retail Trade (Store)	3542
COM2	Wholesale Trade (Warehouse)	3516
COM3	Commercial Personal and Repair Services (Service Station/Shop)	1044
COM4	Professional/Technical Services (Offices)	2756
COM5	Banks	148
COM6	Hospital	42
COM7	Medical Office/Clinic	285
COM8	Entertainment & Recreation (Restaurants/Bars)	876
COM9	Theaters	15
COM10	Parking	20
EDU1	Grade Schools	136
GOV1	Governmental General Services (Office)	13
GOV2	Emergency Response (Police/Fire Station/EOC)	14
IND1	Factory (Heavy)	1135
IND2	Factory (Light)	478
IND3	Factory (Food/Drugs/Chemicals)	21
IND4	Factory (Metals/Minerals Processing)	37
REL1	Church/Non-Profit	40

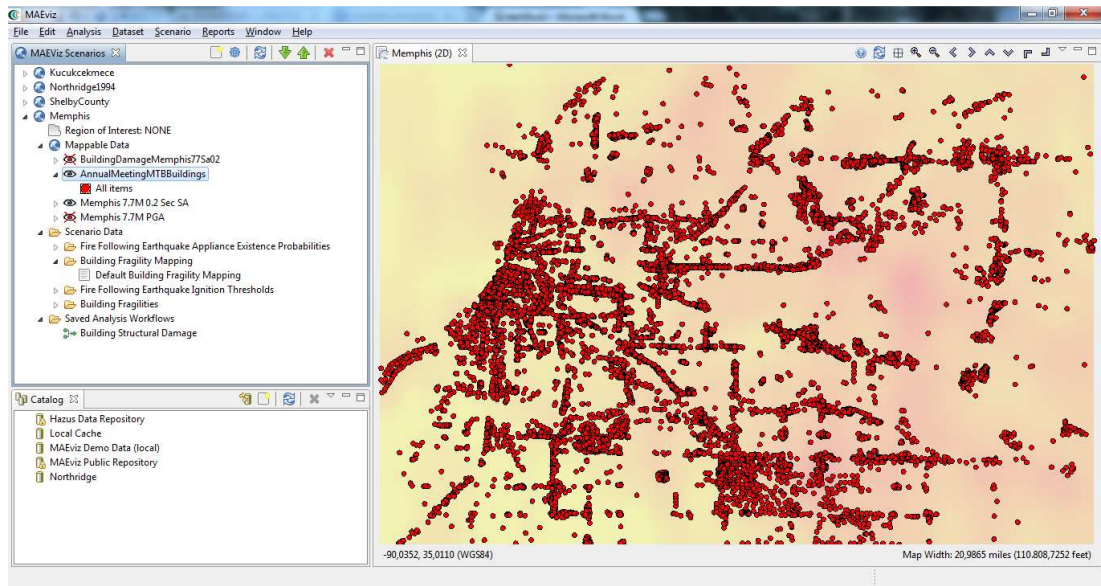


Figure 5.2 : Memphis Test Bed (MTB) building inventory.

0.2 sec S_a and PGA maps of magnitude 7.7 (M_w 7.7) earthquake scenario for NMSZ were obtained from the MAEViz local data. Building damage analysis was carried out to produce damage probabilities for insignificant, moderate, heavy and complete damage states. MAEViz default fragilities and building fragility mapping were used to execute analysis with 0.2 sec S_a hazard map and building inventory as illustrated in Figure 5.3. After analysis, building damage probabilities were obtained (Figure 5.4).

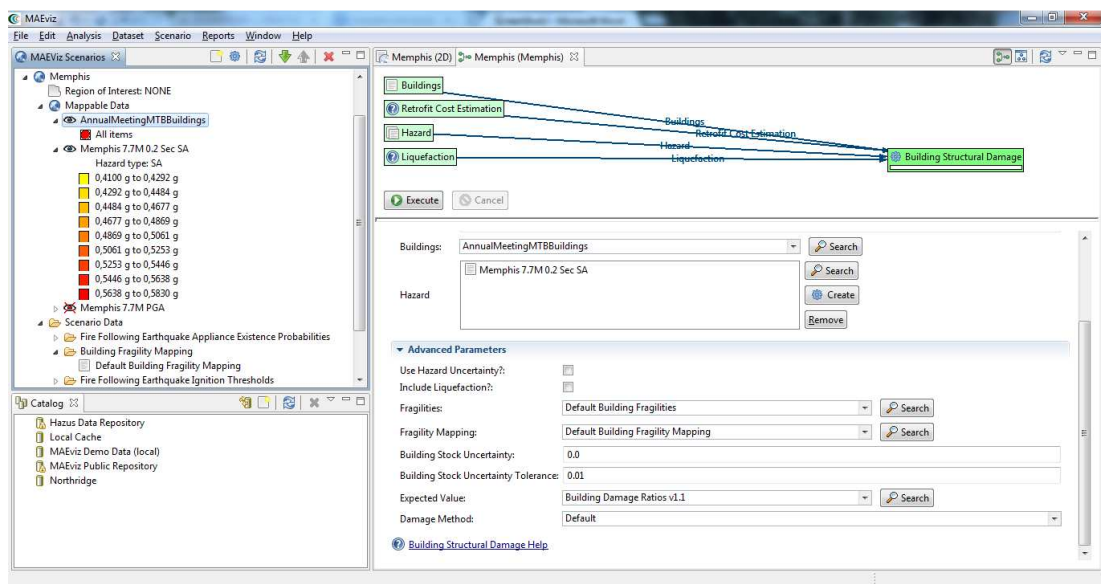


Figure 5.3 : Building damage analysis interface for Memphis application.

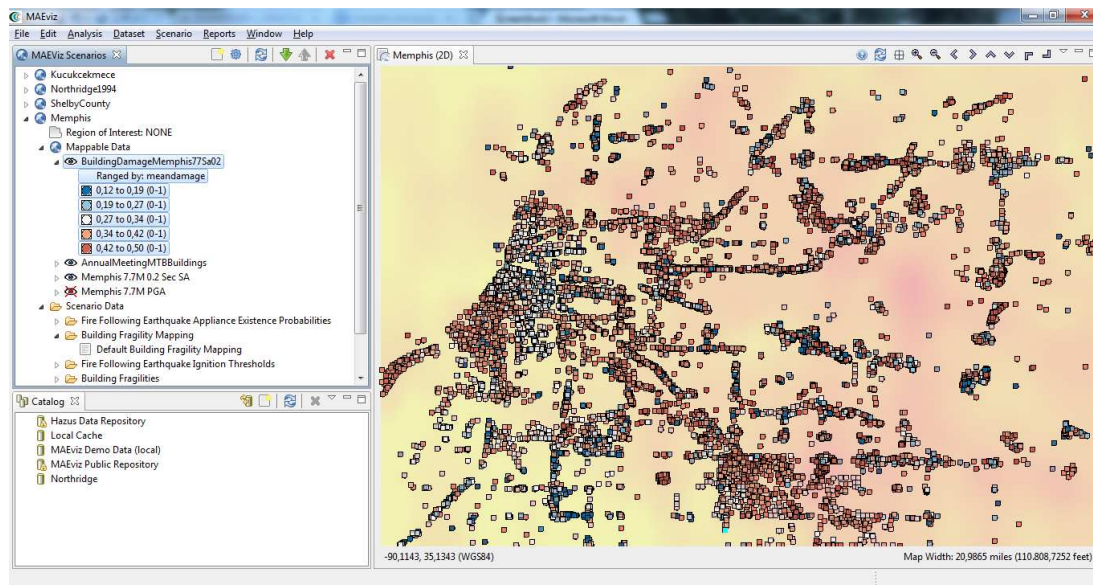


Figure 5.4 : Result of building damage analysis for Memphis.

Post-earthquake ignition analysis was carried out using the building damage file, PGA distribution map, appliance existence probability table and ignition probability thresholds table (Figure 5.5). Because there were lower bound, average and upper bound thresholds table, three different ignition analyses were executed. Ignition probabilities of buildings were same for both three analyses but number of probable ignited buildings differed for each analysis. Result of analysis with ignition probabilities is represented in Figure 5.6.

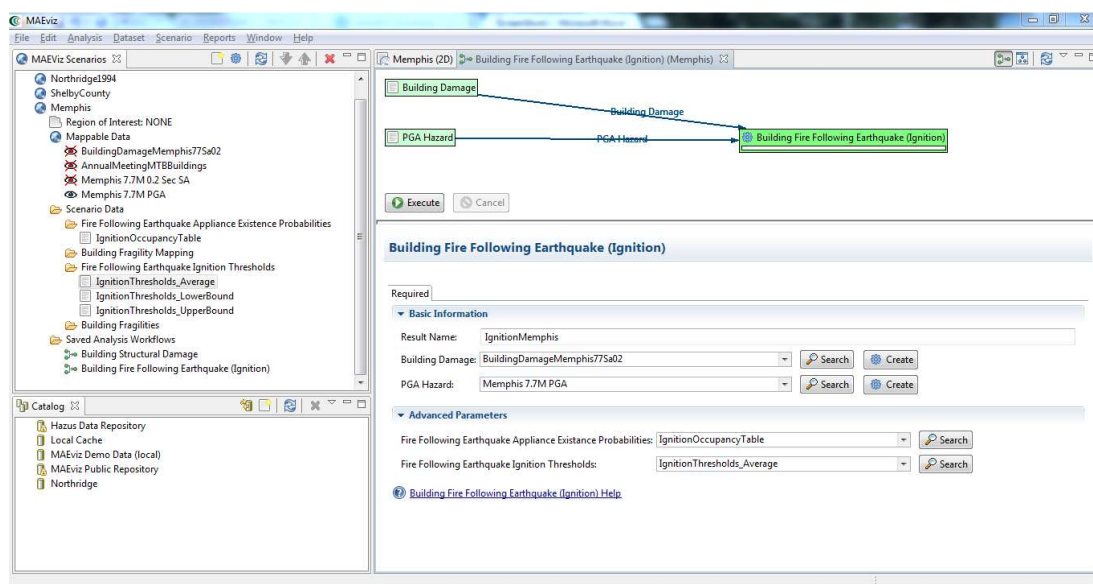


Figure 5.5 : Post-earthquake ignition analysis interface for Memphis application.

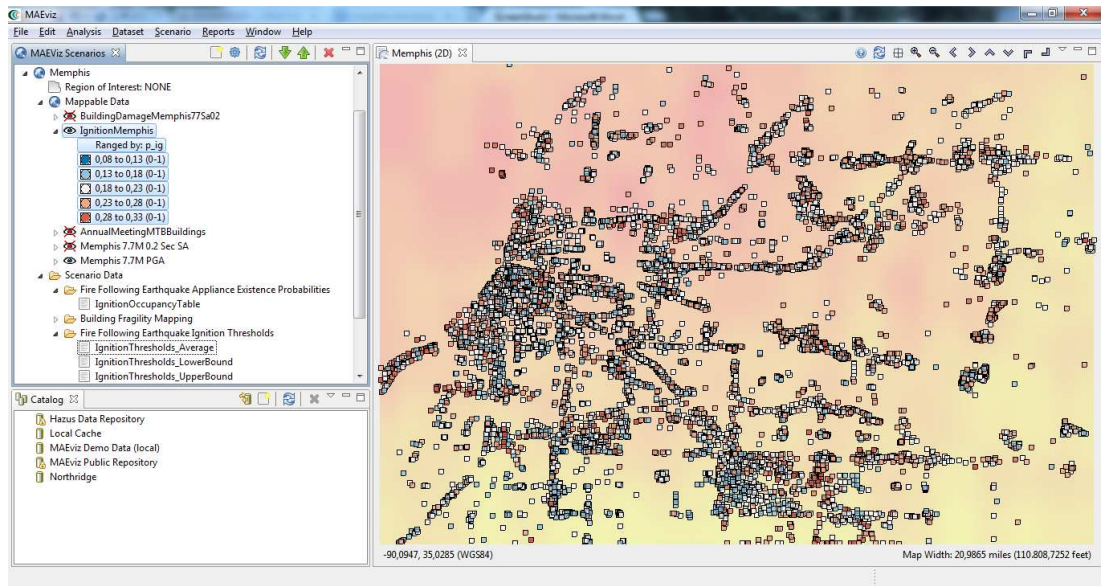


Figure 5.6 : Result of post-earthquake ignition analysis for Memphis application with ignition probabilities.

