

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**CIM BASED EARTHQUAKE RISK MANAGEMENT FOR
RESILIENCE IN SMART CITIES**

MUSTAFA KORKMAZ

A THESIS OF DOCTORATE
DEPARTMENT OF CIVIL ENGINEERING
EARTHQUAKE AND STRUCTURAL ENGINEERING
PROGRAM

ADVISOR: ASSOC. PROF. DR. ABDULLAH CAN ZULFIKAR

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

AKILLI ŞEHİRLERDE DİRENÇLİLİK İÇİN
CIM TABANLI DEPREM RİSK YÖNETİMİ

MUSTAFA KORKMAZ

DOKTORA TEZİ
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*To my Wife Imran
and
Kids Yaren, Yağmur and
Can*

ABSTRACT

Urban resilience is a critical factor in mitigating the impacts of seismic hazards, particularly in regions with high earthquake risk. This study focuses on the development and implementation of a Seismic Risk Digital Twin (SRDT) integrated with City Information Management (CIM) for the Kocaeli region, an area known for its seismic vulnerability. The SRDT-CIM framework combines geospatial, structural, demographic, and dynamic data to create a comprehensive simulation model, enhancing seismic risk management, urban planning, and emergency response.

The SRDT-CIM framework includes key components: a Hazard Model, an Exposure Model, a Vulnerability Model, a Response Model, and a Recovery Model, all supported by a robust CIM backbone. The Hazard Model employed a logictree approach with multiple ground motion prediction equations to assess seismic hazards and optimize predictive accuracy using on-site data. The Exposure Model analyzes building stock, categorized by function and construction era, integrating demographic distributions retrieved via APIs from address-based databases. The Vulnerability Model applies a hybrid approach, integrating standard vulnerability curves with structural analysis methods to assess potential damage and risk levels.

CIM served as the core of the SRDT, enabling the seamless integration, storage, and management of diverse datasets, while ensuring interoperability and accessibility for stakeholders. This CIM-based approach facilitated dynamic updates, ensuring that real-time changes in urban and environmental parameters were reflected in the DT.

The analysis identified critical challenges, including the need for improved planning of emergency muster sites and optimizing evacuation routes. The SRDT-CIM framework also emphasized the importance of real-time information on trapped individuals to enhance the efficiency of search and rescue operations. The SRDT-CIM also highlighted the importance of accurate, real-time information on trapped individuals for optimizing search and rescue operations.

Comparative analysis demonstrated the advantages of the SRDT-CIM over traditional earthquake management techniques, particularly in predictive accuracy, resource allocation, and decision support capabilities. By integrating DT technology with CIM principles, this study underscores the transformative potential of innovative approaches in enhancing urban resilience, disaster preparedness, and cross-sector collaboration.

The findings contribute to the growing body of knowledge on digital twins and City Information Management, offering a replicable framework for regions facing similar seismic risks.

Keywords: Seismic Risk Digital Twin (SRDT), City Information Management (CIM), Urban Resilience, Earthquake Risk Management, Emergency Response Planning, Digital Twin Technology.

ÖZET

Kentsel direnç, özellikle yüksek deprem riski taşıyan bölgelerde, sismik tehlikelerin etkilerini azaltmada kritik bir faktördür. Bu çalışma, sismik açıdan savunmasız bir bölge olan Kocaeli için Şehir Bilgi Yönetimi (CIM) ile entegre edilmiş bir Sismik Risk Dijital İkizi'nin (SRDT) geliştirilmesine ve uygulanmasına odaklanmaktadır. SRDT-CIM çerçevesi, jeo-uzamsal, yapısal, demografik ve dinamik verileri bir araya getirerek kapsamlı bir simülasyon modeli oluşturmakta ve böylece sismik risk yönetimi, kentsel planlama ve acil durum müdahale süreçlerini geliştirmektedir.

SRDT-CIM çerçevesi, bir Tehlike Modeli, Maruziyet Modeli, Zarar Görebilirlik Modeli, Müdahale Modeli ve İyileşme Modeli olmak üzere temel bileşenleri içermektedir; bu bileşenlerin tümü güçlü bir CIM altyapısıyla desteklenmiştir. Tehlike Modeli, sismik tehlikeleri değerlendirmek ve saha verileriyle tahmin doğruluğunu optimize etmek için çoklu yer hareketi tahmin denklemleri içeren bir mantık ağacı yaklaşımı kullanmıştır. Maruziyet Modeli, bina stokunu işlevi ve yapım dönemi temelinde kategorize ederek analiz etmiş ve adres tabanlı veri tabanlarından API'ler aracılığıyla demografik dağılımları entegre etmiştir. Zarar Görebilirlik Modeli, standart zarar görebilirlik eğrilerini yapısal analiz yöntemleriyle birleştiren hibrit bir yaklaşım uygulayarak olası hasar ve risk seviyelerini değerlendirmiştir.

CIM, SRDT'nin çekirdeği olarak, çeşitli veri kümelerinin sorunsuz bir şekilde entegrasyonunu, saklanması ve yönetimini sağlayarak paydaşlar için erişilebilirlik ve birlikte çalışabilirlik sağlamıştır. Bu CIM tabanlı yaklaşım, kentsel ve çevresel parametrelerdeki gerçek zamanlı değişikliklerin dijital ikize yansıtılmasını kolaylaştırmıştır.

Analiz, acil durum toplanma alanlarının iyileştirilmiş planlanması ve tahliye yollarının optimize edilmesi ihtiyacını içeren kritik zorlukları ortaya koymuştur. SRDT-CIM çerçevesi, aynı zamanda enkaz altında mahsur kalan bireyler hakkında gerçek zamanlı bilginin arama ve kurtarma operasyonlarının etkinliğini artırmadaki önemini vurgulamıştır.

Karşılaştırmalı analiz, SRDT-CIM'in özellikle tahmin doğruluğu, kaynak tahsisi ve karar destek yetenekleri açısından geleneksel deprem yönetimi tekniklerine göre avantajlarını göstermiştir. Bu çalışma, dijital ikiz teknolojisinin CIM ilkeleriyle entegrasyonunun, kentsel direnç, afet hazırlığı ve sektörler arası iş birliğini geliştirmedeki dönüştürücü potansiyelini vurgulamaktadır. Bulgular, dijital ikizler ve Şehir Bilgi Yönetimi konusundaki bilgi birikimine katkıda bulunarak benzer sismik risklerle karşı karşıya kalan bölgeler için tekrarlanabilir bir çerçeve sunmaktadır.

Anahtar Kelimeler: Sismik Risk Dijital İkizi (SRDT), Şehir Bilgi Yönetimi (CIM), Kentsel Direnç, Deprem Riski Yönetimi, Acil Durum Müdahalesi, Dijital İkiz Teknolojisi

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	vi
ÖZET	vii
ACKNOWLEDGEMENTS	viii
TABLE OF CONTENTS	ix
LIST OF SYMBOLS AND ABBREVIATIONS	xi
LIST OF FIGURES	xiii
LIST OF TABLES	xv
1. INTRODUCTION	1
1.1. Background And Significance	2
1.2. Problem Statement	10
1.3. Research Objectives and Research Questions	15
1.4. Scope and Limitations	18
1.5. Structure of the Thesis	20
1.6. Significance of the Study	20
1.7. Hypotheses and Assumptions Underpinning the Study	21
2. BACKGROUND and LITERATURE REVIEW	22
2.1. Seismic Risk Management	23
2.1.1. Hazard Assessment	23
2.1.2. Exposure Assessment	32
2.1.3. Vulnerability Assessment	41
2.2. Urban Resilience	46
2.2.1. Quantification of Resilience	49
2.3. Smart Cities	54
2.4. City Information Modeling	56
2.5. Digital Twin Technology	58
2.6. Integration of CIM in Disaster Risk Management	60
3. THEORETICAL FRAMEWORK	62
3.1. Principles of City Information Modeling (CIM)	62
3.1.1. Data-Centric Urban Management	63
3.1.2. Interoperability and Standardization	63
3.1.3. Holistic Representation of Urban Systems	63
3.1.4. Dynamic and Scalable Framework	64
3.1.5. Relevance to Disaster Management	64
3.2. Principles of Digital Twins	65
3.3. Integration of CIM with DT Technology for DRM	68
3.4. Conceptual Model for Resilience in Smart Cities	70
4. METHODOLOGY	72
4.1. Research Design	72
4.2. Data Collection and Sources	100
4.3. System Architecture and CIM Development	106
4.4. 3D Core Model Creation	109
4.5. Simulation and Analysis	110
4.5.1. Hazard Assessment	110
4.5.2. Damage Assessment of Structures	119

4.5.3. Casualty Estimation	122
4.5.4. Capacity for Shelters	126
4.5.5. Search and Rescue Team Requirements in Response	128
4.6. Validation and Verification	131
5. DEVELOPMENT OF KOCAELİ PROVINCE DIGITAL TWIN	134
5.1. Selection of the Case Study Area	134
5.2. Data Collection and CIM Development	137
5.3. Earthquake Risk Management	149
5.4. Simulation of Earthquake Scenarios	153
5.5. Discussion of Results	154
6. APPLICATION OF CIM-BASED FRAMEWORK IN SEISMIC RISK MANAGEMENT	158
6.1. Decision Support for Emergency Response	158
6.2. Comparison with Traditional Seismic Management Techniques	160
7. RESULTS and DISCUSSION	163
7.1. Implications for Smart Disaster Management	163
7.1.1. Data Gaps and Quality	163
7.1.2. Public Awareness and Education	163
7.1.3. Policy and Governance	168
7.1.4. Technological Limitations	170
7.1.5. Resource Constraints	172
7.2. Challenges and Limitations	174
8. CONCLUSION	177
REFERENCES	179
BIOGRAPHY	202
PUBLICATIONS AND PRESENTATIONS FROM THE THESIS	203
APPENDICES	204

LIST OF SYMBOLS AND ABBREVIATIONS

ISO	: International Standardization Organization
DRM	: Disaster Risk Management
DRR	: Disaster Risk Reduction
SRM	: Seismic Risk Management
6M	: Manpower, Money, Materials, Methods, Machines and Management
COP	: Common Operating Picture
km	: Kilometer
CIM	: City Information Model
DT	: Digital Twin
3D	: Three Dimensional
GTÜ	: Gebze Teknik Üniversitesi
LiDAR	: Light Detection and Ranging
GIS	: Geographic Information System
IoT	: Internet of Things
API	: Application Programming Interface
$R(t)$	: Risk at the time of t
P_h	: Hazard function
$E(t)$	: Exposure Function
$V(t)$	: Vulnerability Function
$R_s(t)$	: Resilience Function
DSHA	: Deterministic Seismic Hazard Analysis
M_{CE}	: Maximum Credible Earthquake
NDSHA	: Neo-Deterministic Seismic Hazard Analysis
PSHA	: Probabilistic Seismic Hazard Analysis
PGA	: Peak Ground Acceleration
GMPE	: Ground Motion Prediction Equations
$\lambda(Y > y)$	: Probability of Exceedance
GEM	: Global Earthquake Model
HAZUS	: Hazard United States
ATC	: Applied Technology Council
EMS	: European Macroseismic Scale
WHE	: World Housing Encyclopedia
FEMA	: Federal Emergency Management Agency
RC	: Reinforced Concrete
CEQUID	: The Cambridge Earthquake Impact Database
GAR	: Global Assessment Report
UNDRR	: United Nations Office for Disaster Risk Reduction
UAV	: Unmanned Aerial Vehicle
SAR	: Search and Rescue
DPM	: Damage Probability Matrices
PSI	: Parameterless Scale of Intensity
SSSM	: Seismic Safety Screening System
MMI	: Modified Mercalli Intensity
FaMIVE	: Failure Mechanism Identification and Vulnerability Evaluation
CAPPA	: Comprehensive Approach to Probabilistic Risk Assessment
ELER	: Earthquake Loss Estimation Routine
TELES	: Taiwan Earthquake Loss Estimation System

DBN	: Dynamic Bayesian Network
AGMM	: Adaptive Gaussian Mixture Model
$Q(t_0)$	: Resilience at $t=0$
$Q(t_d)$	: Resilience at $t=d$
4R	: Robustness, Redundancy, Rapidity and Resourcefulness
λ	: Aging rate constant, representing the rate of decay of functionality over time.
$R(t)$	: Recovery function at time t .
$F(t_0)$	: Functionality at the pre-disaster aged state.
L	: Level of functionality immediately after the disaster (damage level).
γ	: Constant recovery rate (functionality restored per unit of time).
t_0	: Time when recovery begins.
A	: Recovery rate constant.
B	: Recovery steepness parameter.
t_m	: Midpoint of recovery.
$R_i(t)$	: Recovery function of subsystem i .
C_i	: Set of subsystems that are causally dependent on i (directly or indirectly).
$D_{ij}(t)$	: Dependency factor representing the extent to which the recovery of subsystem i is influenced by recovery state of subsystem j at time t .
ICT	: Information and Communications Technology
IoT	: Internet of Things
AI	: Artificial Intelligence
VR	: Virtual Reality
BIM	: Building Information Modeling
CAD	: Computer Aided Design
IFC	: International Foundation Classes
AR	: Augmented Reality
DEM	: Digital Elevation Models
NASA	: National Aeronautics and Space Administration
ESA	: European Space Agency
DTM	: Digital Terrain Model
DSM	: Digital Surface Model
$E[D]$	: Probability of Damage State
D_k	: Damage State k
R_k	: Casualty Distribution Coefficients
NAF	: North Anatolian Fault
EAF	: East Anatolian Fault
IBF	: Izmir Bay Fault
AoI	: Area of Interest
KBB	: Kocaeli Metropolitan Municipality
OSM	: Open Street Maps
MTA	: Mineral Research and Exploration General Directorate
LNG	: Liquefied Natural Gas
ELF	: Equivalent Lateral Forces

LIST OF FIGURES

	<u>Page</u>
Figure 1.1: Complexity and interconnected nature of cities.	3
Figure 1.2: Types of effects of disasters.	4
Figure 1.3: Principles of ISO 31000.	5
Figure 1.4: The Framework of ISO 31000.	5
Figure 1.5: The Process of ISO 31000.	6
Figure 1.6: The disaster management cycle.	7
Figure 1.7: The disaster management cycle related task.	8
Figure 1.8: The disaster management cycle data loss.	12
Figure 1.9: CIM and DT representations.	14
Figure 1.10: Thesis structure.	20
Figure 2.1: DSHA workflow schematization.	24
Figure 2.2: PSHA workflow schematization.	27
Figure 2.3: General parameter considerations of GMPEs.	28
Figure 2.4: Simple depiction of resilience.	51
Figure 2.5: Functionality curves (adopted from [194]).	52
Figure 2.6: CIM approach.	57
Figure 3.1: Data lasagna structure of CIM.	70
Figure 4.1: General sub-routines of SRM framework.	73
Figure 4.2: 3D model database sub-routines.	75
Figure 4.3: Hazard assessment sub-routine.	78
Figure 4.4: Exposure assessment sub-routine.	81
Figure 4.5: Vulnerability assessment sub-routine.	84
Figure 4.6: Damage and loss assessment sub-routine.	87
Figure 4.7: Response management sub-routine.	90
Figure 4.8: Recovery management sub-routine.	93
Figure 4.9: Mitigation assessment sub-routine.	96
Figure 4.10: Preparedness assessment sub-routine.	99
Figure 4.11: 3D model creation framework.	105
Figure 4.12: System architecture of the model.	107
Figure 4.13: Core model creation workflow.	111
Figure 4.14: Catalo harmonization workflow.	112
Figure 4.15: SHA preparatory workflow.	115
Figure 4.16: Logictree optimization workflow.	117
Figure 4.17: Hazard assessment workflow.	120
Figure 4.18: Casualty estimation workflow.	125
Figure 5.1: Kocaeli City (AoI).	136
Figure 5.2: Raw and harmonized earthquake catalogs of the AoI.	140
Figure 5.3: Population pyramide of Kocaeli.	141
Figure 5.4: Datasets employed in the model.	142
Figure 5.5: Vs ₃₀ distribution.	142
Figure 5.6: Building taxonomy on the model.	143
Figure 5.7: PGA values of buildings.	144
Figure 5.8: PGA values over infrastructure.	145
Figure 5.9: Distribution of governmental buildings.	146
Figure 5.10: Distribution of building types by construction year.	146
Figure 5.11: Building types on the model.	147

Figure 5.12:	Fragility curves.	148
Figure 5.13:	CIM response support.	151
Figure 5.14:	Response workflow for the model.	153
Figure 5.15:	Damage state distribution of structures.	155
Figure 5.16:	Casualty calculations.	157
Figure 5.17:	Demographics over the model.	158
Figure 6.1:	SAR operations management capabilities of the model.	159
Figure 6.2:	General overview of the models situation and needs analysis.	162



LIST OF TABLES

	<u>Page</u>
Table 2.1: Comparison of PSHA and DSHA	29
Table 2.2: Fault attributes needed for SHA	30
Table 2.3: Catalog attributes needed for SHA	31
Table 2.4: EMS-98 Building Classification System	34
Table 2.5: HAZUS Building Classification System	35
Table 2.6: CEQID Building Classification System	38
Table 2.7: Secondary Attributes for CEQID Taxonomy	38
Table 2.8: GAR 2013 Building Classification System	40
Table 2.9: Data needs for a DT	61
Table 3.1: Key Properties of CIM	63
Table 3.2: Key properties of DTs	68
Table 4.1: Horizontal GMPE Parameters	118
Table 4.2: HAZUS Casualty classification levels	124
Table 4.3: R_k Values for damage states	126

1. INTRODUCTION

Throughout history, natural events such as earthquakes, volcanic eruptions, and torrential rains have posed significant challenges for humankind. The impacts of these phenomena extend far beyond mere casualties and economic losses, affecting various aspects of society, the environment, politics, and even psychological well-being. Recognizing and understanding these events and the associated risks is crucial for enabling societies to take a proactive rather than reactive approach when confronted with such disasters. Societies can obtain useful information to aid their decision-making processes and improve their preparation by recognizing and assessing the risks connected with natural catastrophes. Understanding the likelihood and potential severity of certain disasters, mapping susceptible areas, assessing infrastructure resilience, and analyzing social vulnerability factors are all parts of this. Armed with this knowledge, societies can take proactive measures such as establishing early warning systems, creating comprehensive disaster response plans, strengthening building regulations and infrastructure standards, and teaching populations about disaster preparedness.

Taking a proactive approach to disaster management enables society to lessen the effects of natural disasters, save lives, and reduce socioeconomic and environmental implications. Societies can increase resilience and adaptation by investing in risk reduction techniques, allowing them to recover from disasters more quickly and efficiently. This method also makes catastrophe risk reduction easier to include into broader development planning, ensuring that sustainability and resilience are integral to social growth.

In the end, prompt identification of natural disasters and associated threats serves as a foundation for developing more resilient societies. Recognizing the multifaceted repercussions of these catastrophes and their far-reaching implications allows society to make educated decisions, effectively allocate resources, and take actions that reduce risks and improve overall disaster preparedness.

1.1. Background And Significance

At the core of all living entities lies the fundamental basis of information. Whether it be a single cell organism or a complex life form, collecting and transforming data to information plays a decisive role in their success and survival within their environment. Without access to accurate and relevant information, living things become vulnerable to the whims of their surroundings, struggling to adapt and thrive in an ever-changing world. As such, the ability to gather, process, and utilize information is crucial for the continued existence of all living entities.

Throughout history, civilizations have relied on processed data, such as the formation of clouds or the blooming of certain flowers, as precursors to their actions. This data has been accumulated, refined, and transformed into valuable information over the years, enabling these civilizations to make informed decisions and adapt to their environments with greater ease. In the modern age, the volume and complexity of data can pose significant challenges for decision makers, hindering their ability to extract meaningful insights and act accordingly. Without proper tools and analyses, the relevance of data to a specific area can remain hidden, further complicating the decision-making process. As a result, there is a growing need for advanced data analytics tools and techniques that can help individuals and organizations to better understand and utilize the vast amounts of data at their disposal.

Due to their complex and interconnected nature, cities are often regarded as living systems. Within these systems, various entities, sub-systems, and personnel generate their own data and use their own methods to produce and store their own information (**Figure 1.1**). However, this fragmentation of data can result in a lack of coordination and communication between different sub-systems, leading to inefficiencies and missed opportunities for optimization. As such, there is a growing need for tools and techniques that can help integrate and synthesize these disparate data sources, allowing for more effective decision making and management of city systems.

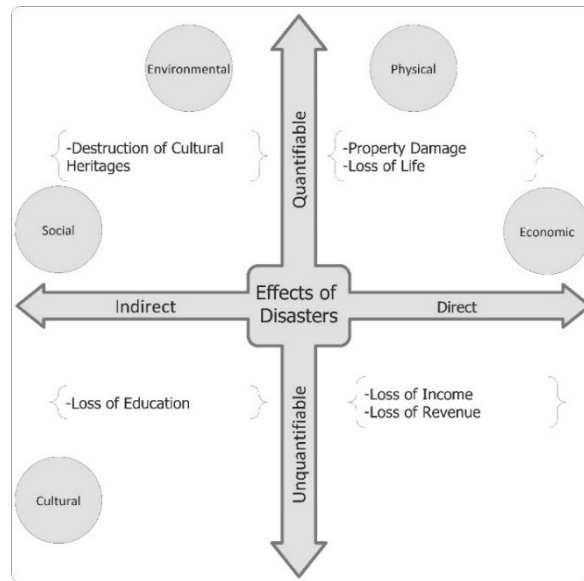


Figure 1.2: Types of effects of disasters.

Risk management is a systematic approach to managing risk that provides principles, a framework, and a process to help organizations to identify, assess and mitigate risks effectively [1], [2]. The fundamental aim of all risk management initiatives is to create and protect value [2]. ISO 31000 offers guidelines that apply to any organization, regardless of its size, industry, or sector. The goal is to help organizations identify, assess, and prioritize risks and implement strategies to mitigate them, ensuring that they meet their objectives. The standard emphasizes the importance of integrating risk management into all aspects of organizational processes, helping organizations to proactively manage both internal and external risks that might affect their objectives.

At the heart of ISO 31000 are eight guiding principles that ensure risk management is effective and aligned with organizational goals (**Figure 1.3**). These principles emphasize that risk management should be an integrated, structured, and systematic process, embedded into an organization's decision-making. Risk management should also be customized, dynamic, and continuously improved based on new knowledge and insights. It is equally important for risk management to be transparent and inclusive, ensuring that all stakeholders are involved in identifying and managing risks, thereby improving accountability and decision-making.



Figure 1.3: Principles of ISO 31000.

The risk management framework outlined in ISO 31000 provides a foundation for building and improving risk management within an organization (**Figure 1.4**). This framework encourages leadership to demonstrate commitment to risk management, integrate risk into decision-making, allocate resources effectively, and establish a culture where risk is proactively considered. The framework also calls for continuous monitoring and reviewing of risks, as well as adapting the process to emerging risks or changing contexts, ensuring that the organization remains resilient in a dynamic environment.



Figure 1.4: The Framework of ISO 31000.

ISO 31000 also details a structured risk management process that includes several key steps: communication and consultation, establishing the context, risk identification, risk analysis, risk evaluation, risk treatment, and monitoring and review (**Figure 1.5**). This process allows organizations to comprehensively assess risks, from identifying potential threats and vulnerabilities to analyzing their likelihood and impact. Based on this analysis, risks are evaluated and prioritized, and appropriate strategies are implemented to manage them—whether by reducing, transferring, accepting, or avoiding the risks. These principles and processes outlined by ISO 31000 are particularly relevant to Disaster Risk Management (DRM), where the unpredictable and often devastating nature of earthquakes requires a proactive, systematic approach. DRM involves applying this structured risk management process specifically to the unique threats posed by events.

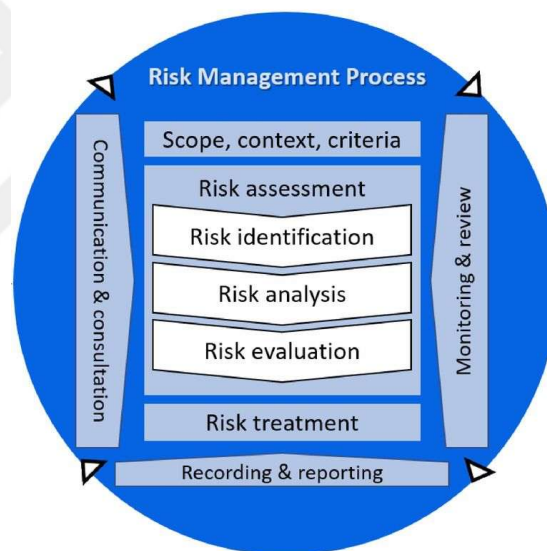


Figure 1.5: The Process of ISO 31000.

DRM is a comprehensive approach that involves the systematic process of using administrative decisions, organization, operational skills, and capacities to implement policies, strategies, and coping capacities of society and communities to lessen the impacts of natural hazards and related environmental and technological disasters (**Figure 1.6**). It encompasses a holistic approach to all hazards throughout the disaster cycle, which includes prevention, mitigation, preparedness, response, and recovery [3]-[5].



Figure 1.6: The Disaster Management Cycle.

The process begins with risk assessment, which involves identifying potential risks and hazards, evaluating their likelihood and impact, and developing strategies to manage these risks across all disaster management phases [3], [6]. Effective DRM requires proactive planning, resource allocation, and the implementation of response measures to foster resilience and efficient disaster response and recovery processes [7]-[10]. Furthermore, DRM is not only about managing the immediate impacts of disasters but also involves integrating disaster risk reduction (DRR) into development policies and strategies to protect economic growth and development benefits [11], [12]. This integration is crucial as disasters, whether natural or human-induced, pose significant threats to development efforts, particularly in vulnerable regions [13]- [15]. The COVID-19 pandemic has highlighted the importance of integrating health into DRM strategies, advocating for a shift from reactive to proactive health risk mitigation by building healthcare capabilities and infrastructure [16]. Additionally, understanding the interdependence of risks and evaluating risk interactions are vital for comprehensive risk management evaluations, as risks are often interconnected rather than independent. DRM aims to minimize vulnerabilities and disaster risks across society, either by avoiding them through prevention or by limiting their adverse impacts through mitigation and preparedness (**Figure 1.7**). These efforts are undertaken within the broader context of sustainable development, with specific actions implemented during the different phases of disaster risk management [17], [18].



Figure 1.7: The Disaster Management Cycle and related tasks.

When applied to DRM, in the context of seismic risk management (SRM), ISO 31000's principles and framework offer a systematic approach to managing the unique risks posed by earthquakes. Seismic events are inherently unpredictable, with the potential for devastating consequences, making it essential for organizations and cities to integrate risk management practices into every aspect of disaster preparedness, response, and recovery.

DRM, guided by ISO 31000, begins with a comprehensive understanding of the context in which seismic risks exist. This involves assessing geographical vulnerabilities, such as fault lines, and evaluating the resilience of infrastructure, buildings, and critical systems. Organizations need to understand not only the physical vulnerabilities but also how social, economic, and institutional factors contribute to risk exposure. By establishing this context, decision-makers can prioritize areas that require the most attention, such as densely populated regions, essential facilities (hospitals, power stations), or economically significant structures.

The risk identification stage is where potential earthquake scenarios are identified based on historical data, geological studies, and expert analyses. This includes identifying risks like ground shaking, liquefaction, landslides, and secondary hazards (e.g., tsunamis, fires). Beyond physical hazards, risk identification also accounts for the cascading effects of earthquakes, such as disruptions to supply chains, health crises, and economic downturns. Understanding the full range of potential impacts ensures that all critical areas are addressed.

Once risks are identified, risk analysis and evaluation focus on understanding the likelihood of various seismic events and their potential impacts on people, property, and infrastructure. In this stage, seismic models and simulations are often used to predict the severity of an earthquake and the extent of damage in different areas. This enables stakeholders to quantify risks in terms of probability and consequences, providing a basis for prioritizing mitigation efforts. For example, risks can be ranked by the likelihood of occurrence and the severity of potential damage to critical structures, like schools or bridges, enabling better resource allocation.

In the risk treatment phase, strategies are developed to either reduce, transfer, accept, or avoid seismic risks. Mitigation measures often include strengthening or retrofitting buildings, updating building codes, and enforcing land-use policies that restrict construction in high-risk areas. Additionally, emergency preparedness plans, public education, and early warning systems are key strategies to minimize harm during and after a seismic event. Risk transfer mechanisms, such as insurance, also play an essential role in managing the financial impact of earthquake damage.

The process also requires continuous monitoring and review to ensure the effectiveness of DRM strategies. As new information and technology becomes available, risk assessments should be updated to reflect improved seismic modeling techniques, emerging data on earthquake behavior, and changes in urban development. Monitoring efforts also extend to ensuring compliance with building codes, emergency response protocols, and public awareness campaigns, ensuring preparedness is maintained over time.

Incorporating communication and consultation is essential throughout the SRM process. Engaging with stakeholders—including government agencies, engineers, urban planners, and the public—ensures that risk management strategies are

transparent and inclusive. Effective communication helps raise awareness, promotes a culture of safety, and facilitates coordination among various sectors during emergency response efforts.

1.2. Problem Statement

In a very broad context, DRM can be understood as the management of the 6Ms, namely, Manpower, Money, Materials, Methods, Machines, and Management, throughout the entire lifecycle of a disaster. Effective management of these six key elements are essential to an effective DRM, as they collectively support the mitigation, preparedness, response, and recovery phases of disaster management.

Manpower refers to the human resources, including trained personnel, emergency responders, and volunteers, who play a critical role in all stages of DRM, from preparedness and response to recovery and rebuilding. Money ensures the availability of financial resources for planning, implementing mitigation measures, and providing relief during and after a disaster. Materials encompass the physical goods required for disaster management, such as medical supplies, construction materials, and relief goods. Methods involve the processes, strategies, and protocols that guide decision-making and actions throughout the disaster cycle, ensuring organized and efficient disaster management efforts. Machines represent the tools, technology, and equipment needed for monitoring hazards, conducting rescue operations, and delivering relief. Management integrates all these resources and processes, ensuring coordination, collaboration, and effective decision-making across all phases of DRM.

The management of the 6Ms is inherently challenging, even in controlled environments. When coupled with the complexity of modern cities and the chaotic nature of disasters, this task becomes exponentially more difficult. Therefore, a successful management framework or model should be capable of accommodating and managing the varied and complex data needs associated with each of these elements. Enhanced capabilities for disaster managers and personnel are essential to collectively model, comprehend, and forecast the interactions of human, infrastructure, and technological systems as an integrated whole [19], [20]. A 'common operating picture' (COP) refers to an ongoing, continually updated summary of an incident, developed

throughout its lifecycle by aggregating data from interconnected systems used for communication, information management, and knowledge sharing [21], [22].

Cities, with their dense populations, intricate infrastructure networks, and interdependent systems, present unique challenges for the coordination and allocation of resources. During disasters, the chaotic environment disrupts normal functioning, complicates communication, and creates a highly dynamic situation where needs and priorities can shift rapidly. For instance, coordinating manpower in a city affected by a large-scale earthquake requires overcoming obstacles like damaged transportation networks and disrupted communication channels. Similarly, ensuring the availability and efficient distribution of materials such as food, water, and medical supplies becomes increasingly difficult in the face of broken supply chains and logistical bottlenecks.

Moreover, integrating these 6Ms in such a high-stakes, rapidly evolving context demands robust management systems that can adapt to uncertainty, optimize resource utilization, and enable real-time decision-making. The combined complexity of cities and the unpredictable nature of disasters underscores the necessity of advanced tools to enhance coordination, reduce inefficiencies, and ensure resilience in disaster management.

DRM is a data-intensive process that requires a comprehensive understanding of both the hazards and vulnerabilities of individual components and their interactions [23]. Regional risk assessments often require gathering information from various stakeholders and components. This data collection involves accessing and analyzing diverse sources of information, including scientific studies, historical data, community surveys, and input from relevant organizations and agencies. Stakeholder collaboration is crucial to ensure the availability of accurate and current data, enhancing the overall effectiveness of DRM. It's important to recognize that each component exhibits dynamic characteristics that evolve over time, influenced by multiple factors. The inherent variability of the situation underscores the need for adaptability within the DRM system, considering both temporal and contextual factors.

Traditional DRM approaches, which often rely on reactive measures, are limited in their ability to predict, respond to, and mitigate the impact of disasters in a timely manner. These typically focus on specific phases of a disaster, reducing their overall

effectiveness. The complexity of urban environments, coupled with the rapid growth of city infrastructure, demands a more integrated and proactive approach to DRM that leverages advanced digital technologies. To truly optimize DRM, it is essential that these approaches concurrently address all phases of a disaster, providing a comprehensive tool for predicting, responding to, and mitigating seismic risks.

Additionally, traditional DRM approaches often impose limitations on the flow of data between stakeholders and across the various phases of disaster management (**Figure 1.8**). This fragmented data transfer hinders the development of a cohesive and efficient disaster response and resilience strategy. The challenges associated with these limitations are increasingly evident in the face of complex urban systems and growing disaster risks.

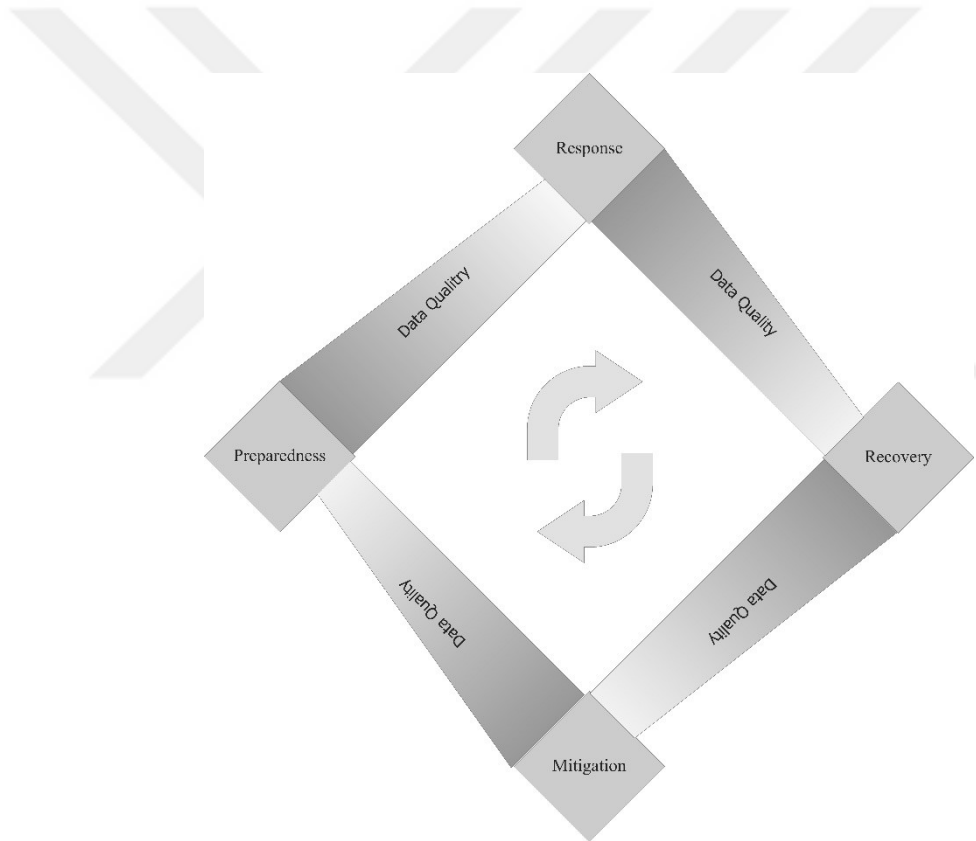


Figure 1.8: The Disaster Management Cycle data loss.

In conventional DRM frameworks, data sharing is often constrained by institutional silos. Stakeholders such as government agencies, emergency responders, and utility providers typically maintain separate data repositories tailored to their specific operational needs. While this ensures internal efficiency, it inhibits the integration of information across domains. For instance, data on infrastructure vulnerabilities held

by municipal agencies may not be readily accessible to emergency services, delaying critical decisions during response operations.

Moreover, the phases of disaster management—prevention, preparedness, response, and recovery—are frequently treated as distinct stages with limited continuity of data flow. Data collected during the response phase, such as real-time damage assessments or casualty reports, is often not systematically integrated into recovery planning or future risk reduction efforts. Similarly, hazard modeling and risk assessments conducted during the prevention phase may not be updated or utilized effectively during emergency response.

The lack of standardized data formats and interoperable platforms exacerbates these challenges. Stakeholders often use different systems for data collection, storage, and analysis, making it difficult to aggregate and synthesize information. This issue is particularly problematic in urban environments, where diverse datasets—ranging from geospatial data and infrastructure inventories to social and economic metrics—are required to develop a comprehensive understanding of disaster impacts.

City Information Modeling (CIM) combined with digital twins (DT) present a promising solution to enhance earthquake resilience in smart cities by integrating data from various urban systems into a unified platform (**Figure 1.9**). Despite its potential, the adoption of CIM in disaster management is still in its infancy, with challenges related to data interoperability, real-time analytics, and decision-making processes. There is a critical need to develop a comprehensive framework that utilizes CIM to optimize earthquake preparedness, response, and recovery, ultimately strengthening urban resilience.

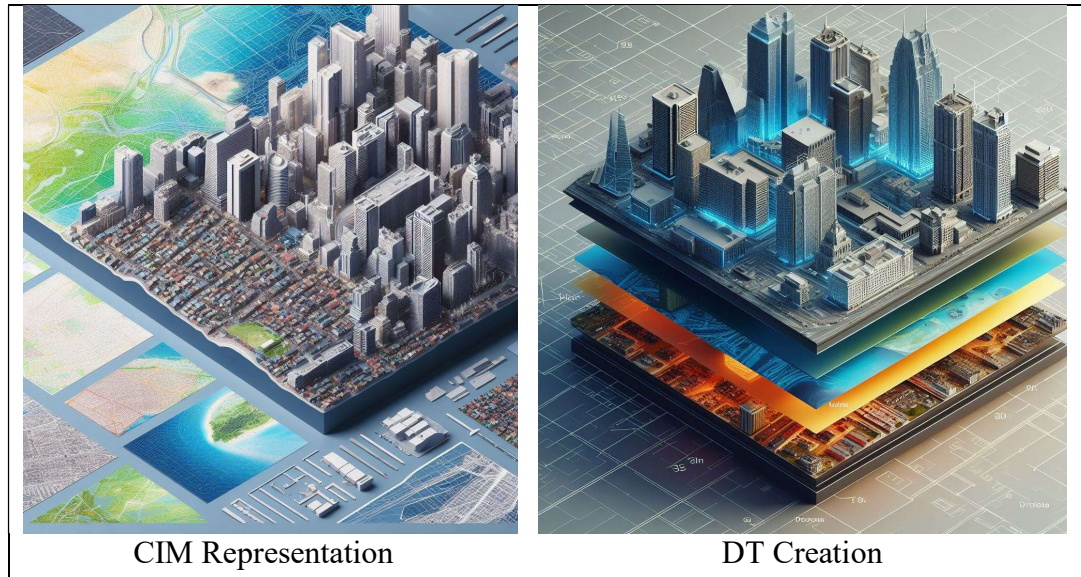


Figure 1.9: CIM and DT Representations

An effective information management system is built upon three essential components: data, models, and ontologies. Data, Model and ontologies are intricately linked in various domains, serving as foundational elements for enhancing data interoperability, model representation, and knowledge management. Ontologies provide a structured framework for representing and managing data, which is crucial for the Semantic Web and open research data, as they enable the sustainable and effective utilization of research data by formalizing metadata and facilitating data sharing across different platforms [24], [25]. Data modeling frameworks are used to create abstractions of reality, and ontologies provide a philosophical foundation for understanding these frameworks by defining the fundamental categories of existence. The use of ontologies in data modeling is not limited to philosophical analysis; they also serve practical purposes in information systems by providing a framework for understanding, comparing, and strengthening data modeling languages. Ontologies, unlike data models, are relatively independent of specific applications, allowing them to be reused across different domains. This independence makes them valuable in contexts like data mining, where they can enhance the adaptability and efficacy of data mining processes by representing context factors that influence data interpretation.

This research seeks to address the gap in existing SRM practices by developing a CIM-based framework (data, model and ontologies) specifically designed to assess and enhance resilience in cities. The study will explore how CIM can be integrated with current disaster management strategies to improve real-time monitoring, predictive

analysis, and resource allocation during and after seismic events. By doing so, this research aims to contribute to the development of more resilient and adaptive urban environments capable of withstanding the challenges posed by earthquakes.

1.3. Research Objectives and Research Questions

The thesis is organized around two categories of objectives: primary and secondary. These objectives outline the key objectives that guide the research and analysis conducted throughout the study. By clearly distinguishing them, the study maintains a focused direction and ensures a comprehensive exploration of the subject matter.

The primary goals represent the core objectives that the thesis aims to achieve. These goals serve as the foundation of the study, shaping the research methodology, data collection, and analysis. They are designed to address central research questions, providing in-depth insights and contributing to the overall understanding of the topic.

In contrast, secondary goals complement the primary goals by including additional objectives that expand the scope and depth of the study. While not directly tied to the main research questions, the secondary goals play an important role in broadening perspective, exploring related aspects, and providing a more well-rounded analysis.

The main objectives of this study are as follows:

1. To develop a CIM-based digital twin for the city of Kocaeli:

- Create a detailed 3D model of Kocaeli and transform it into a DT that can be used to simulate earthquake scenarios.

2. To integrate CIM and DT technology for enhanced earthquake resilience:

- Demonstrate how CIM and DT technologies can be combined to improve disaster preparedness and response in smart cities.

3. To analyze the effectiveness of CIM-based earthquake management strategies:

- Evaluate the impact of using CIM and DT in earthquake management compared to traditional disaster management approaches.

4. To propose recommendations for implementing CIM-based frameworks in urban resilience planning:

- Provide policy and governance suggestions for integrating CIM and DT technologies into the urban resilience planning processes of smart cities.