As seen in Figure 5.7 there is no post-earthquake ignition risk for Memphis with average thresholds. In the analysis with lower bound thresholds, 195 buildings were analyzed as ignited after the Mw 7.7 earthquake that corresponded to 1.38% of building inventory (Figure 5.8). These buildings consist of 19 different detailed occupancies as tabulated in Table 5.3.

Table 5.3 : Ignited buildings with detailed occupancy types for Memphis application.

Detailed Occupancy Type	Number of Ignited Buildings
Fast Food	73
Restaurant	44
Medical Office	22
Manufacture Mill	13
Bar/Lounge	9
Machine Shop	6
Veterinary Clinic	6
Loft Manufacture	5
School	4
Religious	4
Hospital	1
Bowling	1
Chemical Plant	1
Club House	1
Drive in Rest	1
Manufacture	1
Night Club	1
Packing Plant	1
Recreation	1

All of the ignited buildings are wooden. 159 of them are light frame wood and 36 of them are commercial and industrial wood buildings. There are 178 1-storey, 16 2-storey and 1 3-storey ignited buildings.

There is also no post-earthquake ignition risk for Memphis with upper bound thresholds like with average thresholds (Figure 5.9).

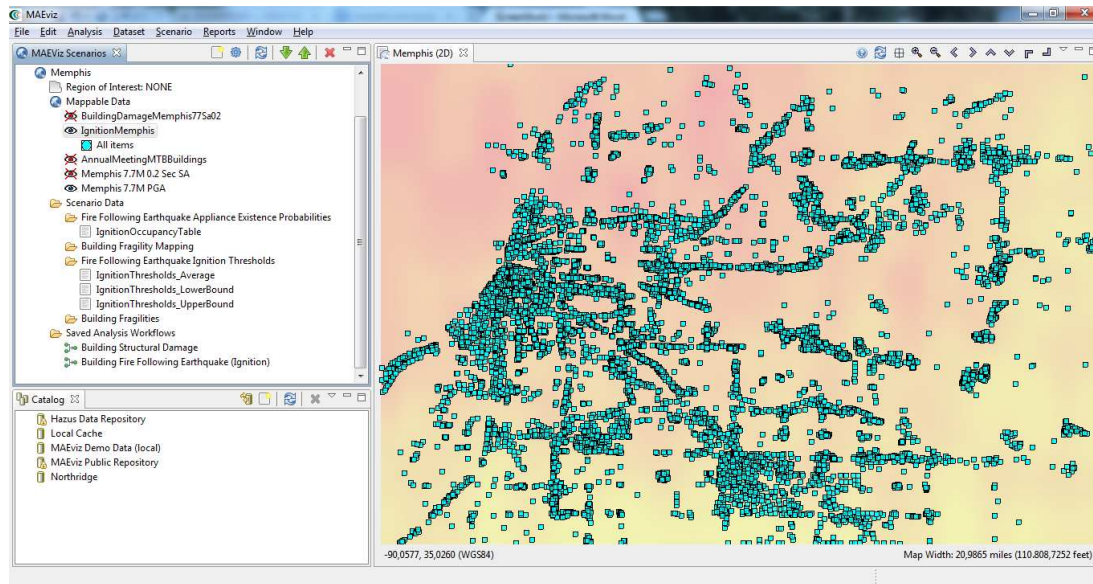


Figure 5.7 : Result of post-earthquake ignition analysis for Memphis application with average thresholds.

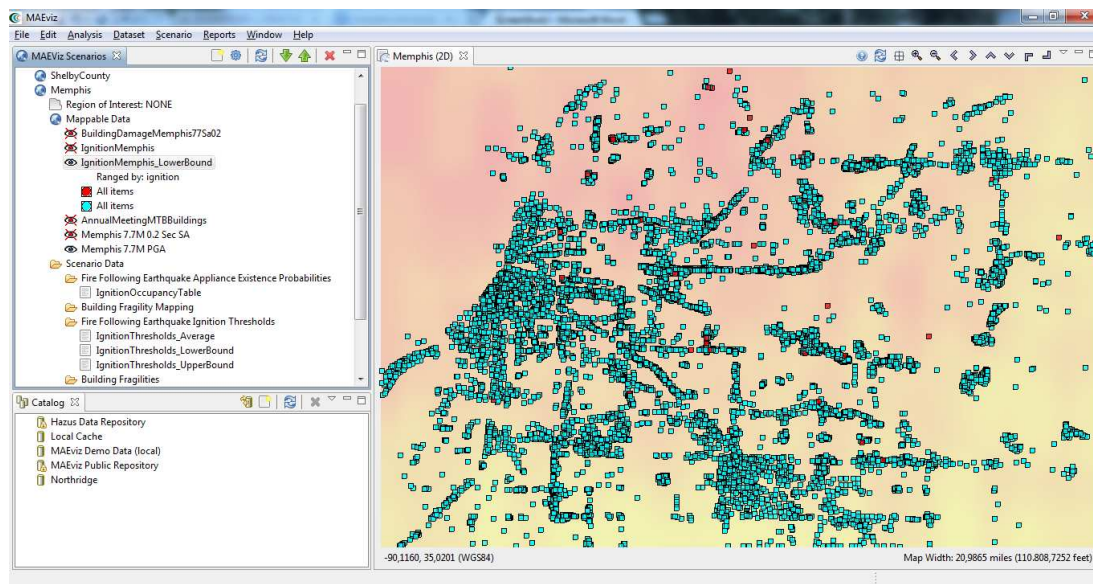


Figure 5.8 : Result of post-earthquake ignition analysis for Memphis application with lower bound thresholds.

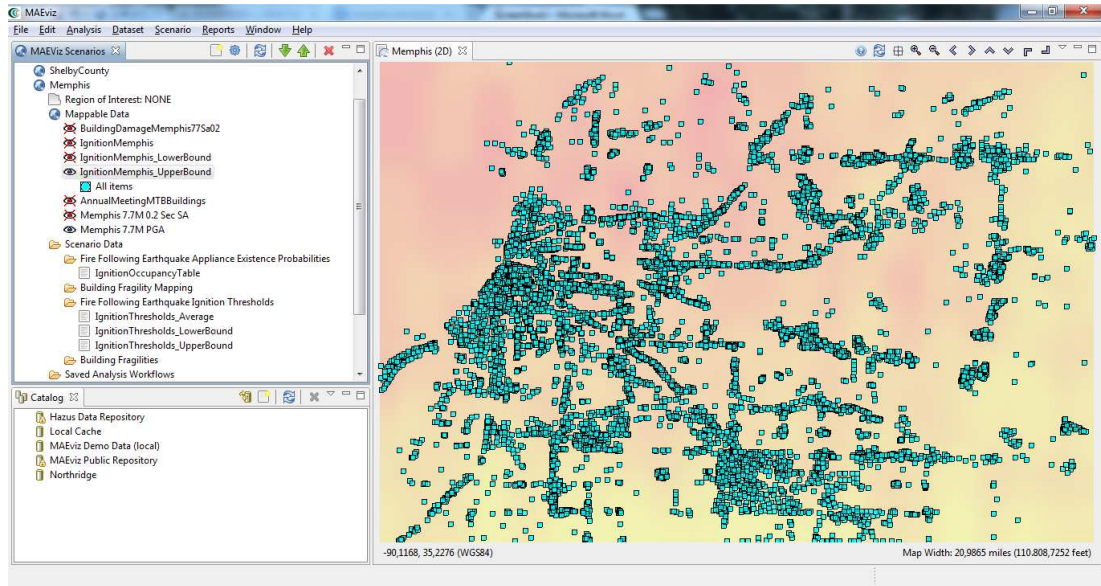


Figure 5.9 : Result of post-earthquake ignition analysis for Memphis application with upper bound thresholds.

5.2 Küçükçekmece, İstanbul (Turkey)

Turkey is one of the most seismically active countries in the world. According to Parsons et al. (2000) and Parsons (2004), the probability of a magnitude 7 earthquake rupturing beneath the Sea of Marmara at the south of Istanbul is approximately 35–70% in the next 30 years. The necessity of comprehensive plans for seismic mitigation, response and recovery tasks after catastrophic events has encouraged researchers to develop scientifically advanced tools to conduct loss assessment analyses (Karaman et al., 2008). There are 36151 buildings in Küçükçekmece data. Most of these are concrete frame with unreinforced masonry infill walls buildings. Numbers of buildings with respect to the structure types are given in Table 5.4. Building inventory is also given in visualized form in Figure 5.10. Most of the buildings were constructed between 1975 and 1997. Number of storeys are between 1 and 7 (Table 5.5).

Table 5.4 : Number and structure types of buildings in Küçükçekmece.

Structure Type (Label)	Structure Type (Description)	Number of Buildings
C3	Concrete Frame With Unreinforced Masonry Infill Walls	30151
PC1	Precast Concrete Tilt-up Walls	75
RM	Reinforced Masonry	369
URM	Unreinforced Masonry Bearing Walls	5534
W1	Wood, Light Frame	22

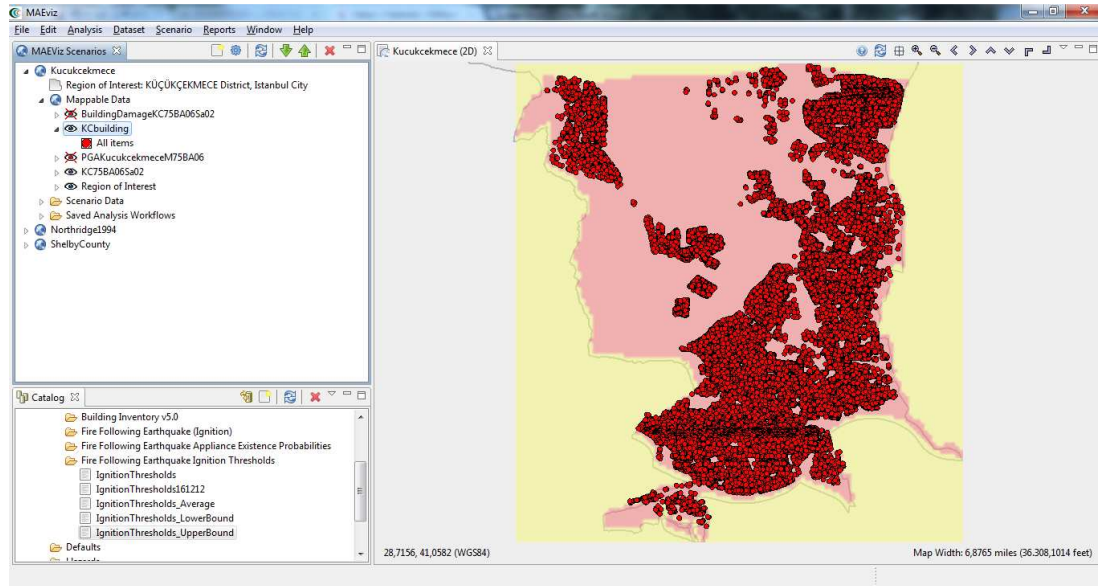


Figure 5.10 : Küçükçekmece building inventory.

Table 5.5 : Number of buildings according to number of storeys in Küçükçekmece.

Number of Storeys	Number of Buildings
1	5108
2	5099
3	6651
4	7547
5	5775
6	3786
7	2185

The majority of the buildings are residential. There are also commercial, governmental and industrial buildings in Küçükçekmece. Number of buildings with respect to occupancy type is tabulated in Table 5.6.

Table 5.6 : Number of buildings according to occupancy type in Küçükçekmece.

Occupancy Type	Descripton	Number of Buildings
COM1	Commercial Retail Trade (Store)	1848
COM3	Commercial Personal and Repair Services (Service Station/Shop)	7584
GOV1	Governmental General Services (Office)	13
IND2	Light Industrial (Factory)	195
RES3	Residential Multi Family Dwelling (Apartment/Condominium)	26511

Distribution of buildings according to the districts is given in Table 5.7.

Table 5.7 : Number of buildings according to district name in Küçükçekmece.

Name of District	Number of Buildings
Atakent	473
Beşyol	265
Cennet	1191
Cumhuriyet	2211
Fatih	626
Fevzi Çakmak	1603
Gültepe	1425
Halkalı Merkez	3154
İkitelli Atatürk	2700
İnönü	3372
İstasyon	2004
Kanarya	3448
Kartaltepe	1005
Kemalpaşa	774
Mehmet Akif	2573
Söğütlüçeşme	2326
Sultan Murat	898
Tevfik Fikret	1743
Yarımburgaz	1207
Yenimahalle	1236
Yeşilova	1917

0.2 sec S_a and PGA maps of magnitude 7.5 (M_w 7.5) earthquake scenario of Küçükçekmece were obtained from Küçükçekmece earthquake risk reduction project data performed by researchers from Istanbul Technical University. Building damage analysis was carried out to produce damage probabilities for insignificant, moderate, heavy and complete damage states. Fragilities and building fragility mapping compatible with Turkish building inventory were used to execute analysis with 0.2 sec S_a hazard map and building inventory as illustrated in Figure 5.11. After analysis, building damage probabilities were obtained (Figure 5.12).

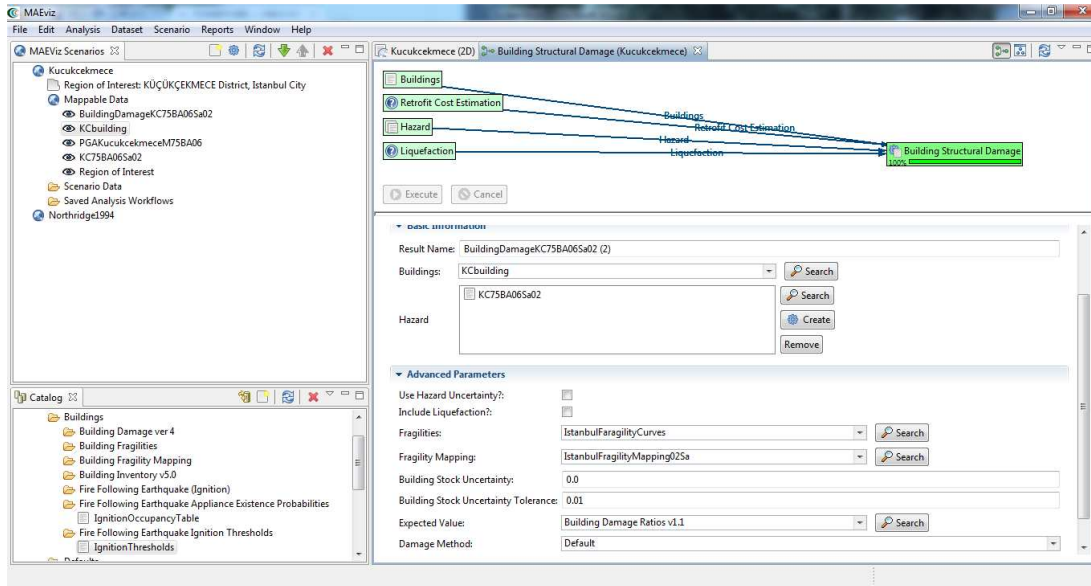


Figure 5.11 : Building damage analysis interface for Küçükçekmece application.

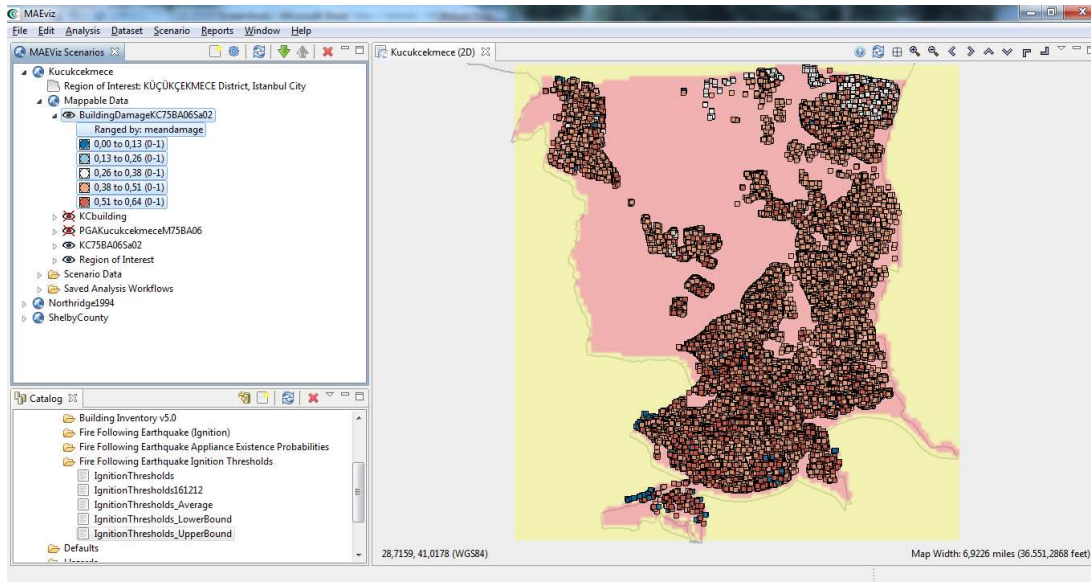


Figure 5.12 : Result of building damage analysis for Küçükçekmece.

Post-earthquake ignition analysis was carried out using the building damage file, PGA distribution map, appliance existence probability table and ignition probability thresholds table (Figure 5.13). Because there were lower bound, average and upper bound thresholds table, three different ignition analyses were executed. Ignition probabilities of buildings were same for both three analyses but number of probable ignited buildings differed for each analysis. Result of analysis with ignition probabilities is represented in Figure 5.14.

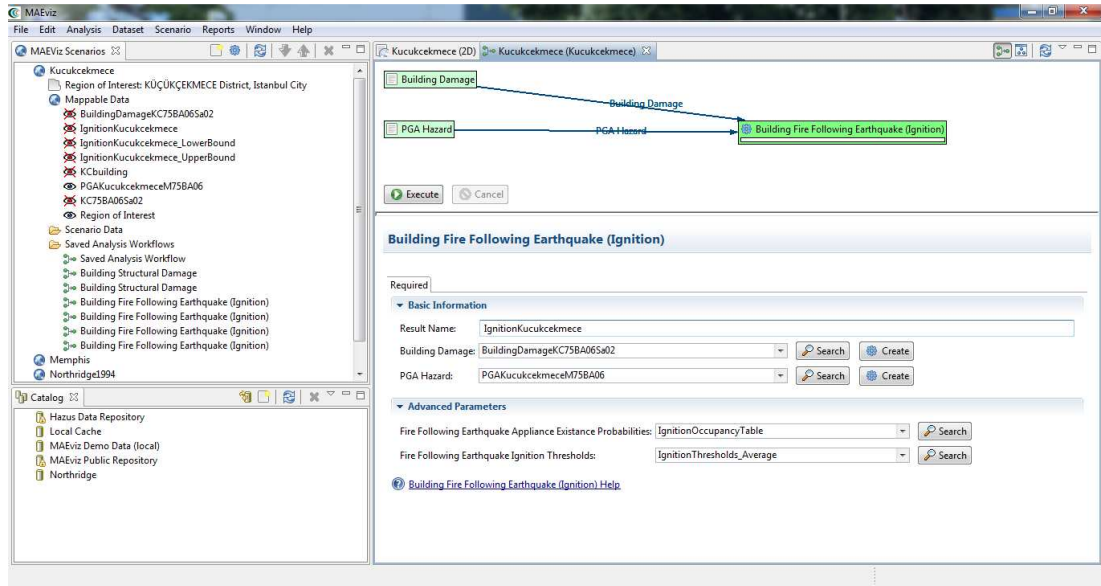


Figure 5.13 : Post-earthquake ignition analysis interface for Küçükçekmece application.

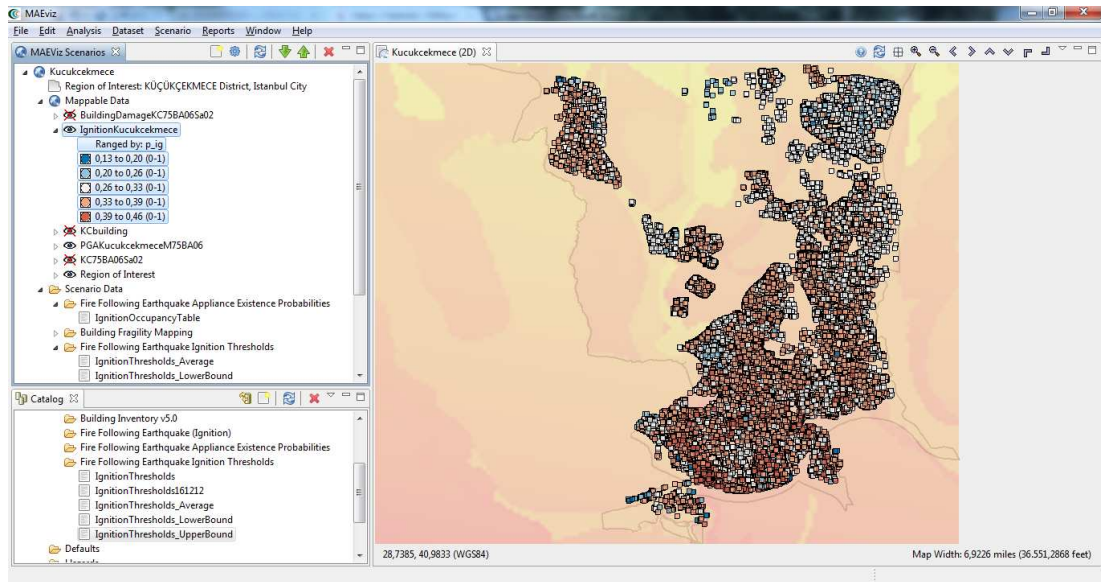


Figure 5.14 : Result of post-earthquake ignition analysis for Küçükçekmece application with ignition probabilities.

In the analysis with average thresholds, 334 buildings were analyzed as ignited after the Mw 7.5 earthquake that corresponded to 0.92% of building inventory (Figure 5.15). Lower screenshot in Figure 5.15 is the zoomed form of upper screenshot. Ignited buildings consist of three different occupancy types as tabulated in Table 5.8.