The secondary goals of this study aim to establish foundational definitions and conceptual clarity on core topics critical to understanding and contextualizing the primary research. These goals are essential in framing the integration of CIM with DT technology for seismic risk management within a smart city context. Specifically, this study seeks to:

1. **Define "Smart":** Articulate the characteristics that qualify a city or system as “smart,” focusing on the interconnectedness, data-driven decision-making, and technological innovations that enhance urban resilience and operational efficiency.
2. **Define Seismic Risk:** Clarify seismic risk as a concept, including its components—hazard, vulnerability, and exposure—and explore the principles of seismic risk assessment and its relevance in urban planning and disaster preparedness.
3. **Define 3D Models:** Outline the structure, capabilities, and advantages of 3D models, particularly in representing urban landscapes, infrastructure, and dynamic processes in a digital environment for enhanced visualization and analysis.
4. **Define CIM (City Information Modeling):** Explain CIM’s role as a comprehensive model of city assets, integrating spatial and attribute data to enable effective city management and planning, especially for resilience-building against natural disasters.
5. **Define Digital Twins:** Establish an understanding of Digital Twin technology as a dynamic, real-time digital representation of physical assets, with a focus on its role in predictive analytics, scenario testing, and adaptive management within smart cities.
6. **Define the State-of-the-Art for Seismic Risk Assessment:** Review the latest advances in seismic risk assessment methodologies, tools, and data integration techniques that enhance the precision and applicability of seismic risk models for urban areas.

7. **Define the State-of-the-Art for 3D City Models:** Summarize recent developments in 3D modeling technologies, such as photogrammetry, LiDAR, and Geographic Information Systems (GIS), and their contributions to detailed, accurate representations of urban environments.
8. **Define the State-of-the-Art for CIM:** Examine contemporary trends, challenges, and advancements in CIM, with particular emphasis on the integration of Internet of Things (IoT), data management practices, and interoperability across systems for urban planning and management.

Together, these secondary goals form a structured foundation for examining how CIM and DT technologies can be effectively integrated and applied for earthquake management and resilience. They also provide the conceptual and technological basis necessary for analyzing the contributions of this study within the broader field of urban DRM and smart city resilience.

The research questions guiding this study are as follows:

1. How can CIM and DT technologies be effectively integrated to enhance earthquake resilience in smart cities?
2. What are the key components of a CIM-based DT for earthquake management?
3. What are the benefits of using a CIM-based DT in earthquake disaster scenarios in comparison to traditional methods?
4. How do FT improve decision-making in emergency response and resource allocation?
5. How can the developed CIM-based DT model for Kocaeli be used to simulate and analyze earthquake scenarios?
6. What specific earthquake effects can be visualized and assessed using the DT of Kocaeli?
7. What are the policy and urban planning implications of implementing CIM-based DTs in smart cities?

How can city planners and policymakers leverage CIM and DT technologies for DRR?

1.4. Scope and Limitations

The scope of this study focuses on the development and implementation of a CIM-based framework to enhance earthquake management and resilience in smart cities, with a specific case study on Kocaeli, Turkey. The research will cover the following key areas:

1. Conceptual Framework Development:

- Defining the role of CIM in disaster management, specifically in the context of earthquake resilience.
- Developing a theoretical model that integrates CIM with existing disaster management practices to improve urban resilience.

2. 3D Modeling and DT Creation:

- Developing a detailed 3D model of the city of Kocaeli, incorporating critical infrastructure, buildings, transportation networks, and other urban elements.
- Transforming the 3D model into a DT to provide a dynamic and interactive representation of Kocaeli, enabling real-time data integration and simulation of earthquake scenarios.

3. Data Integration and Analysis:

- Identifying and categorizing data sources relevant to earthquake management, including real-time monitoring, geospatial data, infrastructure information, and urban systems data.
- Integrating these data sources into the DT of Kocaeli to enable comprehensive visualization, prediction, and decision-making processes.

4. Technological and Computational Aspects:

- Evaluating the technological requirements and computational tools necessary for implementing the DT of Kocaeli.
- Developing algorithms and simulation models that utilize the DT to predict earthquake impacts, assess vulnerabilities, and optimize response strategies.

5. Demonstration of Earthquake Effects Using the Digital Twin:

- Utilizing the digital twin of Kocaeli to simulate the effects of various earthquake scenarios on the city's infrastructure and population.
- Analyzing the potential damage, resource needs, and response strategies based on the simulated outcomes.

6. Decision Support Systems for Emergency Response:

- Designing a decision support system that leverages the DT of Kocaeli to aid city planners, emergency responders, and stakeholders in making data-driven decisions during earthquake events.
- Investigating resource allocation strategies for search and rescue operations, infrastructure repair, and relief distribution using the DT.

7. Evaluation of Resilience:

- Measuring the urban resilience in Kocaeli as a result of the CIM-based DT implementation, focusing on the city's ability to anticipate, withstand, and recover from seismic events.
- Comparing the outcomes of CIM-based strategies with traditional earthquake management approaches to highlight benefits and limitations.

8. Policy and Governance Considerations:

- Analyzing the policy implications of integrating CIM and DT technology into earthquake management practices in smart cities.
- Providing recommendations for governance models, regulatory frameworks, and stakeholder engagement to facilitate the adoption of CIM-based solutions.

9. Limitations and Future Research Directions:

- Identifying the limitations of the proposed CIM-based framework in terms of data availability, technical challenges, and scalability.
- Outlining potential areas for future research to advance the application of CIM and DT technology in disaster management and urban resilience.

The study will primarily focus on urban areas in regions with high seismic activity, using the city of Kocaeli as a case study to develop a practical and scalable CIM-based DT solution. This approach will be adaptable to various urban contexts to improve earthquake resilience.

1.5. Structure of the Thesis

The structure of the thesis is shown at the **Figure 1.10**.

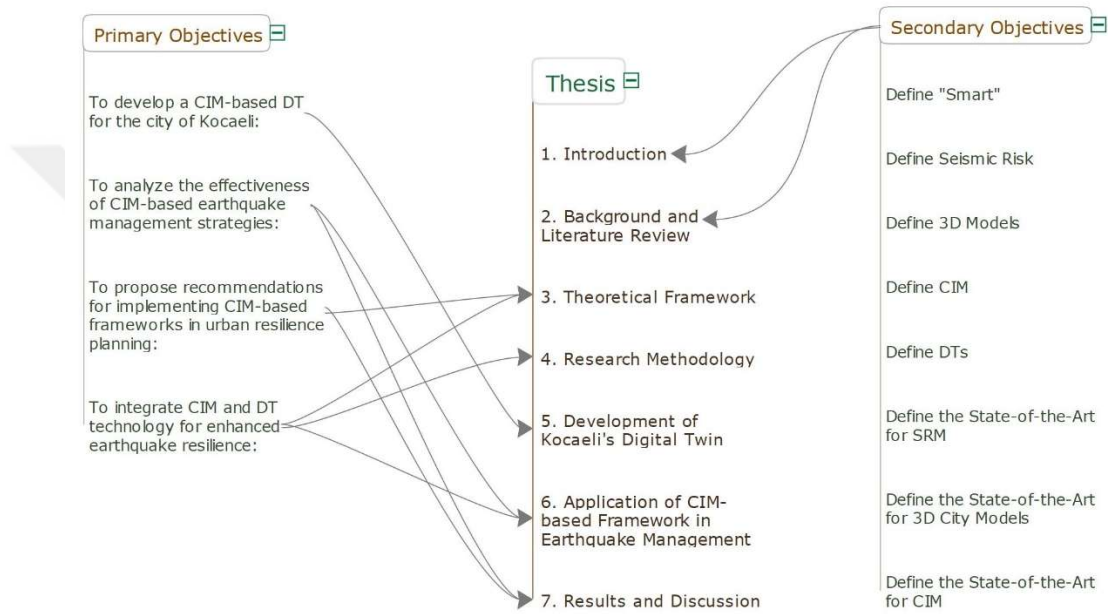


Figure 1.10: Thesis structure.

1.6. Significance of the Study

This study is significant as it bridges the integration of CIM and DT technologies for enhanced earthquake management, focusing on urban resilience. The development and demonstration of a DT for Kocaeli, a region with high seismic activity, serves as a practical example that can influence policy-making, urban planning, and emergency response strategies. The findings and methodology of this research can contribute to more accurate SRM, enabling decision-makers to prioritize resources, plan safer infrastructures, and improve disaster response efficiency. Furthermore, it adds to the existing body of knowledge by providing a comprehensive framework that combines advanced modeling techniques with real-time data for proactive DRM.

The outcomes from this study are expected to enhance the capabilities of smart cities in preparing for, responding to, and recovering from earthquake events. Additionally, the research demonstrates how DTs, connected through application programming interfaces (APIs) to real-time databases, can offer scalable solutions applicable to other urban areas with similar seismic risks. This study's contribution extends to the academic field by enriching the literature on CIM, DTs, and their application in disaster management, serving as a benchmark for future research and technological development in this domain.

1.7. Hypotheses and Assumptions Underpinning the Study

Hypothesis-1: The use of CIM integrated with DT technology will lead to a significant improvement in the city's ability to prepare for and respond to seismic events compared to traditional urban management systems.

Hypothesis-2: DTs, when combined with CIM, will yield more precise simulations of earthquake effects on buildings and infrastructure, enabling more effective risk mitigation strategies.

Hypothesis-3: The continuous feedback loop between CIM and DT systems, incorporating real-time data from sensors and IoT devices, will result in quicker and more informed decision-making during disaster response operations.

Hypothesis-4: The 3D visualization capabilities provided by the integration of CIM with DTs will lead to better engagement and communication among stakeholders, including urban planners, emergency responders, and the public, thereby facilitating coordinated earthquake management efforts.

Hypothesis-5: Cities that implement CIM and DT technology will show a measurable increase in resilience to seismic hazards through proactive risk assessment.

2. BACKGROUND AND LITERATURE REVIEW

The PRISMA protocol was adopted to ensure methodological rigor and enhance the credibility of the research. The PRISMA protocol, a widely recognized framework for conducting systematic literature reviews across various domains, provides a structured approach to systematically identifying, evaluating, and synthesizing evidence from multiple studies. This framework promotes transparency and rigor throughout the review process.

Articles were systematically searched and evaluated based on their relevance to the inclusion criteria and study objectives. A total of 1432 articles were thoroughly reviewed by all authors to ensure consistency, avoid redundancy, and minimize bias in the findings. Key themes were extracted, and similarities and differences across studies were identified. Where appropriate, the results were presented in tabular format to enhance clarity and facilitate comparative analysis.

In the thesis, the databases of Web of Science, Scopus, and Google Scholar constitute the principal sources of data acquisition. The selection of appropriate keywords represents a crucial component of the methodology, as it has a direct bearing on the inclusion or exclusion of specific scientific literature. The objective was to curate a compilation of the most significant and pertinent publications within the discipline while systematically excluding those that are irrelevant. The researchers employed a thorough and systematic iterative methodology to enhance the selection process. The final phase in document selection methodology for discerning pertinent literature entailed the application of stringent criteria: specifically, scholarly studies and articles that incorporated the terms “disaster” or “emergency” in conjunction with “City Information Management,” “Digital Twin,” or “Smart” within their titles were deemed appropriate for consideration. This stipulation implies that only those scholarly works that explicitly encompassed both the notion of “digital twin” and acknowledged either “disaster” or “emergency” contexts were accepted for incorporation into our comprehensive review. This systematic approach facilitated the reduction of the extensive corpus of existing literature, directing our focus solely towards those publications that are directly pertinent to the implementation of digital twin technology in the context of disasters or emergencies, thereby guaranteeing the relevance and precision of our research aggregation.

2.1. Seismic Risk Management

SRM is the process of identifying, assessing, and mitigating the risks posed by earthquakes to minimize their potential impact on human life, property, infrastructure, and the environment. It involves a combination of strategies, tools, and frameworks aimed at reducing vulnerabilities and enhancing resilience in areas prone to seismic activity. The primary components include seismic hazard assessment, vulnerability and exposure analysis, and the development of mitigation strategies. To effectively capture the interplay among these critical components and quantify seismic risk, SRM can be represented mathematically (**equation (2.1)**). The following equation integrates hazard probability, exposure, vulnerability, and resilience into a cohesive framework for assessing seismic risk.

$$R(t) = P_h(t) \times E(t) \times V(t) \times \frac{1}{R_s(t)} \quad (2.1)$$

2.1.1. Hazard Assessment

Hazard assessment aims to quantitatively determine the intensity by estimating probabilities and magnitudes of earthquake scenarios, considering factors like fault lines, tectonic activity, and historical records [26]-[32]. This analysis can be conducted using either deterministic or probabilistic approaches, each with its own methodologies and applications.

Deterministic Seismic Hazard Analysis (DSHA) focuses on estimating the maximum credible earthquake (M_{CE}) and the associated ground motion at a site, often using empirical attenuation curves or advanced simulations like the Neo-Deterministic Seismic Hazard Analysis (NDSHA) [33]- [36]. Unlike probabilistic seismic hazard analysis (PSHA), which considers a range of possible earthquakes and their probabilities, DSHA focuses on specific seismic events and their expected impacts.

One of the key features of DSHA is its emphasis on a single earthquake scenario (**Figure 2.1:**). This analysis typically evaluates the effects of a well-defined earthquake event, such as a major fault rupture, which could be based on historical earthquakes or hypothetical scenarios to estimate M_{CE} . The analysis involves calculating the expected

ground motion—such as peak ground acceleration or spectral acceleration—at a site based on the characteristics of the M_{CE} , including its magnitude, distance, and depth, as well as the geological conditions of the area (**equation (2.2)**).

$$PGA = f(D, M, R, Z) \quad (2.2)$$

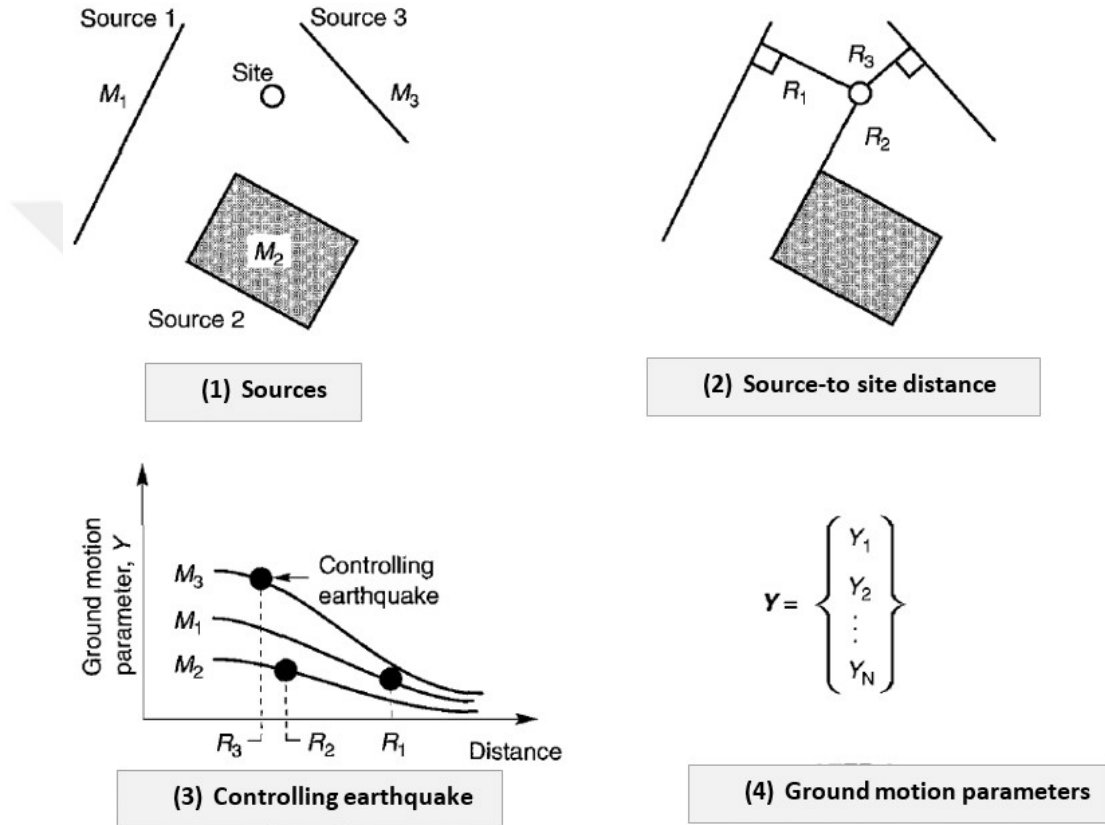


Figure 2.1: DSHA workflow schematization

In conducting DSHA, site-specific considerations are paramount. The method considers local site conditions, such as soil type, geological features, and topography, which can significantly influence ground shaking. This site-specific approach allows for a more accurate assessment of how the expected ground motion will affect structures and infrastructure.

The deterministic nature of DSHA means that it provides a specific estimate of ground shaking for the chosen earthquake scenario without incorporating the uncertainties associated with the occurrence of different earthquakes. This characteristic makes DSHA particularly useful in engineering design, especially for critical infrastructure

such as bridges, dams, and nuclear power plants, where understanding the potential impact of a specific seismic event is crucial. Additionally, DSHA can be employed for risk assessments and emergency planning.

The process of conducting a DSHA typically involves several steps. First, M_{CE} scenarios are selected, which may include historical events and potential future ruptures that could affect the site. Next, ground motion modeling is performed using ground motion prediction equations (GMPEs) to estimate the expected ground shaking based on the selected earthquake scenarios [37]-[39]. Following this, site response analysis is conducted to evaluate how local geological conditions will amplify or attenuate ground motion. Finally, the findings are compiled into a report that outlines the expected seismic hazards and their implications for design and safety.

Despite its advantages, DSHA has some limitations. One notable drawback is its lack of probabilistic context, as it does not account for the likelihood of different earthquakes occurring. This can lead to an incomplete understanding of seismic risk. Additionally, focusing on worst-case scenarios may result in overly conservative designs that may not be necessary for all situations. Furthermore, DSHA may not capture the full range of seismic hazards that could affect a site over time.

PSHA has emerged as a fundamental methodology in the field of earthquake engineering and risk assessment, providing a systematic approach to estimate the likelihood of various levels of ground shaking at specific sites due to seismic events over defined time periods. Unlike DSHA, PSHA incorporates the inherent uncertainties and variabilities associated with seismic sources, ground motion, and site response [40]-[44]. The methodology accounts for both epistemic uncertainties, such as those arising from different modeling approaches, and aleatory uncertainties, which are due to the natural variability of seismic phenomena [45]. This probabilistic framework allows for a more comprehensive understanding of seismic risk (**equation (2.3)**), making it a valuable tool for engineers, urban planners, and policymakers [40], [41], [46]. For instance, the Southern California Earthquake Center's efforts to include site effects in PSHA highlight the importance of local geological conditions, such as basin depth and shear-wave velocity, in influencing seismic hazard estimates [47]. Similarly, the probabilistic assessment for Portugal utilizes a logic tree approach to incorporate various seismic zonations and attenuation models, reflecting the complexity and variability of seismic sources [48]. The use of Bayesian inference in

PSHA further enhances the ability to integrate diverse data sources and model uncertainties, providing a more robust hazard assessment [45], [49]. Additionally, the comparison of different computational methods, such as the Kernel method versus the traditional Cornell-McGuire approach, underscores the impact of methodological choices on hazard results [50].

$$\lambda(Y > y) = \sum_i v_i \cdot P(Y > y \mid \text{Source } i) \quad (2.3)$$

The first critical component of PSHA is seismic source characterization (**Figure 2.2**). This process includes identifying and characterizing the geometry, seismicity, and tectonic features of the source zones, which can be linear, areal, or fault-based, depending on the region's geological and seismotectonic context [51], [52]. The characterization process often requires integrating various data sources, such as earthquake catalogs, geological maps, and expert judgment, to define the source models accurately. Researchers typically estimate the frequency of earthquakes of different magnitudes from these sources, often employing probabilistic magnitude-frequency distributions, such as the Gutenberg-Richter law [53]. Additionally, the use of virtual fault ruptures in PSHA calculations helps ensure compatibility between seismic source models and ground-motion prediction models, which is essential for accurately estimating seismic hazards [54]. The characterization of seismic sources also involves understanding the source mechanism and moment magnitude, as demonstrated in studies of the Arabian Peninsula, where regional seismic data were used to derive these parameters [55]. This foundational step is crucial for understanding the potential seismic activity in a given region and serves as the basis for subsequent analyses (**equation (2.4)**).

$$\lambda(Y > y) = \sum_i \int_{M_{\min}}^{M_{\max}} \int_0^{R_{\max}} P(Y > y \mid M, R) \cdot f_M(M) \cdot f_R(R) dR dM \quad (2.4)$$

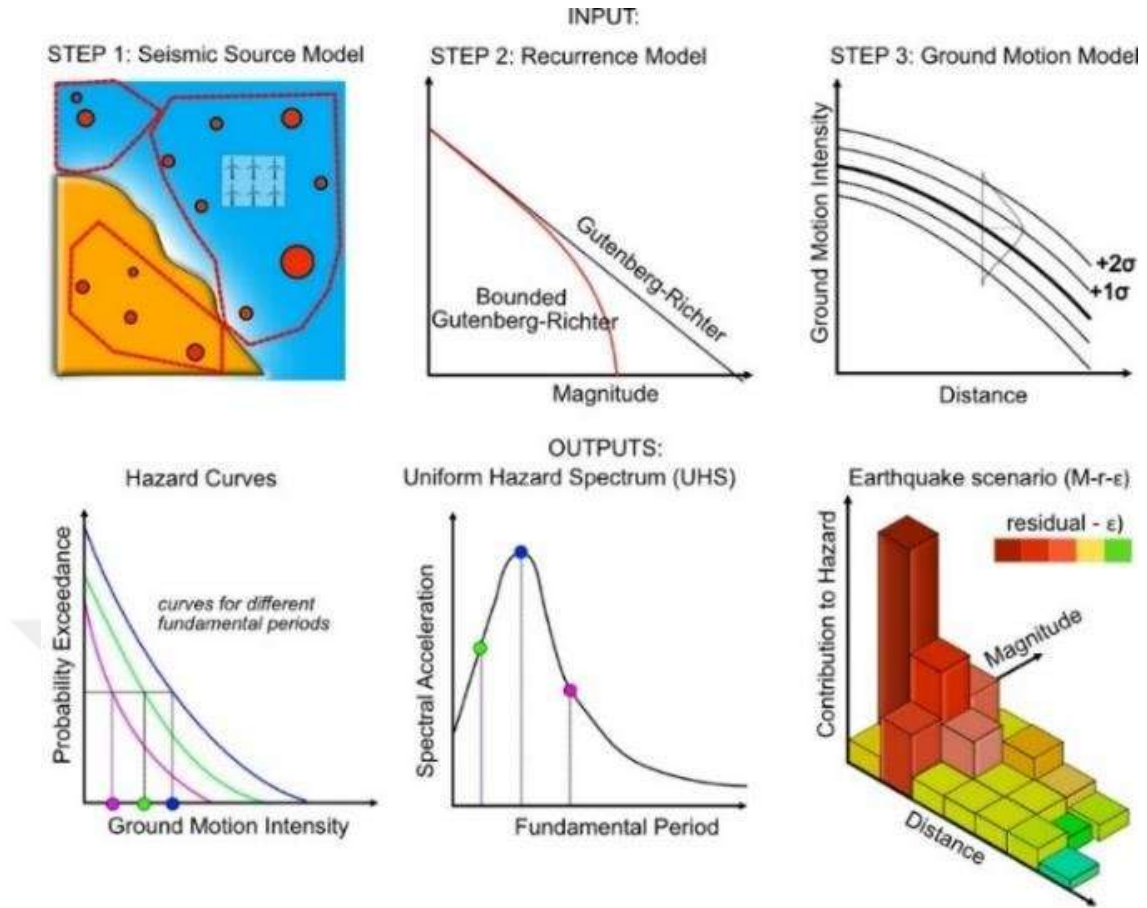


Figure 2.2: PSHA workflow schematization

GMPEs are utilized to estimate the expected ground shaking at a site for various magnitudes and distances from seismic sources. These equations are empirical relationships derived from recorded ground motion data and consider factors such as distance, magnitude, and local site conditions [39], [56]. Additionally, site response analysis assesses how local geological conditions, including soil type and depth to bedrock, influence ground motion at the site. This can involve site-specific studies or the application of generic site response models to ensure accurate predictions [57], [58]. These equations are crucial for seismic hazard analysis and the design of earthquake-resistant structures [43], [59]. GMPEs are typically developed through regression analysis of strong motion data specific to a region's tectonic and geological conditions (Figure 2.3) [60]-[62]. Both approaches rely heavily on GMPEs.

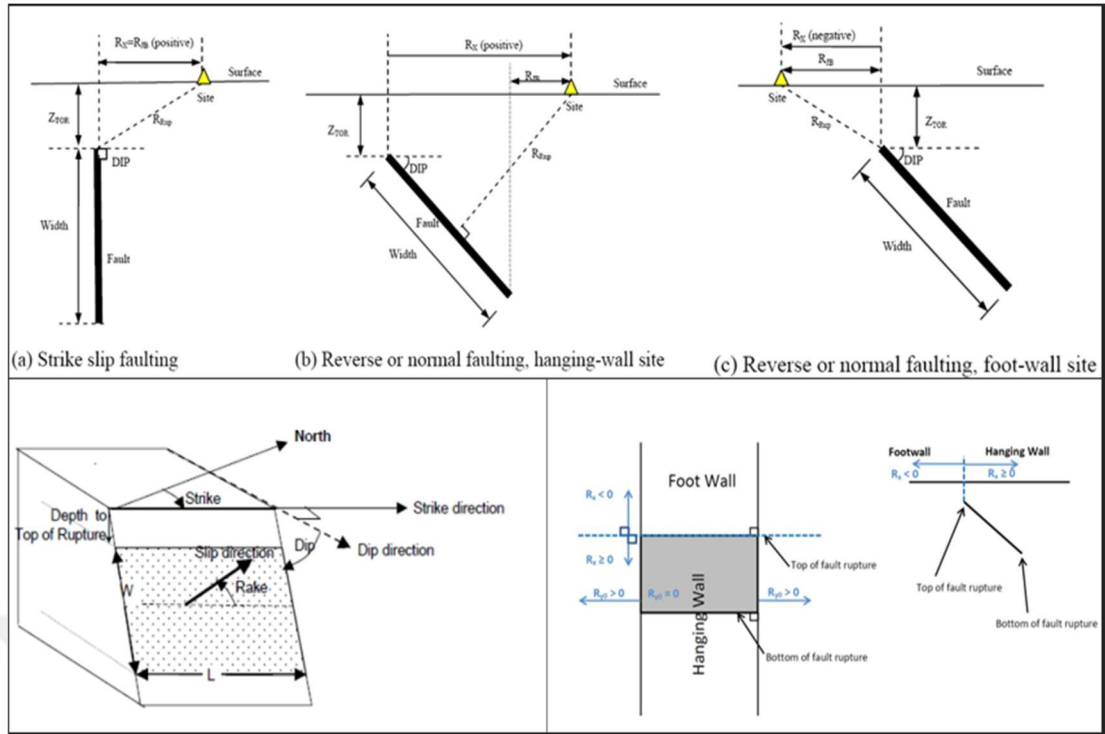


Figure 2.3: General parameter considerations of GMPEs

The outputs of PSHA are typically presented in the form of hazard curves and hazard maps. A hazard curve illustrates the probability of exceeding different levels of ground shaking, such as peak ground acceleration or spectral acceleration, over a specified time period (e.g., 50 years) [63]. Conversely, hazard maps provide a geographic representation of expected ground shaking levels across a region, which is particularly useful for land-use planning and the development of building codes [64]-[66]. These outputs enable stakeholders to make informed decisions regarding construction, infrastructure, and community safety.

DSHA is favored for its transparency and reliability, particularly in regions like California, where it has been successfully applied for decades. PSHA is widely used for its ability to integrate various uncertainties and provide a comprehensive risk assessment. Recent advancements in PSHA include the use of back propagation neural networks to predict peak ground acceleration, enhancing accuracy in areas with unclear geological conditions. Despite the dominance of probabilistic methods, deterministic approaches remain crucial for public safety policies due to their conservative nature and ease of understanding. Both methods are essential in developing seismic hazard maps and designing earthquake-resistant structures, as they provide critical data on peak ground acceleration and other seismic parameters (Table

2.1). Depending on factors such as available data, time constraints, computational resources, and desired output requirements, different approaches to seismic hazard assessment may be preferred.

Table 2.1: Comparison of PSHA and DSHA

Criterion	DSHA	PSHA
Objective	Evaluates the impact of a single, worst-case earthquake scenario.	Provides a comprehensive risk assessment over a specific time frame with varying scenarios.
Regulatory Requirements	Used if mandated by project codes or standards.	Selected if regulations require a probabilistic approach or do not specify a method.
Risk Tolerance	Suitable for projects with low risk tolerance (e.g., critical infrastructure).	Ideal for projects with moderate to high tolerance, requiring a broader risk profile.
Data Availability	Requires detailed fault data, historical records, and maximum credible earthquake details.	Utilizes comprehensive seismic source data, recurrence models, and GMPEs.
Scope of Analysis	Focused on maximum ground motion without considering frequency or probability.	Considers a range of magnitudes, frequencies, and uncertainties for a more holistic view.
Return Periods	Not typically linked to specific return periods.	Essential for analyses involving specific return periods (e.g., 475 or 2,475 years).
Project Examples	Design of critical infrastructure such as hospitals, dams, or nuclear plants.	Urban planning, risk-based insurance, long-term regional assessments.
Site-Specific Adjustments	Adjustments made based on detailed, known site conditions.	Can incorporate site amplification effects for a range of potential scenarios.
Output	Provides peak ground motion for the maximum credible event.	Delivers hazard curves, maps, and exceedance probabilities for different return periods.
Regulatory Compliance	Use when regulatory standards explicitly require DSHA.	Chosen when probabilistic analysis aligns with regulatory needs or broader stakeholder expectations.

The data required for seismic hazard assessment can be broadly categorized into geological, seismological, geophysical, and engineering data.

Geological Data includes information on fault lines, tectonic settings, and historical seismicity (**Table 2.2**). Understanding the geological context is crucial for identifying potential earthquake sources. For instance, the study by Faure Walker et al. emphasizes the importance of detailed geological mapping and fault characterization to assess seismic hazards accurately [67]. This involves analyzing geometry, slip rates, and segmentation of faults, which are critical for understanding the potential for future seismic events.

Table 2.2: Fault attributes needed for SHA

Attribute Category	Attribute	Description
Fault Geometry	Orientation	The angle and direction of the fault plane, described by strike and dip.
	Length and Width	The dimensions of the fault, influencing the size of potential earthquakes.
	Rupture Surface	The area of the fault that slips during an earthquake, varying in size and shape.
Fault Type	Normal Faults	Faults formed due to extensional forces, where the hanging wall moves down.
	Reverse (Thrust) Faults	Faults formed under compressional forces, where the hanging wall moves up.
	Strike-Slip Faults	Faults characterized by horizontal movement, where two blocks slide past each other.
Kinematics	Slip Rate	The average rate at which the fault slips over time.
	Recurrence Interval	The average time between successive earthquakes on a fault.
	Slip Vector	The direction and magnitude of slip during an earthquake.
Seismicity	Earthquake History	The record of past seismic events associated with the fault, including magnitude, frequency, and distribution.
	Seismic Moment	A measure of the size of an earthquake, related to fault area, average slip, and rock rigidity.
Physical Properties	Rheology	The study of how materials deform under stress, affecting fault behavior and stability.
	Fracture and Fault Rock Properties	Characteristics of the rocks in the fault zone, including strength, porosity, and permeability.
	Surrounding Geology	The type of rocks and structures adjacent to the fault, influencing its behavior.
Geological Context	Tectonic Setting	The broader tectonic environment, such as plate boundaries or intraplate settings.
	Geophysical Surveys	Techniques like seismic reflection and ground-penetrating radar to study the fault's structure.
Geophysical Attributes	Inversion Models	Mathematical models using seismic data to infer fault properties and behavior.
	Surface Rupture	Visible displacement on the ground surface caused by fault movement.
Environmental Impact	Secondary Hazards	Potential hazards associated with fault movement, such as landslides, tsunamis, or liquefaction.

Seismological Data involves the collection of earthquake catalogs, which provide historical records of seismic events, including their magnitudes, locations, and depths (**Table 2.3**). Various studies highlight the necessity of comprehensive earthquake catalogs to model seismic sources and assess the probability of future events. Additionally, seismological data helps in understanding the frequency and distribution of past earthquakes, which is essential for both probabilistic and deterministic seismic hazard analysis (PSHA and DSHA).

Table 2.3: Catalog attributes needed for SHA

Attribute Category	Attribute	Description
Event Identification	Event ID	A unique identifier for each earthquake event in the catalog.
	Date and Time	The exact date and time of the earthquake occurrence, typically recorded in UTC.
Location Information	Epicenter	The geographical coordinates (latitude and longitude) of the earthquake's epicenter.
	Coordinates	The depth at which the earthquake occurred, measured in kilometers.
	Depth	The magnitude of the earthquake, quantifying the energy released during the event.
Magnitude	Magnitude Value	The type of magnitude measurement used (e.g., local magnitude, body-wave magnitude).
	Magnitude Type	Measures of shaking intensity at various locations, often reported using the Modified Mercalli Intensity (MMI) scale.
Intensity and Ground Motion	Shake Intensity	The maximum ground acceleration recorded during the earthquake, expressed in units of g (gravity).
	Peak Ground Acceleration (PGA)	
Seismic Source Information	Fault	Details about the fault that caused the earthquake, including fault name and type.
	Information	The focal mechanism that describes the orientation and movement along the fault during the earthquake.
	Source	Information about any aftershocks that occur following the main event.
Aftershocks and Foreshocks	Mechanism	Significant seismic activity that precedes the main shock.
	Aftershock Sequence	
Event Impact and Damage	Foreshocks	Information on the extent of damage caused by the earthquake, including structural damage and economic impact.
	Reported Damage	Data on human casualties, including injuries and fatalities resulting from the earthquake.
	Casualties	The organization or network that compiled the earthquake data (e.g., USGS, local seismic networks).
Data Source and Quality	Data Source	Information about the quality and reliability of the data, including confidence levels.
	Data Quality Indicators	Information about the tectonic setting of the region where the earthquake occurred.
Regional and Temporal Context	Regional Context	Analysis of patterns over time, such as clusters of seismic activity or long-term trends.
	Temporal Patterns	

Geophysical surveys, such as seismic reflection and refraction studies, provide insights into the subsurface structures and properties. Abolfazlzadeh et al. discuss the use of geophysical data to model the Earth's crust and identify areas of potential seismic activity [68]. This data is crucial for understanding the propagation of seismic waves and the potential impact on different regions.

Engineering Data includes information on soil properties, building codes, and infrastructure resilience. Trifonova et al. emphasize the role of site-specific studies, which involve assessing local soil conditions and their impact on seismic wave amplification [69]. Engineering data is vital for evaluating the vulnerability of structures and designing earthquake-resistant buildings [70].

Regional and Local Studies are essential for understanding specific seismic hazards in different regions. For example, Yazdani et al. highlights the importance of regional seismic hazard assessments that consider local geological and seismological conditions [71]. These studies help in tailoring hazard assessments to the unique characteristics of each area. Each type of data provides unique insights into the potential for seismic activity and its impact, allowing for a comprehensive evaluation of seismic hazards. The integration of these data types through probabilistic models and regional studies ensures that assessments are both accurate and relevant to specific areas, ultimately aiding in the development of effective mitigation strategies and policies.

2.1.2. Exposure Assessment

Exposure assessment involves evaluating the elements at risk, such as buildings, population, and infrastructure, within a given area [72], [73]. The exposure model captures the spatial distribution of these elements, along with their structural characteristics and valuation, which are necessary for a comprehensive seismic risk assessment [74], [75]. Various methodologies have been developed to enhance the precision and efficiency of exposure models [76]-[79]. For instance, exposure models often place assets at the centroids of administrative units, and data are spatially disaggregated using proxy datasets like population distribution or night-time lights to improve resolution [80]. In urban areas, where the density and complexity of interactions between socio-economic assets and infrastructure can amplify risks, innovative approaches such as statistical modeling and machine learning have been employed to improve exposure estimation [81]. The use of high-resolution satellite imagery and ancillary datasets, such as LiDAR and orthophotos, has also been explored to stratify cities into homogeneous regions and compile detailed exposure databases [82]-[84]. Moreover, exposure models must be adaptable to different scales, from detailed building-by-building databases to aggregated models for larger geographical entities, to ensure computational efficiency and manageability [78]. In regions like China, township-level exposure models have been developed to address limitations in spatial resolution and structural characterization, providing detailed information on building typologies and construction vintage [75]. These models are crucial for scenario-based seismic risk assessments, as they help in estimating direct

economic losses and understanding the uncertainties imposed by exposure models compared to other seismic parameters [85].

The use of building taxonomies and classification systems, as developed by the Global Earthquake Model (GEM) foundation and HAZUS, facilitates a uniform approach to categorizing structures, which is crucial for consistent exposure modeling across different regions [86], [87]. Moreover, the uncertainty in exposure data, particularly epistemic uncertainty related to building class compositions, plays a critical role in the variability of loss estimations in earthquake loss models [88]. This uncertainty can be addressed through stochastic modeling approaches, which consider the probabilistic nature of asset locations and attributes, thereby refining the estimation of average annual losses and catastrophe bond pricing [89].

A notable initiative in ATC-13 involved the development of a facility classification scheme tailored for California, integrating engineering and social function classifications. This framework emphasizes critical engineering factors for assessing structural resilience, encompassing attributes such as materials, soil conditions, and structural configurations, while also noting the building's age and spatial relationships. The system comprises 78 structural classes, with a unique labeling approach, yet its regional specificity limits broader applicability beyond California's unique structural and environmental conditions.

FEMA 154, established in 1988, serves as a straightforward facility assessment instrument, encompassing merely 15 structural categories, which facilitates expedited evaluations despite its inherent limitations due to broad classifications. Primarily concentrating on vertical structural systems, it inadequately addresses diaphragm types, with substantial specificity only found within reinforced masonry classes, resulting in potential oversights for other materials. While the detailed descriptions and illustrations of structural systems enhance the tool's utility for sidewalk surveys, its U.S.-centric design may restrict its relevance in international contexts with divergent building regulations.

The European Macroseismic Scale 1998 (EMS-98), established by Grünthal, offers a simplified 15-category classification system for structural types, facilitating widespread use; however, its overly generalized definitions may inadequately reflect the seismic performance of diverse structures (**Table 2.4**). While EMS-98 effectively

distinguishes seismic performance in reinforced concrete structures, it inadequately addresses critical nuances in steel and timber constructions, thereby limiting its applicability for comprehensive seismic evaluations [90].

Table 2.4: EMS-98 Building Classification System

Primary Material	Material Details
Masonry	Rubble stone, field stone
	Adobe (earth brick)
	Simple stone
	Massive stone
	Unreinforced masonry with manufactured stone units
	Unreinforced masonry, with RC floors
	Reinforced or confined masonry
	RC frame without earthquake resistant design (ERD)
	RC frame with moderate level of ERD
	RC frame with high level of ERD
Reinforced Concrete	RC Walls without ERD
	RC walls with moderate level ERD
	RC walls with high level ERD
Steel	Steel structures
Wood	Timber structures

The World Housing Encyclopedia (WHE) serves as a thorough repository of structural and non-structural building data, addressing facets such as architectural design, socio-economic factors, and retrofitting methodologies across 14 primary construction types with 45 subtypes. While the database offers extensive choices for structural elements, it demonstrates deficiencies in seismic-resistant classifications, lacking detailed descriptions for systems like shear walls, which limits its analytical applicability. Moreover, the descriptive nature of data entry enhances contextual understanding but may hinder uniform data analysis, despite the inclusion of visual documentation for each building type and relevant non-structural seismic performance factors.

Coburn and Spence (2002) propose a vulnerability-based classification system for buildings, distinguishing between non-engineered and engineered types, yet the categorization of pre-engineered structures within this schema remains ambiguous, thereby limiting the system's comprehensiveness as supplementary vulnerability factors are not formally incorporated into the primary framework [91].

The HAZUS methodology, formulated by FEMA in 2003, is predicated on the classification framework established in FEMA 178 (1992) and delineates building types across 36 distinct structural categories, with particular classifications for low-rise, mid-rise, and high-rise edifices (Table 2.5). Nevertheless, HAZUS could be

enhanced by disentangling height classifications from structural taxonomy, thereby facilitating a more generalized approach to building classification [92].

Although relatively uncomplicated, HAZUS is not structured to accommodate collapsible classifications. The model predominantly emphasizes U.S. conditions, with inherent assumptions regarding materials such as concrete strength and ductility that may not be applicable in an international context. Importantly, certain materials and construction methodologies, including earthen or stone structures, are absent from this classification system.

Broadening the taxonomy to encompass further configuration details or material characteristics, such as levels of ductility, would necessitate an increased number of structural types, thereby adding significant complexity to the framework. This predicament underscores the necessity of balancing simplicity with inclusivity in structural classification, particularly for applications extending beyond the U.S. context.

Table 2.5: HAZUS Building Classification System

Structure	Height*	Design Level**
Wood, light frame (<5000 sq ft)	OG	PC, LC, MC, HC
Wood, commercial and industrial (> 5000 sq. ft)	OG	PC, LC, MC, HC
Steel moment frame	LR, MR, HR	PC, LC, MC, HC
Steel braced frame	LR, MR, HR	PC, LC, MC, HC
Steel light frame	OG	PC, LC, MC, HC
Steel frame with cast-in-place concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Steel frame with unreinforced masonry infill walls	LR, MR, HR	PC, LC
Concrete moment frame	LR, MR, HR	PC, LC, MC, HC
Concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Concrete frame with unreinforced masonry infill walls	LR, MR, HR	PC, LC
Precast concrete tilt-up walls	OG	PC, LC, MC, HC
Precast concrete frames with concrete shear walls	LR, MR, HR	PC, LC, MC, HC
Reinforced masonry bearing walls with wood or metal deck diaphragms	LR, MR, HR	PC, LC, MC, HC
Reinforced masonry bearing walls with precast concrete diaphragms	LR, MR, HR	PC, LC, MC, HC
Unreinforced masonry bearing walls	LR, MR, HR	PC, LC
Mobile homes	OG	PC, LC, MC, HC

*OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise

**PC: pre-code, LC: low-code, MC: moderate-code, HC: high-code

The classification framework established by Gunel and Ilgin (2007) is particularly concerned with contemporary high-rise edifices, delineating six distinct structural systems, of which five are exclusive to this classification and absent in alternative models [93]. This schema is tailored to encompass solely three fundamental materials, including composite construction (which integrates reinforced concrete and steel). The restricted material range and concentration on high-rise constructions render it exceptionally specialized, addressing structural systems that remain unclassified within prevailing taxonomies.