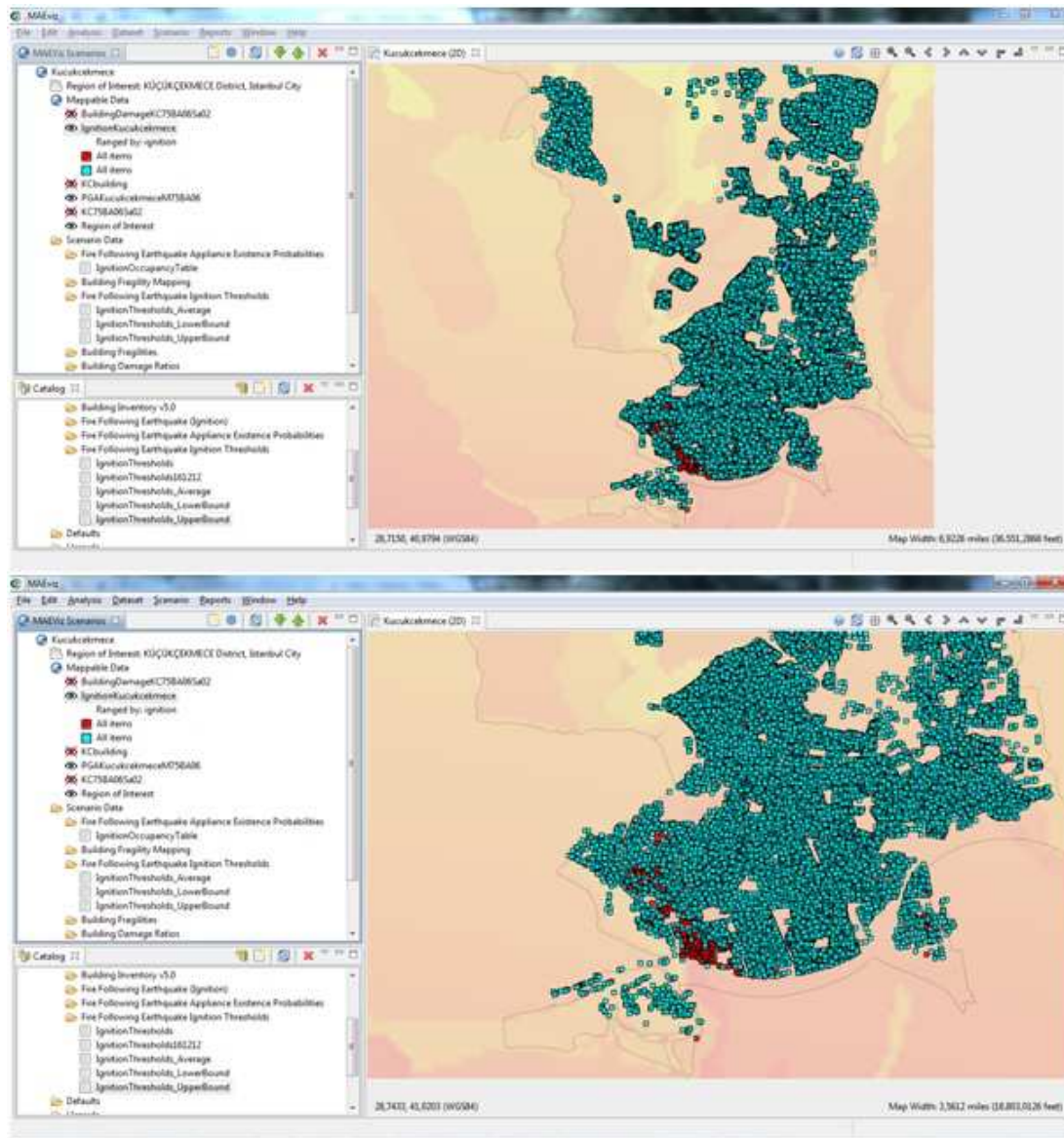


Figure 5.15 : Result of post-earthquake ignition analysis for Küçükçekmece application with average thresholds.

Table 5.8 : Ignited buildings with occupancy types for Küçükçekmece application (average thresholds).

Occupancy Type	Description	Number of Ignited Buildings
COM1	Commercial Retail Trade (Store)	4
IND2	Light Industrial (Factory)	16
RES3	Residential Multi Family Dwelling (Apartment/Condominium)	314

Number of ignited buildings with respect to the structure type, building code, number of storeys and district are tabulated from Table 5.9 to Table 5.12, respectively.

Table 5.9 : Number and structure types of ignited buildings in Küçükçekmece (average thresholds).

Structure Type (Label)	Structure Type (Description)	Number of Ignited Buildings
C3	Concrete Frame With Unreinforced Masonry Infill Walls	35
URM	Unreinforced Masonry Bearing Walls	286
W1	Wood, Light Frame	13

Table 5.10 : Number of ignited buildings according to building code in Küçükçekmece (average thresholds).

Building Code	Number of Ignited Buildings
Pre-Code	323
Low-Code	4
Moderate-Code	6
High-Code	1

Table 5.11 : Number of ignited buildings according to number of storeys in Küçükçekmece (average thresholds).

Number of Storeys	Number of Ignited Buildings
1	196
2	79
3	39
4	14
5	5
6	1

Table 5.12 : Number of ignited buildings according to district name in Küçükçekmece (average thresholds).

Name of District	Number of Ignited Buildings
Beşyol	14
Cennet	201
Cumhuriyet	84
Fatih	3
Halkalı Merkez	1
İkitelli Atatürk	1
Kanarya	2
Kartaltepe	2
Tevfik Fikret	1
Yarımburgaz	1
Yenimahalle	16
Yeşilova	8

In the analysis with lower bound thresholds, 2130 buildings were analyzed as ignited after the Mw 7.5 earthquake that corresponded to 5.89% of building inventory (Figure 5.16). Lower screenshot in Figure 5.16 is the zoomed form of upper screenshot. Ignited buildings consist of four different occupancy types as tabulated in Table 5.13.

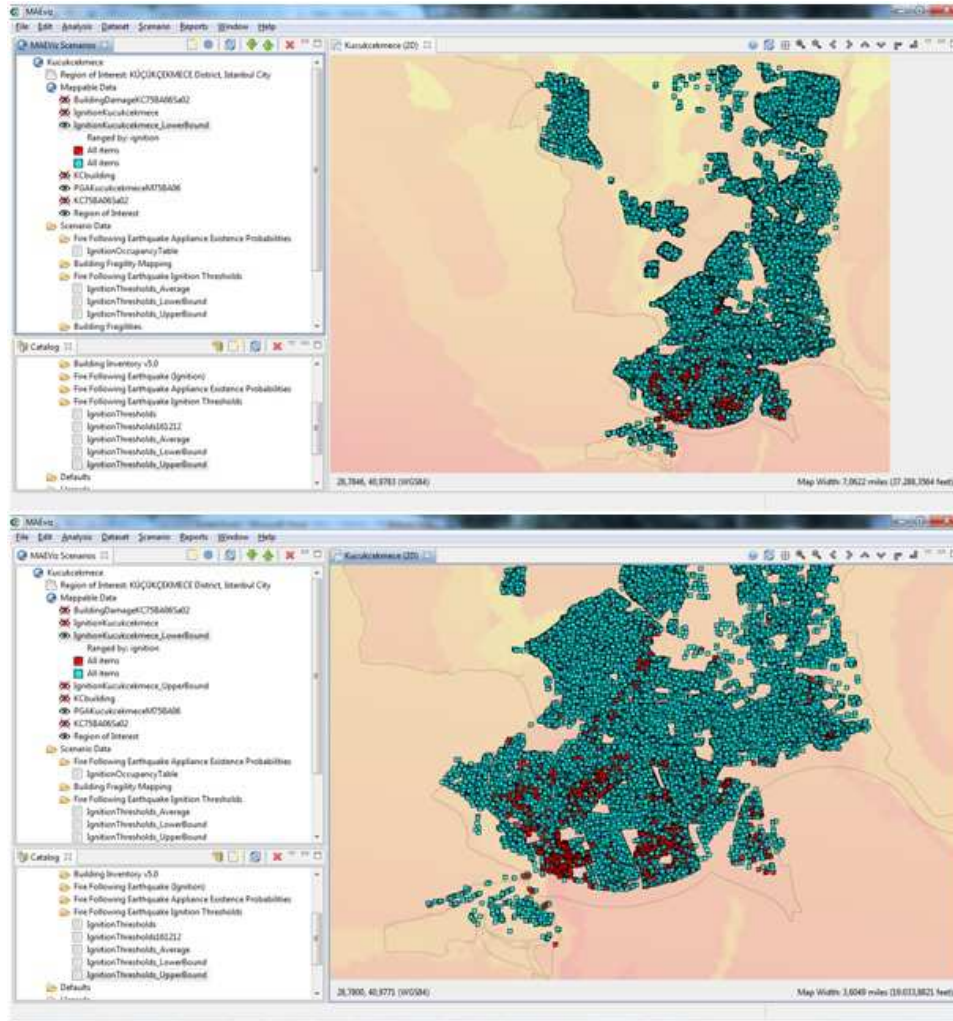


Figure 5.16 : Result of post-earthquake ignition analysis for Küçükçekmece application with lower bound thresholds.

Table 5.13 : Ignited buildings with occupancy types for Küçükçekmece application (lower bound thresholds).

Occupancy Type	Description	Number of Ignited Buildings
COM1	Commercial Retail Trade (Store)	10
COM3	Commercial Personal and Repair Services (Service Station/Shop)	7
IND2	Light Industrial (Factory)	37
RES3	Residential Multi Family Dwelling (Apartment/Condominium)	2076

Number of ignited buildings with respect to the structure type, number of storeys and district and building code are tabulated from Table 5.14 to Table 5.17, respectively.

Table 5.14 : Number and structure types of ignited buildings in Küçükçekmece (lower bound thresholds).

Structure Type (Label)	Structure Type (Description)	Number of Ignited Buildings
C3	Concrete Frame With Unreinforced Masonry Infill Walls	326
PC1	Precast Concrete Tilt-up Walls	2
RM	Reinforced Masonry	7
URM	Unreinforced Masonry Bearing Walls	1774
W1	Wood, Light Frame	21

Table 5.15 : Number of ignited buildings according to number of storeys in Küçükçekmece (lower bound thresholds).

Number of Storeys	Number of Ignited Buildings
1	1072
2	504
3	426
4	116
5	9
6	3

Table 5.16 : Number of ignited buildings according to district name in Küçükçekmece (lower bound thresholds).

Name of District	Number of Ignited Buildings
Beşyol	50
Cennet	380
Cumhuriyet	232
Fatih	15
Fevzi Çakmak	5
Gültepe	132
Halkalı Merkez	1
İkitelli Atatürk	3
İstasyon	5
Kanarya	99
Kartaltepe	41
Kemalpaşa	1
Söğütlüçeşme	3
Sultan Murat	45
Tevfik Fikret	29
Yarımburgaz	2
Yenimahalle	472
Yeşilova	615

Table 5.17 : Number of ignited buildings according to building code in Küçükçekmece (lower bound thresholds).

Building Code	Number of Ignited Buildings
Pre-Code	2069
Low-Code	49
Moderate-Code	7
High-Code	5

In the analysis with upper bound thresholds, 84 buildings were analyzed as ignited after the Mw 7.5 earthquake that corresponded to 0.23% of building inventory (Figure 5.17). Lower screenshot in Figure 5.17 is the zoomed form of upper screenshot. Ignited buildings consist of two different occupancy types as tabulated in Table 5.18. Building code of all ignited buildings is Pre-code. 83 ignited buildings are in Cennet District and one ignited building is in Yeşilova District.

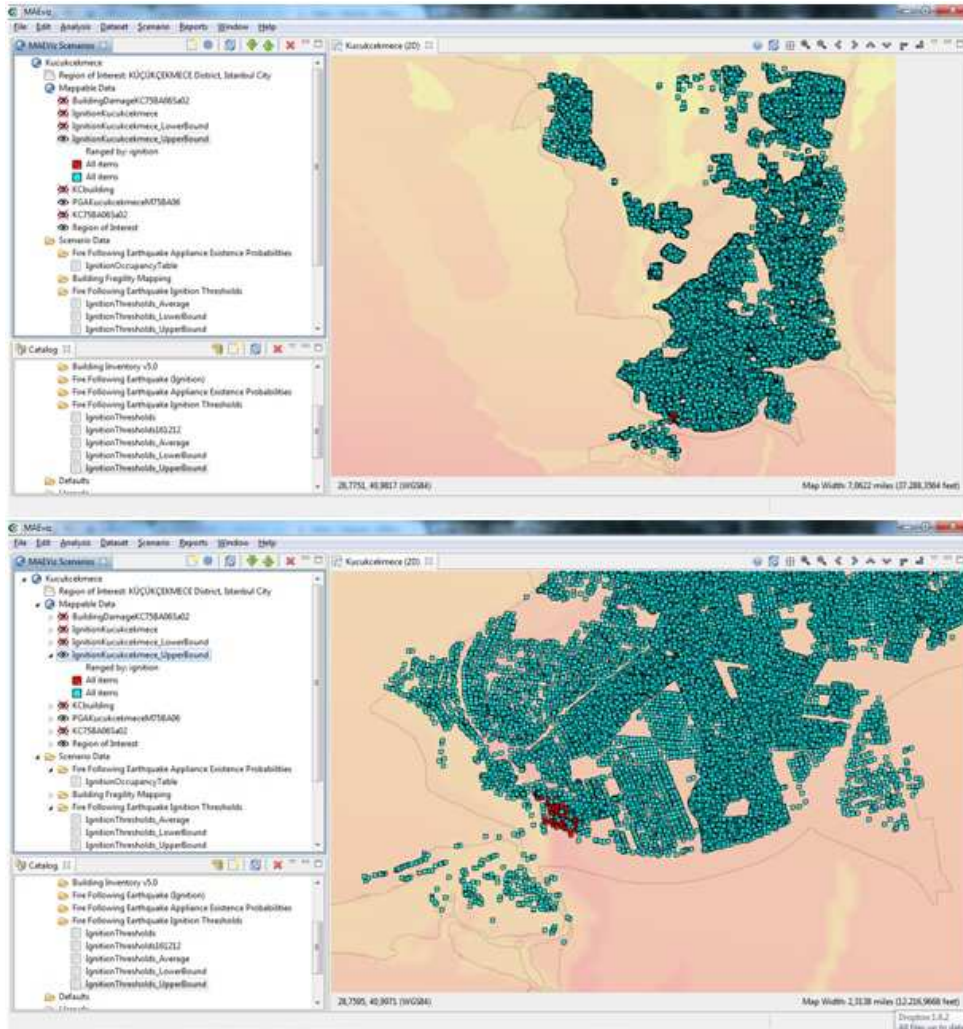


Figure 5.17 : Result of post-earthquake ignition analysis for Küçükçekmece application with upper bound thresholds.

Table 5.18 : Ignited buildings with occupancy types for Küçükçekmece application (upper bound thresholds).

Occupancy Type	Description	Number of Ignited Buildings
IND2	Light Industrial (Factory)	1
RES3	Residential Multi Family Dwelling (Apartment/Condominium)	83

Number of ignited buildings with respect to the structure type, number of storeys and district are tabulated in Table 5.19 and Table 5.20, respectively.

Table 5.19 : Number and structure types of ignited buildings in Küçükçekmece (upper bound thresholds).

Structure Type (Label)	Structure Type (Description)	Number of Ignited Buildings
C3	Concrete Frame With Unreinforced Masonry Infill Walls	1
URM	Unreinforced Masonry Bearing Walls	83

Table 5.20 : Number of ignited buildings according to number of storeys in Küçükçekmece (upper bound thresholds).

Number of Storeys	Number of Ignited Buildings
1	56
2	14
3	10
4	3
5	1

6. RESULTS AND DISCUSSIONS

Post-earthquake ignition analyses were carried out for Memphis and Küçükçekmece with developed tool in HAZTURK software. Numerical results are given in chapter 5. These numerical results are calculated as percentages to evaluate them according to different attributes. Percentages of ignited buildings versus different properties in attributes were calculated for Memphis and Küçükçekmece. Percentages are the ratio of number of ignited buildings for a specific property in an attribute to total number of buildings for given attribute. As mentioned before, lower bound, average and upper bound thresholds were used in analyses because of limited historical records. Analysis results are for NMSZ Mw 7.7 scenario earthquake for Memphis and Marmara Fault Zone Mw 7.5 scenario earthquake for Küçükçekmece.

Table 6.1 shows the percentage of the ignited buildings versus occupancy type for Memphis.

Table 6.1 : Percentage of the ignited buildings versus occupancy type for Memphis.

Occupancy Type	Description	Percentage of Ignited Buildings (%)		
		Lower Bound	Average	Upper Bound
COM6	Hospital	2.38	0	0
COM7	Medical Office/Clinic	9.82	0	0
COM8	Entertainment & Recreation (Restaurants/Bars)	14.95	0	0
EDU1	Grade Schools	2.94	0	0
IND1	Factory (Heavy)	1.23	0	0
IND2	Factory (Light)	2.30	0	0
IND3	Factory (Food/Drugs/Chemicals)	4.76	0	0
IND4	Factory (Metals/Minerals Processing)	2.70	0	0
REL1	Church/Non-Profit	10.00	0	0

According to percentages in Table 6.1, there is no post earthquake fire risk for average and upper bound thresholds in Memphis. The most vulnerable occupancy types are COM8 (restaurants/bars), REL1 (Church/Non-Profit) and COM7 (medical office/clinic) for lower bound thresholds. Buildings having these three occupancy

types are both public places. Number of people in these buildings can vary depending on the occurrence time of earthquake.

When the results are evaluated in terms of number of storeys, 1.50 % of 1-storey, 1.04 % of 2-storey and 0.27 % of 3-storey buildings are ignited. Furthermore, 16.46 % of light frame wooden buildings and 13.69 % of commercial and industrial wooden buildings are ignited. Therefore, there is also fire spread risk for these buildings because of the construction material. Construction year of all ignited buildings are before 1992. It means that building code of all ignited buildings are pre-code and the age of the building directly affect the ignition risk. Finally, Total appraised value of these ignited 195 buildings is \$65458168.

Table 6.2 and 6.3 shows the percentage of the ignited buildings versus occupancy type and structure type for Küçükçekmece, respectively.

Table 6.2 : Percentage of the ignited buildings versus occupancy type for Küçükçekmece.

Occupancy Type	Description	Percentage of Ignited Buildings (%)		
		Lower Bound	Average	Upper Bound
COM1	Commercial Retail Trade (Store)	0.54	0.22	0
COM3	Commercial Personal and Repair Services (Service Station/Shop)	0.09	0	0
GOV1	Governmental General Services (Office)	0	0	0
IND2	Factory (Light)	18.97	8.21	0.51
RES3	Residential Multi Family Dwelling (Apartment/Condominium)	7.83	1.18	0.31

Table 6.3 : Percentage of the ignited buildings versus structure type for Küçükçekmece.

Structure Type	Description	Percentage of Ignited Buildings (%)		
		Lower Bound	Average	Upper Bound
C3	Concrete Frame With Unreinforced Masonry Infill Walls	1.08	0.12	0.003
PC1	Precast Concrete Tilt-up Walls	2.67	0	0
RM	Reinforced Masonry	1.90	0	0
URM	Unreinforced Masonry Bearing Walls	32.06	5.17	1.50
W1	Wood, Light Frame	95.45	59.09	0

Table 6.2 illustrates that there is a significant post-earthquake ignition risk in light industrial buildings both for lower bound and average thresholds. These buildings are small-scale industrial buildings that have around 50 working people. When the total number of these ignited buildings is considered, number of people under post-earthquake fire risk is so remarkable. There is also a significant risk for multi family dwellings. Even if the percentages of ignited buildings are small for average and upper bound thresholds, they correspond to great number of buildings.

According to Table 6.3, the most vulnerable buildings are unreinforced masonry and light frame wooden buildings with respect to the structure types. Wooden buildings are more critical than the others because of the fire spread risk. Spread of fire in wooden buildings is faster than the other structure types. This makes people in wooden buildings under noteworthy risk.

Table 6.4 : Percentage of the ignited buildings for districts in Küçükçekmece.

Name of District	Percentage of Ignited Buildings (%)		
	Lower Bound	Average	Upper Bound
Atakent	0	0	0
Beşyol	18.87	5.28	0
Cennet	31.91	16.88	6.97
Cumhuriyet	10.49	3.80	0
Fatih	2.40	0.48	0
Fevzi Çakmak	0.31	0	0
Gültepe	9.26	0	0
Halkalı Merkez	0.03	0.03	0
İkitelli Atatürk	0.11	0.04	0
İnönü	0	0	0
İstasyon	0.25	0	0
Kanarya	2.87	0.06	0
Kartaltepe	4.08	0.20	0
Kemalpaşa	0.13	0	0
Mehmet Akif	0	0	0
Söğütlüçeşme	0.13	0	0
Sultan Murat	5.01	0	0
Tevfik Fikret	1.66	0.06	0
Yarımburgaz	0.17	0.08	0
Yenimahalle	38.19	1.29	0
Yeşilova	32.08	0.42	0.05

Table 6.4 represents that, the most vulnerable districts are Cennet, Yenimahalle and Yeşilova. Beşyol and Cumhuriyet districts also have significant risk for lower and

average thresholds. Cennet district is so critical for both thresholds and it is so necessary to take measures in there.

Table 6.5 : Percentage of the ignited buildings versus number of storeys for Küçükçekmece.

Number of Storeys	Percentage of Ignited Buildings (%)		
	Lower Bound	Average	Upper Bound
1	20.99	3.84	1.10
2	9.88	1.55	0.27
3	6.41	0.59	0.15
4	1.54	0.19	0.04
5	0.16	0.09	0.02
6	0.08	0.03	0.00

Table 6.5 demonstrates that in 1-storey buildings are more vulnerable to post-earthquake ignitions than higher ones. 2-storey and 3-storey buildings also have significant ignition percentages.

Table 6.6 : Percentage of the ignited buildings versus building code for Küçükçekmece.

Building Code	Percentage of Ignited Buildings (%)		
	Lower Bound	Average	Upper Bound
Pre-Code	26.53	4.14	1.08
Low-Code	0.18	0.01	0.00
Moderate-Code	100	85.71	0.00
High-Code	100	20.00	0.00

It is obvious that, buildings constructed according to pre-code are more vulnerable than the others as in Table 6.6. It is interesting that all of the buildings constructed according to moderate and high are ignited. This can be caused by limited number of buildings. There are only 7 buildings with moderate-code and 5 buildings with high-code. The risk for these buildings is 0 for upper bound thresholds but there is still a risk for buildings with pre-code.

When analyses for both Memphis and Küçükçekmece are examined, it is clear that post-earthquake ignition probability is inversely proportional to the number of storeys and construction year depending on the building code. Results of analyses for both two cities show that wooden buildings are so vulnerable to both ignition and spread.

7. CONCLUSIONS AND RECOMMENDATIONS

This study aims determining the sources of post-earthquake ignitions, modeling and prioritizing these sources in a hierarchical way and calculating the ignition probability of each building for particular scenario earthquakes. Past earthquake reports show that most of the post-earthquake ignitions caused by damage in electrical and gas distribution systems and overturning of appliances in buildings. This study models all the sources aforementioned. The 1994 Northridge earthquake fire reports were used to calculate the thresholds in order to obtain the number and locations of possible ignitions.

Most of existing ignition models estimate the number of ignitions for a particular area such as a census tract according to PGA, MMI or building collapse ratio. Some models use the real sources to calculate the ignition probability of a building but they are not capable of determining the ignited buildings. Number and locations of ignited buildings were estimated by integrating both approaches. This existing approach does not consider the structure types of buildings in the determination of the ignited buildings. Ignition probabilities of buildings and number of ignitions are calculated for a particular area. Then, calculated numbers of buildings from the top ignition probability are considered as ignited. On the contrary, ignited buildings in this study were estimated by comparing their ignition probabilities with threshold probabilities calculated for different structure types separately.