The PAGER-STR classification system, conceived by Jaiswal and Wald in 2008, is esteemed as one of the most exhaustive frameworks for categorizing structures based on their seismic performance attributes [94]. It incorporates a wide array of essential structural characteristics that affect seismic behavior, although it omits certain pivotal elements, such as the strength of concrete, specific ductile detailing, and factors pertaining to irregular configurations. By making a broad distinction between ductile and non-ductile frames, the taxonomy generically addresses these elements. PAGER-STR is characterized by its simplicity and adaptability, offering applicability across global contexts and encompassing various structural forms that are prevalent outside of more economically advanced regions [94], [95].

Nevertheless, the system's capacity for extension poses difficulties; should a higher degree of precision be necessitated regarding ductility and configuration, the number of classifications may escalate significantly, rendering the taxonomy unwieldy. For contemporary structural systems such as reinforced concrete (RC), PAGER-STR organizes buildings into categories based on height: low-rise (1–3 stories), mid-rise (4–7 stories), and high-rise (8+ stories). Distinguishing height from the structural classification could potentially streamline the taxonomy, thereby improving its practicality without undermining its descriptive efficacy.

SYNER-G (2011) classification system was formulated specifically for European edifices. It represents the sole reviewed classification that is non-hierarchical in nature. It encompasses fifteen distinct facets or categories [96]. The quantity of facets will necessitate augmentation to encompass all vulnerabilities and additional data required by GEM, a task that can be accomplished with relative ease. The current configuration of the database would be enhanced to a degree of reorganization. It possesses the

capacity to address non-edifices due to its structural composition. This classification system exhibits the greatest potential for comprehensiveness and adaptability.

The Cambridge Earthquake Impact Database (CEQID), established by Lee, Pomonis, So, and Spence in 2011, serves as a comprehensive repository intended to compile damage data from over 70 investigations spanning more than 600 sites affected by 53 notable earthquakes of the 20th century [97]. CEQID has amassed close to 300 distinct building classifications, with the objective of offering extensive structural and seismic performance information across diverse building categories and geographical regions (**Table 2.6**).

Each building classification within CEQID is characterized by intricate parameters. For example, the primary construction material is identified, differentiating between materials such as adobe, brick, and reinforced concrete. The structural system of every building is also documented, encompassing types such as steel moment-resisting frames and shear walls. Moreover, supplementary attributes are integrated to encapsulate further specifics such as the composition of walls, floors, and roofs, thereby providing a more profound insight into the structural configuration.

The database further categorizes buildings by age, referencing particular construction epochs (e.g., 1941–56, pre-1941, post-1976) or adherence to codes (e.g., pre-code, modern code), which can be crucial for comprehending the impact of advancing building regulations on seismic resilience. Buildings are classified according to height ranges, such as 2–3 floors or 4–10 stories, and by occupancy type, delineating structures based on their functionality, such as rural or residential environments [97], [98].

Notwithstanding its meticulous methodology, CEQID's classification system encounters challenges stemming from inconsistencies among building class labels (**Table 2.7**). These include variations in label formatting, discrepancies between descriptions and labels, and inconsistent use of delimiters in component descriptors across different areas. Such inconsistencies may impede the clarity and comparability of CEQID's classifications, presenting a challenge for users who endeavor to obtain standardized seismic data across various regions [99], [100].

Table 2.6: CEQID Building Classification System

Main Construction Material	Structural System	Secondary Attributes	Age Reference	Height	Occupancy Type
Adobe	Unreinforced masonry	Walls, floors, roofs	Pre-1941	1-2 floors	Rural
Brick	Reinforced masonry	Walls, floors, roofs	Pre-1976	1-3 floors	Residential
Reinforced Concrete	Steel moment-resisting frame	Walls, floors, roofs	Post-1976	4-10 stories	Commercial
Wood	Light-frame construction	Walls, floors, roofs	Pre-code	1-2 stories	Residential
Steel	Steel shear wall	Walls, floors, roofs	Modern code	3-4 stories	Mixed-use
Masonry	Shear wall	Walls, floors, roofs	Various	2-3 stories	Institutional

Table 2.7: Secondary Attributes for CEQID Taxonomy

Attribute Type	Description
Walls	Type of wall construction (e.g., load-bearing, non-load bearing, material type such as brick, concrete, wood).
Floors	Type of floor construction (e.g., reinforced concrete, timber, composite materials).
Roofs	Type of roof construction (e.g., flat, pitched, material type such as tile, metal, asphalt).
Foundation Type	Type of foundation system used (e.g., shallow, deep, pile foundations).
Configuration	Architectural features such as irregular shapes, number of stories, and asymmetry in design.
Ductility	Assessment of the building's capacity to undergo deformation without collapsing (e.g., ductile, non-ductile).
Seismic Resisting Features	Specific features that contribute to seismic resistance (e.g., shear walls, cross-bracing, moment-resisting frames).
Occupancy Load	Number of occupants the building is designed to accommodate (e.g., residential, commercial).
Age or Age Reference	Construction period or significant design code changes affecting structural integrity.
Building Height	Specific range of height, further categorizing the building within the height classifications (e.g., 1-2 stories, 3-4 stories).

The Global Assessment Report on Disaster Risk Reduction (GAR) 2013 by the United Nations Office for Disaster Risk Reduction (UNDRR) [101], established a categorization framework for buildings aimed at improving the comprehension and administration of disaster risk, particularly within the sphere of urban resilience and emergency response (**Table 2.8**). This framework aspires to furnish a standardized approach for evaluating building typologies in relation to disaster risk mitigation.

Buildings are categorized according to their fundamental structural systems, which encompass masonry, reinforced concrete, steel frames, and timber frames. Masonry structures are characterized by load-bearing walls constructed from brick, stone, or concrete blocks, while reinforced concrete edifices employ concrete frameworks augmented with steel reinforcement. Steel frame structures predominantly rely on steel columns and beams for support, whereas timber frame constructions utilize timber as the principal structural component.

The classification further accounts for the materials utilized in construction, which can profoundly influence a building's capacity for resilience against hazards. Buildings are classified by their vertical dimensions, which may affect their susceptibility to particular risks, such as seismic events and flooding. Common categories include low-rise, mid-rise, and high-rise constructions.

Moreover, buildings are classified according to their designated function, such as residential, commercial, industrial, or institutional. This functional classification aids in the evaluation of risks pertinent to the building's purpose during emergencies. In addition, the system incorporates considerations for the extent of seismic design and construction methodologies applied to the building, which is vital for regions susceptible to earthquakes.

Table 2.8: GAR 2013 Building Classification System

Description	Height*	Design level**
Wood, light frame (<450m2)	OG	P, L, M, H
Wood, commercial and industrial (>450m2)	OG	P, L, M, H
Steel moment frame	LR, MR, HR	P, L, M, H
Steel braced frame	LR, MR, HR	P, L, M, H
Steel light frame	OG	P, L, M, H
Steel frame with cast-in place concrete shear walls	LR, MR, HR	P, L, M, H
Steel frame with unreinforced masonry walls	LR, MR, HR	P, L, M, H
Concrete moment frames	LR, MR, HR	P, L, M, H
Concrete shear walls	LR, MR, HR	P, L, M, H
Concrete frame with unreinforced masonry infill walls	LR, MR, HR	P, L, M, H
Reinforce concrete frames and concrete shear walls	LR, MR, HR	P, L, M, H
Flat slab structure	LR, MR, HR	P, L, M, H
Precast concrete tilt-up walls	LR, MR, HR	P, L, M, H
Precast concrete frames with concrete shear walls	LR, MR, HR	P, L, M, H
Reinforced concrete frames and steel truss girder (warehouse)	OG	P, L, M, H
Reinforce masonry bearing walls with wood or metal deck diaphragms	LR, MR	P, L, M, H
Reinforced masonry bearing walls with precast concrete diaphragms	LR, MR, HR	P, L, M, H
Unreinforced masonry bearing walls	LR, MR	P, L, M
Confined masonry walls	OG	P, L, M
Adobe	OG	P, L, M
Tapia	OG	P, L, M

* OG: one group, LR: low-rise, MR: medium-rise, HR: high-rise

**P: poor, L: low, M: medium, H: high

The GEM taxonomy refers to a comprehensive classification system designed to assess the seismic vulnerability of buildings. This taxonomy, known as GEM Building Taxonomy V2.0, was initially developed to categorize buildings based on attributes that influence their susceptibility to earthquake damage, such as construction material, lateral load-resisting system, construction date, and number of stories [102]. Over time, the taxonomy was expanded into a more inclusive system called GED4ALL, which incorporates additional attributes to address multi-hazard risk assessments beyond just earthquakes. This expanded taxonomy has been instrumental in international initiatives, aiding in the identification of common building classes worldwide and ensuring compatibility between exposure models and vulnerability databases [102], [103]. The term "GEM" is also used in various other contexts unrelated to building taxonomy, such as in geospatial data matching, metadata visualization, microcircuit emulation, and event monitoring systems, each serving distinct purposes in their respective fields [104]-[107]. However, in the context of

building classification for risk assessment, the GEM taxonomy specifically refers to the structured approach developed under the GEM initiative to systematically classify buildings for better understanding and mitigation of natural hazard risks.

The primary data needed for assessment of exposure effectively includes detailed building characteristics, such as structural type, construction period, and number of floors, height [108]. This information can be gathered through various methods, including traditional surveys, remote sensing, and newer technologies like virtual surveys using omnidirectional imagery and UAV-derived 3D models. Furthermore, many governments provide access to a wealth of data through APIs, which can be integrated into seismic exposure assessments. Open data portals often include information on building permits, land use, population statistics, and more, while GIS databases offer layers for land use, infrastructure, demographics, and hazards. Census data is often used as a foundational source for exposure information, although it can be outdated or incomplete, particularly in regions with non-seismically designed buildings [109].

The level of detail in exposure data significantly influences the accuracy of DRM. High-resolution data, such as building-by-building inventories, provide more precise risk estimates but require substantial computational resources. Conversely, aggregated data at larger spatial scales may lead to less accurate assessments but are more feasible for large-scale analyses. Both resolutions are necessary for an effective DRM. While low LoD is effective for the general assessment of the impact area, high LoDs are required for DRM tasks such as Search and Rescue (SAR) operations etc.

Remote sensing, combined with field surveys, offers a cost-effective and time-efficient method for data collection, although it may require validation against traditional datasets to ensure accuracy [84] information on the economic value of exposed assets is necessary to estimate potential financial losses from seismic events. This includes data on the replacement cost of buildings and infrastructure, which can be derived from national statistics and local datasets [77], [109].

2.1.3. Vulnerability Assessment

Vulnerability denotes the projected extent of destruction under a specified level of seismic demand and is intricately linked to the quality of the constructed environment.

At the core of this evaluation are vulnerability curves, which establish the correlation between the likelihood of loss at a defined level of seismic motion intensity measure (IM), such as response spectral acceleration for a particular period and damping ratio. Moreover, fragility curves illustrate the likelihood of surpassing specific limit states, such as physical damage thresholds, contingent upon the intensity of the seismic motion. Collectively, vulnerability and fragility curves—whether analyzed separately or in conjunction—function as dependable indicators of damage for a collection of structures exhibiting analogous structural characteristics and dynamical responses, varying with the context.

Vulnerability functions are developed using one of three primary approaches: empirical, analytical, or expert opinion, or a mix of the three (hybrid methods) [110]-[112]. The selection of methods often depends on the quality and type of information, the expertise, the resources available and the scale of the field of study. Vulnerability functions derived empirically are typically the most credible from a risk management perspective, as they are entirely based on observations of the actual performance of buildings amidst significant seismic events. For the vulnerability assessment of diverse constructed entities [113], pipelines [114], bridges [115], energy systems [116]-[118] etc., empirical approaches can be employed.

In the early 1970s, seismic vulnerability assessments for large-scale geographic buildings began utilizing analytical methods based on macroseismic intensities due to the limitations of earlier attempts to correlate intensity with physical quantities. Two key analytical approaches emerged for seismic risk assessment: Damage Probability Matrices (DPM) and the Vulnerability Index Method.

DPM express the conditional likelihood of a building sustaining a specific level of damage based on ground motion intensity. Initially suggested in 1973 after analyzing damage from the San Fernando earthquake, DPMs categorize buildings into vulnerability classes and provide a probabilistic estimate of damage [119]. Over the years, they have been adapted to incorporate data from various earthquakes and damage scales, enhancing their applicability for diverse structural typologies [90], [120]-[125]. Despite their utility, DPMs have limitations, including dependence on observed damage data, difficulty in modeling changes to the building stock, and challenges in relating ground motion to building vulnerabilities.

The Vulnerability Index Method, on the other hand, correlates seismic activity to building response through a vulnerability index determined by significant building parameters [59], [126], [127]. This index, normalized from 0 to 100, assesses vulnerability based on historical data and structural features. The Vulnerability Index Approach has been adopted in several European cities, allowing for a more nuanced evaluation of building vulnerabilities beyond simple typological classifications. However, expert judgment is often required in the methodology, and its implementation can be time-consuming, especially in data-scarce regions. Continuous Vulnerability Curves, developed later, offer a way to express vulnerability continuously rather than discretely. These curves are derived from observed damage in past earthquakes and utilize parameters like the Parameterless Scale of Intensity (PSI) to relate observed damage to ground motion.

In addition to these analytical methods, rapid screening methods have been developed to evaluate the seismic performance of existing buildings [128], [129]. The Japanese Seismic Index Method, used since 1975 for reinforced concrete buildings with fewer than six floors, calculates a seismic performance index, I_s , based on basic structural performance, structural design, and time-dependent deterioration. Similarly, in Turkey, the Priority Index and Capability Index have been proposed to assess buildings based on their structural characteristics, such as wall and column areas, as well as design and construction quality [130], [131]. Buildings are classified as either low or high risk, guiding prioritization for further evaluations.

Another noteworthy method is the Seismic Safety Screening System (SSSM), an adaptation of the Japanese method that assesses buildings with reinforced concrete frames, shear walls, or dual systems to quickly determine their seismic safety [132]. While these rapid screening methods are beneficial for prioritizing buildings for more detailed evaluations, their application in large-scale seismic risk models is limited due to the need for individual deterministic assessments, which may not be economically feasible.

The emergence of attenuation equations and seismic hazard maps based on spectral ordinates has enhanced both empirical and analytical methods for assessing seismic risk. Analytical techniques offer algorithms with direct physical significance that facilitate detailed susceptibility studies tailored to various building types and hazard

characteristics. This flexibility makes them particularly suitable for parametric studies related to urban planning, retrofitting, insurance, and other initiatives.

Historically, vulnerability curves and DPMs have been derived from observed damage data, but recent approaches incorporate computational analyses to mitigate previous limitations. For example, [133] used Monte Carlo simulations to develop fragility curves and DPMs for three types of reinforced concrete frame structures. Their method involved nonlinear dynamic analysis with multiple ground motion scenarios, using Modified Mercalli Intensity (MMI) for DPMs and spectral acceleration for fragility generation. Key components of this technique include characterizing the structure under dynamic loads, modeling potential ground movements, and quantifying the structural response.

Subsequent studies, such as those by Masi (2003), employed similar methodologies to assess the seismic vulnerability of reinforced concrete frames based on European design codes [134]. These assessments utilized the EMS98 and involved measuring seismic responses through nonlinear dynamic analyses. Rossetto and Elnashai (2005) created adaptive pushover curves for European buildings, comparing them to a calibrated damage scale using a variety of ground-motion records [135].

Despite their advantages, deriving analytical vulnerability curves is often time-consuming and computationally intensive, limiting their applicability across different regions with varying construction characteristics. As a result, these analytical methods are frequently used to support empirical DPMs and vulnerability curves rather than replace them, leading to hybrid approaches that combine both data types for improved seismic risk assessment.

Hybrid DPMs and vulnerability functions combine observational damage statistics from past earthquakes with analytical damage predictions based on mathematical models of building types. This approach is particularly beneficial when the damage data is scarce for specific geographic areas at certain intensity levels, allowing for calibration of the analytical model. Additionally, using observational data can reduce the computational effort required to develop comprehensive DPMs and analytical vulnerability curves.

Kappos et al. (1998) employed a hybrid approach to create harm probability matrices [136]. They integrated data from past earthquakes using a "Vulnerability Index

Procedure" for various intensity levels, supplemented by nonlinear dynamic analyses to model the behavior of different construction classes. This methodology scaled time-history records to PGA values, allowing for comparisons of structural responses, such as ductility and displacements, against failure, quantified in terms of repair costs.

Recent analytical vulnerability assessment methods have increasingly focused on collapse mechanisms, utilizing collapse multipliers derived from mechanical principles to evaluate potential damage. Tools like VULNUS apply fuzzy-set principles and collapse multipliers specifically to unreinforced masonry buildings [137]. Similarly, the Failure Mechanism Identification and Vulnerability Evaluation (FaMIVE) method identifies likely collapse mechanisms for historic structures by measuring load factors [138].

Capacity spectrum-based methods, such as HAZUS, have been developed to estimate potential earthquake losses on a regional basis [139]. HAZUS assesses direct physical damage across various building groups, estimating the likelihood of different damage states and calculating direct and indirect economic losses. The system is based on the ATC-40 Capacity Spectrum System and has been tailored primarily for U.S. conditions [140].

Other initiatives, such as the Comprehensive Approach to Probabilistic Risk Assessment (CAPPA) [141]. and the Earthquake Loss Estimation Routine (ELER) [142], aim to perform both deterministic and probabilistic assessments across various regions. While numerous earthquake disaster loss assessment tools (e.g., SELENA, OPENRISK, PAGER, RADIUS, OpenQuake) have been created, the challenge remains in applying a single software solution globally due to diverse seismic, architectural, and economic contexts. In high-seismicity regions like China and Taiwan, localized systems have been developed, such as the Taiwan Earthquake Loss Estimation System (TELES) and HAZ-China, to better address specific regional characteristics and enhance the accuracy of seismic risk assessments. However, these systems often rely on existing seismic damage data, limiting their applicability to new structures or areas without such data.

While it is abundantly evident that there remains a significant deficiency in the number of models accessible for a comprehensive range of geographical areas as well as various types of construction methodologies, it is noteworthy to observe that the

distribution of fragility and vulnerability assessment models is predominantly concentrated within the confines of the western hemisphere, thereby suggesting a pronounced disparity in the availability of such critical resources across different global contexts.

The assessment of vulnerability of the built environment and population involves evaluating the susceptibility of buildings, infrastructure, and communities to seismic events. Factors such as building design, code compliance, construction materials, and the socio-economic characteristics of the population are considered to determine the potential impact of earthquakes [143], [144].

2.2. Urban Resilience

Resilience, as a concept, has evolved from its origins in fields like ecology and psychology to become a foundational principle in disaster risk management. Broadly, resilience refers to the capacity of systems, communities, or entities to withstand, adapt, and recover from adverse events [145]-[147]. This adaptability, often conceptualized as the ability to "bounce back," has become increasingly vital in urban environments where complex systems interact. Urban resilience refers to the capacity of urban areas to withstand, adapt to, and recover from seismic events [148], [149]. This resilience is crucial for minimizing the impact of earthquakes on urban populations and infrastructure. In SRM, resilience emphasizes not only recovery but the continuous improvement of response mechanisms to reduce future vulnerability [150]. Applied specifically to seismic resilience, this concept focuses on preparing urban areas to anticipate, endure, and recover from the impacts of earthquakes, with the goal of minimizing loss and disruption [149].

The components of seismic urban resilience can be broadly categorized into engineering, institutional, and socio-economic systems, each playing a vital role in enhancing a city's ability to cope with seismic hazards.

In terms of the Engineering System, resilience is reflected in both infrastructure and buildings. Urban infrastructure systems—such as power, water, gas and communication—are critical for maintaining societal functions during and after earthquakes. This concept is increasingly critical as systems face uncertainties such as new missions, unplanned environments, and unexpected events [151]. By

implementing seismic retrofitting and strategic planning, cities can enhance the resilience of these essential services, ensuring their continued operation even under seismic stress [152], [153]. The resilience of engineering systems is often evaluated through frameworks like the principles-means-ends diagram, which helps stakeholders, designers, and operators understand their roles in achieving resilience [153]. Additionally, resilience measurement methods, such as the resilience cube, assess system performance during disturbances and recovery, focusing on system design attributes and their ability to handle multi-mode shocks [154]. The importance of resilience is underscored by the need for sustainable and resilient infrastructure, which is vital for delivering essential services and supporting societal prosperity [155], [156]. Moreover, resilience engineering frameworks have demonstrated significant improvements in organizational resilience capacity, as evidenced by pilot testing and simulation studies [157].

Building resilience, on the other hand, is influenced by structural integrity and other external factors, such as a community's disaster relief capacity and economic level, which contribute significantly to a building's ability to withstand earthquakes [158]-[160].

The Institutional System focuses on policy, governance, and emergency management. Effective governance frameworks are essential for implementing resilience strategies, setting clear goals, assessing current resilience levels, and continually improving measures to protect urban areas from seismic risks [161], [162]. Additionally, robust emergency response and recovery plans play a critical role in minimizing recovery time and losses after an earthquake, ensuring that affected communities can return to normalcy as swiftly as possible [163].

The Socio-Economic System encompasses aspects of community preparedness and economic stability. Public awareness and education on disaster preparedness significantly enhance community resilience, as communities that are well-informed and prepared can respond more effectively to seismic events [164]-[166]. Local seismic cultures, such as those seen in regions like Bima Regency, serve as models, illustrating how regional practices and knowledge can bolster resilience efforts [164]. Economic stability and development further support resilience initiatives by providing the resources necessary for rapid post-disaster recovery [163].

Assessment and Evaluation of urban seismic resilience involves using resilience indicators and quantitative models to measure and predict resilience under various scenarios. Indicators such as recovery time and systemic vulnerability help in understanding resilience's dynamic nature and guide decision-making [116], [167]-[171]. Quantitative models, including the Dynamic Bayesian Network and system dynamics models, provide structured frameworks for evaluating urban resilience, allowing cities to plan effectively for seismic hazards [158], [172]-[177].

At the building level, Jia and Zhan emphasize the importance of integrating environmental, economic, and social losses into functionality loss models, proposing a mixed functionality model to better simulate recovery processes and reduce assessment uncertainties [178]. Wang et al. extend this to a regional scale by introducing a methodology that categorizes buildings based on damage states and uses parameters like reconstruction rate to predict functional recovery time, aiding in policy formulation for disaster management [179]. Forcellini's work highlights the interdependency of infrastructure systems, proposing an algebraic matrix form to calculate seismic resilience, which is crucial for understanding how failures in one system can propagate to others [180]. Liu et al. use a multidimensional approach to assess urban resilience in China's North-South Seismic Belt, employing the entropy weight method to evaluate resilience across social, economic, infrastructure, and ecological dimensions, revealing spatial and temporal trends in resilience levels [181]. Baldassarre et al. apply GIS-based methods to assess seismic risk at an urban scale, emphasizing the integration of vulnerability assessments into urban planning to enhance resilience [182]. Tasmen et al. utilize a Dynamic Bayesian Network to quantify the time-varying resilience of housing infrastructure, demonstrating the dynamic nature of resilience and the importance of geographic location in resilience planning [172]. Koren and Resman Rus propose a holistic framework for assessing a city's seismic performance, incorporating human perspectives and temporal aspects to evaluate urban performance and resilience comprehensively [183]. Pan et al. introduce a Restored Quality of Life-based Approach, using performance-based methods to assess urban seismic resilience by comparing desired and actual city performance post-earthquake [184]. Lastly, Singh employs a hybrid MCDM model to study resilience in Tehran, identifying key criteria affecting resilience and providing insights into the causal relationships between these criteria [185]. Furthermore, the functionality of city

building portfolios post-earthquake is evaluated using a novel method that considers structural and nonstructural components, guiding recovery processes and enhancing city-wide resilience [186]. Collectively, these studies underscore the complexity of urban seismic resilience assessment and the necessity of integrating diverse methodologies and metrics to develop effective resilience strategies.

The interdependency between infrastructure systems is another critical factor, as failures in one system can propagate to others, necessitating a resilience-based methodology to assess these interdependencies [180]. For instance, the disruption of an electric power system can lead to failures in water supply systems, as demonstrated in a study of Incheon, South Korea, which highlighted the importance of considering functional interdependencies and estimating cascading impacts from a regional perspective [187]. Similarly, healthcare infrastructure, which is crucial during disaster response, is often interdependent with other systems like water infrastructure, yet existing protocols may not adequately address these interdependencies, as observed in Chile [188]. The complexity of these interdependencies is further illustrated by the case of Christchurch, New Zealand, where coastal flooding events showed a significant increase in the number of end users losing utilities due to cascading failures across electricity, water, and wastewater networks [189]. Moreover, the risk of cascading effects is not limited to direct physical impacts but also includes indirect losses, such as communication failures resulting from power disruptions. Various models have been developed to assess these interdependencies, but challenges remain in their practical application due to inconsistent usage and a lack of technical guidance [189]-[192]. The adoption of various methodologies aims to analyze and mitigate cascading effects within critical infrastructures, emphasizing the need for comprehensive risk assessments and resilience management. Furthermore, the conceptualization of multiple hazards and cascading effects often lacks practical implementation, suggesting a gap between scientific research and local disaster risk management practices [193].

While the focus is often on engineering and institutional resilience measures, it is equally important to consider socio-cultural aspects that contribute to a community's resilience. Local practices and cultural adaptations, as seen in Bima, offer valuable insights into sustainable disaster mitigation strategies, highlighting the importance of

integrating traditional knowledge and community-based approaches in building seismic urban resilience.

2.2.1. Quantification of Resilience

Quantifying seismic resilience involves a multifaceted approach that integrates various methodologies and frameworks to assess the ability of structures and systems to withstand and recover from seismic events. A common theme across literature is the use of probabilistic frameworks and dynamic models to evaluate resilience. For instance, the seismic resilience of petroleum depots is quantified through a component–subsystem–system model that relates damage indices to functional loss and recovery time, providing a comprehensive assessment of resilience levels [194]. Similarly, the Dynamic Bayesian Network (DBN) approach is employed to assess the time-varying resilience of housing infrastructure, highlighting the dynamic nature of resilience and the impact of geographic location on resilience levels [172]. In the context of Society 5.0, a systems dynamics model evaluates seismic resilience by considering fragility, consequence, and recoverability stages, emphasizing the importance of critical infrastructure in resilience planning [195]. For ultra-high voltage converter stations, a multi-model probabilistic framework assesses resilience by analyzing connectivity and power transmission capacity, using Bayesian networks to model functional reliability and recovery processes [196]. Individual buildings' resilience is quantified by integrating environmental, economic, and social losses into functionality loss models, with a focus on simulating recovery processes under various conditions [197]. The stiffness-flexibility indicator (SFI) is used to assess the seismic resilience of steel frame structures, linking structural characteristics to repair costs and recovery time [198]. Seismic fragility analysis, using methods like the Adaptive Gaussian Mixture Model (AGMM), provides precise fragility curves that inform resilience assessments by estimating failure probabilities under different seismic intensities [199]. Simplified frameworks, such as those using fragility curves and recovery models, offer expeditious assessments of structural configurations, aiding in pre- and post-earthquake evaluations [200]. The impact of mainshock-aftershock sequences on transmission tower-line systems is assessed through a probabilistic framework that considers functionality loss and recovery time, highlighting the significant influence of aftershocks on resilience [201]. Lastly, the resilience of coastal

bridges is evaluated by considering scour and corrosion effects, with a resilience loss ratio quantifying the impacts of these factors on seismic resilience across different ground motion intensities [202]. Collectively, these studies underscore the importance of integrating probabilistic models, dynamic assessments, and multi-parameter evaluations to effectively quantify seismic resilience across various infrastructure systems.

At a conceptual level, several proposals in the literature suggest quantitative methods for estimating resilience, often utilizing a functionality-versus-time plot, such as the one depicted in **Figure 2.4**. In this model, a disruptive event occurs at time t_0 , where pre-event functionality is typically considered as $Q(t_0)=100\%$. Immediately after the event, functionality is reduced to a minimum or residual level, denoted $Q(t_d)$, which it maintains until recovery operations begin at time t_i . For seismic events, and in the absence of other system influences, t_d often coincides with t_0 , meaning the system reaches its lowest functionality level immediately after the event. Full recovery is then achieved at time t_r .

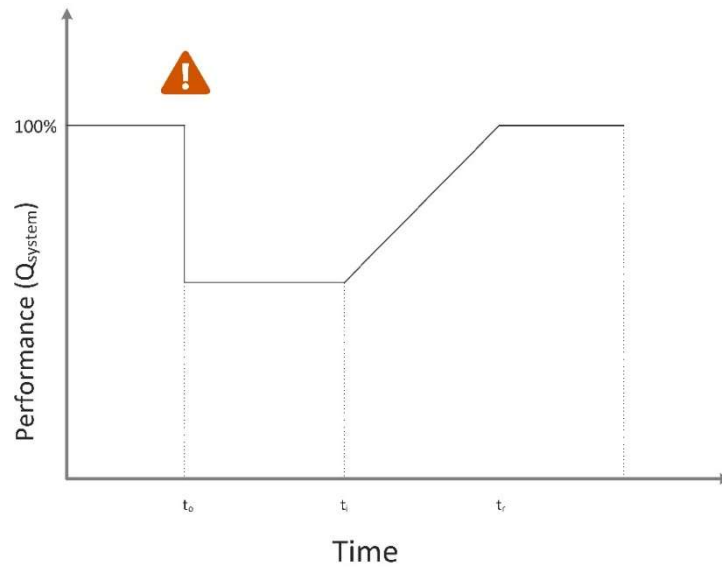


Figure 2.4: Simple depiction of resilience

The concept of resilience is characterized by four fundamental attributes: robustness, rapidity, redundancy, and resourcefulness (the "4R") [176], [203]. These attributes are not isolated but are rather interrelated and mutually influential. For example, robustness, which indicates a system's ability to withstand external disturbances

without considerable functional impairment, has a direct impact on the speed of recovery. Likewise, redundancy, which denotes the presence of alternative resources, and resourcefulness, which pertains to the efficient utilization of these resources, are pivotal in influencing both the capability and velocity of the recovery process.

The assessment of resilience generally emphasizes the quantification of functionality loss and the simulation of the recovery process, which are encapsulated through functionality models. These models offer a structured approach for evaluating a system's performance when subjected to stress and its proficiency in resuming operations effectively. Functionality models are often visualized using functionality curves (Figure 2.5), where the horizontal axis represents time, and the vertical axis denotes the level of functionality. These curves highlight key phases, including the initial functionality loss due to the event, the stabilization period, and the recovery process. Metrics such as time to recovery, extent of functionality loss, and rate of recovery are commonly derived from these models to analyze system resilience.

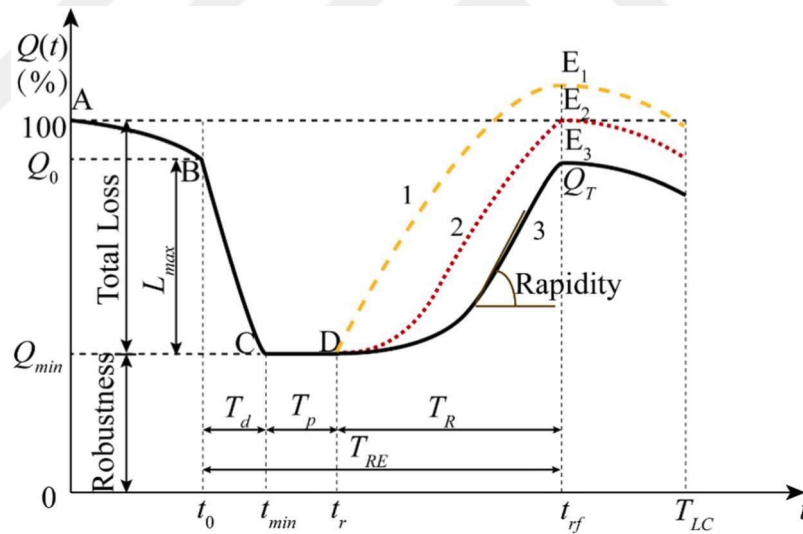


Figure 2.5: Functionality Curves (adopted from [197])

The functionality of an aging system, $F(t)$, decays over time due to wear and tear or degradation. The pre-disaster functionality can be modeled as a decreasing function:

$$F(t) = \begin{cases} F_0 \cdot e^{-\lambda(t-t_1)}, & t_i \leq t < t_0 \\ F(t_0) - L, & t = t_0 \\ F(t_0) - L + R(t), & t > t_0 \end{cases} \quad (2.5)$$

- t_i : Initial time when aging begins.
- λ : Aging rate constant, representing the rate of decay of functionality over time.

The recovery of an aging system may not fully restore functionality to the original level F_0 . Instead, recovery aims to restore functionality to the pre-disaster aged state $F(t_0)$. The recovery function can be expressed as:

For linear recovery:

$$R(t) = \min[F(t_0) - L, \gamma \cdot (t - t_0)] \quad (2.6)$$

- $R(t)$: Recovery function at time t .
- $F(t_0)$: Functionality at the pre-disaster aged state.
- L : Level of functionality immediately after the disaster (damage level).
- γ : Constant recovery rate (functionality restored per unit of time).
- t_0 : Time when recovery begins.

For exponential recovery:

$$R(t) = (F(t_0) - L) \cdot (1 - e^{-\alpha(t-t_0)}) \quad (2.7)$$

- $R(t)$: Recovery function at time t .
- $F(t_0)$: Functionality at the pre-disaster aged state.
- L : Level of functionality immediately after the disaster (damage level).
- α : Recovery rate constant.
- t_0 : Time when recovery begins.

For logarithmic recovery:

$$R(t) = \frac{F(t_0) - L}{1 + e^{-\beta(t-t_m)}} \quad (2.8)$$

- $R(t)$: Recovery function at time t .
- $F(t_0)$: Functionality at the pre-disaster aged state.
- L : Level of functionality immediately after the disaster (damage level).

- β : Recovery steepness parameter.
- t_m : Midpoint of recovery.

In cascading systems, failures propagate from one subsystem to others, leading to secondary or tertiary failures. The recovery function for cascading systems must account for this interdependency and the compounded effect of failures. Here's an example of a recovery function model for cascading systems:

General recovery for cascading systems:

$$R(t) = \sum_{i=1}^n R_i(t) \cdot \prod_{j \in C_i} D_{ij}(t) \quad (2.9)$$

- **$R(t)$** : Total recovery of the system at time t .
- **$R_i(t)$** : Recovery function of subsystem i .
- **C_i** : Set of subsystems that are causally dependent on i (directly or indirectly).
- **$D_{ij}(t)$** : Dependency factor representing the extent to which the recovery of subsystem i is influenced by the recovery state of subsystem j at time t .
 - For example, $D_{ij}(t) \in [0,1]$, where 0 means complete dependency (no recovery without j) and 1 means full independence.

Dependency factor with time lag:

$$D_{ij}(t) = f(R_j(t - \tau_{ij})) \quad (2.10)$$

2.3. Smart Cities

Information serves as the foundation for action across all living systems. Without it, these systems struggle to prepare for or adapt to their surroundings, effectively becoming subject to the whims of their environment. For an entity to be deemed intelligent, it must exhibit fundamental capabilities such as information gathering, information recording, and learning from the acquired data. Beyond these skills, systems that demonstrate creativity, defined as the ability to generate something novel and valuable from seemingly unrelated elements, and planning, encompassing the

coordination of tools and methods for future applications are regarded as exhibiting higher intelligence.

Cities, viewed as living ecosystems, embody complex structures and intricate dynamics among their various components. To be classified as "smart," cities must not only gather and record data about their subsystems but also learn from this information, develop innovative tools and methodologies, and strategize for their implementation. This multifaceted approach enables cities to adapt and thrive in an ever-changing environment, enhancing their resilience and overall functionality.

A smart city is an advanced urban area that leverages a combination of information and communication technologies (ICT), IoT, and artificial intelligence (AI) to enhance the quality of life for its residents while promoting sustainable development. Cloud computing [204], big data [204]-[208], virtual reality (VR) [209], [210], and AI [209] are all examples of advanced technology being used to develop smart cities. At its core, a smart city employs a robust ICT infrastructure comprising sensors, networks, and protocols to monitor and manage urban spaces, thereby improving safety and resource management while addressing challenges such as privacy and data security [211]. The concept of a smart city encompasses various dimensions, including smart governance, smart economy, smart mobility, smart environment, and smart living, all of which are integrated to create a cohesive urban ecosystem [212]-[215]. These cities utilize IoT technologies to gather and analyze data from numerous sensors and devices, enabling efficient management of urban services such as transportation, energy, water, and waste management [216]-[220]. The integration of AI further enhances these capabilities by providing predictive analytics and automation, which improves public safety, healthcare, and environmental monitoring [221], [222]. The concept extends beyond technology, emphasizing human-centered approaches that foster collaboration between governments and citizens to co-design innovative solutions for sustainable living conditions [223]. Smart cities also emphasize the importance of smart governance, which involves using digital platforms for e-governance and e-democracy to foster better communication between city administrations and citizens [212].

Smart cities are seen as dynamic systems of interconnected subsystems, each contributing to the city's overall competitiveness and adaptability in a sustainable manner [224]. The implementation of smart city initiatives is driven by policy, societal needs, and technological advancements, aiming to achieve outcomes like

sustainability, livability, and economic productivity by connecting people, information, and city elements through state-of-the-art technologies, promoting greener environments and enhancing life quality [225]-[227]. Moreover, smart cities are characterized by their adaptability and competitiveness, which are essential for addressing the challenges posed by rapid urbanization and external impacts [224], [227]. The development of smart cities is driven by the need to address the challenges of rapid urbanization, such as resource management and infrastructure strain, by implementing innovative solutions that ensure sustainability and resilience.

Human-centered smart cities emphasize collaboration between governments and citizens, fostering mutual trust and cooperation to design innovative solutions that enhance the urban experience [223]. The integration of smart technologies also supports the development of smart governance, which centralizes and streamlines public services to improve government performance [228].

In practice, smart cities are characterized by their ability to integrate diverse data sources to provide high-level services to both citizens and municipal authorities, thereby creating an intelligent digital system that supports urban life [229]-[231]. The ongoing evolution of smart cities is marked by the continuous exploration of new technologies and methodologies to further enhance urban living and sustainability. As cities continue to evolve, the smart city model offers a promising pathway to creating more efficient, sustainable, and inclusive urban environments [232].

2.4. City Information Modeling (CIM)

City Information Modeling (CIM) is a parametric, 3D modelling based, infographic representation of cities that allows users to simulate accurate data driven representations of cities and its surrounding environment. CIM is an advanced digital framework that extends the principles of Building Information Modeling (BIM) to the urban scale, creating a comprehensive 3D representation of city environments. CIM integrates various data layers (**Figure 11**), including buildings, infrastructure, mobility, environmental factors, and social aspects, into a unified model that aids in urban planning and management [233]-[235].

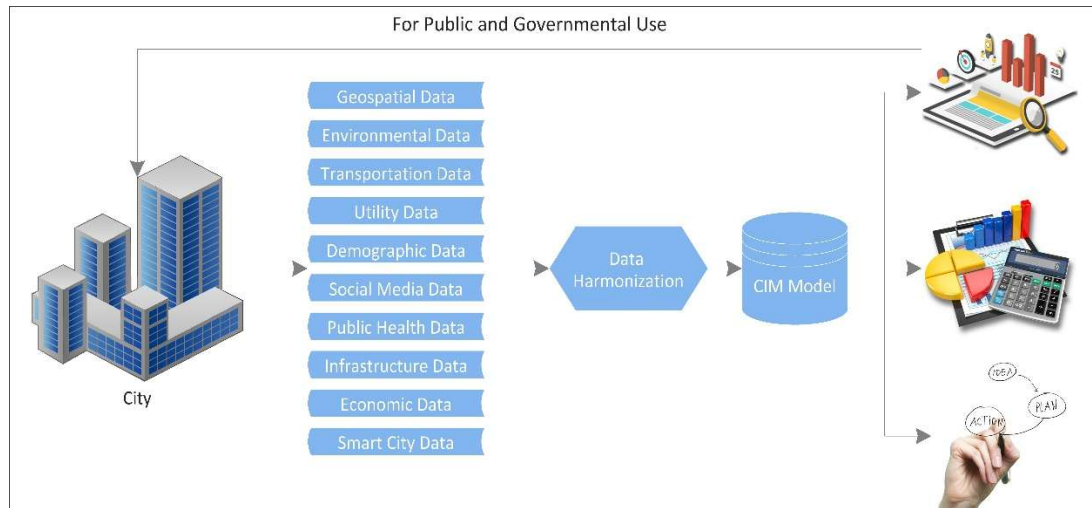


Figure 11: CIM approach.

In 2007, Khemlani introduced the concept of CIM, expanding the scope of information modeling beyond individual buildings to encompass entire urban areas [210], [236], [237]. Building on the advancements in BIM, Khemlani adapted BIM principles to support urban-scale projects, initially framing CIM as an extension of BIM technology applied specifically to cities. This approach enabled a broader application of information modeling techniques to address the complexities of urban infrastructure and planning.

CIM can be established by integrating BIM and GIS [238]. Internal component-level building information can be provided via BIM, whereas external building information can be provided using GIS. Consequently, by combining micro-BIM and macro-GIS data, a trans-scale CIM covering internal and external buildings can be built [239]. Additionally, by incorporating contemporary complementary data, CIM facilitates the creation of dynamic city models. CIM is a comprehensive digital approach that integrates data, technologies, and processes to model, simulate, and manage urban environments.