Developed model was also verified by applying model to the 1994 Northridge earthquake records. Most of the burned buildings in this report were estimated as ignited but some of them were not seen as ignited. This was caused by heat radiation from normal equipment operation or fire spread from the neighboring buildings. These reasons are also defined in different sections in the FFNRE database too.

With respect to calculation of the thresholds, number of data points for past earthquake ignition records have a significant role in determining the number and location of possible ignitions. The accuracy and the reliability of the determined thresholds of the study can be improved by increasing the number of past earthquake

ignition records increases. This reveals that the data collection quality and quantity, before and after the earthquakes should be increased following the international spatial data standards.

Developed post-earthquake ignition model was implemented to HAZTURK (MAEViz) software. HAZTURK (MAEViz) has become the only seismic loss assessment software which has fire following earthquake tool. There have been no studies for fire following earthquake applied in Turkey in detail until today. With the help of this new ignition tool, it is possible to estimate the number and locations of ignited building for any given scenario earthquake.

Parsons et al. (2000) and Parsons (2004) declared that the probability of an M7 earthquake from the Main Marmara fault is approximately 35–70% within the next 30 years, with an estimation of a rupture beneath the Sea of Marmara to the south of Istanbul. The seismic activity around the city of Istanbul also encouraged the researchers to develop advanced scientific models to estimate the possible losses during and following such an earthquake (Karaman et al., 2008). According to the second article of 6306 regeneration of areas under the disaster risk law, Küçükçekmece District was determined as one of the most risky area within the city of Istanbul. That's why; the Küçükçekmece District was selected as the pilot study region for the application of the thesis in Turkey. Dominant cause of earthquake damage for the buildings in the history of Istanbul was the main reason of the changes in the construction materials used for buildings since sixteenth century. Most of the buildings were built with stones and bricks until the 1509 Istanbul earthquake that damaged these types of structures hazardously. After this earthquake, constructors were encouraged to build wooden buildings which are safer than stone and brick buildings with respect to loss of life (Yılmaz, 2002; Genç, 2007). A regulation published in 1826 mention gave clues about the building construction strategies which are resistant to earthquake and fire. In this context, it was encouraged to decrease the number of wooden buildings while the numbers of masonry low-rise buildings at most two storeys were encouraged to increase (Ambraseys and Finkel, 1999; Genç, 2007). Developed ignition assessment tool can be used as a decision support system by emergency managers in urban planning and disaster management.

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APPENDICES

APPENDIX A: Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake

APPENDIX B: Java Codes of Developed Post-Earthquake Ignition Model

APPENDIX A: Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake

Table A.1 : Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake.

Ignited Building	P _{ignition}	P _{US}	P _{HA}	P _{LHA}	PGA	Occupancy	Cons. Typ	Struct. Typ2
10157 Wisner Ave	0,41458	0,290472	0,537096	0,584034	0,76	RES1	V	W1
10490 N Ilex Ave	0,30086	0,260429	0,291232	0,5456	0,56	COM4	V	W1
10630 Louise Ave	0,40545	0,312983	0,487468	0,567123	0,68	RES1	V	W1
10763 Forbes Ave	0,41257	0,326798	0,487468	0,567123	0,68	RES1	V	W1
10845 N Burnet Ave	0,30228	0,240508	0,361936	0,391747	0,48	RES1	V	W1
10949 McVine Ave	0,14212	0,210925	0,085659	0,004334	0,24	RES1	V	W1
10th Ave	0,11090	0,150414	0,085659	0,004334	0,24	RES1	V	W1
1118 W 3rd St	0,10104	0,137741	0,077548	0,002231	0,20	RES1	V	W1
11742 Luanda St	0,27310	0,217402	0,352581	0,255482	0,44	RES1	V	W1
119 Anchorage St	0,23067	0,161573	0,342901	0,156678	0,40	RES3	V	W1
12036 Ventura Blvd	0,29156	0,204083	0,381446	0,397512	0,48	COM7	V	W1
1324 Idaho Ave	0,28329	0,161573	0,383464	0,525932	0,56	RES3	V	W1
1340 Exposition Blvd	0,11090	0,150414	0,085659	0,004334	0,24	RES1	V	W1
14005 Ventura Blvd	0,27177	0,245735	0,273461	0,399105	0,48	COM1	V	W1
14225 Ventura Blvd	0,25323	0,240508	0,262916	0,281597	0,44	COM4	V	W1
14424 W Terra Bella St	0,30228	0,240508	0,361936	0,391747	0,48	RES1	V	W1
1446 7th St	0,33250	0,171579	0,487468	0,567123	0,68	RES3	V	W1
14569 Benefit St	0,28222	0,235086	0,352581	0,255482	0,44	RES3	V	W1
15445 Cobalt St	0,39383	0,290472	0,487468	0,567123	0,68	RES2	V	W1
1622 N Serrano Ave	0,23769	0,189048	0,333006	0,123174	0,36	RES3	V	W1
17221 Willard St	0,32787	0,265044	0,371261	0,484937	0,52	RES1	V	W1
1725 Clear View Dr	0,12465	0,210925	0	0,157831	0,40	COM10	V	W1

Table A.1 (cont.): Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake.

Ignited Building	P _{ignition}	P _{US}	P _{HA}	P _{LHA}	PGA	Occupancy	Cons. Typ	Struct. Typ2
17515 Enadia Way	0,28772	0,245735	0,352581	0,255482	0,44	RES1	V	W1
17730 W Lassen St	0,36337	0,265044	0,444955	0,556872	0,64	RES3	V	W1
18111 Nordhoff St	0,47036	0,530275	0,372373	0,537097	0,56	EDU2	I	PC2L
18111 Nordhoff St	0,43085	0,453695	0,372373	0,537097	0,56	EDU2	I	RM2L
18111 Nordhoff St	0,41693	0,42671	0,372373	0,537097	0,56	EDU2	I	C2L
18111 Nordhoff St	0,46919	0,528004	0,372373	0,537097	0,56	EDU2	I	PC1
18111 Nordhoff St	0,47804	0,545157	0,372373	0,537097	0,56	EDU2	I	S1L
18111 Nordhoff St	0,45317	0,496959	0,372373	0,537097	0,56	EDU2	I	S4L
18111 Nordhoff St	0,47120	0,531905	0,372373	0,537097	0,56	EDU2	I	S5L
18111 Nordhoff St	0,48151	0,551894	0,372373	0,537097	0,56	EDU2	I	C1L
18111 Nordhoff St	0,44355	0,478312	0,372373	0,537097	0,56	EDU2	I	S2L
1818 Stoner Ave	0,25847	0,189048	0,352581	0,255482	0,44	RES3	V	W1
18400 Malden St	0,32787	0,265044	0,371261	0,484937	0,52	RES3	V	W1
19603 Turtle Springs Way	0,34740	0,265044	0,406583	0,544503	0,60	RES1	V	W1
20033 Gypsy Ln	0,24885	0,196816	0,342901	0,156678	0,40	RES1	V	W1
21213 Lassen St	0,32671	0,245735	0,383464	0,525932	0,56	RES3	V	W1
2134 W 54th St	0,11090	0,150414	0,085659	0,004334	0,24	RES1	V	W1
21601 San Jose St	0,45504	0,494495	0,383464	0,525932	0,56	RES1	III	C3L
21601 San Jose St	0,43265	0,451104	0,383464	0,525932	0,56	RES1	III	URML
21601 San Jose St	0,40402	0,395609	0,383464	0,525932	0,56	RES1	III	RM1L
21617 Saticoy St	0,27310	0,217402	0,352581	0,255482	0,44	RES3	V	W1
2324 Chariton St	0,24169	0,196816	0,333006	0,123174	0,36	RES1	V	W1
2400 S Beverly Dr	0,24544	0,204083	0,333006	0,123174	0,36	RES1	V	W1
2421 Creston Way	0,24169	0,196816	0,333006	0,123174	0,36	RES1	V	W1
2517 W 54th St	0,11090	0,150414	0,085659	0,004334	0,24	RES3	V	W1

Table A.1 (cont.): Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake.

Ignited Building	P _{ignition}	P _{US}	P _{HA}	P _{LHA}	PGA	Occupancy	Cons. Typ	Struct. Typ2
2741 S Palm Grove Ave	0,23337	0,180679	0,333006	0,123174	0,36	RES1	V	W1
3024 Livonia Ave	0,24544	0,204083	0,333006	0,123174	0,36	RES3	V	W1
3232 Broadway	0,27142	0,180679	0,361936	0,391747	0,48	RES3	V	W1
365 W 47th Pl	0,10437	0,137741	0,085659	0,004334	0,24	RES1	V	W1
3845 Bobstone Dr	0,30498	0,245735	0,361936	0,391747	0,48	RES1	V	W1
4360 Ventura Canyon Ave	0,30228	0,240508	0,361936	0,391747	0,48	RES3	V	W1
4500 Woodman Ave	0,28222	0,235086	0,352581	0,255482	0,44	RES3	V	W1
457 Lincoln Blvd	0,27449	0,161573	0,371261	0,484937	0,52	RES1	V	W1
566 N Kingsley Dr	0,21838	0,137741	0,342901	0,156678	0,40	RES3	V	W1
5842 Harold Way	0,23769	0,189048	0,333006	0,123174	0,36	RES1	V	W1
6132 De Longpre Ave	0,23769	0,189048	0,333006	0,123174	0,36	RES3	V	W1
6660 Reseda Blvd	0,25043	0,235086	0,262916	0,281597	0,44	COM4	V	W1
7138 Greeley St	0,12652	0,180679	0,085659	0,004334	0,24	RES3	V	W1
7237 Anatola Ave	0,28772	0,245735	0,352581	0,255482	0,44	RES1	V	W1
7624 N Goodland Ave	0,24544	0,204083	0,333006	0,123174	0,36	RES1	V	W1
7651 Reseda Blvd	0,30498	0,245735	0,361936	0,391747	0,48	RES3	V	W1
7655 Delia Ave	0,23769	0,189048	0,333006	0,123174	0,36	RES1	V	W1
7820 De Longpre Ave	0,22329	0,189048	0,32308	0,01762	0,32	RES1	V	W1
829 Pacific St	0,35794	0,180679	0,537096	0,584034	0,76	RES1	V	W1
838 9th St	0,29403	0,161573	0,406583	0,544503	0,60	RES3	V	W1
8801 N Eton Ave	0,26976	0,210925	0,352581	0,255482	0,44	RES2	V	W1
8901 N Eton Ave	0,41487	0,492204	0,352581	0,255482	0,44	RES2	IV	S3
908 14th St	0,28329	0,161573	0,383464	0,525932	0,56	RES3	V	W1
909 Euclid St	0,28329	0,161573	0,383464	0,525932	0,56	RES3	V	W1
9108 W 25th St	0,24544	0,204083	0,333006	0,123174	0,36	RES1	V	W1

Table A.1 (cont.): Ignition Probabilities of Ignited Buildings in the 1994 Northridge Earthquake.

Ignited Building	P _{ignition}	P _{US}	P _{HA}	P _{LHA}	PGA	Occupancy	Cons. Typ	Struct. Typ2
9108 W 25th St	0,24544	0,204083	0,333006	0,123174	0,36	RES1	V	W1
914 14th St	0,28329	0,161573	0,383464	0,525932	0,56	RES3	V	W1
9250 Owensmouth Ave	0,46267	0,593098	0,281059	0,486725	0,52	COM1	IV	S3
9740 Tunney Ave	0,33667	0,265044	0,383464	0,525932	0,56	RES1	V	W1
Canby Ave	0,32787	0,265044	0,371261	0,484937	0,52	RES3	V	W1

APPENDIX B: Java Codes of Developed Post-Earthquake Ignition Model

Code of New Post-Earthquake Ignition Model in Eclipse Platform

ModelCalculation.java

```
import java.io.File;
import java.io.FileInputStream;
import java.io.FileNotFoundException;
import java.io.FileOutputStream;
import java.io.IOException;
import java.io.InputStream;
import java.util.Hashtable;
import java.util.List;

import org.apache.commons.io.FileUtils;

import com.linixense.javadbfs.DBFException;
import com.linixense.javadbfs.DBFField;
import com.linixense.javadbfs.DBFReader;
import com.linixense.javadbfs.DBFWriter;

import umontreal.iro.lecuyer.probdist.LognormalDist;

public class ModelCalculation {

    private Hashtable<String, OccupancyData> occVals;

    private double HazardVal;
    private double Insignific;
    private double Moderate;
    private double Heavy;
    private double Complete;
    private String Occ_Type;
    private double ObjectID;
    private double ignition;

    private DBFWriter writer;

    // READING DATA FROM DBF FILE

    public void processDbfFile() {
        InputStream inputStream;
        DBFReader reader;
        try {
            inputStream = new
FileInputStream("files/75HasarliBina.dbf");
            reader = new DBFReader(inputStream);

            // get the field count if you want for some reasons
            // following
            //
            int numberOfFields = reader.getFieldCount();

            int columnHazardVal = 0;
```

```

    int columnInsignific = 0;
    int columnModerate = 0;
    int columnHeavy = 0;
    int columnComplete = 0;
    int columnOcc_Type = 0;
    int columnObjectID = 0;

    for (int i = 0; i < numberOfFields; i++) {

        DBFField field = reader.getField(i);

        String fieldname = field.getName();
        if (fieldname.equals("HazardVal"))
            columnHazardVal = i;
        else if (fieldname.equals("Insignific"))
            columnInsignific = i;
        else if (fieldname.equals("Moderate"))
            columnModerate = i;
        else if (fieldname.equals("Heavy"))
            columnHeavy = i;
        else if (fieldname.equals("Complete"))
            columnComplete = i;
        else if (fieldname.equals("Occ_Type"))
            columnOcc_Type = i;
        else if (fieldname.equals("OBJECTID"))
            columnObjectID = i;

    }

    Object[] rowObjects;

    //int n = 0;
    while ((rowObjects = reader.nextRecord()) != null) {
        //n += 1;
        //System.out.println(n);
        ObjectID = Double.parseDouble("" +
+rowObjects[columnObjectID]);
        HazardVal = Double.parseDouble("" +
rowObjects[columnHazardVal]);
        Insignific = Double.parseDouble("" +
rowObjects[columnInsignific]);
        Moderate = Double.parseDouble("" +
rowObjects[columnModerate]);
        Heavy = Double.parseDouble("" +
rowObjects[columnHeavy]);
        Complete = Double.parseDouble("" +
rowObjects[columnComplete]);
        Occ_Type = ("" +
rowObjects[columnOcc_Type]).trim();

        ignition = calculateBuildingIgnition();

        Object rowData[] = new Object[8];
        rowData[0] = new Double(ObjectID);
        rowData[1] = new Double(HazardVal);
        rowData[2] = new String(Occ_Type);
        rowData[3] = new Double(Insignific);
        rowData[4] = new Double(Moderate);
        rowData[5] = new Double(Heavy);

```

```

        rowData[6] = new Double(Complete);
        rowData[7] = new Double(ignition);

        writer.addRecord(rowData);

    }

    // By now, we have iterated through all of the rows

    inputStream.close();

} catch (DBFException e1) {
    // TODO Auto-generated catch block
    e1.printStackTrace();
} catch (FileNotFoundException e) {
    // TODO Auto-generated catch block
    e.printStackTrace();
} catch (IOException e) {
    // TODO Auto-generated catch block
    e.printStackTrace();
}

}

// READING DATA FROM OCCUPANCY FILE

private void readOccupancyToTable() {
    occVals = new Hashtable<String, OccupancyData>();

    File f = new File("files/Occupancy.csv");
    List<String> lines = null;
    try {
        lines = FileUtils.readLines(f);
    } catch (IOException e) {
        e.printStackTrace();
    }
    String line;
    int index;
    for (index = 1; index < lines.size(); index++) {
        line = lines.get(index);
        String[] columns = line.split(";");
        OccupancyData occupancyData = new OccupancyData();
        occupancyData.readFromString(line);

        occVals.put(columns[0], occupancyData);
    }
}

// CALCULATION OF IGNITION PROBABILITIES

// UTILITY RELATED IGNITIONS

public double calculateUtility() {

    return ((Math.pow((0.05 + 0.014142 * Insignific), 2))
            + (Math.pow((0.05 + 0.50 *
Moderate), 2))

```

```

2)) + (Math.pow(
+ (Math.pow((0.05 + 0.95 * Heavy),
(0.05 + 1.00 * Complete), 2)));

}
// APPLIANCES & CONTENTS RELATED IGNITIONS

public double calculateWaterHeater() {
    LognormalDist dist = new LognormalDist(Math.Log(0.613),
0.742);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).WH);
}

public double calculatePortableHeater() {
    LognormalDist dist = new LognormalDist(Math.Log(0.071),
0.306);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).PH);
}

public double calculateCookingStove() {
    LognormalDist dist = new LognormalDist(Math.Log(0.298),
0.003);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).CS);
}

public double calculateShelvesContainingFlammableMaterial() {
    LognormalDist dist = new LognormalDist(Math.Log(0.655),
0.085);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).SCFM);
}

public double calculateIndustrialProducts() {
    LognormalDist dist = new LognormalDist(Math.Log(0.415),
0.753);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).IP);
}

public double calculateMicrowave() {
    LognormalDist dist = new LognormalDist(Math.Log(1.643),
0.270);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).MW);
}

public double calculateTV() {
    LognormalDist dist = new LognormalDist(Math.Log(1.088),
0.737);

    return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).TV);
}

public double calculatePC() {

```

```

        LognormalDist dist = new LognormalDist(Math.Log(0.333),
0.023);

        return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).PC);
    }

    public double calculateRefrigerator() {
        LognormalDist dist = new LognormalDist(Math.Log(0.506),
0.263);

        return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).RE);
    }

    public double calculateLightingFixtures() {
        LognormalDist dist = new LognormalDist(Math.Log(0.460),
0.094);

        return ((dist.cdf(HazardVal)) * occVals.get(Occ_Type).LF);
    }

    // IGNITIONS CAUSED BY HAZARDOUS APPLIANCES

    public double calculateHazardousAppliances() {
        return 0.22088 * calculateWaterHeater() + 0.28324
            * calculatePortableHeater() + 0.24263 *
calculateCookingStove()
            + 0.12795 *
calculateShelvesContainingFlammableMaterial()
            + 0.12529 * calculateIndustrialProducts();
    }

    // IGNITIONS CAUSED BY LESS HAZARDOUS APPLIANCES

    public double calculateLessHazardousAppliances() {
        return 0.23602 * calculateMicrowave() + 0.20793 *
calculateTV()
            + 0.13098 * calculatePC() + 0.08623 *
calculateRefrigerator()
            + 0.33885 * calculateLightingFixtures();
    }

    // IGNITION PROBABILITY OF BUILDING

    public double calculateBuildingIgnition() {
        return 0.51588 * calculateUtility() + 0.38378
            * calculateHazardousAppliances() + 0.10034
            * calculateLessHazardousAppliances();
    }

    public static void main(String[] args) {

        ModelCalculation newCalculation = new ModelCalculation();

        newCalculation.readOccupancyToTable();
        newCalculation.initDbfFile();
    }

```

```

        newCalculation.processDbfFile();
        newCalculation.finiDbfFile();

    }

// WRITING RESULTS TO A DBF FILE

    public void initDbfFile() {
        try {
            writer = new DBFWriter();

            DBFField fields[] = new DBFField[8];

            fields[0] = new DBFField();
            fields[0].setName("OBJECTID");
            fields[0].setDataType(DBFField.FIELD_TYPE_N);
            fields[0].setFieldLength(10);
            fields[0].setDecimalCount(0);

            fields[1] = new DBFField();
            fields[1].setName("HazardVal");
            fields[1].setDataType(DBFField.FIELD_TYPE_N);
            fields[1].setFieldLength(12);
            fields[1].setDecimalCount(5);

            fields[2] = new DBFField();
            fields[2].setName("Occ_Type");
            fields[2].setDataType(DBFField.FIELD_TYPE_C);
            fields[2].setFieldLength(4);

            fields[3] = new DBFField();
            fields[3].setName("Insignific");
            fields[3].setDataType(DBFField.FIELD_TYPE_N);
            fields[3].setFieldLength(12);
            fields[3].setDecimalCount(5);

            fields[4] = new DBFField();
            fields[4].setName("Moderate");
            fields[4].setDataType(DBFField.FIELD_TYPE_N);
            fields[4].setFieldLength(12);
            fields[4].setDecimalCount(5);

            fields[5] = new DBFField();
            fields[5].setName("Heavy");
            fields[5].setDataType(DBFField.FIELD_TYPE_N);
            fields[5].setFieldLength(12);
            fields[5].setDecimalCount(5);

            fields[6] = new DBFField();
            fields[6].setName("Complete");
            fields[6].setDataType(DBFField.FIELD_TYPE_N);
            fields[6].setFieldLength(12);
            fields[6].setDecimalCount(5);

            fields[7] = new DBFField();
            fields[7].setName("IGNITION");
            fields[7].setDataType(DBFField.FIELD_TYPE_N);
            fields[7].setFieldLength(12);
            fields[7].setDecimalCount(5);

```

```

        writer.setFields(fields);
    }
    catch(DBFException e)
    {
        e.printStackTrace();
    }
}

public void finiDbfFile() {
    FileOutputStream fos;
    try {
        fos = new FileOutputStream("files/ignition.dbf");
        writer.write(fos);
        fos.close();
    } catch (FileNotFoundException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
    } catch (DBFException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
    } catch (IOException e) {
        // TODO Auto-generated catch block
        e.printStackTrace();
    }
}
}

```

OccupancyData.java

```

public class OccupancyData {

    public double WH;
    public double PH;
    public double CS;
    public double SCFM;
    public double IP;
    public double MW;
    public double TV;
    public double PC;
    public double RE;
    public double LF;

    public void readFromString(String line)
    {
        String[] columns = line.split(";");
        WH = Double.parseDouble(columns[1]);
        PH = Double.parseDouble(columns[2]);
        CS = Double.parseDouble(columns[3]);
        SCFM = Double.parseDouble(columns[4]);
        IP = Double.parseDouble(columns[5]);
        MW = Double.parseDouble(columns[6]);
        TV= Double.parseDouble(columns[7]);
        PC = Double.parseDouble(columns[8]);
        RE = Double.parseDouble(columns[9]);
        LF = Double.parseDouble(columns[10]);
    }
}

```

```
public void debugPrint()
{
    System.out.println("Occupancy Data Print:");
    System.out.println(WH);
    System.out.println(PH);
    System.out.println(CS);
    System.out.println(SCFM);
    System.out.println(IP);
    System.out.println(MW);
    System.out.println(TV);
    System.out.println(PC);
    System.out.println(RE);
    System.out.println(LF);
}
}
```