This model is not only a geometric representation but also incorporates real-life attributes and data, enabling a more dynamic and interactive approach to city management [240]. The integration of tangible and intangible data, such as social indicators and citizen feedback, is crucial for creating a human-centered digital replica of the city, which can enhance decision-making processes and improve the quality of life for residents [234]. CIM also supports the development of smart cities by

facilitating the management of urban assets and infrastructure through technologies like the IoT and AI. Moreover, CIM can be enhanced with blockchain technology to ensure transparency and efficiency in data sharing and collaboration among stakeholders [240]. The application of CIM is diverse, ranging from improving thermal comfort in urban planning to supporting sustainable and resilient city development. Despite its potential, challenges remain in data collection, integration, and visualization, as well as in fostering collaboration among the various actors involved in urban projects. Overall, CIM represents a significant advancement in urban informatics, offering a powerful tool for addressing the complexities of modern urban environments and promoting sustainable urban development.

In CIM, data integration is fundamental. Internal building information is largely managed using BIM and computer-aided design (CAD) technologies, while city-level geographic data is typically handled with GIS. To capture dynamic data, CIM leverages IoT technologies, which are used in three primary areas: perception, communication, and application [241]-[245].

Yet, urban environments' complexity and scale challenge the precision and automation capabilities of current CIM data collection methods [246], [247]. Integrating vast, multisource data from various technologies remains a major task, although combining BIM and GIS is seen as a viable solution [248]-[251]. A significant limitation, however, is that most existing structures lack BIM models, making detailed internal data less accessible.

In addition to BIM and GIS, CIM requires new data types, such as IoT-generated data, which necessitate a more flexible approach to data integration [252], [253]. Furthermore, CIM-based applications, including evaluation, prediction, and management, are still underdeveloped. To expand these applications, detailed models and algorithms for specific scenarios are urgently needed, enabling tailored assessment, prediction, and management based on CIM's comprehensive data framework.

2.5. Digital Twin Technology

DT technology is a sophisticated concept that involves creating a virtual replica of a physical object, system, or process, enabling real-time simulation, monitoring, and

analysis of real-world behavior [254]-[256]. This technology, which originated with NASA's Apollo Mission, has evolved significantly and is now applied across various sectors, including healthcare, manufacturing, urban planning, and more [257].

The energy sector benefits from DTs through improved efficiency of energy systems, predictive maintenance, and reduced energy consumption [258], [259]. In transportation, DTs optimize logistics and reduce delivery times, while in construction, they enhance project management, reduce errors, and improve safety [259]. The automotive industry employs DTs for the development, testing, and validation of autonomous vehicles, addressing challenges in algorithm training and validation [260], [261]. Smart cities leverage DTs to control traffic flow, minimize energy consumption, and improve public safety, allowing urban planners to test scenarios and optimize resources for sustainable living. Additionally, agriculture uses DTs to optimize crop yields and resource management, enabling informed decisions on water usage, fertilizer application, and pest control [262], [263]. The defense sector also sees applications of DTs in enhancing decision-making and operational efficiencies [264].

Advancements over the past two decades in high-performance computing, IoT, artificial intelligence, and machine learning have transformed DTs from basic virtual models into complex systems that enhance decision-making and operational efficiency across industries [264], [265]. The proliferation of digital data has further broadened the scope of DT technology (**Table 2.9**), enabling sophisticated simulations, real-time monitoring, and a wide range of applications that underscore DTs' expanding role across diverse fields [266].

Despite their potential, challenges such as data quality, privacy concerns, and the need for standardization remain significant barriers to the widespread adoption of DTs [264]. The historical trajectory of DTs reflects a shift from basic modeling to a comprehensive framework that supports the dynamic interaction between physical and digital entities, underscoring their transformative impact on modern industrial and technological landscapes [267], [268].

The widespread adoption of DTs across various industries is currently hindered by several significant challenges. One of the primary obstacles is the establishment of robust IT infrastructure, which is essential for supporting the complex data ecosystems that DTs require. Additionally, ensuring data quality and consistency is crucial, as

inaccuracies can lead to flawed simulations and decision-making processes. Privacy and cybersecurity concerns also pose substantial barriers, given the sensitive nature of the data involved and the potential for cyber threats in the convergence of physical and virtual realms [269], [270]. The lack of standardization in data formats and definitions further complicates the integration of DTs into existing systems, necessitating interdisciplinary collaboration and the development of universal platforms [271], [272]. Organizational adaptation is another challenge, as companies must adjust their processes and cultures to effectively leverage DT technology [273], [274]. In the manufacturing sector, the emergent stage of DT technology and the need for comprehensive information and clarity in concepts are additional hurdles [273]-[275]. Moreover, the protection of intellectual property and commercial confidentiality is critical, especially in industries where innovation is a competitive advantage. Addressing these challenges requires a concerted effort to develop secure, standardized, and interoperable DT systems, which will enable industries to fully capitalize on their transformative potential.

Table 2.9: Data needs for a DT

Category	Potential Source	Data Types	Access
GIS Data	Local Government GIS Departments	Zoning maps, land use data, infrastructure layouts	Often available through local government websites or GIS portals
	National Mapping Agencies	Topographic maps, elevation data, hydrography	Typically available for free or at a nominal fee
	OpenStreetMap	Building footprints, road networks, points of interest	Free to use; data can be downloaded in various formats
Remote Sensing Data	LiDAR Data Providers	Terrain models, building height information	Often available for free or through purchase
	Satellite Imagery	High-resolution satellite images, multispectral data	Varies by provider; some data is free, others may require a subscription
Photogrammetry	Drone Services	High-resolution images, 3D models	Services may be contracted for specific projects
	University Research Projects	Photogrammetric data from academic studies	Often available through university repositories or publications
BIM Data	Architectural Firms	Detailed BIM models of buildings	May require partnerships or agreements for access
	Industry Standards Organizations	Guidelines and standards for BIM data	Standards documents are often available for free or at a cost
Environmental Data	Environmental Agencies	Vegetation data, water bodies, ecological features	Often available through government websites
	Urban Planning Departments	Parks, green spaces, environmental assessments	Typically available through local government portals
Publicly Available Datasets	Data Portals	Urban planning, demographic data, transportation data	Free access to a variety of datasets
	Open Data Initiatives	Transportation, demographics, urban infrastructure	Free access to datasets
Academic and Research Institutions	Research Publications	Datasets or methodologies for 3D modeling	Often available through academic journals or repositories
	Theses and Dissertations	Original data collection relevant to city modeling	Available through university libraries or repositories
Community Contributions	Citizen Science Projects	Local data contributed by residents	Often available through project websites or platforms
	Local Historical Societies	Historical maps and data	May require direct contact or visits to local archives
Commercial Data Providers	Geospatial Data Companies	Commercial datasets for urban planning and analysis	Typically requires a subscription or purchase
	3D Model Marketplaces	3D models of buildings and urban elements	Models can be purchased or downloaded for free

2.6. Integration of CIM in Disaster Risk Management

As stated before, CIM offers significant benefits in DRM efforts, primarily through its integration with BIM and GIS. This integration facilitates effective information management, enhanced visualization, and improved coordination among stakeholders, which are crucial during disaster scenarios [276], [277]. CIM provides a holistic view of urban environments, enabling better planning and management by simulating future demands and visualizing potential disaster impacts [278]. The use of CIM in disaster management is further enhanced by its ability to merge various data sources, including 3D building models and qualitative data from residents, as demonstrated in the Al Baqa' case study, which aimed to address environmental challenges like water management [279]. However, the implementation of CIM faces several challenges, such as data incompatibility, redundancy, and the loss of semantic information, which can hinder its effectiveness [276], [277]. Additionally, the lack of standardized data formats and interoperability across different stakeholders complicates the rapid exchange of information necessary for effective disaster management [280]. The complexity of defining and operationalizing CIM, as well as the need for precise usage definitions and collaboration among numerous actors, further complicates its deployment. Despite these challenges, CIM's potential to enhance community resilience and urban safety through improved data integration and stakeholder engagement is significant, as it supports decision-making and planning in smart cities. Future research and development efforts are needed to address these challenges, optimize CIM software, and fully realize its potential in urban disaster management [281].

3. THEORETICAL FRAMEWORK

3.1. Principles of (CIM)

CIM is a transformative framework that applies advanced digital technologies to model, manage, and analyze urban systems at a citywide scale. Rooted in the principles of BIM, CIM extends these methodologies beyond individual structures to encompass entire urban environments, integrating diverse datasets that reflect the complexity of cities (**Table 3.1**). Its theoretical foundation lies in the convergence of spatial sciences, urban planning, and information management, making it a vital tool for smart city development and disaster risk management.

Table 3.1: Key Properties of CIM

Category	CIM Properties	Description
Data Integration	Centralized Data Platform	Consolidates urban data from various sources into a unified system for easy access and analysis.
	Interoperability	Supports integration of data from diverse domains using open standards like CityGML, IFC, and GeoJSON.
	Multi-Source Data Fusion	Combines spatial, structural, demographic, and real-time data from sources like GIS, IoT sensors, and remote sensing.
Representation	3D Visualization	Provides detailed 3D models of city infrastructure, landscapes, and urban systems.
	Multiscale Modeling	Scales from individual buildings (micro) to citywide systems (macro) for a comprehensive urban view.
	Layered Data Structures	Represents physical, functional, and operational aspects of urban areas (e.g., buildings, transport, utilities).
Functionality	Real-Time Data Updates	Supports real-time monitoring using IoT and sensor networks for dynamic analysis.
	Scenario Simulation	Enables disaster simulations, urban planning, and development forecasting.
	Analytical Tools	Provides advanced tools for risk assessment, urban planning, and decision-making (e.g., disaster response planning).
Scalability	Modular Architecture	Adapts to different scales and complexities, from local municipalities to large urban regions.
	Dynamic Expansion	Accommodates new data layers, technologies, and use cases as they emerge.

3.1.1. Data-Centric Urban Management

CIM is inherently data-driven, offering a centralized platform for the collection, aggregation, and analysis of diverse urban datasets. It integrates geospatial data, infrastructure models, environmental information, and socio-economic attributes into a cohesive system. This enables a comprehensive understanding of urban dynamics and supports evidence-based decision-making for planning, management, and disaster preparedness. By leveraging structured and unstructured data sources, CIM fosters a holistic perspective on urban systems, bridging the gap between static planning approaches and dynamic urban realities.

3.1.2. Interoperability and Standardization

A critical pillar of CIM is its reliance on interoperability and adherence to open standards, such as Industry Foundation Classes (IFC) and CityGML. These standards ensure seamless integration between various domains, including architecture, engineering, urban planning, and environmental science. The interoperability inherent in CIM facilitates multi-stakeholder collaboration by enabling the exchange of information across platforms, software, and disciplines. This capacity to interlink diverse datasets ensures that urban models remain consistent, accurate, and adaptable over time.

3.1.3. Holistic Representation of Urban Systems

CIM captures the multifaceted nature of urban environments by combining physical, functional, and operational data. It models physical structures, such as buildings, roads, and utilities, while also incorporating functional layers like land use, zoning, and transportation networks. Additionally, CIM can integrate dynamic attributes, including population density, traffic patterns, and environmental conditions, creating a comprehensive representation of the city as a system. This holistic approach enhances the ability to analyze interdependencies among urban components, making CIM an indispensable tool for managing the complexity of modern cities.

3.1.4. Dynamic and Scalable Framework

The scalability of CIM allows it to adapt to various contexts, ranging from small municipalities to large metropolitan areas. Its dynamic framework supports real-time updates and the integration of emerging technologies, such as IoT sensors and remote sensing data. This adaptability ensures that CIM remains relevant in rapidly changing urban environments, providing up-to-date insights for decision-makers.

3.1.5. Relevance to Disaster Management

In the context of disaster risk management, CIM provides an essential foundation for assessing vulnerabilities, planning mitigation strategies, and coordinating response efforts. By integrating spatial and structural data with hazard-specific information, such as fault lines or flood zones, CIM enables the identification of high-risk areas and the simulation of disaster scenarios. This functionality makes it a cornerstone for proactive urban resilience planning.

CIM represents a paradigm shift in urban information management, combining advanced data integration techniques with a comprehensive understanding of urban complexity. By enabling a multidimensional analysis of cities, CIM provides the theoretical and practical framework required for addressing the challenges of urbanization, climate change, and disaster risk, positioning itself as an indispensable tool for 21st-century urban planning and management.

CIM integrates data from various sources, including GIS, 3D building models, sensor networks, environmental data, and social information. This multi-scale data aggregation allows for comprehensive modeling of city dynamics and supports decision-making processes.

A key principle of CIM is the ability to work with diverse data formats and systems, ensuring seamless integration of data from different stakeholders, technologies, and platforms. This interoperability facilitates communication and collaboration between various urban management sectors.

CIM enables the creation of digital twins of urban areas, representing physical assets, infrastructure, and environmental conditions in real-time. These digital twins provide

a dynamic and interactive model of the city, which can be used to simulate scenarios and assess potential impacts of various events, such as earthquakes.

The principle of real-time data integration allows CIM to incorporate live sensor data, IoT devices, and other monitoring technologies to continuously update the digital twin. This ensures that the model reflects the current state of the city, enhancing situational awareness and enabling timely decision-making.

3.2. Principles of Digital Twins

DTs are guided by a set of foundational principles that ensure their effectiveness in representing, analyzing, and optimizing physical systems. These principles establish the framework for maintaining an accurate and functional relationship between the physical and digital counterparts, enabling their application across various domains.

A key principle of DTs is bidirectional synchronization, which ensures a continuous and dynamic exchange of information between the physical asset and its virtual model. Real-time updates from IoT devices and sensors allow the digital model to accurately reflect the current state of the physical system. Conversely, insights and recommendations generated by the digital model can be implemented in the physical counterpart, creating a feedback loop that supports optimization and decision-making.

Data integration and fidelity are critical for the reliability of DTs. They require high-quality, detailed data from diverse sources, such as sensors, databases, and external systems, to create a faithful representation of the physical system. The completeness and accuracy of data across spatial, temporal, and operational dimensions directly influence the fidelity of the digital model.

DTs must also be scalable, accommodating varying levels of complexity from individual components to entire systems or cities. Scalability ensures flexibility, enabling the twin to grow or adapt to new requirements as the system evolves. Closely related to scalability is interoperability, which allows DTs to seamlessly interact with different platforms, systems, and technologies. Standardized communication protocols, APIs, and data formats are essential for ensuring compatibility across systems.

A distinguishing feature of DTs is their ability to perform simulation and predictive analytics. By evaluating "what-if" scenarios and predicting future states, DTs provide valuable insights for proactive decision-making. This capability supports the identification of potential risks, failures, or opportunities for improvement, contributing to the resilience of the system.

Lifecycle integration is another core principle, ensuring that DTs encompass the entire lifecycle of the physical asset—from design and construction to operation, maintenance, and decommissioning. This approach promotes sustainable management and optimization of resources over the long term. Additionally, DTs must maintain context awareness, incorporating spatial, environmental, and situational data to deliver actionable insights tailored to specific applications. Awareness of external factors, such as weather, traffic, or seismic activity, enhances their effectiveness.

To support adaptive management, DTs rely on real-time monitoring, which continuously tracks the physical asset through live data streams. This enables timely detection of anomalies, facilitating swift responses to potential issues. At the same time, robust security and privacy measures are essential to protect sensitive data and mitigate cybersecurity risks. Encryption, access controls, and data anonymization ensure that DTs remain secure and trustworthy.

Collaboration among stakeholders is another critical aspect of DTs. By providing a shared and accurate representation of the system, DTs foster collaboration and stakeholder engagement, enabling informed decision-making and alignment among engineers, operators, planners, and other parties. Moreover, they are designed for continuous improvement and learning, incorporating new data and refining algorithms over time. Machine learning and artificial intelligence play a key role in enhancing predictive accuracy and system performance.

The usability of DTs is also a significant factor. Advanced visualization and usability tools, such as 3D models, dashboards, and augmented reality (AR), make DT intuitive and accessible for decision-makers. To ensure reliability, DTs are built with resilience and robustness, allowing them to handle disruptions, data inconsistencies, or system failures. Redundancy and fault-tolerant designs are critical for maintaining continuous operation.

Finally, DTs must contribute to broader sustainability goals by optimizing resource use, reducing waste, and promoting energy efficiency. By aligning with environmental and social objectives, DTs support sustainable practices and long-term resilience.

Key properties of DTs are shown at **Table 3.2**. The principles of Digital Twins provide a comprehensive framework for their design, implementation, and application. By adhering to these principles, Digital Twins can accurately and reliably represent physical systems, enabling real-time monitoring, predictive analytics, and informed decision-making across various industries.

Table 3.2: Key properties of DTs

Property	Description
Real-Time Data Integration	Ability to synchronize the physical and digital assets in real-time using IoT sensors and other data sources.
Interoperability	Capacity to interact with various systems, platforms, and data standards for seamless operation.
Simulation and Prediction	Capability to perform simulations for predicting system behavior under different scenarios.
Visualization	High-fidelity 3D representations of physical systems for enhanced analysis and decision-making.
Scalability	Adaptability to scale from small systems (e.g., a building) to complex urban systems (e.g., a city).
Historical Data Analysis	Use of archived data to analyze trends, identify inefficiencies, or plan retrofits.
Feedback Loop	Incorporation of insights gained from simulations and analyses into the physical system for optimization.
Data Security and Privacy	Implementation of robust mechanisms to ensure data confidentiality, integrity, and compliance with regulations.
Predictive Maintenance	Identification of potential system failures before they occur by analyzing real-time and historical data.
Integration with AI/ML	Use of machine learning algorithms for advanced analytics, decision-making, and optimization.
Lifecycle Management	Ability to monitor and manage the entire lifecycle of a system or asset, from creation to decommissioning.
User Interactivity	Provides stakeholders with tools and interfaces to interact dynamically with the digital model.
Standardization	Adherence to global data exchange and modeling standards for interoperability and reusability.

3.3. Integration of CIM with DT Technology for SRM

The integration of CIM with DT technology provides a transformative approach to earthquake management in urban areas. CIM, a digital representation of urban infrastructure and spatial data, serves as a foundation for modeling the structural, functional, and social aspects of a city. When paired with DT technology, which offers real-time simulation and monitoring capabilities, the two systems together enable a comprehensive, dynamic model of the city that can adapt to current data and predict potential outcomes in disaster scenarios.

The concept of a DT serving as a data warehouse provides a centralized repository for storing and retrieving static and dynamic urban data. However, when integrated with CIM frameworks, this centralized model evolves into a layered "data lasagne" structure (**Figure 3.1**). This transformation represents a paradigm shift from mere data storage to a multi-dimensional, context-driven approach to data organization and analysis.

In a DT as a data warehouse, data layers are typically organized in a hierarchical or flat structure, enabling straightforward queries and storage of urban information. While effective for storage and retrieval, this approach lacks the flexibility needed for dynamic decision-making and holistic urban analysis.

In contrast, the CIM framework introduces a layered data lasagne structure, where each layer not only represents a distinct category of urban data (such as transportation, utilities, or environmental factors) but also interrelates dynamically with other layers. This interconnectedness allows for real-time integration, contextual analysis, and scenario simulation. For instance, a transportation layer in a CIM framework would not only store road and traffic data but also interact dynamically with environmental layers (e.g., air quality and noise levels) and socio-economic layers (e.g., population density) to provide actionable insights.

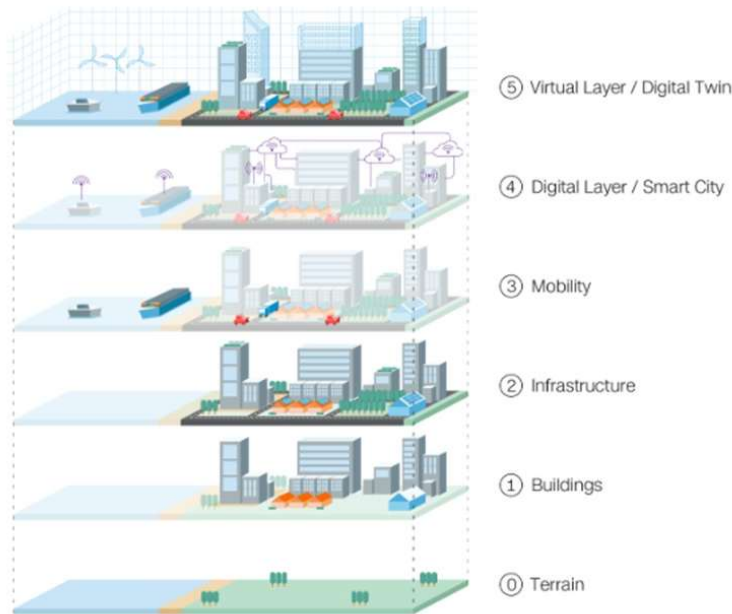


Figure 3.1: Data Lasagne Structure of CIM.

The layered lasagne metaphor underscores the complexity and richness of CIM frameworks. Each "slice" of the lasagne retains its distinct identity (e.g., infrastructure, socio-economics, environmental dynamics), yet the overlapping layers create a cohesive system that supports advanced functionalities like predictive modeling, resource optimization, and resilience planning.

This shift from a data warehouse to a data lasagne structure highlights the added value of CIM frameworks. By enabling dynamic interaction among layers, the lasagne model fosters a holistic understanding of urban systems, facilitating smarter and more resilient city management. This approach not only enhances the utility of Digital Twins but also aligns them with the broader goals of sustainable and adaptive urban development.

In DRM, the CIM-DT integration allows for precise risk analysis, where detailed urban models simulate the physical and environmental factors contributing to earthquake vulnerability. These models provide real-time insights by simulating seismic impacts on city structures, thus helping stakeholders prioritize interventions, manage resources, and coordinate emergency response. For instance, CIM provides static data, such as the location and condition of buildings, utilities, and transportation networks, while DT technology enriches this with real-time data from sensors, historical seismic records, and other sources. This synergy creates a dynamic simulation of urban

resilience to seismic events, making it easier to test the effects of different earthquake scenarios on various types of structures within the city.

Moreover, by integrating CIM with DTs, emergency response teams can receive updates on critical infrastructures, track the availability of evacuation routes, and allocate resources effectively. This continuous data exchange is pivotal for decision-making during and after an earthquake. Additionally, the integration supports proactive measures, including the identification of high-risk zones and vulnerable structures, enabling city planners to enhance seismic resilience through strategic retrofitting and reinforcement measures.

Ultimately, the integration of CIM and DT technology in earthquake management not only streamlines response efforts but also fosters a proactive, data-driven approach to urban planning and risk reduction. This combination serves as a crucial tool for enhancing the adaptability and resilience of smart cities to seismic risks, positioning them to handle future events with greater preparedness and agility.

3.4. Conceptual Model for Resilience in Smart Cities

The development of a seismic risk management DT model is guided by several fundamental theoretical principles to ensure its efficacy and applicability. Firstly, it is rooted in principles of seismic hazard assessment, earthquake dynamics, and structural engineering, guaranteeing a precise representation of potential threats and structural behavior during seismic events. Secondly, empirical data obtained from seismic events, geological surveys, and building inventories inform the model's parameters and algorithms, validating predictions and ensuring realism. Thirdly, adopting a probabilistic framework allows for the quantification of uncertainties in hazard assessments and loss estimations, providing probabilistic forecasts of seismic risks. Fourthly, the model adopts a systems approach, integrating insights from various disciplines to capture the complexity of seismic risk dynamics. Advanced simulation techniques such as numerical modeling and agent-based modeling simulate earthquake scenarios, evacuation dynamics, and socio-economic impacts, facilitating the exploration of mitigation strategies. Additionally, rigorous validation against historical events and observed data ensures accuracy and reliability. The model's adaptability to different contexts and data availability levels, coupled with ethical considerations such

as privacy protection and community engagement, ensures its relevance and fairness. Transparency and openness, characterized by clear documentation and open-access platforms, promote peer review and stakeholder participation, thereby fostering equity and resilience in seismic risk management efforts. By adhering to these principles and theoretical foundations, the seismic risk management DT model can serve as a valuable decision support tool for policymakers, urban planners, emergency responders, and community stakeholders in mitigating seismic risks and enhancing resilience to earthquakes.



4. METHODOLOGY

4.1. Research Design

The SRM framework consists of a comprehensive set of interconnected modules designed to address every phase of disaster management, from hazard assessment to recovery and mitigation (**Figure 4.1**). These modules aim to provide a holistic approach to understanding, mitigating, and managing the risks associated with earthquakes, ensuring the resilience of communities, infrastructure, and systems. Each module is developed with specific objectives, methodologies, and outputs, contributing to the broader goal of minimizing the impacts of seismic events through a data-driven and multidisciplinary strategy.

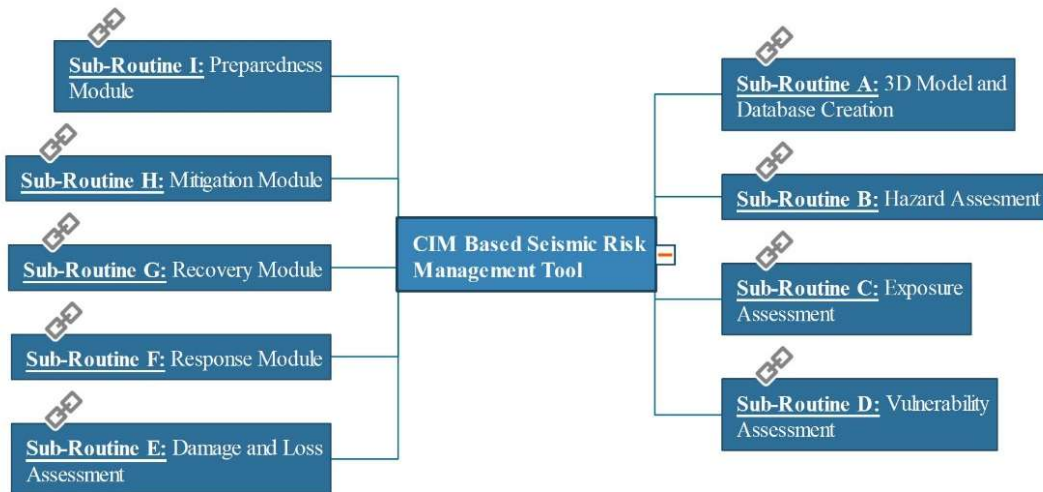


Figure 4.1: General sub-routines of SRM framework.

At the foundation of the framework lies the 3D Database Model, which serves as a central repository for geospatial and non-spatial data. This module underpins all other components by integrating critical information, enabling accurate simulations, and supporting decision-making processes. Building on this foundation, the Hazard Assessment Module evaluates the seismic threats within a given area through advanced modeling and scenario analysis, identifying potential primary and secondary hazards to inform subsequent actions.

The Exposure Assessment Module focuses on quantifying and characterizing the assets at risk, including populations, critical infrastructure, and economic resources, ensuring a detailed understanding of the vulnerabilities present in a seismic event. Complementing this is the Vulnerability Assessment Module, which analyzes the susceptibility of these assets to damage, incorporating methods that range from rapid visual screening to analytical evaluations. Together, these modules provide the critical inputs required for the Damage and Loss Assessment Module, which estimates the physical, economic, and social impacts of earthquake scenarios, offering valuable insights for prioritizing mitigation and response efforts.

Preparedness, response, recovery, and mitigation modules form the operational components of the framework. The Preparedness Module focuses on proactive measures such as emergency planning, training, and resource management to enhance readiness for seismic events. The Response Module ensures rapid and coordinated actions during an earthquake, emphasizing resource allocation, communication, and search-and-rescue operations. In the aftermath of a disaster, the Recovery Module guides efforts to rebuild infrastructure, restore services, and promote long-term resilience. Finally, the Mitigation Module outlines strategies to reduce future risks, including structural retrofitting, land-use planning, and public awareness campaigns.

This modular framework is designed to be both scalable and adaptable, accommodating the unique characteristics of different regions and seismic contexts. By addressing the entire disaster management cycle, it provides a robust foundation for building resilience, minimizing losses, and ensuring sustainable development in earthquake-prone areas.

The 3D Database Model serves as a central component in seismic risk management, functioning as a comprehensive repository for spatial, structural, and temporal data (**Figure 4.2**). This system supports the integration, processing, and management of data from multiple sources, enabling advanced analyses and decision-making across various subroutines.

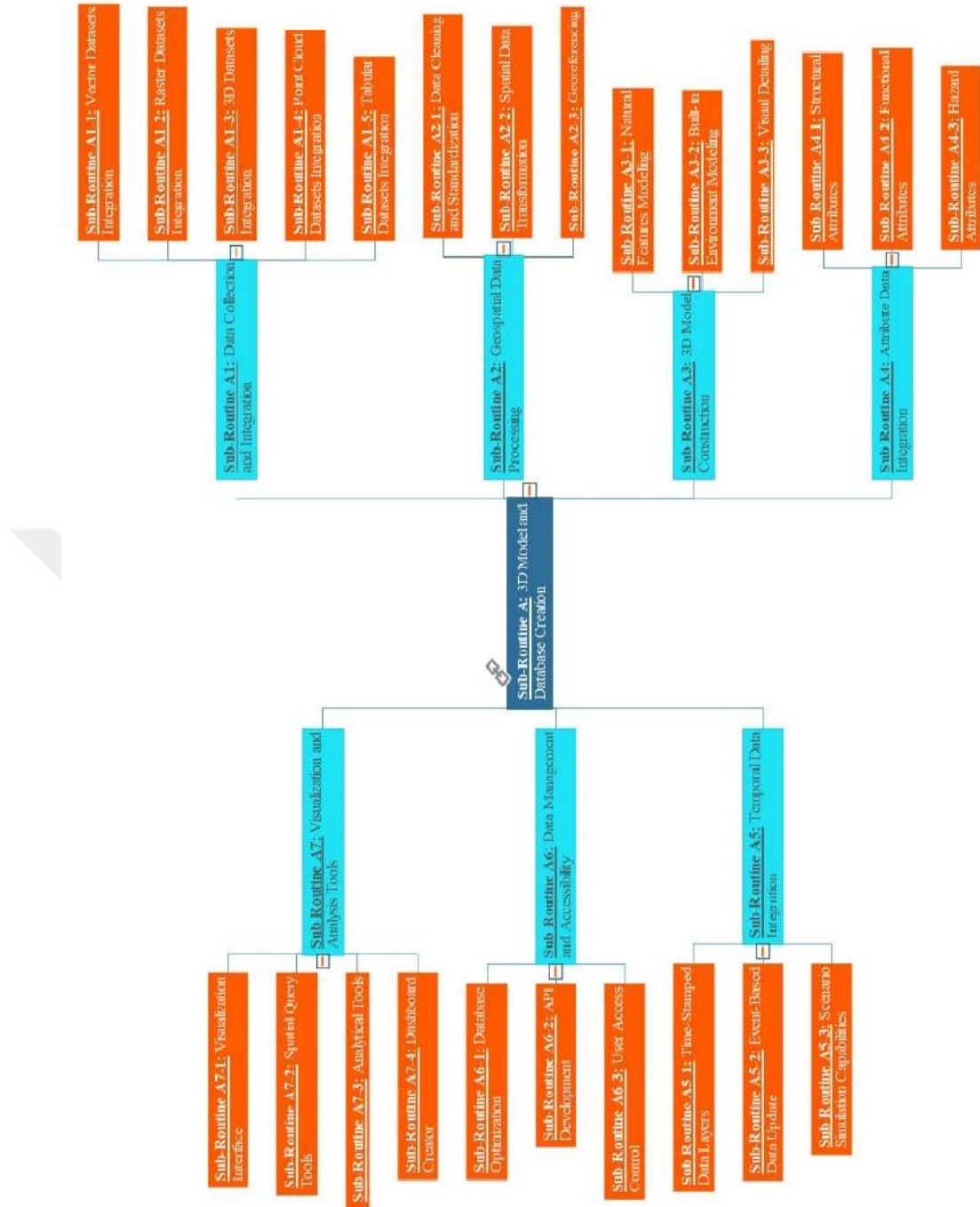


Figure 4.2: 3D Model database sub-routines.

The development of the 3D database begins with data collection and integration, where topographic, building, infrastructure, and geological data are gathered from diverse sources. Digital Elevation Models (DEMs) and LiDAR data are incorporated to define terrain features, while building attributes such as height, materials, and uses are collated. Additionally, utility networks and fault line data are integrated to provide a

comprehensive understanding of the physical and seismic environment. This stage ensures that all necessary datasets are consolidated for subsequent processing.

Geospatial data processing ensures consistency and usability of the gathered information. This involves cleaning and standardizing data formats, transforming 2D geospatial data into 3D formats, and georeferencing all datasets to align with a common spatial reference system. These steps are critical to ensure the accuracy and reliability of the 3D model.

The actual construction of the 3D model involves generating a base terrain layer, creating 3D representations of buildings and infrastructure, and modeling networks such as roads, bridges, and utilities. These components provide a realistic and detailed spatial representation of the urban environment, which serves as the foundation for further analysis.

To enhance the functionality of the 3D model, attribute data integration is performed. Structural attributes, such as material types and building age, are attached to the 3D elements, along with functional attributes detailing the use of each structure. Hazard-related attributes, including seismic vulnerability and ground motion intensity, are also incorporated, linking physical data with hazard assessment.

The inclusion of temporal data further extends the capabilities of the 3D model by enabling dynamic updates and scenario simulations. Time-stamped layers allow for changes over time, such as construction updates or hazard event progression. Event-based updates enable real-time integration of aftershock or damage data, while scenario simulation capabilities support preparedness and recovery planning.

Finally, robust data management and accessibility systems are implemented to optimize database performance and enable seamless integration with other models. This includes developing APIs for inter-module communication and establishing user access controls to manage permissions and maintain data security. Additionally, visualization and analysis tools are integrated to provide intuitive interfaces for interacting with the 3D model. These tools enable users to query specific spatial elements, run analyses, and generate visual outputs for decision-making.

The 3D Database Model acts as a data warehouse for seismic risk management, linking hazard, exposure, vulnerability, and response modules. Its detailed spatial representation and attribute integration facilitate advanced analysis, while its temporal

and visualization capabilities support dynamic simulations and informed decision-making. This model forms the backbone of a robust SRM framework.

The Hazard Assessment Module is designed to evaluate seismic hazards associated with a given area, providing critical data to inform decision-making and mitigation strategies (**Figure 4.3**). This module integrates various scientific and analytical methods to ensure a comprehensive understanding of the earthquake risks that may affect a region.



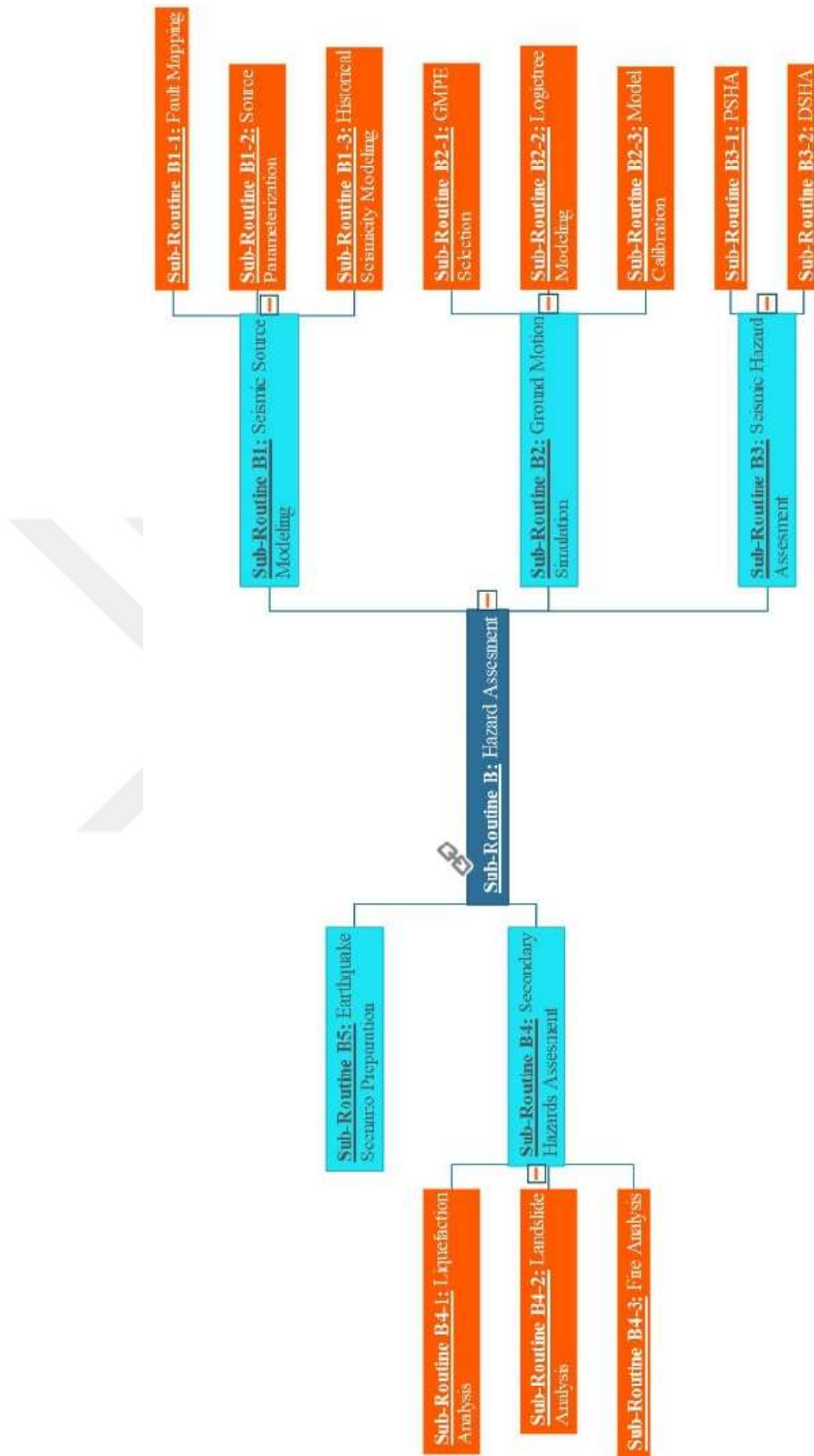


Figure 4.3: Hazard assessment sub-routine.

The first component of the module, Seismic Hazard Identification, focuses on identifying and mapping active fault lines through geological surveys and remote sensing data. This step involves systematic analysis of historical earthquake data, allowing for the identification of trends, magnitudes, and recurrence intervals. Additionally, seismotectonic zoning is performed to classify regions based on seismic activity and tectonic characteristics, creating a detailed foundation for hazard modeling.

Ground Motion Modeling represents another critical element of the module. This includes the application of attenuation relationships, which estimate ground motion parameters such as peak ground acceleration at varying distances from the source. Advanced methodologies, including PSHA, assess the likelihood of exceeding specific ground motion levels within a given timeframe, while Deterministic Seismic Hazard Analysis (DSHA) models worst-case scenarios based on predefined fault rupture characteristics. These approaches provide robust frameworks for understanding the potential impacts of seismic events.

The module also incorporates Earthquake Scenario Simulations, which enable the modeling of plausible earthquake events. This involves selecting representative scenario events based on regional seismicity and fault activity, generating synthetic earthquakes through numerical simulations, and modeling ground motion fields to assess spatial distributions of shaking intensity. These simulations play a vital role in visualizing the potential impacts of earthquakes on infrastructure and communities.

A comprehensive hazard assessment must also account for secondary hazards associated with earthquakes. This includes evaluating liquefaction susceptibility, where soil properties and shaking levels are analyzed to determine the likelihood of liquefaction. Similarly, landslide hazard mapping identifies areas prone to earthquake-induced landslides using topographic and geological data. For coastal regions, tsunami hazard analysis assesses the potential for tsunami generation and inundation, ensuring that all aspects of earthquake-related risks are considered.

Data Integration and Validation is crucial for ensuring the reliability and accuracy of hazard assessments. This involves the integration of multi-source geological, geophysical, and seismological data into unified models. Subsequently, model calibration and validation are conducted by comparing the results against observed

data and historical events. To enhance model robustness, sensitivity analyses are performed, identifying how variations in input parameters influence hazard outcomes.

The final component of the module focuses on Hazard Mapping and Reporting. Detailed seismic hazard maps are created to illustrate expected ground motion intensities and associated risks spatially. These maps are supplemented by risk communication tools, such as GIS platforms and interactive dashboards, to ensure stakeholders and decision-makers can easily access and interpret the information. Additionally, comprehensive reports are compiled, documenting all findings and providing actionable insights for authorities, organizations, and the public.

The Exposure Assessment module is a critical component of seismic risk management, tasked with identifying and quantifying the elements at risk, including populations, buildings, and infrastructure (**Figure 4.4**). This module provides essential data for downstream analyses, such as vulnerability, damage, and loss estimation, ensuring a comprehensive understanding of potential impacts from seismic hazards.

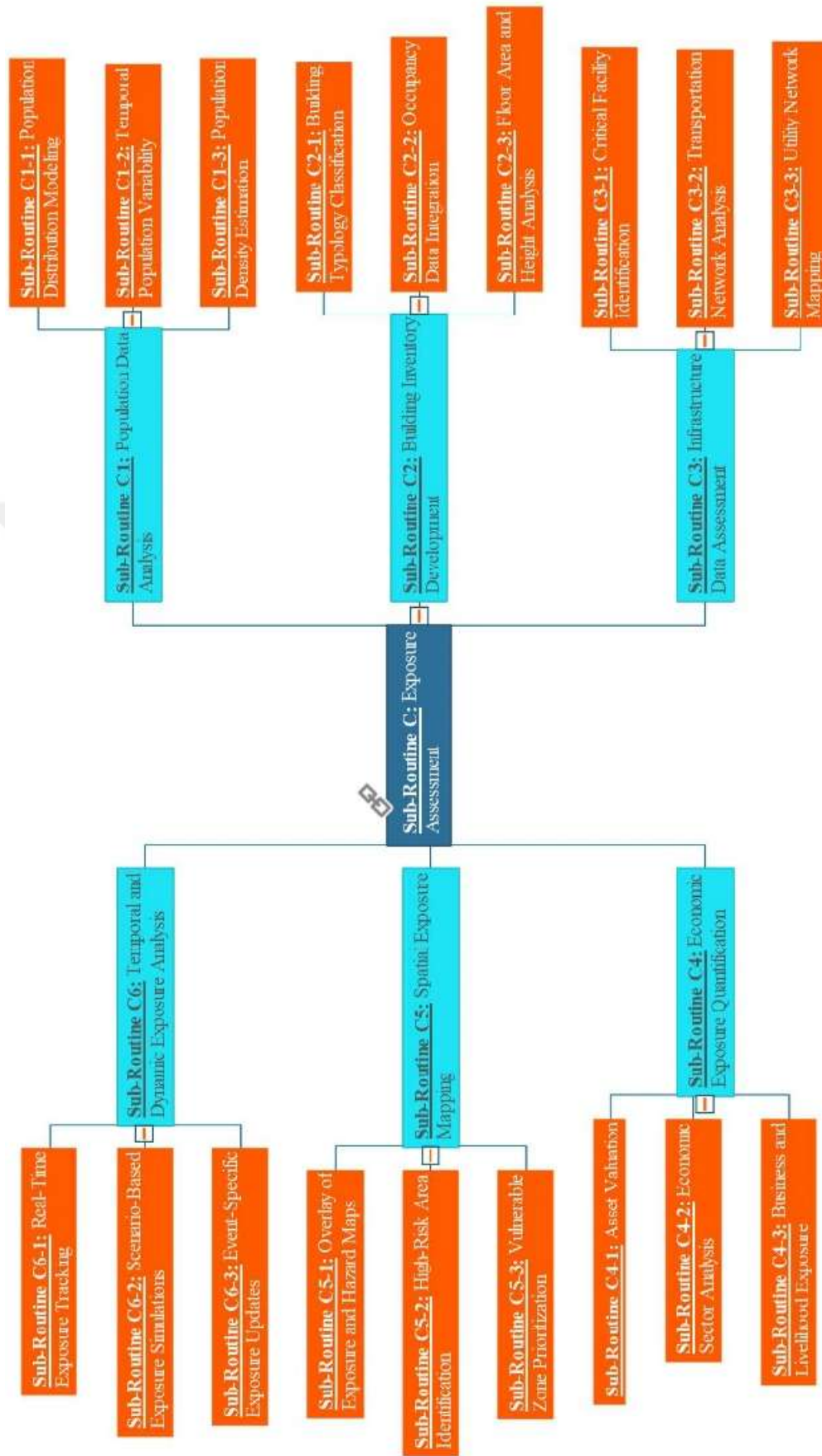


Figure 4.4: Exposure assessment sub-routine.

The first subroutine, Population Data Analysis, addresses the spatial and temporal distribution of population exposure. Demographic data, including attributes such as age, gender, and disabilities, are mapped to understand the spatial concentration of vulnerable groups. Temporal variability is also modeled, recognizing that exposure changes depending on time of day, such as higher occupancy in residential areas at night and workplaces during the day. Population density is further estimated using census data and mobility patterns to identify areas with the highest risk concentrations.

The Building Inventory Development subroutine focuses on characterizing the built environment to assess exposure. Buildings are categorized based on typology, which includes structural type, age, material, and usage. Occupancy data, specifying whether buildings are residential, commercial, or mixed-use, are integrated into the analysis. Furthermore, the subroutine evaluates parameters such as building height and floor area to quantify exposure levels effectively.

The Infrastructure Data Assessment subroutine evaluates critical infrastructure systems that support societal functions. This includes the identification and mapping of essential facilities such as hospitals, schools, and emergency response stations. Transportation networks, including roads, bridges, and railways, are analyzed to assess exposure and connectivity risks. Similarly, utility networks such as power, water, gas, and communication systems are mapped to identify their susceptibility to seismic events.

Economic exposure is quantified through the Economic Exposure Quantification subroutine, which assigns monetary values to assets, including buildings, infrastructure, and contents. Economic sector analysis identifies exposure across industrial, agricultural, and service sectors, while specific risks to businesses and livelihoods are assessed to evaluate potential economic disruption.

Finally, the Spatial and Temporal Exposure Mapping subroutine integrates exposure data with hazard maps to provide a comprehensive view of risk distribution. This includes overlaying hazard and exposure datasets to highlight regions of high risk and prioritizing zones that require immediate mitigation efforts. Temporal and dynamic exposure analyses further enhance the module by enabling real-time tracking and scenario-based simulations, accounting for changes in exposure during and after seismic events.

The Exposure Assessment module provides a robust framework for evaluating elements at risk in the context of seismic hazards. By integrating population, building, infrastructure, economic, and spatial-temporal data, this module supports effective decision-making for risk mitigation, emergency response, and resilience planning.

The Vulnerability Assessment module plays a pivotal role in seismic risk management by evaluating the susceptibility of exposed elements—such as buildings, infrastructure, and populations—to damage or loss caused by seismic events (**Figure 4.5**). This module systematically examines vulnerabilities across multiple domains, integrating structural, social, infrastructure, and economic factors to provide a holistic understanding of risks.



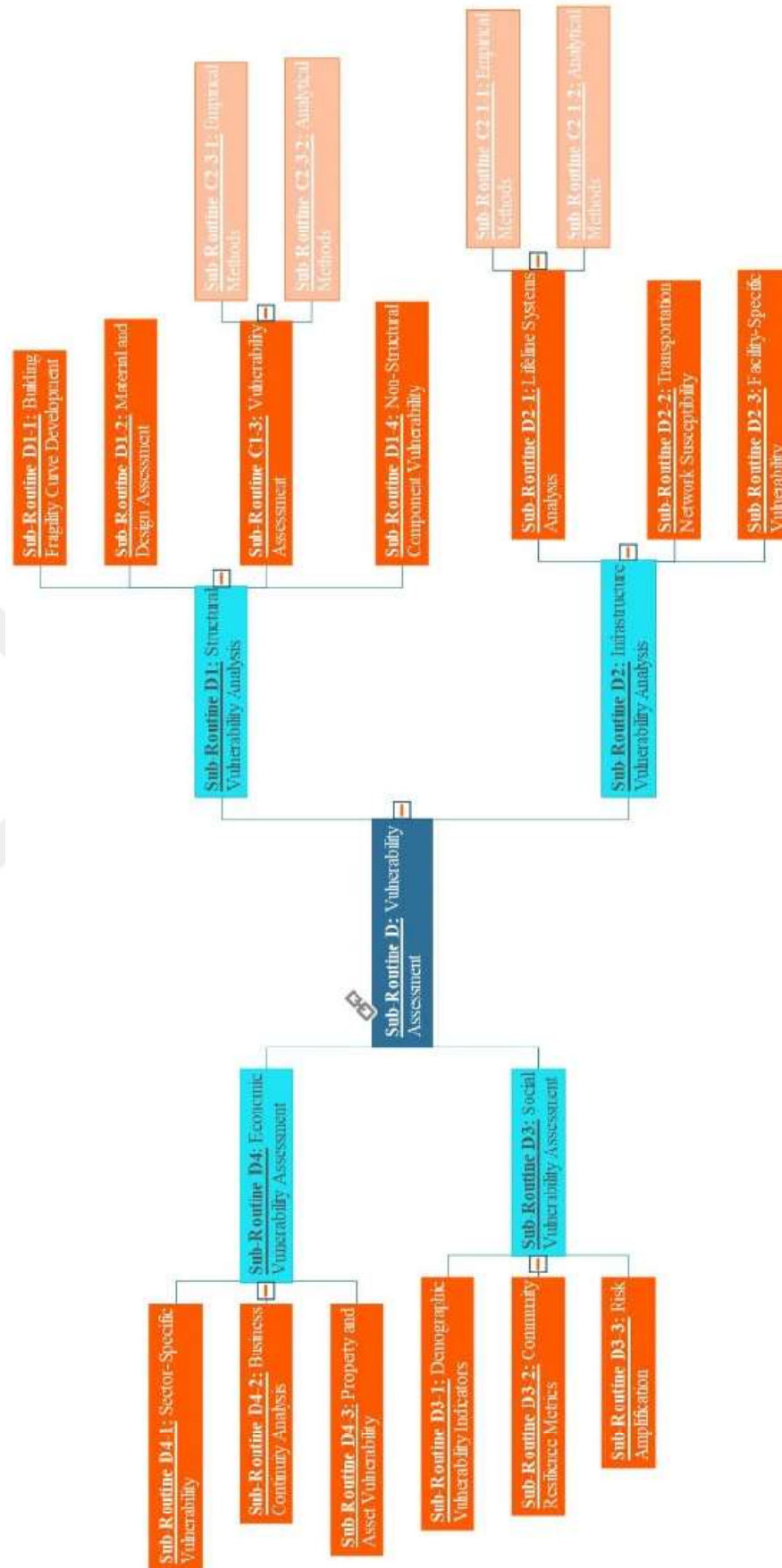


Figure 4.5: Vulnerability assessment sub-routine.

The Structural Vulnerability Analysis subroutine focuses on understanding the behavior of buildings under seismic loads. Fragility curves are developed to estimate the probability of damage for various building types and intensities of seismic shaking. In addition, the assessment considers structural materials, construction quality, and compliance with design standards to identify potential weaknesses. Non-structural components, such as facades and interior fixtures, are also evaluated for their vulnerability to damage. Rapid visual screening methods, such as FEMA 154 or ATC-21, are employed for quick assessments of observable structural characteristics, while advanced analytical methods, including nonlinear dynamic analysis and pushover analysis, are utilized for detailed evaluations of structural performance.

The Infrastructure Vulnerability Assessment subroutine focuses on critical lifeline systems and facilities. This includes assessing the vulnerability of power, water, and communication networks to seismic disruptions, as well as transportation systems such as roads, bridges, and railways. Facility-specific evaluations are conducted for key structures, including hospitals, schools, and emergency response centers. Visual screening methods provide a rapid overview of potential vulnerabilities in infrastructure components, while analytical modeling techniques, such as finite element analysis, allow for a more in-depth understanding of potential failure mechanisms and resilience under seismic stress.

The Social Vulnerability Assessment subroutine evaluates the human and community dimensions of vulnerability. This includes analyzing demographic indicators such as age, disability, income levels, and social marginalization, which contribute to differential impacts of seismic events. Community resilience metrics are also considered, measuring the capacity of local populations to respond to and recover from disasters. High population density areas are further analyzed to account for amplified risks and evacuation inefficiencies.

The Economic Vulnerability Assessment subroutine examines the potential for financial and economic losses resulting from seismic events. Sector-specific vulnerabilities are analyzed, focusing on industries, agriculture, and service sectors. Business continuity risks are assessed to identify potential disruptions to supply chains, operations, and productivity. Furthermore, the vulnerability of physical and financial assets is evaluated, ensuring that exposure to direct and indirect economic losses is thoroughly understood.

The Vulnerability Assessment module employs a multi-faceted approach to evaluate the susceptibility of exposed elements to seismic hazards. By combining rapid screening methods with detailed analytical techniques across structural, infrastructure, social, and economic domains, this module provides essential insights for effective risk mitigation and disaster preparedness planning.

The Damage and Loss Assessment module is a critical component of seismic risk management, designed to estimate physical damage to structures and infrastructure, as well as the associated economic, social, and human losses resulting from seismic events (**Figure 4.6**). This module encompasses multiple subroutines, each focused on a specific domain, ensuring a comprehensive evaluation of impacts across structural, infrastructural, economic, and human dimensions.



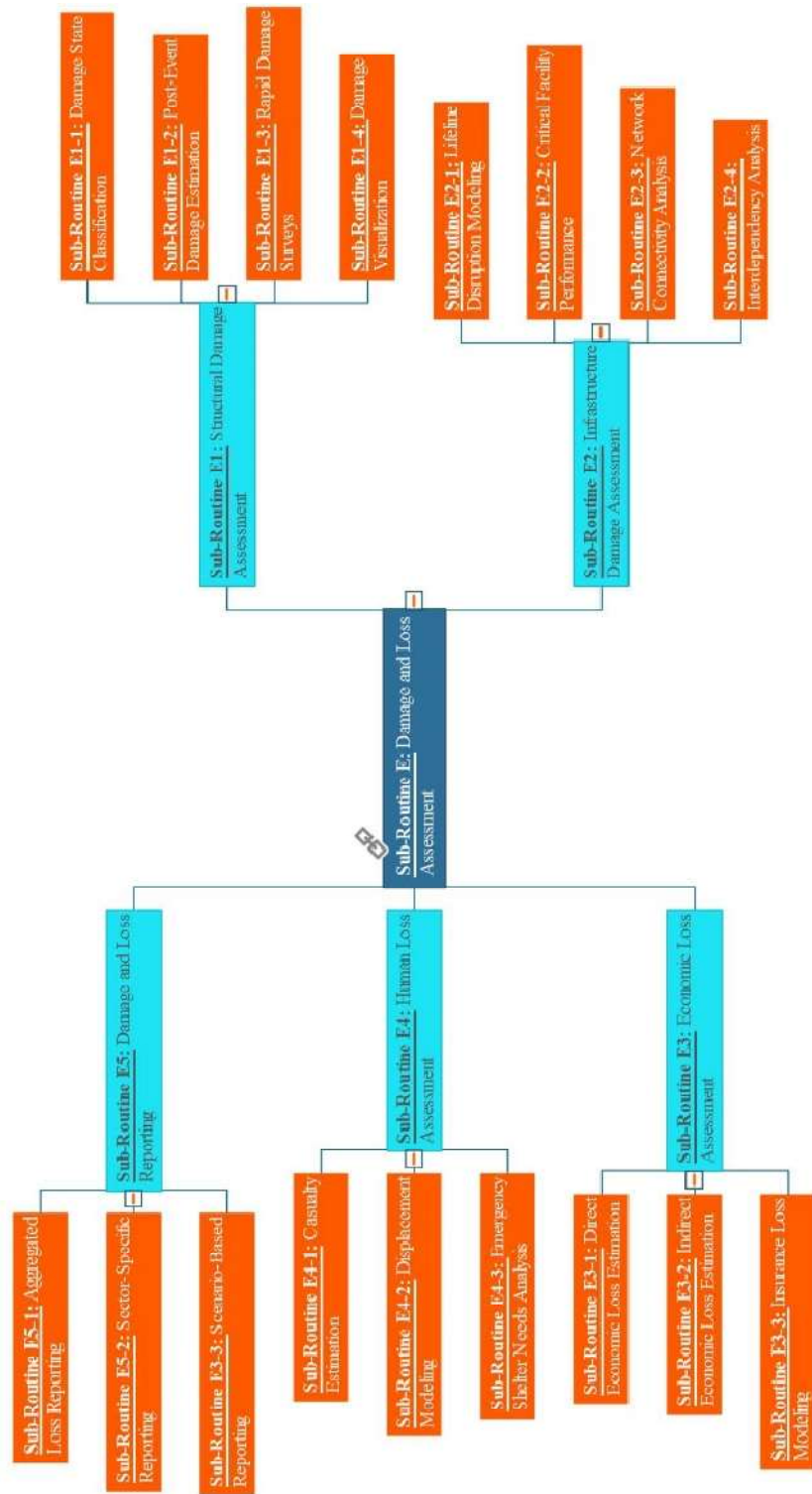


Figure 4.6: Damage and loss assessment sub-routine.

The Structural Damage Assessment subroutine focuses on evaluating the extent of damage to buildings and other structures. A classification system is used to categorize damage states (e.g., slight, moderate, extensive, or collapse) based on fragility curves and seismic intensity data. Post-event damage estimation integrates ground motion data with vulnerability models to provide a detailed picture of structural performance. Protocols for rapid damage surveys, such as drone-based or satellite imaging, facilitate quick validation of damage estimates. Spatial mapping tools are used to visualize the extent and severity of structural damage, while residual capacity analyses help determine the usability of damaged structures for short-term needs.

The Infrastructure Damage Assessment subroutine examines the impact of seismic events on lifeline systems and critical facilities. Lifeline disruption modeling is employed to understand the cascading effects of damage to power, water, and communication networks. The operational status of critical facilities, such as hospitals and fire stations, is assessed to prioritize response efforts. Network connectivity analyses identify disruptions in transportation and utility systems, while interdependency modeling evaluates cascading failures across interconnected systems (e.g., power outages affecting water supply systems).

The Economic Loss Assessment subroutine estimates both direct and indirect financial losses resulting from seismic events. Direct losses include repair and replacement costs for damaged structures and infrastructure, while indirect losses account for business interruptions, reduced productivity, and supply chain disruptions. Insurance loss modeling differentiates between insured and uninsured losses, providing insights into economic resilience. Additionally, cost-benefit analyses are conducted to compare projected losses with the potential benefits of implementing mitigation measures, informing future disaster risk reduction strategies.

The Human Loss Assessment subroutine evaluates the impacts on human lives and communities. Casualty estimation models are used to predict fatalities and injuries, incorporating factors such as building damage, population distribution, and the timing of the event. Displacement modeling estimates the number of individuals and households requiring temporary relocation, while emergency shelter needs analyses calculate the demand for temporary housing. Health impact assessments further evaluate the short- and long-term health consequences, including physical injuries, mental health effects, and the potential for disease outbreaks in affected areas.

The Damage and Loss Reporting subroutine ensures that the results of assessments are effectively communicated to stakeholders. Aggregated loss reports provide a comprehensive overview of total damage and losses, while sector-specific reports offer detailed insights into specific domains such as housing, industry, or infrastructure. Scenario-based reporting enables stakeholders to understand the potential impacts of various earthquake scenarios, supporting planning and decision-making. Advanced visualization tools, such as GIS-based dashboards and interactive charts, enhance the accessibility and clarity of damage and loss data.

Finally, the Post-Assessment Validation subroutine focuses on improving the accuracy and reliability of damage and loss assessments. Field validation studies are conducted to compare model predictions with observed outcomes, refining future assessment methodologies. Stakeholder feedback from local authorities, emergency responders, and affected communities is integrated into the assessment process to enhance its relevance and applicability. Data reconciliation efforts ensure that modeled estimates align with observed data from past seismic events, contributing to the continuous improvement of the damage and loss assessment framework.

This comprehensive approach ensures that damage and loss assessments are thorough, accurate, and actionable, providing a critical foundation for response planning, recovery strategies, and mitigation efforts in the aftermath of seismic disasters.

The Response Module encompasses several subroutines that address various aspects of emergency response, including communication, search and rescue, medical assistance, relief operations, situational awareness, logistics, and post-response valuation (**Figure 4.7**).



Figure 4.7: Response management sub-routine.

Emergency Communication and Coordination serves as the foundation of the response effort. Real-time early warning systems disseminate alerts to the public and emergency services, allowing timely evacuation and preparedness. Activation of the Emergency Operations Center (EOC) ensures centralized decision-making and coordination among response agencies. Collaboration between government authorities, non-governmental organizations (NGOs), and international responders is facilitated through multi-agency coordination mechanisms. Simultaneously, public communication strategies ensure that affected populations receive consistent and reliable updates through various media channels.

The Search and Rescue Operations subroutine focuses on locating and saving individuals trapped in damaged structures. Rapid damage and hazard assessments are conducted to prioritize areas requiring immediate attention. Specialized search and

rescue teams are deployed, equipped with tools and technologies such as drones, robotics, and thermal imaging to enhance operational efficiency. Additionally, resource allocation optimization ensures the effective use of personnel and equipment in rescue efforts.

Medical Response is integral to addressing the health needs of affected populations. Casualty triage and management protocols are implemented to prioritize treatment for critically injured individuals. Temporary medical facilities, such as field hospitals and emergency medical centers, are established to provide immediate care. Medical supply chain management ensures the timely availability of essential medicines and equipment, while psychological first aid addresses the mental health needs of survivors and responders.

The Relief Operations subroutine focuses on meeting the basic needs of affected communities. Temporary emergency shelters are established to house displaced individuals, and systems are put in place to ensure the distribution of food and water. Efforts to restore energy and utility services are initiated promptly, while targeted programs address the specific needs of vulnerable populations, such as children, the elderly, and people with disabilities.

Maintaining situational awareness and monitoring is crucial for effective response management. Real-time data collection from field teams, sensors, and the affected population provides ongoing updates. Damage and resource mapping integrates this data into GIS systems for better visualization and decision-making. Progress tracking ensures that response efforts remain on schedule, while aftershock monitoring provides critical information for ongoing safety.

Efficient logistics and resource management is another critical component of the response module. Transportation coordination ensures the timely movement of personnel, equipment, and supplies. Warehouse and supply chain management optimizes resource availability, while fuel and energy logistics address the energy needs of response operations. Additionally, volunteer and donation management facilitates the effective use of public contributions during the disaster response.

Finally, the Post-Response Review and Reporting subroutine focuses on evaluating the effectiveness of response activities. Response effectiveness evaluations identify strengths and areas for improvement, while stakeholder feedback from responders and

affected populations provides valuable insights. Comprehensive documentation and reporting of activities, challenges, and lessons learned contribute to refining future response strategies. Post-response policy recommendations are also formulated to enhance disaster preparedness and resilience.

This integrated and comprehensive approach ensures a well-coordinated and adaptive response to seismic disasters, addressing immediate needs, facilitating collaboration among stakeholders, and laying the groundwork for effective recovery and future resilience planning.

The Recovery Module is a critical component of seismic risk management, focusing on the long-term rebuilding and restoration of communities, infrastructure, and ecosystems after an earthquake (**Figure 4.8**). This module is structured to address multiple dimensions of recovery, including infrastructure, economy, society, environment, resilience building, and monitoring, to ensure sustainable and effective outcomes.

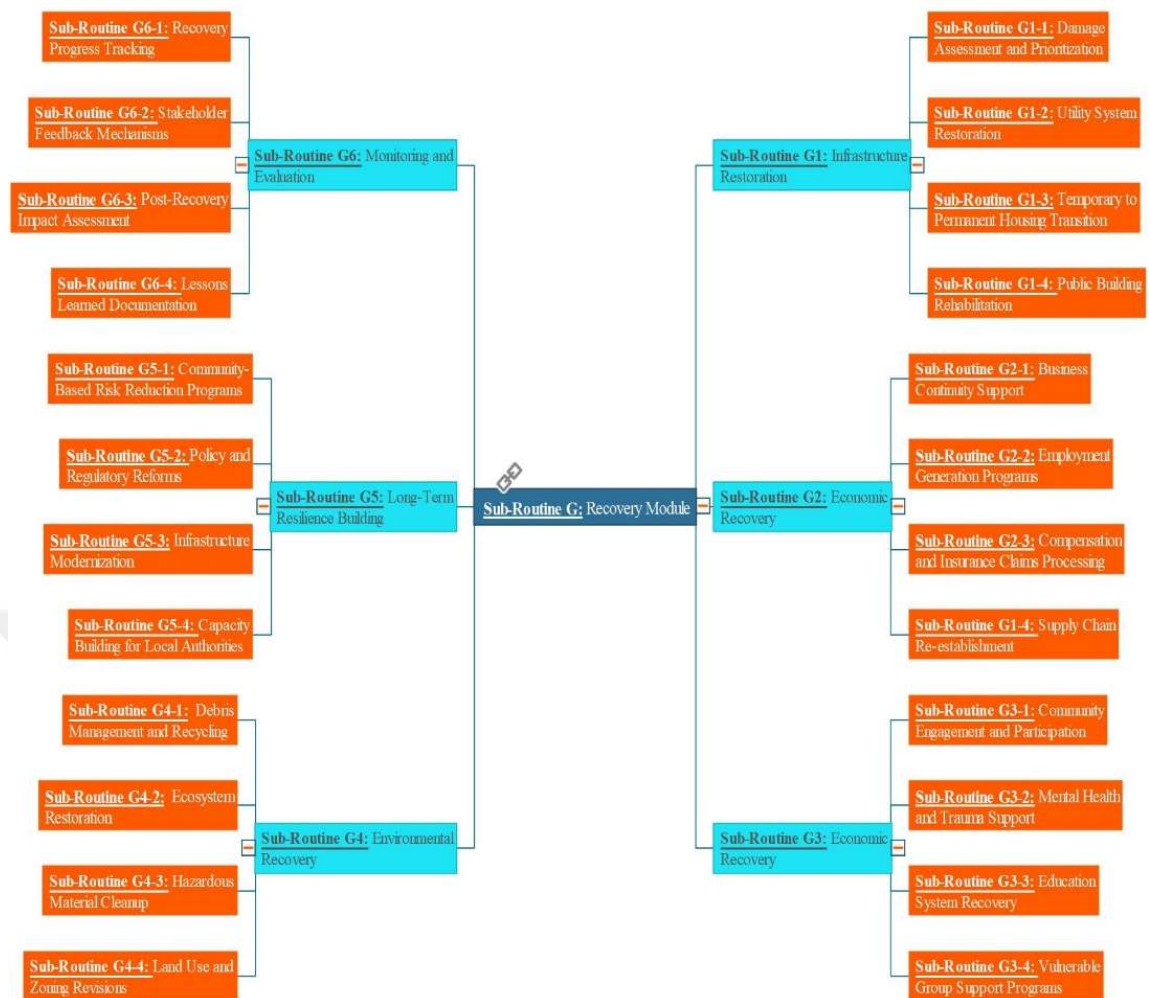


Figure 4.8: Recovery management sub-routine.

Infrastructure restoration is the cornerstone of recovery efforts, prioritizing the repair and reconstruction of damaged systems. Detailed damage assessments guide the prioritization of repair work, ensuring that critical infrastructure such as transportation networks, utility systems, and public facilities are restored efficiently. Efforts also include facilitating the transition from temporary shelters to permanent housing for displaced populations. Public buildings, such as schools, hospitals, and government offices, are rehabilitated to resume essential services and support community recovery.

Economic recovery emphasizes revitalizing local economies disrupted by the disaster. Support mechanisms are provided to help businesses resume operations, including financial assistance, logistical support, and incentives. Employment generation programs are implemented through recovery projects, providing income and economic stability to affected populations. Compensation systems and streamlined insurance claims processes are established to address financial losses. Additionally, efforts are

made to re-establish disrupted supply chains, ensuring the availability of goods and services essential for recovery.

Social recovery focuses on restoring the well-being of affected communities. Recovery planning incorporates active community engagement to ensure that local needs and priorities are addressed. Mental health and trauma support programs are implemented to assist individuals coping with the psychological impacts of the disaster. The education system is prioritized through the rebuilding of schools and resumption of educational activities. Special programs are designed to support vulnerable groups, including children, the elderly, and people with disabilities, to ensure that no section of society is left behind.

Environmental recovery addresses the ecological consequences of seismic events. Debris management strategies are implemented to safely dispose of or recycle materials from collapsed structures. Ecosystem restoration efforts rehabilitate damaged natural environments, such as forests, rivers, and agricultural lands, to support long-term sustainability. Hazardous material cleanup ensures the removal of contaminants, reducing health and environmental risks. Land-use and zoning regulations are revised to incorporate lessons learned, mitigating future risks in high-impact areas.

The module also emphasizes long-term resilience building to reduce future vulnerabilities. Community-based risk reduction programs educate local populations on disaster preparedness and adaptive strategies. Policy and regulatory reforms, such as updating building codes and urban planning guidelines, integrate resilience into development processes. Infrastructure modernization projects incorporate advanced technologies and materials to enhance seismic resistance. Capacity-building initiatives strengthen the ability of local governments and agencies to manage recovery and future disasters effectively.

Monitoring and evaluation processes ensure the accountability and effectiveness of recovery efforts. Progress tracking systems monitor the implementation of recovery projects, ensuring they are completed on time and meet their objectives. Stakeholder feedback mechanisms gather input from affected communities to refine strategies and address emerging challenges. Post-recovery impact assessments evaluate the social,

economic, and environmental outcomes of recovery initiatives. Lessons learned are documented to inform and improve future disaster management frameworks.

This comprehensive approach to recovery ensures that post-disaster efforts address immediate needs while fostering long-term resilience and sustainable development. By integrating multiple dimensions of recovery into a cohesive framework, the Recovery Module enables communities to rebuild stronger, more adaptive, and better prepared for future seismic events

The Mitigation Module aims to proactively reduce the potential impacts of seismic events by implementing targeted measures that address structural, non-structural, and community-centered aspects of risk reduction (**Figure 4.9**). This module integrates scientific research, engineering solutions, community engagement, and policy reforms to minimize vulnerabilities and enhance resilience against earthquakes.

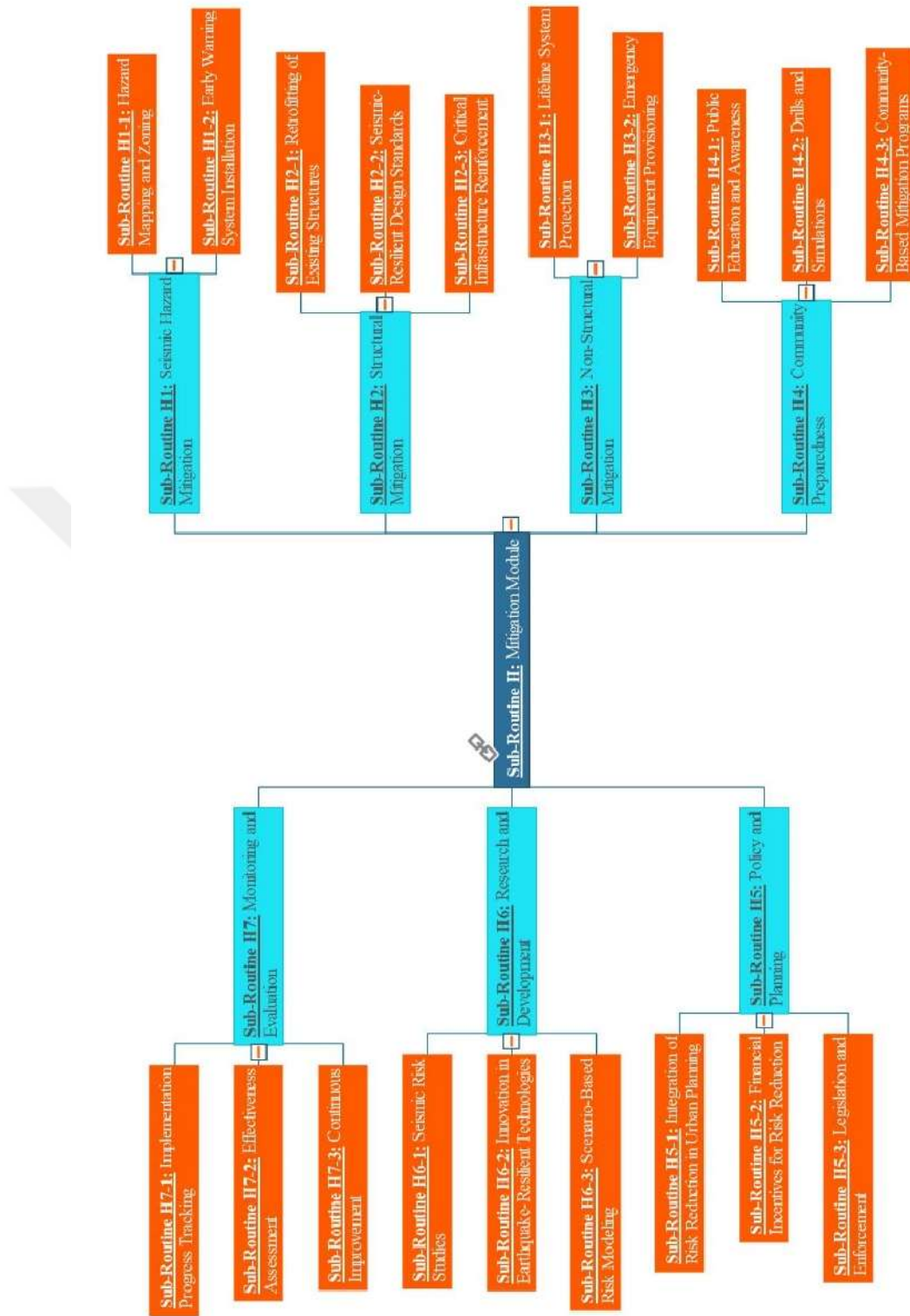


Figure 4.9: Mitigation assessment sub-routine.

A key component of mitigation is seismic hazard mitigation, which focuses on understanding and managing earthquake risks at a regional and local scale. Hazard mapping and zoning play a central role by identifying high-risk areas and restricting development in zones prone to severe ground shaking, fault rupture, or liquefaction. These efforts are complemented by the installation of early warning systems, which provide real-time earthquake detection and notification, allowing communities and emergency services to take timely protective actions.

Structural mitigation strategies are designed to enhance the resilience of physical infrastructure. Retrofitting existing buildings and infrastructure is a critical subroutine, strengthening vulnerable structures to meet modern seismic safety standards. Simultaneously, enforcing seismic-resilient design standards for new constructions ensures that future developments incorporate advanced earthquake-resistant techniques. Critical infrastructure, including hospitals, power plants, and transportation systems, is prioritized for reinforcement to maintain functionality during and after seismic events.

Non-structural mitigation addresses the safeguarding of essential utility systems and emergency provisioning. Lifeline system protection focuses on securing power, water, and communication lines to minimize disruptions during an earthquake, ensuring that communities retain access to vital services. Emergency equipment provisioning equips buildings and facilities with resources such as fire suppression systems, evacuation tools, and emergency kits to enhance immediate response capabilities.

Community preparedness is an integral part of the mitigation process, emphasizing the importance of public engagement and education. Public awareness campaigns inform communities about earthquake risks and safety measures, empowering individuals to take proactive steps in risk reduction. Regular drills and simulations familiarize communities with emergency response protocols, ensuring preparedness during real events. Community-based mitigation programs foster local participation in identifying vulnerabilities and implementing tailored risk reduction strategies. Effective mitigation also requires robust policy and planning frameworks. Incorporating seismic risk assessments into urban and regional planning ensures that land-use decisions align with hazard mitigation objectives. Financial incentives, such as subsidies or grants, encourage stakeholders to invest in risk reduction measures, including retrofitting and

hazard-resistant construction. Enforcing updated regulations and building codes further strengthens compliance with seismic safety standards.

To support ongoing advancements in mitigation, research and development initiatives are essential. Seismic risk studies enhance understanding of local vulnerabilities and inform evidence-based mitigation strategies. Innovation in earthquake-resilient technologies, such as advanced construction materials and monitoring systems, further strengthens the capacity to withstand seismic impacts. Scenario-based risk modeling provides valuable insights into potential earthquake scenarios, guiding policymakers and planners in designing effective mitigation strategies.

Lastly, continuous monitoring and evaluation ensures the success of mitigation measures. Progress tracking monitors the implementation of mitigation projects, identifying areas requiring additional focus or resources. Effectiveness assessments evaluate the tangible impact of these measures on reducing risks, while continuous improvement processes incorporate lessons learned and emerging research to refine mitigation strategies over time.

By addressing seismic risk from multiple dimensions, the Mitigation Module establishes a comprehensive framework for reducing vulnerabilities and building resilient communities. This integrated approach ensures that mitigation efforts are evidence-based, adaptive, and inclusive, contributing to long-term risk reduction and sustainable development.

The Preparedness Module aims to enhance the ability of communities, organizations, and governments to effectively respond to and recover from seismic events through systematic planning, training, and resource allocation (**Figure 4.10**). This module focuses on building capacities that minimize vulnerabilities and ensure swift and efficient actions during and after an earthquake.

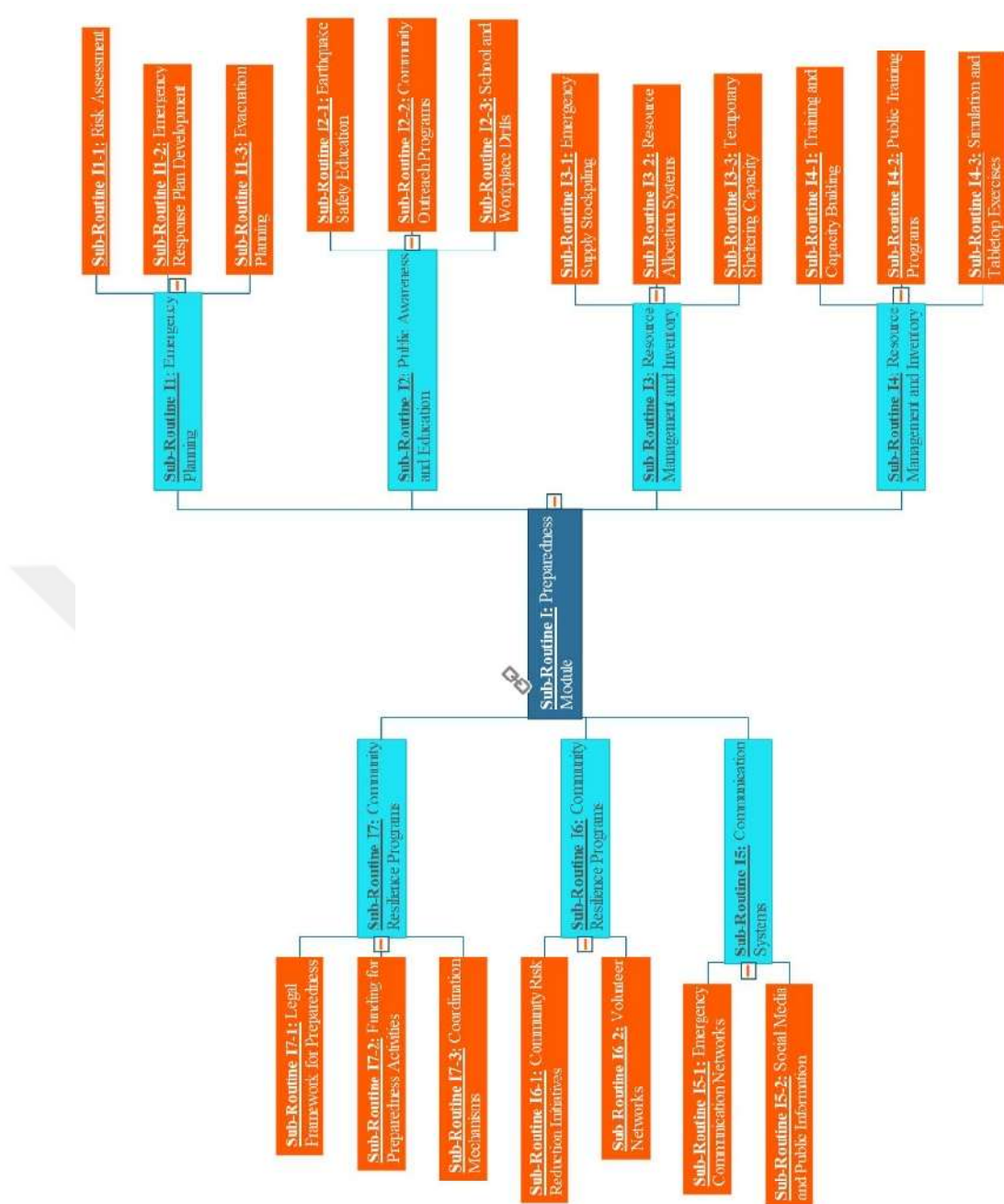


Figure 4.10: Preparedness assessment sub-routine.

A cornerstone of preparedness is emergency planning, which involves a series of strategic actions to anticipate and mitigate the impacts of earthquakes. This includes conducting detailed risk assessments to identify vulnerabilities and inform targeted interventions. Comprehensive emergency response plans are then developed, outlining roles, responsibilities, and protocols for coordination across local, regional, and national levels. Furthermore, evacuation planning ensures that affected populations

can be relocated to safety efficiently, with well-designed routes, shelters, and transportation logistics in place.

Public awareness and education are crucial for fostering a culture of preparedness. Through earthquake safety education, individuals and communities are equipped with the knowledge needed to protect themselves during seismic events. Community outreach programs, such as workshops and public information campaigns, further enhance engagement and understanding. Regular school and workplace drills familiarize individuals with emergency procedures, ensuring that responses are swift and well-coordinated when needed.

To support effective preparedness, the module emphasizes resource management and inventory. Strategic emergency supply stockpiling ensures the availability of essential goods such as food, water, and medical supplies in critical areas. Efficient resource allocation systems are developed to enable the rapid delivery of resources during emergencies. Additionally, temporary sheltering capacity is established, providing safe spaces equipped with essential services like healthcare and sanitation for displaced populations.

Training and capacity building are integral to preparedness efforts, focusing on enhancing the skills and readiness of both responders and the public. Emergency response training equips first responders and volunteers with specialized skills for earthquake scenarios, including search and rescue, medical triage, and logistics. Complementary public training programs empower individuals with life-saving skills such as first aid and emergency communication. Simulation-based exercises, including tabletop drills, provide practical opportunities to refine coordination, identify gaps, and improve decision-making processes under simulated emergency conditions.

Effective communication systems are essential for preparedness, particularly in the context of disseminating timely and accurate information. Robust emergency communication networks are established to facilitate seamless coordination among stakeholders during emergencies. Additionally, strategies for social media and public information are developed to ensure the dissemination of critical updates and warnings to the public in real-time.

Building resilient communities is another focus of the Preparedness Module. Community risk reduction initiatives involve engaging local populations in identifying

vulnerabilities and implementing targeted mitigation measures, such as retrofitting structures and clearing hazardous materials. Volunteer networks are developed and maintained to provide a pool of trained individuals ready to assist in response and recovery activities. Furthermore, community-based disaster risk management empowers local leaders to take active roles in preparedness efforts, fostering grassroots ownership of risk reduction strategies.

Lastly, the module underscores the importance of policy and legislation in institutionalizing preparedness. A robust legal framework mandates preparedness actions at various levels, ensuring compliance and accountability. Funding mechanisms are established to support long-term preparedness activities, while coordination mechanisms facilitate collaboration among government agencies, NGOs, and the private sector.

By integrating emergency planning, resource management, training, communication, community resilience, and policy frameworks, the Preparedness Module provides a comprehensive approach to seismic risk reduction. This holistic strategy not only enhances response capabilities but also ensures that communities are better equipped to face the challenges of earthquake scenarios.

4.2. Data Collection and Sources

The implementation of a robust file management system is integral to the functionality of a CIM framework, enabling systematic organization, secure storage, and efficient utilization of diverse datasets. A key component of this system is **data categorization**, where all acquired data is organized based on type, format, and source. Geospatial data, including vector datasets (e.g., shapefiles, GeoJSON), raster datasets (e.g., satellite imagery, digital elevation models), and 3D models (e.g., CityGML, OBJ), forms a significant part of this categorization. Similarly, tabular datasets, such as demographics, census records, and socio-economic indicators, complement sensor-generated data like IoT readings and environmental measurements. Additionally, documentation such as policy manuals, operational guidelines, and historical reports are systematically cataloged. This categorization ensures clarity, facilitates retrieval, and enhances data usability.

A critical aspect of the file management system is metadata management, which ensures proper documentation and traceability of datasets. Metadata provides essential information such as dataset titles, descriptions, sources, acquisition dates, formats, and geospatial extents. These attributes not only enhance dataset discoverability but also ensure their integrity and compatibility with analytical tools. For example, geospatial metadata might include bounding coordinates, enabling precise mapping and spatial analysis. Comprehensive metadata management fosters trust in data quality while ensuring compliance with established standards.