Edited Code of New Post-earthquake Ignition in HAZTURK Source Code

```
package ncsa.maeviz.buildings.fireignition.tasks;

import java.util.List;

import javax.swing.table.DefaultTableModel;

import ncsa.analysis.ogrescript.tasks.core.SimpleFeatureTask;
import ncsa.gis.datasets.RasterDataset;
import ncsa.gis.datasets.TableDataset;
import ncsa.maeviz.buildings.Building;
import ncsa.maeviz.hazard.datasets.HazardDataset;
import ncsa.maeviz.hazard.exceptions.UnsupportedHazardException;
import ncsa.maeviz.hazard.types.SpectrumMethods;
import ncsa.maeviz.hazard.util.HazardUtil;
import ncsa.maeviz.solvers.LogNormalSolver;
import ncsa.maeviz.types.FragilityHazardSet;
import ncsa.tools.elf.core.exceptions.ScriptExecutionException;

import org.apache.log4j.Logger;
import org.eclipse.core.runtime.IProgressMonitor;

import com.vividsolutions.jts.geom.Point;

public class BuildingFireIgnition extends SimpleFeatureTask
{
    private static final Logger logger = Logger.getLogger(
BuildingFireIgnition.class );
    private static int WH_COL = 1;
    private static int PH_COL = 2;
    private static int CS_COL = 3;
    private static int SCFM_COL = 4;
    private static int IP_COL = 5;
    private static int MW_COL = 6;
    private static int TV_COL = 7;
    private static int PC_COL = 8;
    private static int RE_COL = 9;
    private static int LF_COL = 10;
    private String strType2;
    private String occType;
    private double pgaVal;
    private double insignific;
    private double moderate;
    private double heavy;
    private double complete;
    private LogNormalSolver dist;

    // Inputs
    private TableDataset fireIgnitionTable;
    private FragilityHazardSet hazardSet = new FragilityHazardSet();
    private TableDataset ignitionThreshold;
    // Outputs
    private double utility;
    private double pHazardAppliances;
    private double pIgnition;
    private double pLessHazardAppliances;
    private int ignition;
```

```

@Override
protected void handleFeature( IProgressMonitor monitor ) throws
ScriptExecutionException
{
    // Building Occupancy
    int occType_col = feature.getFeatureType().find(
Building.OCCUPANCY_TYPE );
    if ( occType_col == -1 ) {
        throw new ScriptExecutionException( "No occupancy type column
found for building" );
    }

    occType = (String) feature.getAttribute( occType_col );

    int strType2_col = feature.getFeatureType().find(
Building.HAZUS_STR_TYPE_COL );
    if( strType2_col == -1 ) {
        throw new ScriptExecutionException( "No hazus structure type
column found, this is required for the ignition threshold table." );
    }
    strType2 = (String) feature.getAttribute( strType2_col );

    // insignificant Damage
    int insignificantDamageCol = feature.getFeatureType().find(
Building.INSIGNIFICANT );
    insignific = (Double) feature.getAttribute( insignificantDamageCol
);

    // moderate Damage
    int moderateDamageCol = feature.getFeatureType().find(
Building.MODERATE );
    moderate = (Double) feature.getAttribute( moderateDamageCol );

    // heavy Damage Probability
    int heavyDamageCol = feature.getFeatureType().find( Building.HEAVY
);
    heavy = (Double) feature.getAttribute( heavyDamageCol );

    // Complete Damage Probability
    int completeDamageCol = feature.getFeatureType().find(
Building.COMPLETE );
    complete = (Double) feature.getAttribute( completeDamageCol );

    // create log normal solver
    dist = new LogNormalSolver();

    Point location = (Point) feature.getAttribute( 0 );
    //try {
        pgaVal = hazardSet.getHazardVal( location, 0.0, HazardUtil.PGA,
HazardUtil.units_g, SpectrumMethods.SPECTRUM_DEFAULT );//.getValueAt(
location, HazardUtil.PGA );
    //} catch ( UnsupportedHazardException e ) {
    //    throw new ScriptExecutionException("PGA hazard not supported
by the hazard input, check your input dataset.");
    //}
    //System.out.println( "pga_val = " + pgaVal );

    pIgnition = calculateBuildingIgnition();
    ignition = checkIgnition();
}

```

```

        resultMap.put( "p_us", utility );
        resultMap.put( "p_ha", pHazardAppliances );
        resultMap.put( "p_lha", pLessHazardAppliances );
        resultMap.put( "p_ig", pIgnition );
        resultMap.put( "ignition", ignition );
        resultMap.put( "pga-val", pgaVal );
    }

    private int checkIgnition()
    {
        if ( hasRange() ) {
            double[] range = getThresholdRange();
            if ( pIgnition > range[0] && pIgnition < range[1] ) {
                return 1;
            }
        } else {
            double threshold = getThreshold();
            if ( pIgnition > threshold ) {
                return 1;
            }
        }

        return 0;
    }

    private double[] getThresholdRange()
    {
        double[] range = { 1.0, 1.0 };
        DefaultTableModel table = ignitionThreshold.getTableModel();
        for ( int row = 0; row < table.getRowCount(); row++ ) {
            String hazusStrType = (String) table.getValueAt( row, 0 );
            if ( hazusStrType.equalsIgnoreCase( strType2 ) ) {
                double thresholdLB = Double.parseDouble( (String)
table.getValueAt( row, 2 ) );
                double thresholdUB = Double.parseDouble( (String)
table.getValueAt( row, 3 ) );

                return new double[] {thresholdLB, thresholdUB };
            }
        }

        return range;
    }

    private double getThreshold()
    {
        DefaultTableModel table = ignitionThreshold.getTableModel();
        for ( int row = 0; row < table.getRowCount(); row++ ) {
            String hazusStrType = (String) table.getValueAt( row, 0 );
            if ( hazusStrType.equalsIgnoreCase( strType2 ) ) {
                double threshold = Double.parseDouble( (String)
table.getValueAt( row, 3 ) );
                return threshold;
            }
        }

        return 1.0;
    }
}

```

```

private boolean hasRange()
{
    DefaultTableModel table = ignitionThreshold.getTableModel();
    for ( int row = 0; row < table.getRowCount(); row++ ) {
        String hazusStrType = (String) table.getValueAt( row, 0 );
        if ( hazusStrType.equalsIgnoreCase( strType2 ) ) {
            String range = (String) table.getValueAt( row, 1);
            return range.equalsIgnoreCase( "yes" );
        }
    }
    return false;
}

public double getOccupancyData( int col )
{
    DefaultTableModel table = fireIgnitionTable.getTableModel();
    for ( int row = 0; row < table.getRowCount(); row++ ) {
        String occupancy = (String) table.getValueAt( row, 0 );
        if ( occupancy.equalsIgnoreCase( occType ) ) {
            return Double.parseDouble( (String) table.getValueAt( row,
col ) );
        }
    }
    logger.warn( "Could not find occupancy data for building " +
feature.getID() );
    return 0;
}

/*
private double calculateBuildingIgnition()
{
    double hazard = 0.45;

    return dist.getValue( Math.log( 1.088 ), 0.737, hazard );
} */

// IGNITION PROBABILITY OF BUILDING

public double calculateBuildingIgnition()
{
    utility = calculateUtility();
    pHazardAppliances = calculateHazardousAppliances();
    pLessHazardAppliances = calculateLessHazardousAppliances();

    return 0.51588 * utility + 0.38378 * pHazardAppliances + 0.10034 *
pLessHazardAppliances;
}

// UTILITY RELATED IGNITIONS

public double calculateUtility()
{
    return ((Math.pow( (0.05 + 0.014142 * insignific), 2 )) +
(Math.pow( (0.05 + 0.50 * moderate), 2 ))
+ (Math.pow( (0.05 + 0.95 * heavy), 2 )) + (Math.pow(
(0.05 + 1.00 * complete), 2 ))));
}

```

```

    }

    // IGNITIONS CAUSED BY HAZARDOUS APPLIANCES

    public double calculateHazardousAppliances()
    {
        return 0.22088 * calculateWaterHeater() + 0.28324 *
calculatePortableHeater() + 0.24263 * calculateCookingStove() + 0.12795
        * calculateShelvesContainingFlammableMaterial() + 0.12529
* calculateIndustrialProducts();
    }

    // IGNITIONS CAUSED BY LESS HAZARDOUS APPLIANCES

    public double calculateLessHazardousAppliances()
    {
        return 0.23602 * calculateMicrowave() + 0.20793 * calculateTV() +
0.13098 * calculatePC() + 0.08623 * calculateRefrigerator()
        + 0.33885 * calculateLightingFixtures();
    }

    // APPLIANCES & CONTENTS RELATED IGNITIONS

    public double calculateWaterHeater()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.613 ), 0.742
);

        return dist.getValue( Math.Log( 0.613 ), 0.742, pgaVal ) *
getOccupancyData( WH_COL );
    }

    public double calculatePortableHeater()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.071 ), 0.306
);

        return dist.getValue( Math.Log( 0.071 ), 0.306, pgaVal ) *
getOccupancyData( PH_COL );
    }

    public double calculateCookingStove()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.298 ), 0.003
);

        return dist.getValue( Math.Log( 0.298 ), 0.003, pgaVal ) *
getOccupancyData( CS_COL );
    }

    public double calculateShelvesContainingFlammableMaterial()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.655 ), 0.085
);

```

```

        return dist.getValue( Math.Log( 0.655 ), 0.085, pgaVal ) *
getOccupancyData( SCFM_COL );
    }

    public double calculateIndustrialProducts()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.415 ), 0.753
    );

        return dist.getValue( Math.Log( 0.415 ), 0.753, pgaVal ) *
getOccupancyData( IP_COL );
    }

    public double calculateMicrowave()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 1.643 ), 0.270
    );

        return dist.getValue( Math.Log( 1.643 ), 0.270, pgaVal ) *
getOccupancyData( MW_COL );
    }

    public double calculateTV()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 1.088 ), 0.737
    );

        return dist.getValue( Math.Log( 1.088 ), 0.737, pgaVal ) *
getOccupancyData( TV_COL );
    }

    public double calculatePC()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.333 ), 0.023
    );

        return dist.getValue( Math.Log( 0.333 ), 0.023, pgaVal ) *
getOccupancyData( PC_COL );
    }

    public double calculateRefrigerator()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.506 ), 0.263
    );

        return dist.getValue( Math.Log( 0.506 ), 0.263, pgaVal ) *
getOccupancyData( RE_COL );
    }

    public double calculateLightingFixtures()
    {
        //LognormalDist dist = new LognormalDist( Math.log( 0.460 ), 0.094
    );

        return dist.getValue( Math.Log( 0.460 ), 0.094, pgaVal ) *
getOccupancyData( LF_COL );
    }

    // BEAN Methods

```

```

public void setFireIgnitionTable( TableDataset fireIgnitionTable )
{
    this.fireIgnitionTable = fireIgnitionTable;
}

public void setHazard( RasterDataset hazardList )
{
    hazardSet.setDatasets( hazardList );
}

//public HazardDataset getHazard()
//{
//    return hazard;
//}

//public void setHazard( HazardDataset hazard )
//{
//    this.hazard = hazard;
//}

public TableDataset getIgnitionThreshold()
{
    return ignitionThreshold;
}

public void setIgnitionThreshold( TableDataset ignitionThreshold )
{
    this.ignitionThreshold = ignitionThreshold;
}
}

```

CURRICULUM VITAE



Name Surname: Selim Serhan YILDIZ

Place and Date of Birth: Osmaniye, 20.06.1983

Address: İTÜ İnşaat Fakültesi
Geomatik Mühendisliği Bölümü
34469 Maslak / İstanbul

E-Mail: yildizsel@itu.edu.tr

B.Sc.: 2006 - Istanbul Technical University
Geodesy and Photogrammetry Engineering

M.Sc.: 2008 - Istanbul Technical University
Institute of Science and Technology
Geomatics Engineering

Professional Experience and Rewards:

Vehbi Koç Foundation's Scholarship (2004-2006)

TUBITAK National Scholarship for MSc Students (2006-2008)

TUBITAK International PhD Fellowship Programme (2011-2012)

TUBITAK National Scholarship for PhD Students (2008-...)

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