The data storage and indexing mechanisms of the file management system rely on a hierarchical structure, where files are stored based on thematic areas such as transportation, utilities, health infrastructure, and environmental management. This structured approach facilitates logical organization and reduces redundancy. Indexing tools further enable rapid data retrieval, optimizing system performance for high-demand environments. To manage long-term storage efficiently, older datasets are compressed or archived without compromising accessibility.

To ensure data security and controlled access, the file management system incorporates role-based access control (RBAC). This approach defines user permissions based on roles, ensuring data confidentiality and integrity. For instance, administrators are granted full access to all datasets, while analysts are restricted to datasets required for their specific tasks. Public users may access open datasets through web portals, enabling transparency while safeguarding sensitive information. This layered access ensures that data remains secure and accessible to authorized stakeholders.

The integration of data from diverse sources is a cornerstone of the CIM framework. Primary sources, including high-resolution satellite imagery, LiDAR scans, and field survey data, provide direct and precise inputs. Secondary sources, such as government databases, research institutions, and public records, offer supplementary information to enrich the dataset repository. Additionally, the system incorporates automated updates via APIs and web scraping tools, ensuring real-time data synchronization and keeping the repository current.

The organized file management system underpins the CIM framework's ability to support advanced analytical and decision-support tools. Risk assessments, which

evaluate the vulnerability of critical infrastructure, rely on accurate and accessible datasets. Scenario modeling is another key application, allowing simulation of potential disaster impacts to inform planning and mitigation strategies. Resource optimization analyses enable efficient allocation of assets and personnel, particularly during emergency response operations.

To ensure system reliability, the CIM framework undergoes rigorous testing and validation. Functional testing verifies core operations such as file uploads, retrieval, and indexing. Performance testing evaluates the system's ability to handle large datasets and concurrent user interactions without compromising speed or accuracy. Usability testing gathers feedback from stakeholders to refine the interface and improve workflow efficiency. These iterative testing processes ensure that the system is both robust and user-friendly.

The final CIM system, with its integrated file management capabilities, delivers significant benefits. By providing organized and easily accessible data, it eliminates redundancies and enhances usability across a range of stakeholders. Real-time insights generated by the system improve emergency response efficiency and inform long-term planning efforts. Furthermore, the system's scalable design allows it to accommodate new data types and technologies, ensuring its relevance and adaptability to evolving demands. This comprehensive framework exemplifies the critical role of data management in enhancing infrastructure resilience and disaster preparedness.

To develop an accurate and comprehensive 3D DT of a city, it is essential to adopt a multi-faceted data collection approach (**Figure 4.11**). This methodology focuses on gathering various types of data to create a realistic and interactive digital representation. The first step involves geospatial data collection. High-resolution aerial and satellite imagery is crucial for mapping the city's surface and landscape in detail. This data can be sourced from commercial satellite providers such as Maxar Technologies and Airbus, as well as national space agencies like National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Complementing this, LiDAR scanning provides precise 3D point cloud data that captures the city's terrain and building exteriors. LiDAR-equipped drones or aircraft are commonly used for this purpose, delivering data that is essential for creating accurate elevation models and detailed surface structures.

Ground-level data acquisition enhances geospatial data by adding detail to street-level views and building facades. Mobile mapping systems, utilizing vehicles equipped with LiDAR sensors, cameras, and GPS, can capture 360-degree street-level data and provide accurate images of building exteriors. Additionally, photogrammetry techniques extract 3D spatial information from overlapping 2D images, using both drone and ground-based photography to refine model accuracy. This processed imagery can be converted into detailed 3D models through specialized software.

Incorporating architectural and structural data adds depth to the model, with BIM playing a significant role. BIM data provides detailed insights into the construction and layout of buildings, including structural elements and materials. This data can be sourced from local government databases, architectural firms, and construction companies. GIS data also contributes by supplying spatial information on building footprints, land use, infrastructure, and zoning. Municipal GIS departments and open data platforms, such as OpenStreetMap, are primary sources for this data, which can be processed using GIS software like Esri ArcGIS.

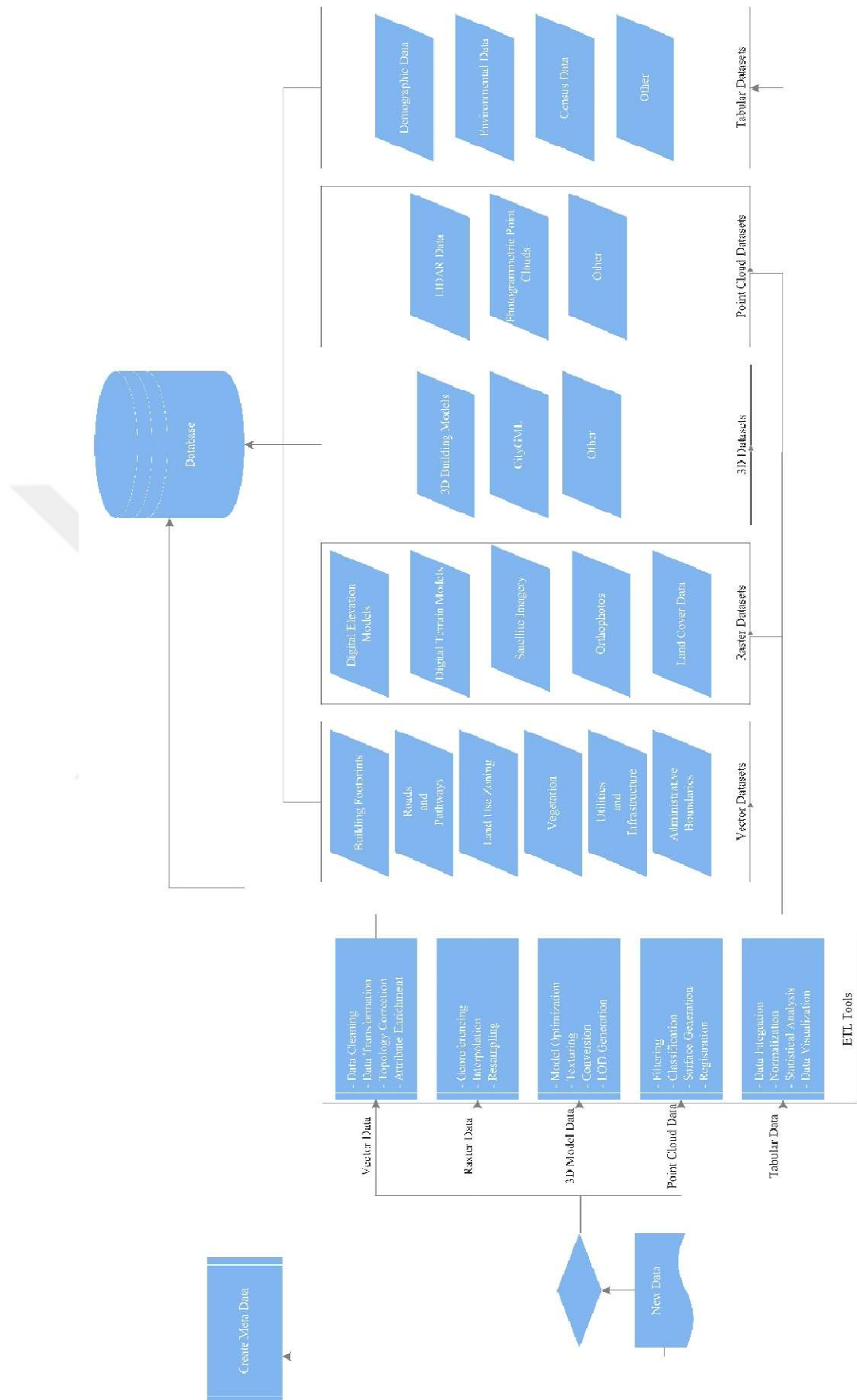


Figure 4.11: 3D Model creation framework.

Integrating sensor and IoT data ensures that the digital twin reflects real-world environmental conditions. This includes information from environmental sensors monitoring air quality, weather, and noise levels, sourced from city monitoring stations and IoT networks. Utility data from power grids and water management systems is also important for representing city infrastructure accurately. Data from these sources can be ingested through APIs and integrated using custom data processing pipelines to create a dynamic model that can simulate real-time changes.

Field data collection through ground surveys provides further verification and captures details not accessible through remote sensing. These surveys, conducted by engineering teams or surveying firms, use total stations, GPS devices, and handheld laser scanners. For more detailed indoor mapping, stationary laser scanning can capture the structure of key buildings. This type of data is particularly useful for critical infrastructure and public buildings.

Demographic and urban data enriches the 3D digital twin with socioeconomic context. Population data sourced from national statistical institutes and city planning offices can be analyzed and integrated to support simulations that reflect urban dynamics. Land use and zoning information, obtained from municipal databases, defines the intended purposes and regulatory constraints of different city areas. This data is essential for planning scenarios and policy analysis.

Finally, incorporating both historical and real-time data ensures the digital twin remains relevant over time. Historical records, including archival maps and city planning documents, provide context and track urban evolution. Real-time data feeds from IoT devices and city management systems make the digital twin dynamic, allowing for simulations and real-time monitoring. Connecting these live data streams to the model through middleware and data pipelines ensures that it can reflect current conditions and support decision-making processes effectively.

This methodology underscores the importance of a structured and comprehensive approach to data collection, addressing challenges such as data quality, integration, and privacy. Ensuring precision and consistency across multiple sources, aligning disparate data formats, and protecting sensitive information are all critical aspects of successful 3D digital twin development.

4.3. System Architecture and CIM Development

The proposed CIM framework is designed with a five-layered architecture, each layer performing distinct yet interdependent functions (**Figure 4.12**). This architecture enables efficient data acquisition, processing, and dissemination while providing a seamless interface for various user groups. The layered approach ensures scalability, adaptability, and comprehensiveness in addressing the multifaceted challenges of disaster management.

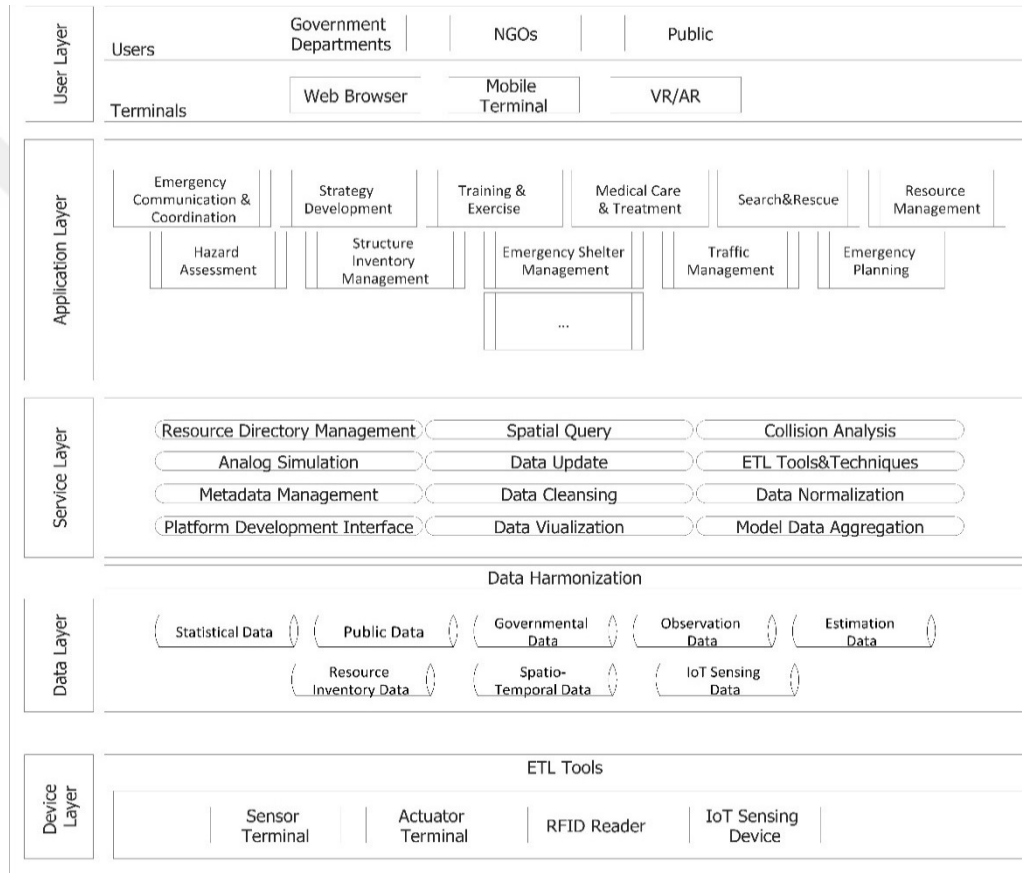


Figure 4.12: System architecture of the model.

At the foundation lies the device layer, which comprises all hardware and digital devices responsible for data acquisition. This layer includes sensors, RFID readers, and IoT devices deployed across the environment to monitor critical parameters such as seismic activity, structural integrity, weather patterns, and population movement. These devices generate real-time data streams, enabling the system to remain responsive and dynamic in disaster scenarios. By ensuring continuous monitoring, the device layer provides the raw data essential for further analysis and decision-making.

The data layer serves as the central repository for all collected data. It is responsible for aggregating, organizing, and storing information from the device layer. Employing secure databases and cloud-based solutions, this layer ensures the centralization and integrity of data, allowing for effective management and accessibility. The data layer also prepares the information for subsequent processing, laying the groundwork for advanced analysis and decision support.

The service layer acts as the analytical core of the framework. It is tasked with transforming raw data into actionable insights through various computational processes, including analog simulations, data normalization, model data aggregation, and metadata management. This layer integrates advanced analytical tools and algorithms to process diverse datasets, enabling predictive modeling, damage assessment, and optimization of resource allocation. The outputs of the service layer are critical for supporting operational planning and decision-making across disaster management phases.

At the operational forefront is the application layer, which provides tools and solutions tailored to specific disaster management tasks. This layer hosts functionalities such as emergency shelter management, resource distribution, evacuation planning, and incident response coordination. By translating processed data into user-centric applications, the application layer ensures that stakeholders can address operational challenges effectively and efficiently.

The **user layer** serves as the interface between the CIM framework and its end-users, facilitating access to information and applications. Through platforms such as web browsers, mobile terminals, and dedicated dashboards, users—including government agencies, NGOs, private organizations, and the public—can interact with the system. This layer prioritizes usability and accessibility, ensuring that users with varying technical expertise can leverage the system's capabilities to inform decision-making and action.

By structuring the CIM framework into these five layers, the system ensures a clear delineation of functions and a seamless flow of information. This architecture not only promotes efficient data management and analysis but also fosters collaboration among diverse stakeholders, enhancing the overall resilience and effectiveness of disaster management efforts. Such a comprehensive and scalable design underscores the

potential of integrated frameworks to address the complexities of modern disaster management scenarios.

4.4. 3D Core Model Creation

3D city models provide a sophisticated framework for representing urban environments, offering structured layers that capture diverse elements of urban life. These layers enable detailed visualization, analysis, and decision-making, making them indispensable tools for applications such as urban planning, disaster management, and smart city initiatives. Each layer in a 3D city model focuses on a specific aspect of the urban environment, contributing to a comprehensive understanding of the city's dynamics and infrastructure.

The foundational layers, often referred to as geospatial layers, include Digital Terrain Models (DTM), Digital Elevation Models (DEM), and Digital Surface Models (DSM). These layers provide essential information on topography, terrain heights, and the inclusion of natural and built objects, respectively. The buildings layer adds further detail by incorporating building footprints, heights, detailed architectural models, and classifications based on usage, such as residential or commercial. These building attributes are critical for assessing urban density, land use, and structural vulnerabilities in scenarios like natural disasters.

Transportation layers capture the complexity of urban mobility systems, including road networks, public transit routes, railways, bridges, tunnels, and pedestrian pathways. These layers are complemented by utilities and infrastructure layers, which map essential services such as water supply, sewage systems, power grids, telecommunications networks, and gas pipelines. Together, these layers provide a comprehensive overview of the city's physical and operational infrastructure, supporting both daily urban functions and emergency planning.

Environmental and green space layers emphasize sustainability and ecological considerations. Parks, forests, individual trees, rivers, and flood zones are mapped to balance urban development with natural ecosystems. Similarly, land use and zoning layers delineate residential, commercial, industrial, and recreational zones, providing a spatial framework for city planning and regulatory enforcement. The integration of

socio-economic data, including population density, demographics, and activity patterns, further enhances the model's utility for equitable urban development.

Dynamic and real-time layers, such as traffic flow, pedestrian movement, and IoT sensor data, add a temporal dimension to the static elements of 3D city models. These layers enable real-time monitoring and adaptive management of urban systems, which is particularly useful for addressing traffic congestion, air quality issues, and disaster response. Additionally, hazard and risk layers, including seismic zones, flood-prone areas, and emergency evacuation routes, are indispensable for resilience planning, ensuring cities can anticipate and mitigate risks effectively.

Finally, planning and development layers capture future urban initiatives, including redevelopment projects, infrastructure upgrades, and proposed zoning changes. These layers facilitate scenario modeling and decision-making, allowing stakeholders to assess the impact of proposed developments on the city's spatial and socio-economic dynamics.

The structured layering of 3D city models enables a holistic representation of urban environments, integrating physical, social, environmental, and dynamic elements (**Figure 4.11**). By providing an interactive and scalable platform, these models serve as valuable tools for urban management, resilience planning, and sustainable development. Their adaptability to specific use cases, such as seismic risk management or smart city implementation, underscores their importance in addressing the challenges of modern urbanization.

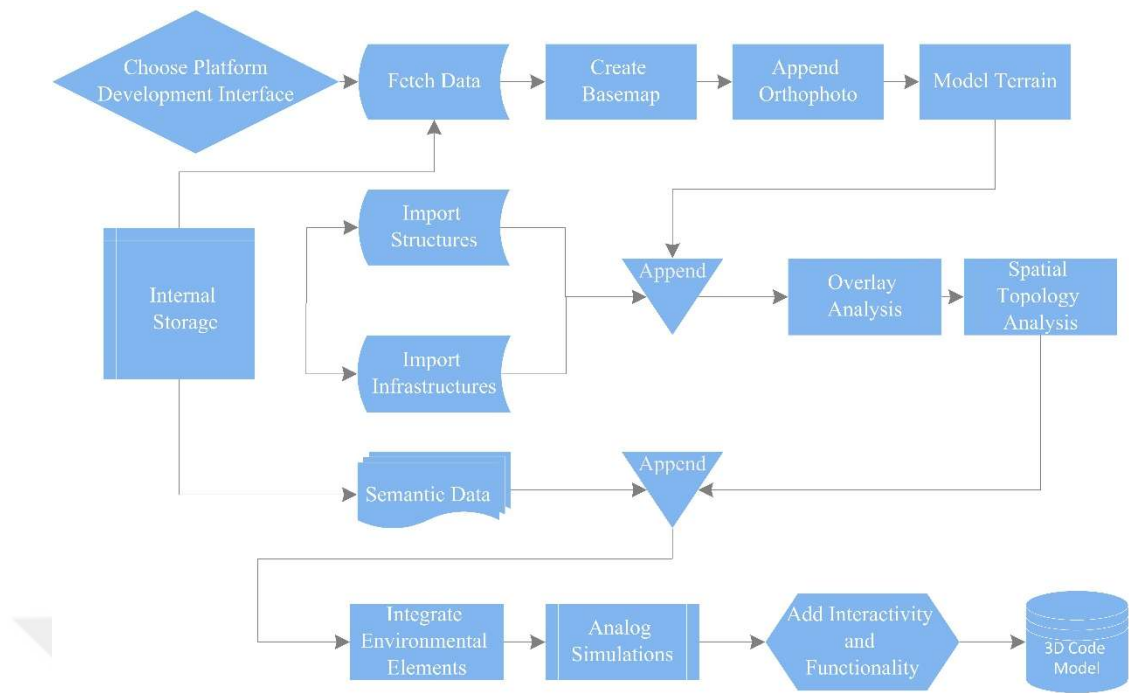


Figure 4.13: Core model creation workflow.

4.5. Simulation and Analysis

4.5.1. Hazard Assessment

SHA is a complex process that begins with preparatory workflows to ensure the quality and consistency of input data. Among these, the harmonization of earthquake catalogs is a foundational step (**Figure 4.14**). Earthquake catalogs compile seismic event data from diverse sources, including national and international seismic networks, historical records, and research institutions. However, these sources often vary in format, completeness, and reporting standards. Harmonization addresses these disparities, enabling the development of a unified dataset that is essential for accurate hazard analysis.

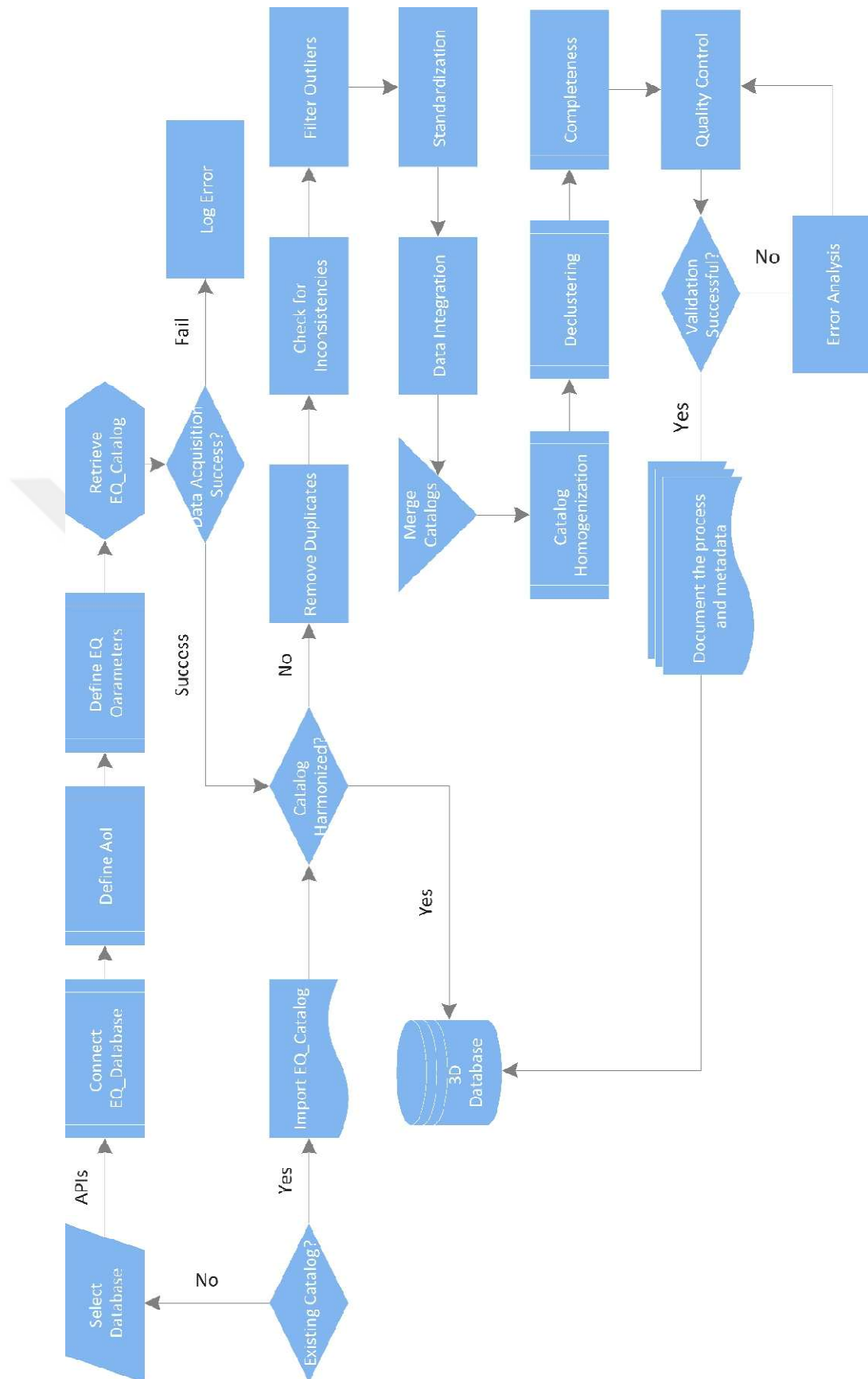


Figure 4.14: Catalog harmonization workflow.

The harmonization process starts with the collection and compilation of earthquake data from multiple catalogs. This stage emphasizes comprehensive coverage, including both recent instrumental records and historical events, to capture long-term seismic activity in the region of interest. The collected data is then standardized to a common format, ensuring consistency across fields such as event ID, date, time, location (latitude, longitude, and depth), magnitude, and data source. This step mitigates discrepancies that could arise from the varied structures of different catalogs.

One of the most critical tasks in harmonization is magnitude homogenization. Since earthquake magnitudes are often reported using different scales—such as the Richter scale, moment magnitude (M_w), or body-wave magnitude—conversion to a uniform scale is necessary. Moment magnitude (M_w) is typically preferred due to its ability to represent large earthquakes accurately and its compatibility with modern hazard assessment methodologies. Empirical relationships are applied to convert magnitudes from other scales, ensuring comparability across datasets.

To enhance the reliability of the catalog, duplicate records must be identified and removed. Overlapping data from multiple sources can lead to redundant entries for the same seismic event. Criteria such as temporal proximity, spatial similarity, and magnitude consistency are used to detect and eliminate these duplicates. Quality control measures are also implemented, filtering out events with insufficiently precise location or magnitude information, thereby improving the overall robustness of the dataset.

Another essential aspect of harmonization is completeness analysis, which evaluates the catalog for periods and magnitude ranges where reporting is consistent and unbiased. This analysis often employs statistical methods to identify underreporting or gaps in historical data. Once completeness is established, the catalog is filtered to align with the geographical boundaries and coordinate systems relevant to the study area. This step ensures that the dataset focuses on seismic events pertinent to the region of interest.

Uncertainty quantification is a vital component of harmonization, particularly for parameters such as event location, depth, and magnitude. Assigning and propagating uncertainties ensures that subsequent modeling efforts accurately reflect the inherent

variability in the data. The final stage involves merging the harmonized catalogs into a single dataset while retaining metadata to trace the origin and quality of each record.

The harmonized earthquake catalog is indispensable for a range of applications in hazard assessment. It serves as the basis for seismicity analysis, enabling the identification of patterns in earthquake activity and recurrence intervals. It is also critical for probabilistic seismic hazard assessment (PSHA), which estimates the likelihood of ground motion exceeding specified thresholds. Additionally, the catalog supports source characterization, facilitating the delineation of seismogenic zones and fault behavior, and it provides a reliable foundation for validating and calibrating ground motion and damage models.

The harmonization of earthquake catalogs is a meticulous but essential process in hazard assessment workflows. By addressing inconsistencies and ensuring data quality, it enables the creation of a unified, robust dataset that supports reliable seismic risk evaluation and decision-making. Without this preparatory step, subsequent analyses could be compromised, leading to inaccuracies in hazard estimation and mitigation planning.

Source parametrization in seismic source modeling is the process of defining and quantifying the physical and geometrical properties of seismic sources that generate earthquakes (**Figure 4.15**). These parameters encompass the spatial, mechanical, and temporal characteristics of faults and seismic zones, serving as the foundation for understanding seismic hazards and modeling earthquake scenarios. Accurate parametrization is essential for assessing seismic risk, as it enables the simulation of realistic earthquake events and their potential impacts on the built environment and natural systems.

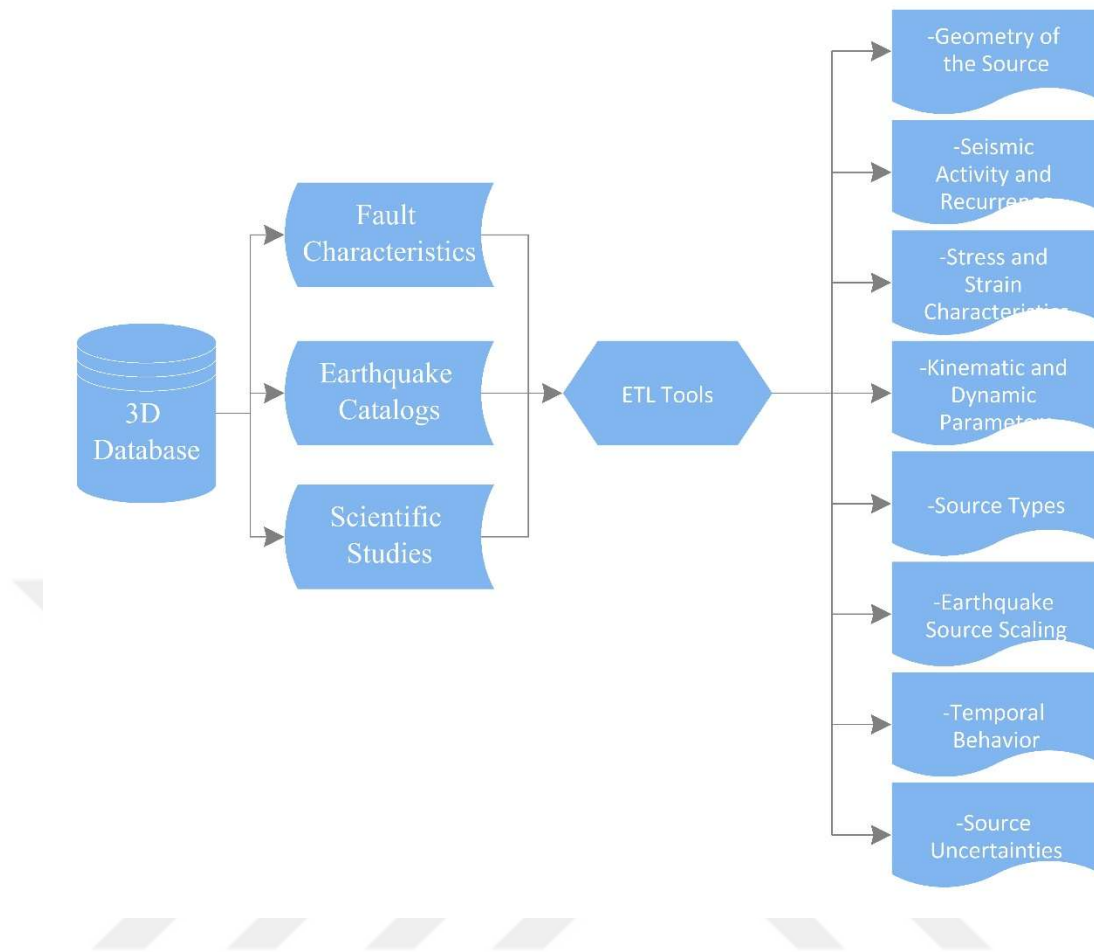


Figure 4.15: SHA preparatory workflow.

One key aspect of source parametrization is the geometry of the seismic source, which includes defining the fault's location, orientation, and dimensions. The fault's spatial position is typically described using geographic coordinates and depth, while its orientation is expressed through strike, dip, and rake angles, which capture the fault's alignment and movement. Additionally, the dimensions of the fault plane, such as its length and width, are crucial for estimating the potential rupture area. Fault segmentation, which identifies discrete sections of a fault that may rupture independently, is also a critical consideration in characterizing the seismic source geometry.

Another essential component is the seismic activity and recurrence characteristics of the fault or source zone. Parameters such as seismicity rates, recurrence intervals, and slip rates provide insight into the likelihood and frequency of earthquake events. Seismicity rates quantify the number of earthquakes occurring over a given time period, while recurrence intervals describe the time between characteristic events,

often modeled using probabilistic distributions such as the Gutenberg-Richter law. Slip rates, which represent the long-term rate of displacement along a fault, are a fundamental input for assessing accumulated stress and potential earthquake magnitudes.

The stress and strain characteristics of the fault are equally important in source parametrization. Stress drop, which quantifies the stress released during an earthquake, influences the magnitude and intensity of seismic waves. Regional stress fields, describing the prevailing stress regime (e.g., compressional, extensional, or strike-slip), determine the driving forces behind fault activity. These parameters provide a mechanical basis for understanding fault behavior and earthquake generation.

In addition to static parameters, dynamic and kinematic characteristics of fault behavior play a pivotal role in source parametrization. Parameters such as rupture velocity, which describes the speed at which the rupture propagates along the fault, and slip distribution, which captures the variation in displacement across the fault plane, are essential for modeling the spatial variability of ground motions. Moment magnitude (M_w), derived from seismic moment calculations, serves as a standardized measure of earthquake size, integrating fault area, average slip, and shear modulus.

Seismic sources can be represented in different forms, depending on the scale and complexity of the event. Point sources are simplified representations used for small or distant seismic events, whereas finite sources provide detailed models of fault plane geometry and slip distribution, necessary for modeling large or near-field events. Scaling relationships, such as those proposed by Wells and Coppersmith, provide empirical links between fault dimensions, slip, and earthquake magnitude, enabling the estimation of one parameter from another.

Finally, source parametrization incorporates the temporal behavior of faults, distinguishing between creeping sections with continuous motion and locked sections accumulating stress that may eventually result in large earthquakes. Uncertainties in source parameters, stemming from data limitations or model assumptions, are addressed using probabilistic or stochastic methods to improve the robustness of seismic hazard assessments.

The process of selecting GMPEs and constructing a logic tree involves several key steps, each designed to ensure the reliability and robustness of seismic hazard

assessments (**Figure 4.16**). This workflow integrates systematic data collection, performance evaluation, and iterative validation to optimize the selection of GMPEs for a specific region and tectonic setting (**Table 4.1**).

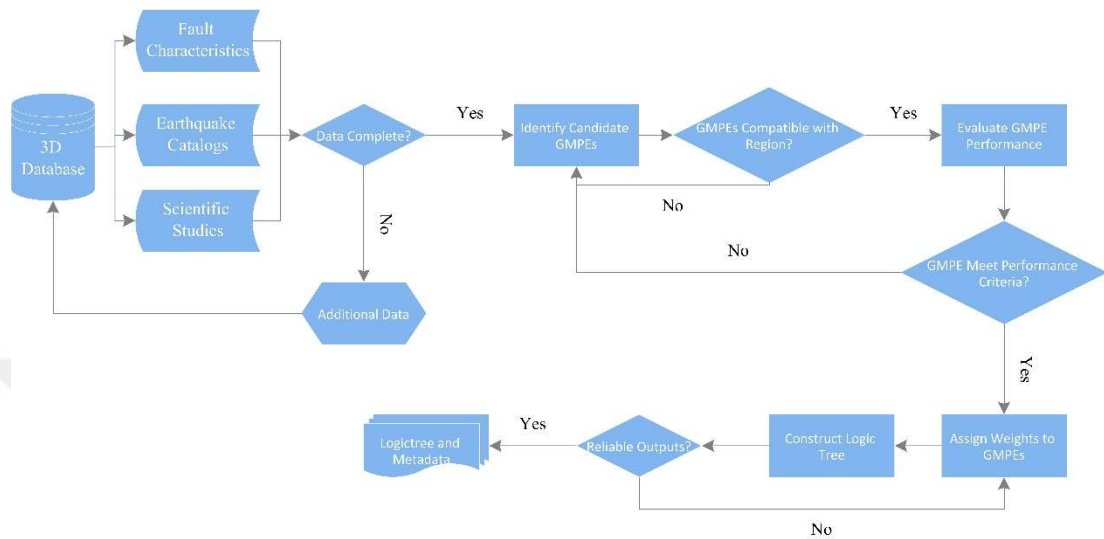


Figure 4.16: Logictree optimization workflow

Table 4.1: Horizontal GMPE Parameters

Parameter	ASK14	BSSA14	CB14	CY14	I14
Magnitude	M_w	M_w	M_w	M_w	M_w
Top of Rupture (km)	Z_{tor}	-	Z_{tor}	Z_{tor}	-
Style of faulting	$F_{\text{RV}}, F_{\text{NM}}, \text{SS}$	$U, F_{\text{RV}}, F_{\text{NM}}, \text{SS}$	$F_{\text{RV}}, F_{\text{NM}}, \text{SS}$	$F_{\text{RV}}, F_{\text{NM}}, \text{SS}$	$F_{\text{RV}}, F_{\text{NM}}, \text{SS}$
Dip (deg)	Dip	-	Dip	Dip	-
Down-dip rupture width (km)	W	-	W	-	-
Closest distance to rupture(km)	R_{rup}	-	R_{rup}	R_{rup}	R_{rup}
Hor. dist. to surface proj. (km)	R_{JB}	R_{JB}	R_{JB}	R_{JB}	-
Hor. dist. from edge of rupture (km)	R_x	-	R_x	R_x	-
Hor. dist. off end of rupture (km)	R_{y0}	-	-	-	-
Hanging wall model	F_{HW}	(R_{JB})	F_{HW}	F_{HW}	-
V_{S30}	V_{S30}	V_{S30}	V_{S30}	V_{S30}	V_{S30}
V_{S30} for reference rock (m/s)	1100	760	1100	1130	-
Depth to V_s (km)	$Z_{1.0}$	$Z_{1.0} (dz_{1.0})$	$Z_{2.5}$	$Z_{1.0}$	-
Hypocentral depth (km)	-	-	Z_{hyp}	-	-
Directivity term	-	-	(Z_{hyp})	DDPP	-
Regional variations	Region	Region	Region	Region	-
Aftershock factor	F_{AS}	-	-	-	-

The first step involves defining the scope of the project. This includes determining the purpose of the GMPE selection, such as its application in PSHA or scenario-based modeling. Clear project objectives ensure that subsequent decisions align with the intended outcomes. If the scope is not adequately defined, this step involves consultation with stakeholders and a reassessment of project goals.

Following the definition of scope, the next step is the collection of regional seismic data. This includes gathering information on regional seismicity, tectonic settings, and geological characteristics. Adequate and representative data are critical for selecting GMPEs that are well-suited to the study area. If data gaps are identified, additional resources or datasets are obtained to address deficiencies.

With the data in place, candidate GMPEs are identified based on their relevance to the study region and tectonic environment. The available GMPEs are reviewed, focusing on their compatibility with the local conditions, such as soil types and fault mechanisms. If suitable models are not available, this step may involve exploring global GMPEs or developing custom models tailored to the region.

Once a list of candidate GMPEs is established, their performance is evaluated using statistical metrics such as residual analysis, goodness-of-fit, and alignment with observed seismic data. Only models that meet established performance criteria are retained for inclusion in the logic tree. Any models that fail to perform adequately are eliminated, and alternative GMPEs are evaluated as necessary.

The retained GMPEs are assigned weights based on expert judgment, regional applicability, and their statistical performance. These weights reflect the relative confidence in each GMPE's ability to predict ground motion accurately. If the assigned weights appear inconsistent or lack sufficient justification, this step involves revisiting the weighting process in collaboration with experts.

The next phase is the construction of a logic tree. This hierarchical model incorporates GMPE branches, each associated with its assigned weight. The logic tree serves as a structured framework for integrating multiple GMPEs, capturing uncertainties in ground motion predictions. Once the tree is constructed, it is subjected to validation through sensitivity analysis or comparison with past earthquake events. If the outputs of the logic tree are unreliable, earlier steps such as GMPE selection, weighting, or the structure of the tree are revisited and refined.

Finally, the validated logic tree and the rationale behind the selection of GMPEs are documented comprehensively. The report includes a detailed description of the scope, data collection, GMPE evaluation, weighting methodology, and validation results. This documentation is crucial for ensuring transparency and facilitating stakeholder understanding of the model.

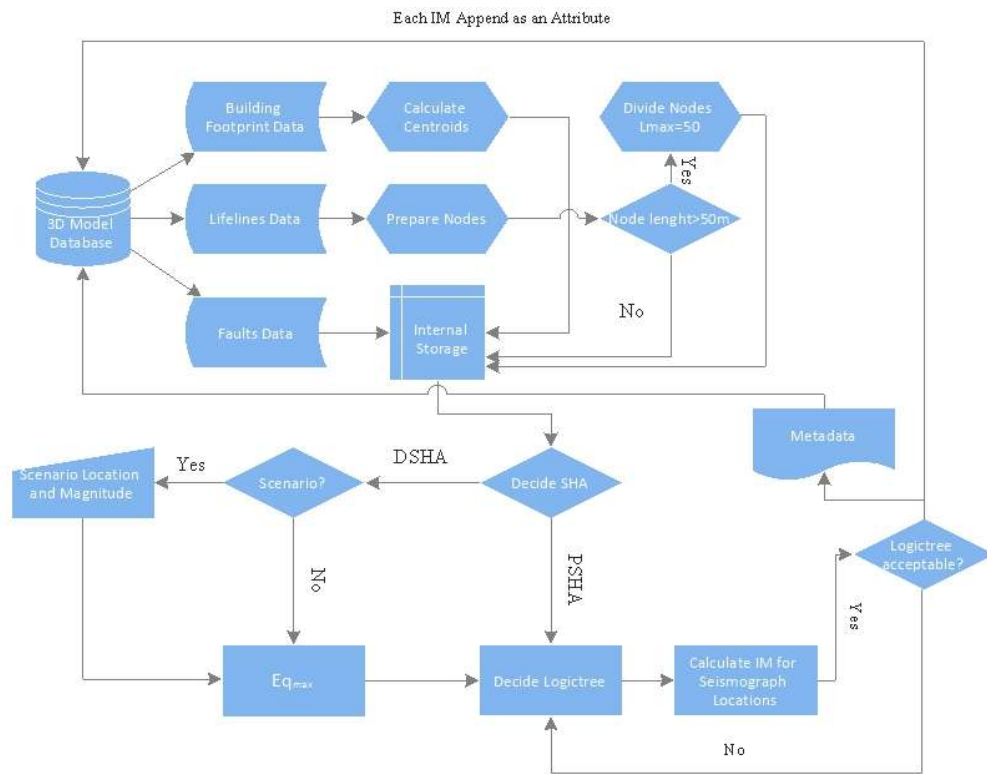


Figure 4.17: Hazard assessment workflow.

4.5.2. Damage Assessment of Structures

As stated earlier, there are several methods for damage assessment of structures following an earthquake. Selecting the appropriate methodology for damage assessment depends on the context, data availability, desired accuracy and computational resources. Often, a hybrid approach combining multiple methods can yield a more comprehensive and reliable damage assessment, enabling targeted, effective responses to earthquake impacts.

Damage assessment of structures after an earthquake is a critical step in understanding the impact of seismic events and planning for effective response and recovery. This

process involves multiple preparatory workflows that ensure the reliability and precision of assessments. These workflows range from data harmonization and integration to the development of analytical tools and classification systems. Together, they form a comprehensive framework for evaluating structural damage and informing mitigation strategies.

A fundamental preparatory step in damage assessment is the harmonization of data from diverse sources. Building inventories, historical earthquake records, and seismic ground motion data often vary significantly in format and detail. Harmonizing these datasets involves standardizing structural attributes such as construction materials, building age, design standards, and structural systems. This ensures consistency in assessment, enabling meaningful comparisons and reducing uncertainties.

Another critical element is the development of fragility curves, which are probabilistic tools that describe the likelihood of structural damage at different levels of seismic intensity. These curves are derived through empirical studies, analytical modeling, or a combination of both. Inputs such as peak ground acceleration (PGA) or spectral acceleration (SA) are used to define these relationships, with the choice of method influenced by data availability and the precision required for the analysis.

Accurate integration of ground motion data is also essential. Ground motion characteristics, including intensity, frequency content, and duration, significantly influence structural performance during an earthquake. Site-specific hazard assessments and microzonation maps can provide additional granularity for localized damage predictions. By incorporating these inputs, the assessment process accounts for variations in seismic shaking across different geographical areas.

The vulnerability of structures is assessed based on a range of factors, including construction type, building height, compliance with seismic codes, and structural age. Classification systems such as the European Macroseismic Scale (EMS-98) or HAZUS methodologies are often employed to standardize these evaluations. Such classifications help identify the structural typologies most at risk, forming the basis for targeted interventions.

Advanced simulation and modeling techniques, such as finite element analysis (FEA), play a vital role in damage assessment. These techniques allow for the detailed simulation of structural behavior under seismic loads, enabling the identification of

critical failure modes and the estimation of residual capacity. The results of these simulations are combined with empirical data to refine damage predictions, making them more robust and reliable.

The classification and quantification of damage involve categorizing structural impacts into predefined levels, ranging from minor cosmetic damage to complete collapse, namely none, slight, moderate, extensive and collapse. Internationally recognized standards are used to ensure uniformity in reporting. Quantification extends to estimating repair costs, loss of functionality, and the displacement of occupants, providing a holistic understanding of the earthquake's impact (**equation 4.1**).

$$P(D \geq D_k | IM) = \Phi\left(\frac{\ln(IM) - \mu_k}{\beta_k}\right) \quad (4.1)$$

The outputs of structural damage assessment have wide-ranging applications. During the disaster response, the findings guide rescue prioritization and resource allocation. In recovery planning, they inform decisions on retrofitting, demolition, and reconstruction. Additionally, the results contribute to the enhancement of seismic design codes and the development of strategies for future risk reduction.

To quantify (discretize) the expected damage level based on the calculated probabilities, a numerical value is assigned to each damage state as follows: 0 for no damage, 1 for slight damage, 2 for moderate damage, 3 for severe damage, and 4 for total loss. The expected damage level, denoted as $E[D]$, can then be computed using the following formula (**equation 4.2**):

$$E[D] = \sum_{k=1}^N P(D \geq D_k | IM) \cdot D_k \quad (4.2)$$

The damaged buildings and infrastructure were then prioritized based on factors such as severity of damage, criticality of infrastructure, population density and vulnerability, and economic importance. This prioritization allowed for the most

critical areas to be addressed first, ensuring that response and recovery efforts were targeted and effective.

As on-ground data becomes available, the IM distribution should be updated to reflect real-time conditions. This involves the integration of data from various sources, including sensor data from buildings and infrastructure, IoT devices, and reports from emergency responders and inspectors. Sensor data, such as measurements from accelerometers and GPS, provided critical information on ground motion and structural response. IoT data from drones, cameras and social media offers real-time insights into building and infrastructure conditions, while reports from emergency responders contribute valuable observations regarding damage and safety. The COP was then refined and reclassified.

4.5.3. Casualty Estimation

The process of casualty estimation in earthquake scenarios involves a series of methodical steps, represented effectively through a structured flowchart. Each step in the workflow corresponds to specific tasks or decision points, which can be mapped using standard flowchart elements to ensure clarity and logical progression.

Casualty estimation following an earthquake is a critical component of disaster response planning, requiring a robust framework that integrates hazard, exposure, and vulnerability data. This process can be modeled mathematically to predict the number of casualties based on the intensity of the earthquake, the characteristics of the affected buildings, and the population at risk. The model is structured around the interplay between the earthquake's ground motion intensity, the probability of building damage, and the corresponding casualty rates associated with different damage states.

The probability of casualties occurring in a building is primarily a function of the building's vulnerability and the IM of ground motion. This relationship can be expressed as:

$$P(C | IM) = f(V, IM) \quad (4.3)$$

where V represents the vulnerability of the building, and f is a function linking these parameters to the casualty probability. The building's vulnerability is typically

quantified using fragility curves, which relate the probability of exceeding certain damage states to the intensity of ground motion.

In disaster management, it is crucial to categorize casualties based on the severity of their injuries to ensure an effective and prioritized response (**Table 4.2**). The following table outlines the different levels of casualty severity, ranging from injuries requiring basic medical aid to immediate fatalities. Understanding these levels helps emergency responders assess the situation and allocate resources appropriately, ensuring timely and appropriate care for affected individuals.

Table 4.2: HAZUS Casualty classification levels

Casualty Level	Casualty Description
Severity 1	Injuries requiring basic medical aid, but without hospitalization (treat and release)
Severity 2	Injuries requiring medical attention and hospitalization, but not considered to be life-threatening
Severity 3	Casualties that include entrapment and require expeditious rescue and medical treatment to avoid death
Severity 4	Immediate deaths

Casualty rates associated with each damage state (R_k) are then applied to estimate the expected number of casualties. For a single building, the casualty count for a given damage state is calculated as:

$$C_{m,k} = R_{m,k} \cdot P(D = D_k | IM) \cdot O \quad (4.4)$$

$$C_{f,k} = R_{f,k} \cdot P(D = D_k | IM) \cdot O \quad (4.5)$$

where O is the building's occupancy. Summing up these values across all damage states provides the expected number of injuries and casualties for the building:

$$C_m = \sum_{k=1}^N C_{m,k} \quad (4.6)$$

$$C_f = \sum_{k=1}^N C_{f,k} \quad (4.7)$$

The inputs to this model include detailed hazard data, such as IM values from seismic ground motion simulations, exposure data (e.g., population distributions and building occupancy rates), and vulnerability data (e.g., building fragility curves). Casualty rates for each damage state are derived from empirical studies or expert judgment based on historical earthquake data.

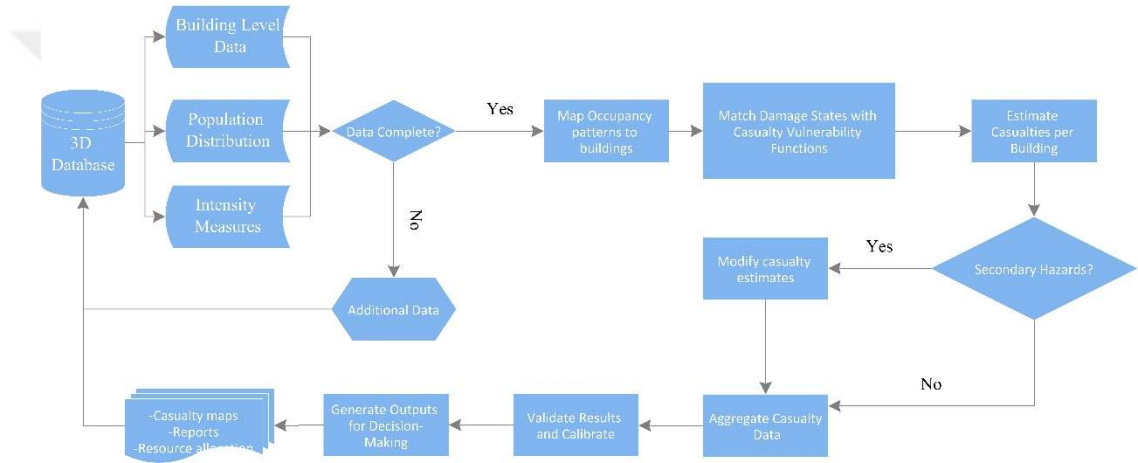


Figure 4.18: Casualty estimation workflow

This framework offers flexibility for incorporating additional factors, such as time-dependent population distribution, secondary hazards, or refined fragility data. By providing actionable insights, the model supports emergency planners in prioritizing resources and optimizing disaster response efforts in earthquake-affected regions.

R_k values, presented in the **Table 4.3**, are essential coefficients used to estimate casualty distributions across severity levels and damage states. These values reflect the probabilistic relationships between structural damage and resulting casualties, enabling a more precise analysis of disaster impacts.

Table 4.3: R_k Values for damage states

Damage State	Mean Damage Value
None	0.003
Slight	0.041
Moderate	0.314
Extensive	0.696
Collapse	0.814

The first major task is querying and extracting relevant data from the 3D database. This step involves retrieving building-level attributes, population distribution, and IMs critical for casualty estimation.

A critical decision point follows to assess the completeness of the extracted data. If the data is incomplete, the process loops back to the data extraction step to ensure all necessary information is obtained. Once the data is verified as complete, the workflow progresses to mapping occupancy patterns to buildings, a process step that dynamically assigns occupant numbers to each building based on time-dependent usage patterns and building types.

The next step involves matching building damage states with casualty vulnerability functions. This task applies probabilistic models to estimate the likelihood of casualties based on the severity of damage experienced by each structure. Following this, casualty estimation per building is conducted, where occupancy numbers are multiplied by casualty probabilities to derive figures for fatalities, severe injuries, and minor injuries.

The workflow then encounters another decision point to evaluate the presence of secondary hazards, such as fire or landslides, which may necessitate adjustments to casualty estimates. If such hazards are identified, casualty figures are modified accordingly; otherwise, the workflow continues. Subsequently, casualty data is aggregated spatially, summarizing estimates across defined geographic or administrative regions.

To ensure the accuracy and reliability of the estimates, the next step involves validating results and calibrating the model. This task compares the generated casualty estimates against historical data from similar events, enabling adjustments to model parameters for improved precision. The final step is generating outputs for decision-making,

including casualty maps, detailed reports, and recommendations for resource allocation.

4.5.4. Capacity Analysis for Shelters

Emergency shelter capacity analysis is a critical component of disaster response planning. This analysis evaluates whether the available shelter resources can accommodate the population displaced by a disaster. A comprehensive model integrates the estimation of shelter demand, supply, and spatial distribution while considering factors such as displacement rates and accessibility.

The demand for emergency shelters is determined by the total population in the affected area, the proportion of the population displaced due to the disaster, and the fraction of displaced individuals seeking shelter in public facilities. Mathematically, this demand can be expressed as:

$$D_s = P_t \cdot \alpha \cdot \beta \quad (4.8)$$

where D_s represents the total shelter demand, P_t is the total population in the affected area, α denotes the fraction of the population displaced, and β indicates the fraction of displaced individuals who seek shelter in public facilities. These parameters are derived from post-disaster assessments and behavioral patterns observed in previous disasters.

The supply side of the model accounts for the total shelter capacity, calculated as the sum of the capacities of all shelters in the region. The total shelter capacity, C_s , can be represented as:

$$C_s = \sum_{i=1}^N C_i \quad (4.9)$$

where C_i is the capacity of the i -th shelter, and N is the total number of shelters available. This aggregate capacity must be compared to the estimated demand to determine sufficiency.

To assess whether the available shelter capacity meets the demand, a shelter sufficiency ratio (S_r) is computed:

$$S_r = \frac{C_s}{D_s} \quad (4.10)$$

If $S_r \geq 1$, the shelter capacity is sufficient to accommodate the displaced population. However, if $S_r < 1$, the capacity is inadequate, and additional resources or alternative shelter arrangements must be identified. In cases where the capacity is insufficient, the model estimates the overflow (O_s), representing the number of individuals who cannot be accommodated:

$$O_s = D_s - C_s \quad (4.11)$$

Spatial distribution of demand and supply is also an essential consideration. The affected region can be divided into zones to account for variations in population density, displacement rates, and shelter availability. For a given zone z , the shelter demand and capacity are calculated as:

$$D_{s,z} = P_{t,z} \cdot \alpha_z \cdot \beta_z \quad (4.12)$$

$$C_{s,z} = \sum_{i=1}^{N_z} C_{i,z} \quad (4.13)$$

where $P_{t,z}$, α_z , and β_z represent the population, displacement fraction, and shelter-seeking fraction in zone z , respectively. $C_{i,z}$ denotes the capacity of the i -th shelter in zone z , and N_z is the total number of shelters in that zone.

Finally, accessibility to shelters is a vital aspect of the analysis. Accessibility is evaluated by calculating the distance (d_{ij}) between each demand location (j) and shelter (i) and applying a maximum acceptable distance threshold ($d_{\max}$). An accessibility indicator (A_{ij}) is defined as:

$$A_{ij} = \begin{cases} 1, & \text{if } d_{ij} \leq d_{max} \\ 0, & \text{if } d_{ij} > d_{max} \end{cases} \quad (4.14)$$

This indicator ensures that shelters are not only sufficient in capacity but also accessible to the affected population within a reasonable distance.

This mathematical framework provides a systematic approach to evaluating emergency shelter capacity and identifying gaps in resource allocation. It enables emergency planners to make informed decisions, prioritize resource distribution, and implement strategies to address potential shortfalls in shelter availability during disaster response.

4.5.5. Search and Rescue Team Requirements in Post-Earthquake Response

This chapter provides a comprehensive model for determining the necessary number of SAR teams in post-earthquake scenarios. By incorporating building dimensions, SAR team capabilities, shift cycles, and essential rest and recovery (R&R) periods, the approach offers a sustainable and effective method for resource allocation across an earthquake-affected region. The following sections detail the calculation methodology, assumptions, and implications of each factor.

To accurately estimate SAR team requirements, the model begins by establishing key parameters specific to both the buildings in need of assessment and the SAR teams:

- **Building Area (A):** The total area of each building measured in square meters. This dimension allows the model to approximate the scope of the search area that must be covered within each structure.
- **Number of Floors (F):** The number of levels within each building, which affects the total time for SAR operations due to increased vertical search needs.
- **Baseline Search Time Per Square Meter (t_{area}):** This factor estimates the time necessary for a team to search for a single square meter on one floor, accounting for challenges in visibility, navigation, and systematic search requirements (e.g., 0.1 hours per square meter).

- Additional Search Time Per Floor (t_{floor}): An adjustment for each additional floor, capturing the time needed for vertical movement, structural stability checks, and search complexity (e.g., 0.5 hours per floor).
- Efficiency Factor (E_i): Search efficiency factor for building i , depending on damage state (D_k). Efficiency accounts for additional difficulty in heavily damaged buildings.

$$E_i = 1 + \alpha_k \quad (4.15)$$

For a given building, total search time t_{ij} integrates both the building area and the number of floors:

$$t_{i,j} = (A_i \cdot H_i \cdot T_{\text{base}} + H_i \cdot t_{\text{floor}}) \cdot E_i \quad (4.16)$$

where t_{ij} represents the total search time for a SAR team assigned to building B_i .

SAR team capabilities and working hours define their effective operational period within each cycle:

- Team Capacity Per Shift (C_{team}): The total area or time a SAR team can cover within a single shift (e.g., 8 hours).
- Work Shift Duration (t_{shift}): The total hours in one SAR work shift.
- Rest and Recovery (R&R) Time ($t_{\text{R\&R}}$): Essential downtime needed following each shift to maintain team effectiveness and safety, typically equivalent to or matching shift duration (e.g., 8 hours).
- Operational Cycle (t_{cycle}): The combined period of work and R&R, given by:

$$t_{i,j} = (A_i \cdot H_i \cdot T_{\text{base}} + H_i \cdot t_{\text{floor}}) \cdot E_i \quad (4.17)$$

The proposed mathematical model also aims to optimize the allocation of SAR teams in disaster-affected areas, focusing on maximizing rescue efficiency and minimizing response times. Central to the model is an objective function that balances two critical priorities: rapid response to buildings where individuals are confirmed to be trapped

and strategic resource allocation to locations with a probabilistic likelihood of entrapment. By addressing both certainty and uncertainty, the model ensures that SAR operations are both targeted and comprehensive.

The objective function can be expressed as follows:

$$\min \sum_{i=1}^n \sum_{j=1}^m C_i \cdot t_{ij} \cdot x_{ij} - \lambda \cdot \sum_{i=1}^n \sum_{j=1}^m (1 - C_i) \cdot P_i \cdot x_{ij} \quad (4.18)$$

The first term minimizes the response time to buildings where individuals are confirmed to be trapped, denoted by $C_i=1$. The second term, weighted by a parameter λ , encourages resource allocation to buildings with uncertain entrapment, based on the probability P_i . This dual focus ensures a balanced allocation of SAR resources, addressing both confirmed emergencies and potential risks.

The model employs binary decision variables:

$$x_{ij} \in \{0,1\}, \quad z_i \in \{0,1\} \quad (4.19)$$

Here, x_{ij} represents whether SAR team j is allocated to building i , while z_i indicates the success of rescue operations at building i . To ensure effective and practical resource allocation, the model incorporates several constraints.

First, every building with confirmed trapped individuals must receive at least one SAR team:

$$\sum_{j=1}^m x_{ij} \geq 1 \quad \forall i \text{ where } C_i = 1 \quad (4.20)$$

Second, each SAR team must operate within its capacity, which limits the total workload they can handle:

$$\sum_{i=1}^n x_{ij} \cdot t_{ij} \leq R_j \quad \forall j \quad (4.21)$$

Additionally, the prioritization of confirmed trapped locations is enforced through the following condition:

$$z_i = 1 \quad \text{if and only if } C_i = 1 \text{ and a team is allocated to building } i \quad (4.22)$$

These constraints ensure that confirmed emergencies are prioritized while maintaining realistic operational limits for SAR teams.

The model's primary objective is to optimize SAR operations by leveraging both deterministic and probabilistic data. It seeks to allocate resources efficiently, ensuring no confirmed trapped location is neglected while directing attention to high-probability unconfirmed sites. This balanced approach enables effective planning in pre-disaster scenarios, real-time decision-making during active operations, and post-disaster performance evaluation.

Potential enhancements to the model include dynamic reallocation of teams based on real-time updates, the integration of multi-criteria optimization to address additional factors such as team fatigue and geographic clustering, and the incorporation of stochastic elements to account for uncertainties in travel times and team performance. Such refinements could further enhance its practical applicability and robustness.

The proposed model provides a comprehensive framework for optimizing SAR operations. By combining deterministic and probabilistic approaches, it ensures that resources are allocated effectively and equitably in complex disaster scenarios. Its implementation has the potential to significantly improve response efficiency and rescue outcomes.

4.6. Validation and Verification

Validation and verification of estimation models are essential to ensure that the calculations are accurate, reliable, and representative of real-world conditions. Validation ensures that the model reflects reality, while verification confirms that the model has been implemented correctly. Together, these processes provide confidence in the model's predictions and its utility for disaster response planning.

To validate the estimation model, historical data comparison serves as a primary approach. The model outputs are compared against casualty data from past earthquakes

with similar characteristics, such as building types, population densities, and seismic intensities. This comparison provides a benchmark to assess the model's performance. Expert opinion also plays a crucial role in validation, as structural engineers, seismologists, and disaster response professionals can review the model's parameters—such as fragility curves and casualty rates—and provide feedback to improve accuracy. Sensitivity analysis further supports validation by testing the model's behavior under varying input parameters, such as intensity measures or building vulnerabilities, to identify whether changes lead to logical variations in outputs. Scenarios that appear overly sensitive to minor input changes can highlight areas for refinement. Additionally, running the model on realistic, hypothetical earthquake scenarios and comparing outputs to expected trends ensures alignment with practical expectations. When possible, field validation can be performed by comparing model predictions with post-disaster field observations to calibrate parameters and refine assumptions.

Verification focuses on ensuring that the model's implementation is consistent with its theoretical framework. A thorough review of the mathematical equations and their computational implementation is fundamental. This process involves performing code reviews and logical checks to identify errors in the calculation process. Simplified test cases with known inputs and outputs are valuable for verifying each component of the model, such as fragility curve calculations or casualty rate applications. Testing each component in isolation ensures intermediate results are correct before integrating them into the complete model.

Cross-validation with alternative models offers an additional layer of verification. By comparing the outputs of different models, discrepancies can be identified and addressed, potentially improving the robustness of the casualty estimation framework. Dimensional analysis also aids verification by ensuring consistency in the units used within equations. For example, casualty estimates should result in dimensionless quantities rather than physical units such as meters. Monte Carlo simulations provide another means of verification, enabling probabilistic testing of the model under varying scenarios to ensure consistency and robustness.

These processes of validation and verification are iterative. As new data, methods, and empirical observations become available, the model can be recalibrated and improved. This iterative refinement ensures the model remains accurate and relevant, supporting

effective disaster response planning and resource allocation in the aftermath of an earthquake.



5.DEVELOPMENT OF KOCAELİ PROVINCE DIGITAL TWIN

5.1. Selection of the Case Study Area

Kocaeli is located in the Çatalca-Kocaeli Section of the Marmara Region, between 29°22'-30°21' east longitude, 40° 31' - 41°13' north latitude (**Figure 5.1:** Kocaeli City (AoI)). It is surrounded by Sakarya in the east and southeast, Bursa in the south, Yalova, the Gulf of İzmit, the Sea of Marmara and Istanbul in the west, and the Black Sea in the north. The surface area of Kocaeli is 3.397 km². Kocaeli Province has a population of 2,079,072 people as of 2023, and a population density of 612 people per square kilometer, making it the second most densely populated province in Turkey. The province is strategically located at an important road junction that connects Asia and Europe, and İzmit Bay, a natural harbor, is a busy sea route for commerce and transportation. The province is dominated by the Samanlı Mountains, which stretch from the western bank of the Sakarya River to Bozburun in the north of Pamukova and İzmit Lake and form a depression area that includes the cities of İzmit, Sapanca, and Adapazarı. Kocaeli is the seventh smallest province in Turkey in terms of surface area. Despite its small size, it plays an important role in the country's economy and transportation infrastructure.

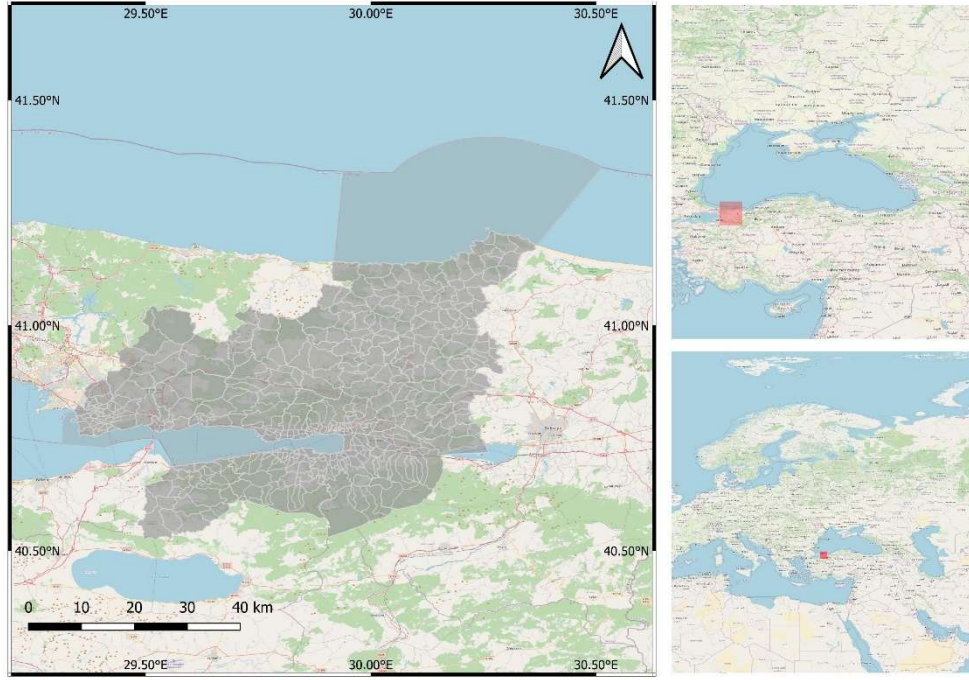


Figure 5.1: Kocaeli City (AoI)

There are 12 counties in and around Izmit District, namely Başiskele, Çayırova, Darıca, Derince, Dilovası, Gölcük, Gebze, Gölcük, Kandıra, Karamürsel, Kartepe and Körfez. According to the 2019 data, Kocaeli Province ranked fifth in terms of gross domestic product (GDP) with ₺156.7 billion, representing 3.63% of Turkey's total GDP. Kocaeli also ranks second in per capita income with ₺81,228. The industry sector is the largest contributor to the province's GDP, accounting for 69.9% of its total output. Kocaeli is a major player in Turkey's export market, with 5.7% of the country's total exports originating from the province. In terms of exports per capita, Kocaeli ranks second after Istanbul with \$5,164, indicating its strong export capacity. The province's significant economic contributions reflect its strategic location and importance as a transportation hub, as well as its well-developed industry and export sectors. In 2020, Kocaeli Province ranked third after Istanbul and Bursa in Turkey's export league, exporting a total of \$12.2 billion worth of goods to 184 countries. This impressive export performance highlights Kocaeli's economic significance in Turkey and the global market.

The northern part of Kocaeli province is a geologically diverse region with a unique landscape. It is a plateau area that is situated between the Black Sea and the Gulf of Izmit (Sea of Marmara), making it a crucial water section area. This plateau area is the

highest part of the Kocaeli Peninsula and has an erosional surface origin. The area was peneplated during the Pliocene period and was subsequently uplifted during the "Post-Alpine" tectonic movements, with the southern part experiencing greater uplift than the northern part. The uplifting created a plateau that was further shaped by the rivers, which split and fragmented it into distinct sections.

The average elevation in the western part of the plateau is around 200-300 meters above sea level, making it relatively flat. As one moves towards the eastern part of the plateau, the altitude value increases, and the terrain takes on a hilly appearance. The area is deeply split by valleys, with a high slope, creating a dramatic landscape. This hilly terrain is a result of the intense tectonic activity that has shaped the region over millions of years. The unique geology of the region has contributed to its rich biodiversity and has made it an important area for scientific research and conservation.

Kocaeli province is in the eastern part of the Marmara region, which is one of the most seismically active areas in Turkey. The province is characterized by a complex tectonic structure due to the intersection of the North Anatolian Fault (NAF), East Anatolian Fault (EAF), and Izmit Bay Fault (IBF) systems. The NAF is the most prominent tectonic feature in the region, and it runs parallel to the northern coast of the Marmara Sea. The fault is a major strike-slip fault and is responsible for many of the large earthquakes in the region, including the devastating M7.4 earthquake that struck the province in 1999. The total length of the fault in the province is around 60 km, and it cuts through all the rocks in the region, controlling the Quaternary units. The EAF intersects with the NAF at the eastern end of the province, near the Karliova triple junction point. The EAF is a major east-west trending strike-slip fault that runs along the eastern part of Turkey. The intersection of these two faults has resulted in a complex tectonic regime in the region.

The IBF is a north-south trending normal fault that runs along the eastern shore of Izmit Bay. The fault has a length of around 20 km and a maximum displacement of 5 km. It is believed that the fault played a significant role in the 1999 earthquake.

The tectonic structure of Kocaeli province is further complicated by the presence of several smaller faults and folds, which result in previously mentioned diverse topography. The NAF is a major tectonic feature in Turkey, with a total length of approximately 1000 km and varying displacement between 25 km and 80 km. The

fault is characterized by narrow linear appearances and features with reverse components, which are typically several hundred meters in width in the east but expand to up to 5 km in the west, where it exhibits normal components. The fault originates at the triple junction point of Karlıova, where it intersects with the East Anatolian Fault in the east, and follows a convex arc to the western end of the Mudurnu Valley segment.

At the western end of the Mudurnu Valley segment, the fault divides into two main branches. The northern branch runs along the north of Sapanca and the Armutlu Peninsula, extends through the Marmara Sea along the Saros Bay, and continues towards the Corinth Gulf within the Aegean Sea. The fault is clearly visible along the south of Sapanca Lake to the Gulf of İzmit. The general strike of the fault changes between N80E-N80W and EB. The fault length between Sapanca and Gölcük is approximately 60 km, and it cuts through all the rocks in the region, controlling the Quaternary units.

The fault jumps to the left around Gölcük, forming a small pull-apart that developed between the Sapanca-Gölcük segment and the Gölcük-Karamürsel segment. This pull-apart zone corresponds to the Gölcük and Değirmendere coastlines, which were affected by a major earthquake on 17 August 1999, causing them to slide into the gulf. The fault extends into the sea parallel to the shoreline between Gölcük and Karamürsel, with a general strike of N80-85E, and continues westward between Hereke and Çınarcık, where it also extends into the sea. Landslides are commonly observed in the southern part of the fault, around Yalova.

5.2. Data Collection and CIM Development

The first step to CIM development is the creation of a robust file management system. A well-structured file management system is essential for organizing, accessing, and managing the diverse data types associated with the project. The CIM_Project_Data folder structure outlined below is designed to facilitate this organization, ensuring that all project-related materials are systematically arranged for ease of use. Each primary folder is subdivided into specific subfolders that categorize data by type, source, and purpose, ranging from raw data and processed data to comprehensive documentation.

This structured approach streamlines data retrieval and analysis processes, ultimately contributing to the project's success.

An integral aspect of the CIM_Project_Data folder structure is the implementation of a robust versioning system, which ensures that all data and documentation are consistently updated and easily traceable. By maintaining clear version histories, team members can track changes, revert to previous iterations when necessary, and ensure that they are always working with the most current information. Additionally, comprehensive user guides are provided within the documentation subfolder to assist team members in navigating the file management system effectively. These guides outline best practices for data entry, version control procedures, and tips for efficient data retrieval.

To create the 3D core model, the initial step involves obtaining a DEM of the AoI from the open-source ALOS PALSAR database, which offers a resolution of 12.5 meters [282]. Following this, additional DTM and DSM are acquired. Building footprint datasets from the Kocaeli Greater Municipality (KBB) are seamlessly integrated into the model. The orthophoto of the AoI is obtained from satellite sources and incorporated into the model. Subsequently, datasets containing information about vegetation and water bodies, sourced from Open Street Map (OSM) [283] and KBB, are integrated, along with road and sidewalk datasets from OSM. Land use data from KBB is also seamlessly integrated into the model. This completes the creation of the 3D core model.

Parametric earthquake data for Kocaeli and its neighboring regions have been compiled within a radius of 200 km and a depth of 100 km, covering magnitude types mb, ms, Mw, M_L, and M_D. Approximately 1786 earthquake events in the region and its surroundings have been compiled spanning the years 1900-2024 (**Figure 5.2**). The selection of a 200 km radius aims to encompass all potential seismic sources, including active faults, fault zones, and fault systems. Faults data were sourced from two different sources, namely the GEM [284] and the Mineral Research and Exploration General Directorate (MTA) [285]. The GEM dataset underwent optimization, while the MTA dataset includes information on both active and passive faults in the region.

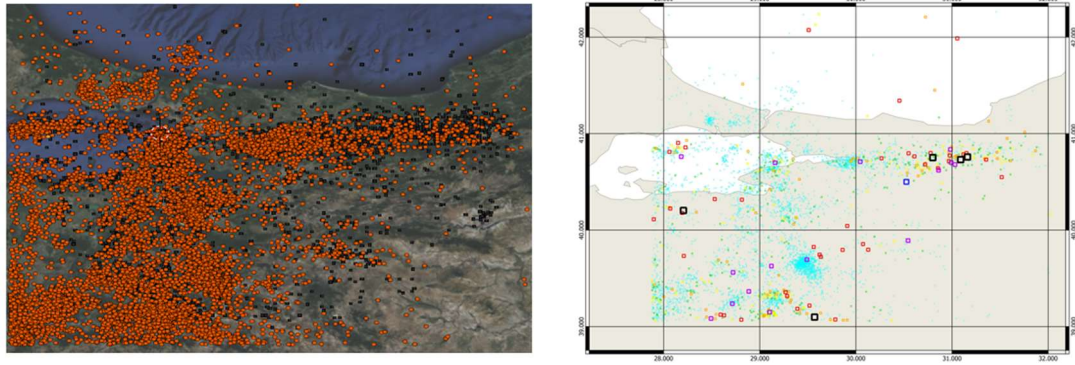


Figure 5.2: Raw and harmonized earthquake catalogs of the AoI.

Socioeconomic data encompasses various sources, including census data, demographic surveys, and socioeconomic indicators representing the distribution of population, income levels, education, and access to healthcare (**Figure 5.3**). While KBB possesses substantial address-based demographic data, the use of this data is sensitive and restricted to government applications. While some of this data is incorporated into the model, the exact data types and outlines were restricted by the data provider (KBB). Building types and structural characteristics datasets of the AoI were also acquired from KBB. This dataset is considered to be 65-80% complete, and the digitization of the KBB building license database is also considered to be around 90% complete. A survey is in progress to assess and categorize buildings in the AoI. It is based on the Turkish Legislation of Regulation on the assessment of risky structures, and the model is also prepared to accommodate this format. Furthermore, the model is configured to support GEM [77], [286] and HAZUS [87] exposure data formats. The lifelines datasets, including gas distribution lines, power grids, potable water, and wastewater data, were also acquired from KBB. Soil characteristics such as V_{s30} (**Figure 5.5**) and borehole data were also acquired from KBB and integrated into the model (**Figure 5.4**).

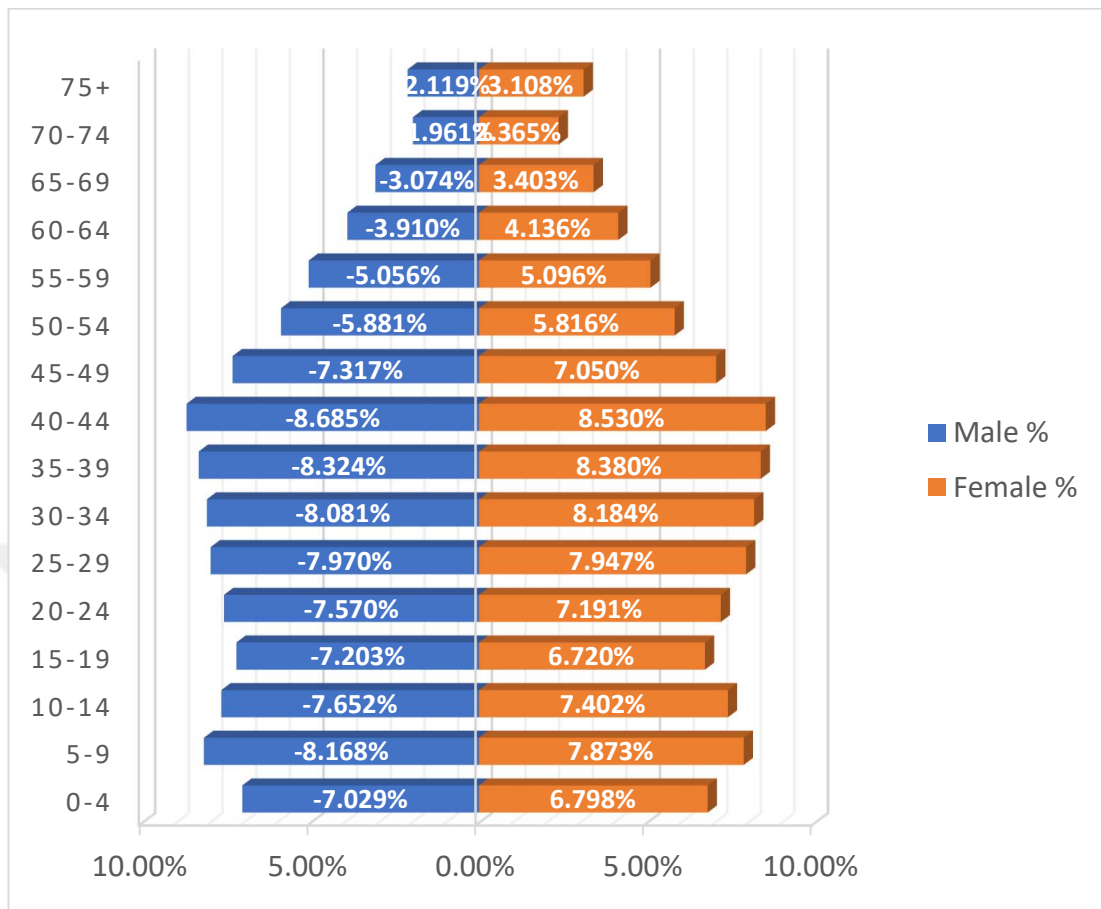


Figure 5.3: Population pyramide of Kocaeli

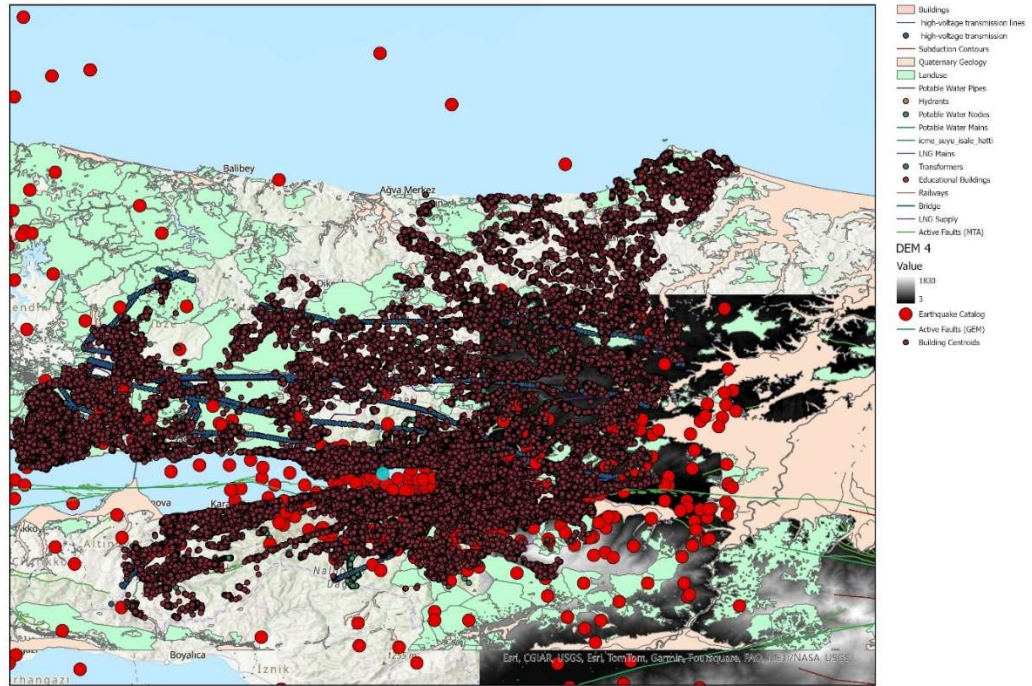


Figure 5.4: Datasets employed in the model.

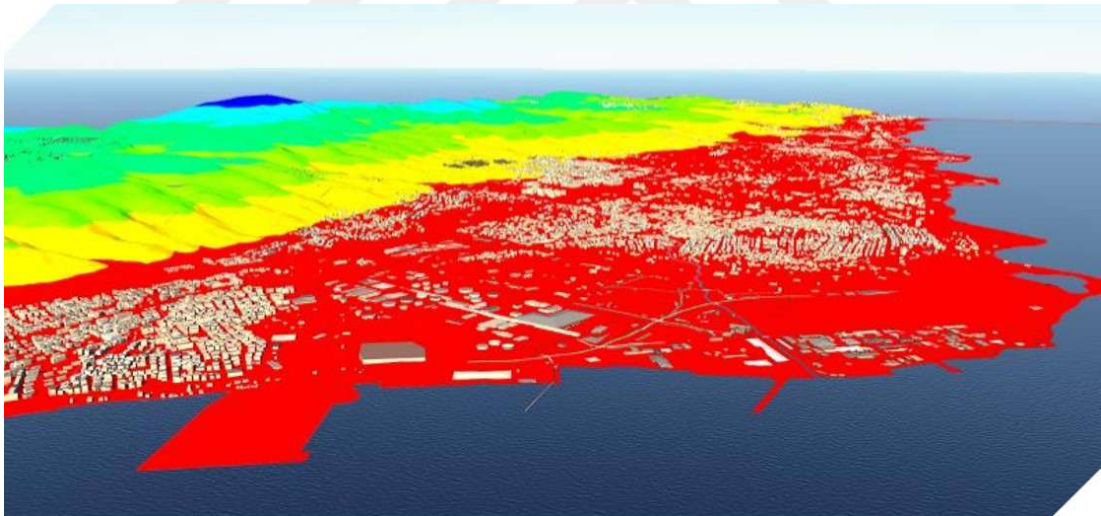


Figure 5.5: Vs₃₀ Distribution

In the development of the Kocaeli Seismic Risk Management Digital Twin, a detailed and expansive model of the region was constructed, covering an area of approximately 40,000 square kilometers. This comprehensive representation incorporated a wide array of urban infrastructure components, reflecting the complexity and scale of the urban environment.

The model included 302,000 buildings, representing the diverse urban fabric of the region. These structures were modeled to capture variations in size, construction type, and usage, enabling precise assessments of seismic vulnerability and risk.

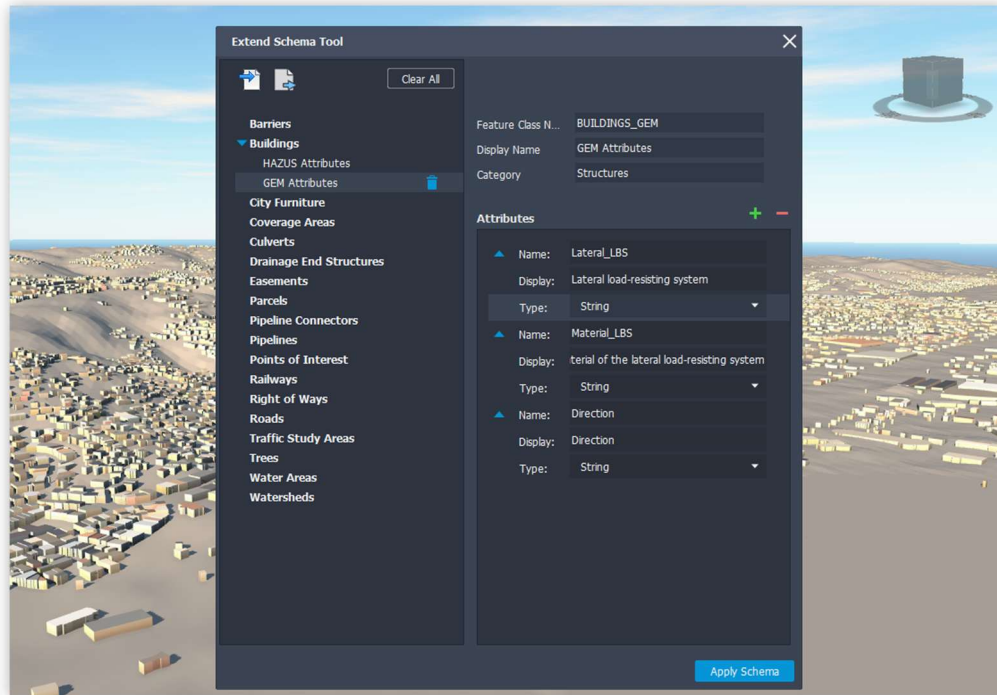


Figure 5.6: Building taxonomy on the model

Transportation and connectivity were integral elements of the model, with approximately 10,000 kilometers of roads and sidewalks incorporated. This allowed for detailed simulations of evacuation scenarios and the assessment of accessibility for emergency response teams.

Energy infrastructure was meticulously detailed, including 10,000 kilometers of liquefied natural gas (LNG) main transmission lines and 2,750 kilometers of LNG distribution lines. These components were critical for evaluating the resilience of energy supply systems under seismic conditions.

Additionally, the model featured around 20,000 kilometers of water and wastewater lines, along with their associated components. This provided a basis for analyzing the impacts of seismic events on water supply and sanitation services, crucial for maintaining public health during and after disasters.

After establishing the physical environment, the Hazard Sub-Routine was applied to assess seismic hazards. This involved employing a logictree approach utilizing four different GMPEs (ASK14, CB14, CY14, I14), each weighing 25%. These equations were utilized to calculate the primary PGA distribution for all structures within the modeled area.

Subsequently, PGA values for seismic stations located in the vicinity were computed and compared with actual PGA values recorded on-site. This comparison served to optimize the logictree, ensuring that the model's predictions aligned closely with observed data. Leveraging the optimized logictree, PGA and SA values for each individual building were calculated and integrated into the model. This process enabled the representation of seismic hazard parameters for all structures within the simulated environment.



Figure 5.7: PGA Values of buildings

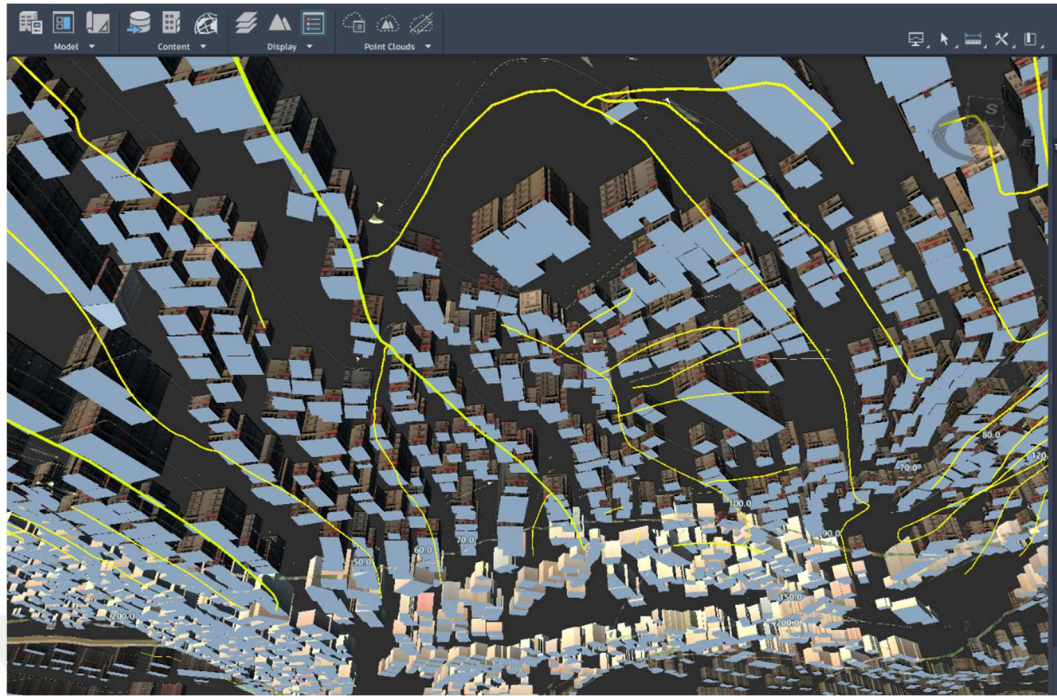


Figure 5.8: PGA Values over infrastructure

In the Exposure Sub-Routine, a comprehensive analysis was conducted considering a total of 302,000 buildings within the model. These buildings were categorized based on their function and purpose. Among them, 5,000 buildings were identified as government buildings (**Figure 5.9**), including approximately 1,500 educational institutions such as schools and universities. Additionally, the government buildings category included 11 hospitals and 48 primary care clinics.

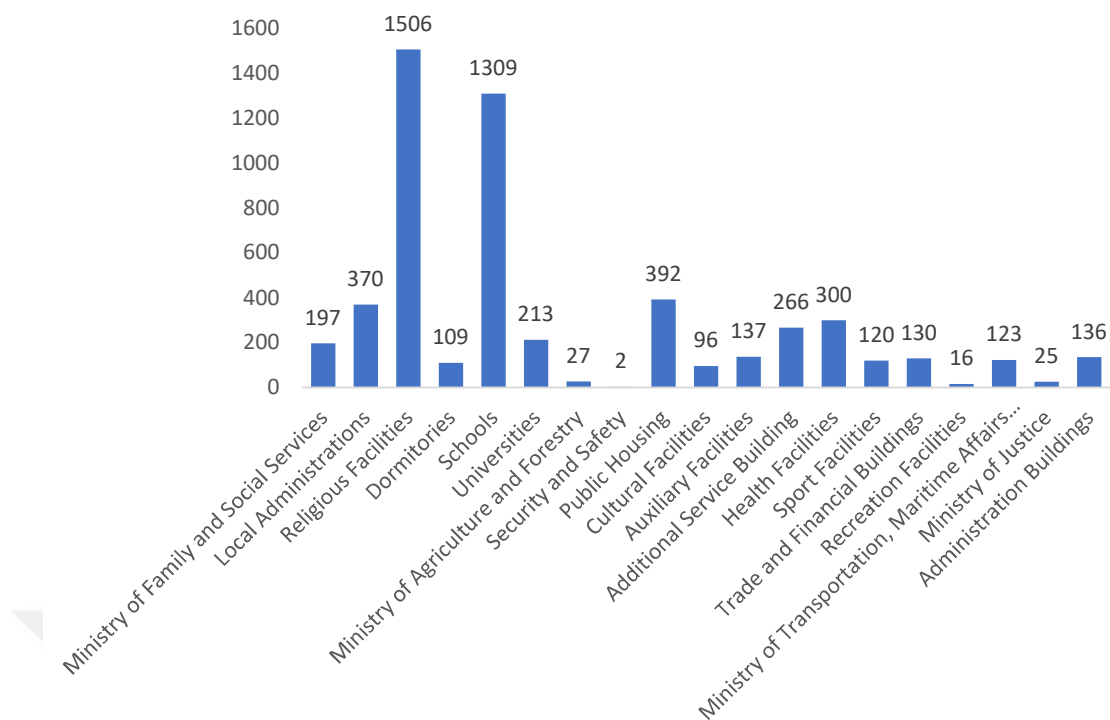


Figure 5.9: Distribution of governmental buildings

The analysis also accounted for the construction timelines of these buildings. To reflect the diversity in construction periods and the associated legislative changes, the buildings were categorized into four distinct groups: those constructed before 1975, between 1976 and 2000, from 2000 to 2007, and post-2007. This categorization aligns with significant changes in construction regulations and practices over time (**Figure 5.10**).

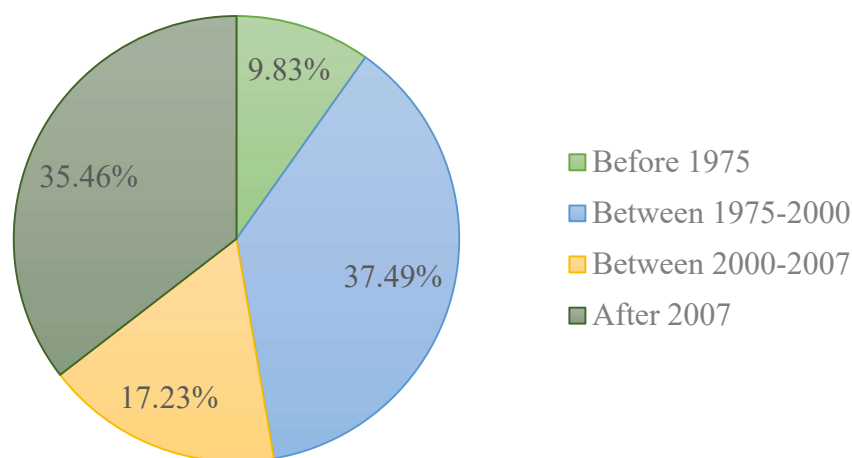


Figure 5.10: Distribution of building types by construction year

Furthermore, demographic distributions were integrated into the model through an address-based population registration system, facilitated via APIs. This system allowed the retrieval of population data linked to specific addresses within the modeled area. To safeguard sensitive data, a generalized population distribution was used for standard user interfaces, while access to detailed demographic information was restricted to users with administrative privileges, ensuring confidentiality and appropriate usage.

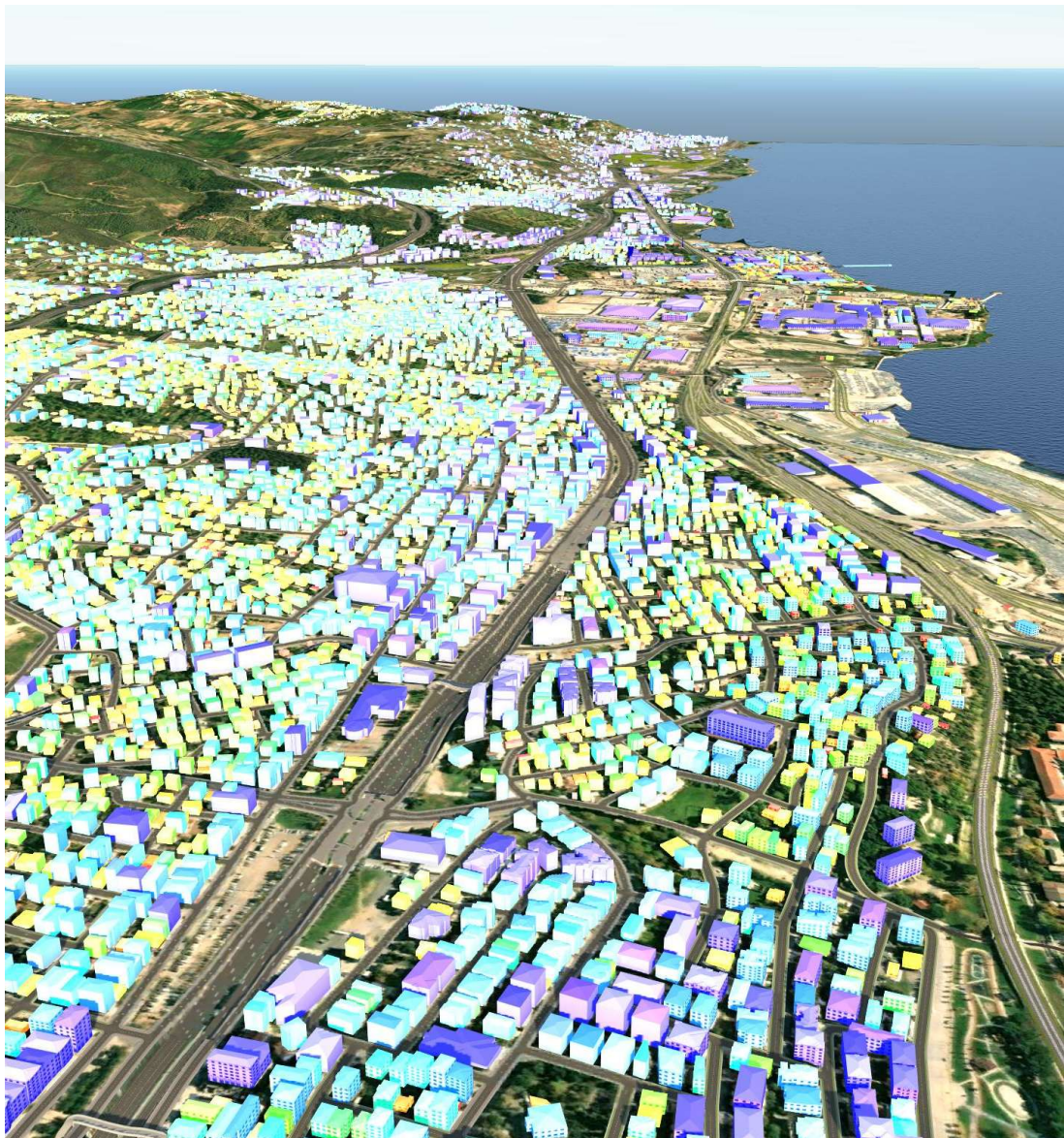


Figure 5.11: Building types on the model

In the Vulnerability Sub-Routine, a hybrid approach was adopted to assess the vulnerability of buildings within the modeled area. Initially, vulnerability curves for

buildings were obtained from the HAZUS database, providing a foundational understanding of building susceptibility to seismic hazards. Due to the limitations in the quality and detail of the available building inventory data, an alternative approach was adopted to ensure the reliability of seismic loss estimation. Specifically, the HAZUS methodology's "no-code" classification combined with a "low material quality" assumption was utilized. This approach is particularly suited for scenarios where comprehensive and high-fidelity data on structural attributes, such as design codes, material quality, and construction practices, is unavailable or unreliable.

The "no-code" category assumes that the buildings lack adherence to modern seismic design standards, reflecting construction practices that do not incorporate resistance to seismic forces. This assumption is aligned with the available data, which could not definitively verify compliance with any specific building codes. Similarly, the adoption of the "low material quality" assumption provides a conservative estimate of the buildings' vulnerability, accounting for potential deficiencies in construction practices and material degradation over time.

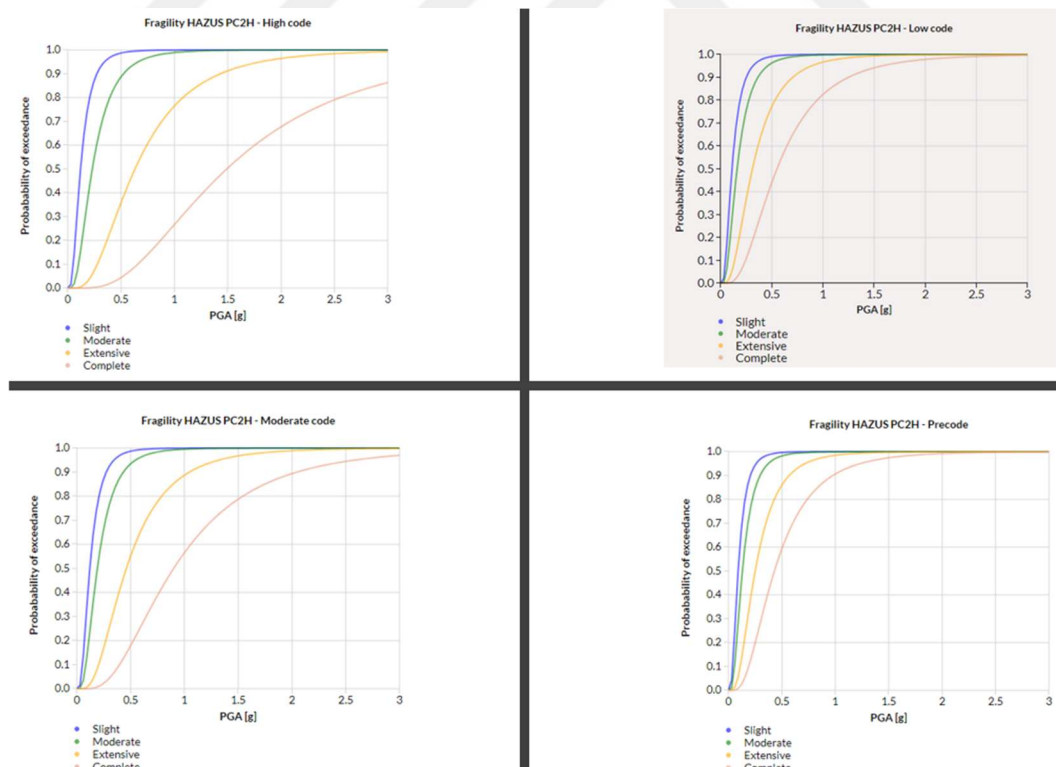


Figure 5.12: Fragility curves

These curves were then utilized to compare building-specific PGA values, enabling an initial evaluation of potential damage levels.

For a more comprehensive analysis, an Equivalent Lateral Forces (ELF) approach was employed, allowing for a detailed assessment of structural response to seismic forces. Engineering Performance Descriptors (EPDs) were calculated based on this approach and compared against relevant building regulations and standards.

The Equivalent Lateral Force (ELF) method is a simplified analytical procedure widely utilized in structural engineering to estimate seismic forces acting on buildings. It is particularly suitable for regular structures in regions of low to moderate seismicity. The procedure involves determining the total lateral force, known as the base shear, and distributing this force across the height of the structure to evaluate the seismic demand at each level.

To calculate the base shear (V), the seismic response coefficient (C_s) is determined, and this is multiplied by the effective seismic weight (W) of the structure. The effective seismic weight typically includes the structure's self-weight, superimposed dead loads, and a portion of live loads. The seismic response coefficient is given by the relationship:

$$C_s = \frac{S_a}{R} \cdot I \quad (5.1)$$

where S_a represents the spectral acceleration at the fundamental period of the structure, R is the response modification factor reflecting the ductility and overstrength of the structural system, and I is the importance factor that accounts for the building's role in the community, with values typically ranging from 1.0 to 1.5.

Once the base shear is established, it is distributed among the different levels of the building as lateral forces (F_x) based on the relative seismic weight and height of each level. The distribution is governed by the formula:

$$F_x = V \cdot \frac{w_x \cdot h_x}{\sum_i w_i \cdot h_i} \quad (5.2)$$

where F_x is the lateral force at a given level x , w_x is the seismic weight at that level, and h_x is the height of the level from the base. The denominator $\sum w_i \cdot h_i$ accounts for the summation of moment arms of all seismic weights.

In cases where torsional effects are present due to an eccentricity between the center of mass and the center of rigidity, additional torsional moments must be included in the analysis. These torsional effects may significantly influence the distribution of forces, especially in irregular buildings. Finally, the base shear is distributed across the building's height using the relative contributions of each story's seismic weight and height.

This extensive modeling and analysis effort aimed to create a high-fidelity digital twin of Kocaeli's urban environment. The resulting model serves as a robust tool for conducting detailed analyses and simulations, supporting seismic risk management, urban resilience planning, and post-disaster recovery operations.

5.3. Earthquake Risk Management

A primary application of CIM in seismic risk management lies in its ability to assess vulnerabilities within the built environment. By combining geospatial data, structural attributes, and seismic hazard models, CIM enables detailed simulations of earthquake impacts on infrastructure. This capability allows for the identification of high-risk zones, prioritization of retrofitting measures, and the enforcement of seismic building codes. Vulnerability assessments can be conducted at multiple scales, from individual structures to entire neighborhoods, ensuring comprehensive risk evaluation.

Emergency preparedness and response planning are significantly enhanced through CIM. The platform can integrate real-time data streams, such as population density, traffic patterns, and sensor readings, to optimize evacuation routes and allocate emergency resources effectively. Simulations of various disaster scenarios provide insights into the efficiency of proposed evacuation plans and resource distribution, reducing casualties and minimizing disruptions. Additionally, CIM supports the coordination of emergency services, ensuring rapid deployment and effective communication during critical moments (**Figure 5.13**).

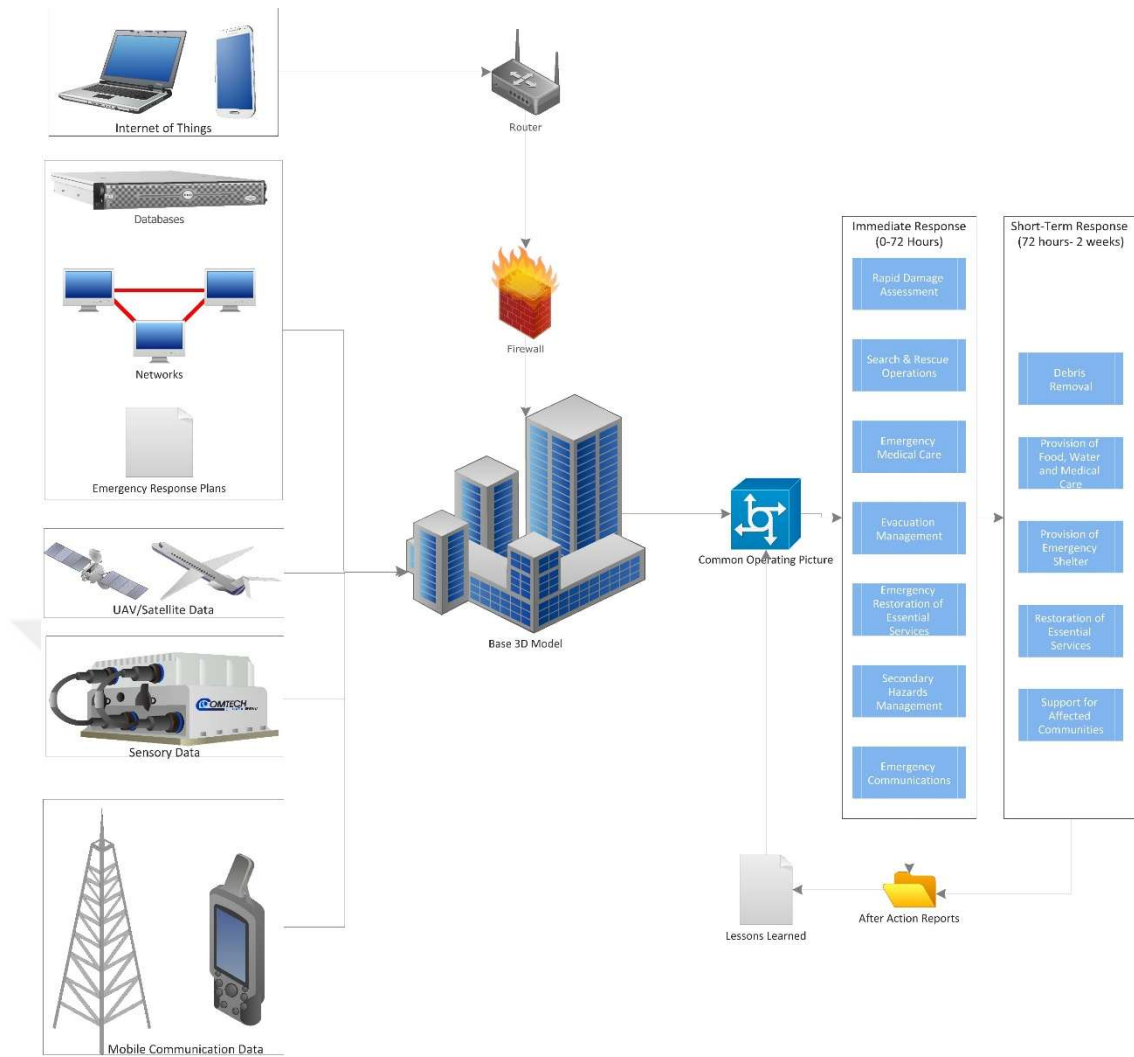


Figure 5.13: CIM response support

CIM also plays a critical role in resilience planning by incorporating hazard maps, zoning regulations, and land use data. This integration supports sustainable urban development by ensuring that new construction projects avoid high-risk areas, such as fault lines and liquefaction-prone zones. Furthermore, CIM can model and evaluate the effectiveness of resilience strategies, such as open spaces for emergency shelter or redundant utility networks, fostering adaptive capacity within urban systems.

Post-disaster recovery and reconstruction efforts are another area where CIM proves invaluable. By serving as a repository for pre- and post-disaster data, CIM facilitates damage assessments and guides recovery priorities. High-resolution 3D models generated by CIM allow stakeholders to identify affected areas accurately and plan the reconstruction process efficiently. Additionally, the platform's collaborative features

enable seamless coordination among government agencies, non-governmental organizations, and other stakeholders involved in recovery operations.

Public engagement is another notable application of CIM. Through interactive 3D visualizations and virtual simulations, CIM helps communicate complex earthquake risks and mitigation strategies to non-experts. These tools enhance community awareness and foster public participation in disaster preparedness initiatives. By empowering residents to understand and address vulnerabilities within their neighborhoods, CIM contributes to a more resilient and informed society.

Finally, CIM serves as a collaborative platform that brings together diverse stakeholders, including urban planners, emergency responders, policymakers, and researchers. By enabling the sharing of data and resources, CIM ensures a cohesive approach to disaster management, reducing redundancies and enhancing inter-agency coordination. The platform also supports training and simulations for disaster response teams, improving their preparedness and operational efficiency during real events.

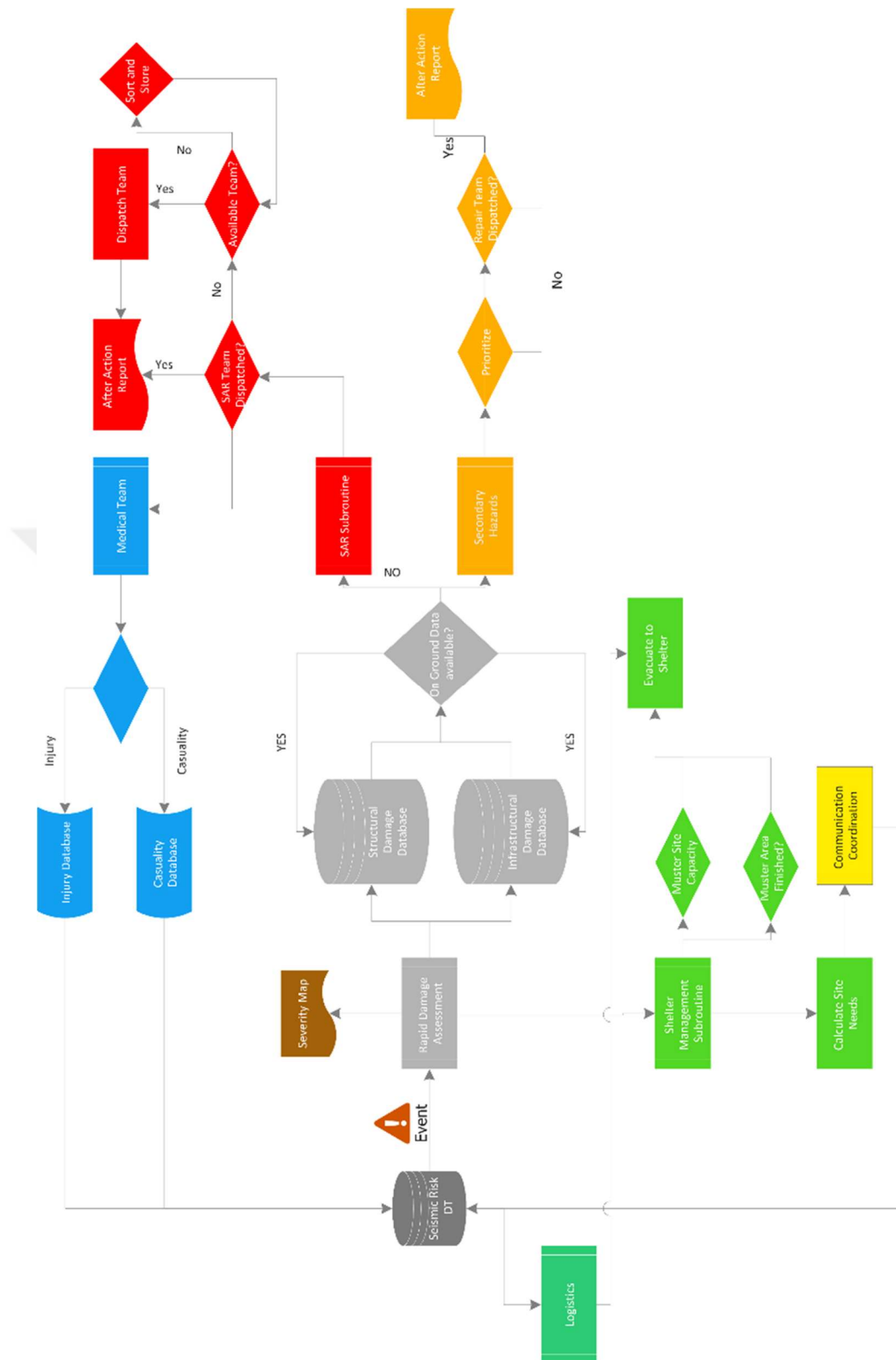


Figure 5.14: Response workflow for the model

5.4. Simulation of Earthquake Scenarios

For the demonstration of the model's capabilities, a scenario-based approach was employed, focusing on the Gölcük Earthquake that struck on August 17, 1999, with a magnitude of 7.6 (Mw). This earthquake's epicenter was situated near the town of Gölcük in northwestern Turkey, and its effects were widely felt across the Marmara region. Below are the details of the earthquake [287]:

Date : 1999-08-17 at 00:01:39.80(UTC), 03:01:37 a.m local time

Surface Wave Magnitude: 7.8 (USGS)

Body Wave Magnitude : 6.3 (USGS)

Duration Magnitude : 6.7 (Kandilli)

Moment Magnitude : 7.4 (USGS, Kandilli)

Epicenter : 40.702N, 29.987E (USGS)

Depth : 17 km. (USGS)

The earthquake scenario will be simulated across two distinct temporal contexts: the original occurrence time and typical working hours. This dual-time simulation approach enables a comprehensive assessment of the disaster's impact under varying societal and operational conditions. Such an analysis is essential for understanding the dynamic nature of vulnerability and risk across different periods, thereby enhancing the effectiveness of disaster management strategies.

Simulating the earthquake at its original occurrence time provides insights into the immediate impacts as they unfolded. This includes evaluating the effects on residential areas, infrastructure, and the population's activities during the time of the event. For instance, if the earthquake occurred during nighttime, a significant proportion of the population would likely be at home, necessitating an emphasis on residential building resilience and nighttime evacuation planning.

Conversely, simulating the same earthquake during typical working hours introduces an alternate scenario where urban dynamics are markedly different. During these hours, a large segment of the population is likely to be in workplaces, schools, or public spaces. This simulation allows for the evaluation of risks to commercial and

institutional buildings, as well as the efficiency of emergency response mechanisms in highly populated areas such as business districts or educational campuses. Additionally, transportation networks and road infrastructure are critical components of this scenario, given the potential for traffic congestion or road blockages during peak hours.

By incorporating these temporal variations, the simulation can identify time-dependent vulnerabilities and resource needs, enabling the development of targeted mitigation measures and contingency plans. For example, the findings may highlight the need for alternate emergency evacuation routes during working hours or increased focus on residential building safety for nighttime scenarios.

5.5. Discussion of Results

The damage assessment conducted for the AoI classified buildings into five categories based on the extent of seismic damage: Complete, Extensive, Moderate, Slight, and No Damage. Among the 302,000 buildings analyzed, the results indicate a diverse distribution of damage levels across the urban landscape.

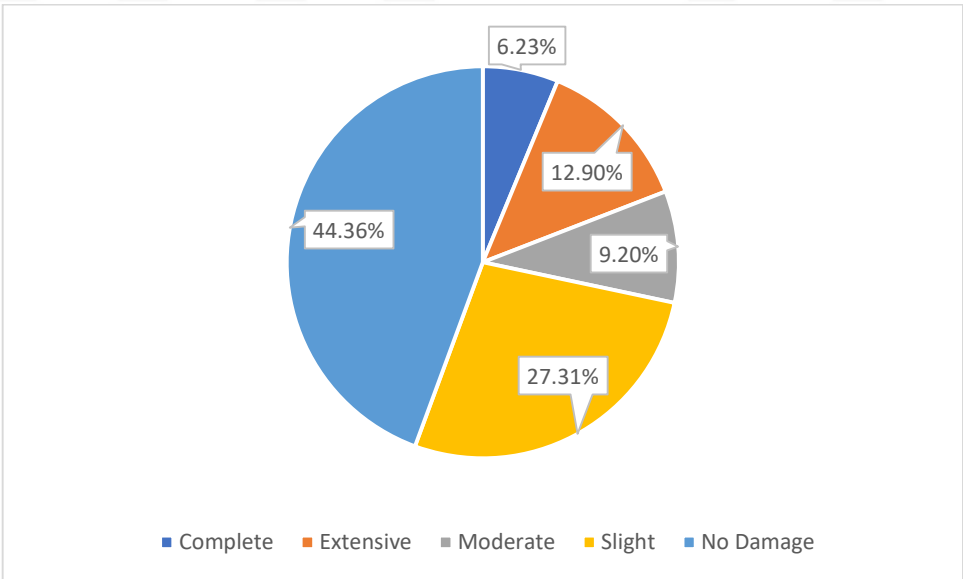


Figure 5.15: Damage state distribution of structures

Approximately **44.36%** of buildings, corresponding to 133,719 structures, were categorized as experiencing **No Damage**. These buildings remained structurally unaffected, showcasing a combination of resilient construction practices and favorable

seismic conditions in specific areas. The **Slight damage** category accounted for **27.30%** of the buildings, or 82,300 structures, reflecting minor non-structural impairments such as cracks in walls or dislodged fixtures. These damages are typically repairable and do not compromise the structural integrity of the buildings. Buildings experiencing **Moderate damage** totaled **9.20%** (27,743 structures). These damages included partial structural impairments, such as weakened walls or floors, that require significant repairs but are unlikely to lead to building collapse. The **Extensive damage** category, encompassing **12.90%** (38,878 buildings), represents severe structural impairments. These buildings may have sustained compromised load-bearing elements and are at high risk of collapse or require demolition. Finally, **Complete damage**, indicating total structural failure, was observed in **6.23%** of the buildings, equivalent to 18,769 structures. These buildings are deemed uninhabitable and likely resulted in significant casualties and displacement.

The analysis underscores the necessity for targeted interventions, particularly for buildings in the Extensive and Complete damage categories, to prioritize recovery efforts and enhance future resilience. Furthermore, the high percentage of buildings with No Damage or Slight Damage highlights areas of effective seismic design that could inform broader urban planning and risk reduction strategies.

Understanding the distribution of casualties based on damage severity is essential for effective disaster response and resource allocation. By analyzing the probabilities of casualty severities within various damage states, planners and responders can identify the scale and complexity of medical and logistical needs in the aftermath of a disaster. This process allows for a structured approach to anticipating demands and ensuring that resources are distributed equitably and efficiently.

The stratification of casualty severity into categories ranging from minor injuries to fatalities highlights the nuanced nature of disaster impacts. For instance, in areas of no damage, 127,033 individuals fall into Severity 1, representing minor injuries requiring basic medical attention. Conversely, in areas experiencing complete damage, the number of individuals requiring such attention drops significantly to 939. More severe injuries and fatalities become prominent in higher damage states. In extensive damage scenarios, 6,880 individuals fall under Severity 3, requiring urgent medical attention, while 4,587 fatalities are recorded under Severity 4. These figures reflect the

heightened risk to life in areas experiencing significant structural failure or widespread destruction.

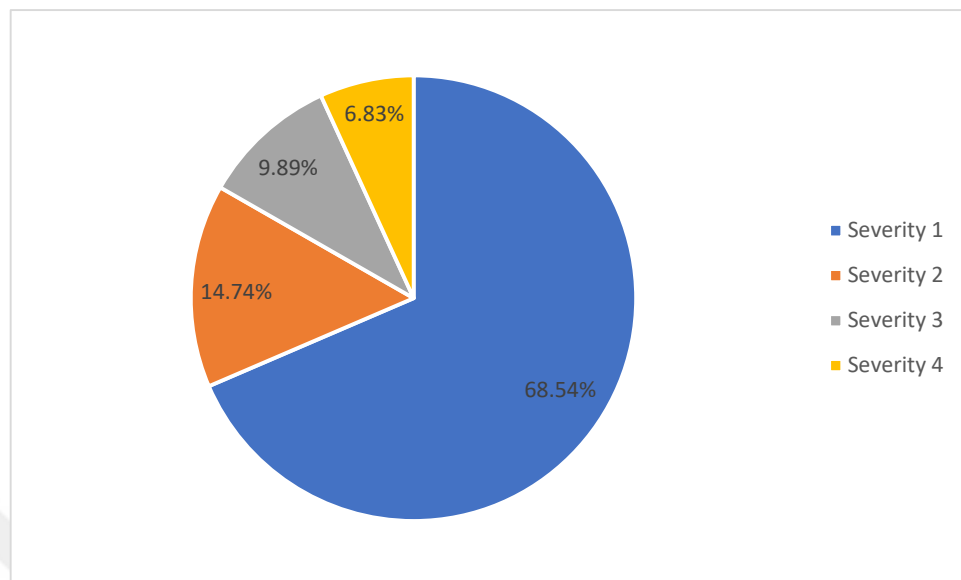


Figure 5.16: Casualty calculations

Such modeling enables responders to forecast the demand for advanced medical facilities and trauma care in areas experiencing extensive or complete damage. For example, casualties in complete damage areas include 7,841 individuals in Severity 4 (immediate fatalities) and 6,569 individuals in Severity 3, requiring expeditious rescue. Similarly, moderate damage results in a more balanced distribution, with 13,872 individuals in Severity 1 and 1,387 in Severity 4. This gradient underscores the varying levels of resources needed across different zones.

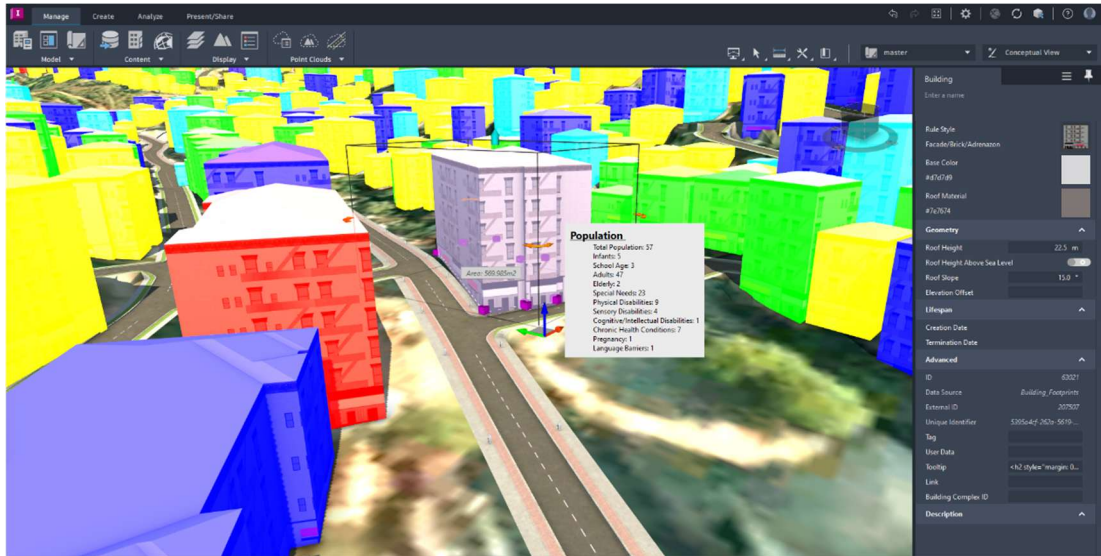


Figure 5.17: Demographics over the model

By aggregating casualty data across all severity levels and damage states, the model reveals the total number of casualties for each severity class: 145,128 for Severity 1, 64,943 for Severity 2, 38,835 for Severity 3, and 14,760 for Severity 4. These aggregates provide a holistic view of the disaster's impact, supporting strategic decision-making for resource allocation. For instance, the high prevalence of Severity 1 injuries highlights the need for mobile clinics and basic medical aid, whereas the significant numbers in Severities 3 and 4 emphasize the necessity for specialized rescue teams and trauma care facilities.

Understanding the interplay between damage states and casualty severities is vital for effective disaster management. It ensures that resources are deployed where they are needed most and helps mitigate the adverse effects on affected populations. This approach not only addresses immediate needs but also strengthens the overall resilience of communities in the face of future disasters.

6. APPLICATION OF CIM-BASED FRAMEWORK in EARTHQUAKE RISK MANAGEMENT

6.1. Decision Support for Emergency Response

Effective emergency response during seismic events necessitates robust decision-support systems (DSS) that integrate real-time data, predictive modeling, and spatial analytics. The seismic risk digital twin (SRDT) developed for the Kocaeli region exemplifies an advanced framework designed to facilitate informed decision-making and optimize emergency response efforts. By providing actionable insights based on comprehensive modeling and live data integration, the SRDT supports the coordination and prioritization of critical response activities.

A key strength of the SRDT is its capacity to incorporate real-time data streams from seismic monitoring stations, infrastructure sensors, and communication networks. This capability allows emergency managers to promptly assess the earthquake's impact, identify high-priority areas, and allocate resources accordingly. For instance, integrating ground motion parameters, such as PGA, into the model enables the rapid identification of regions with heightened structural vulnerability, ensuring that rescue and relief efforts are directed toward areas with the greatest need.

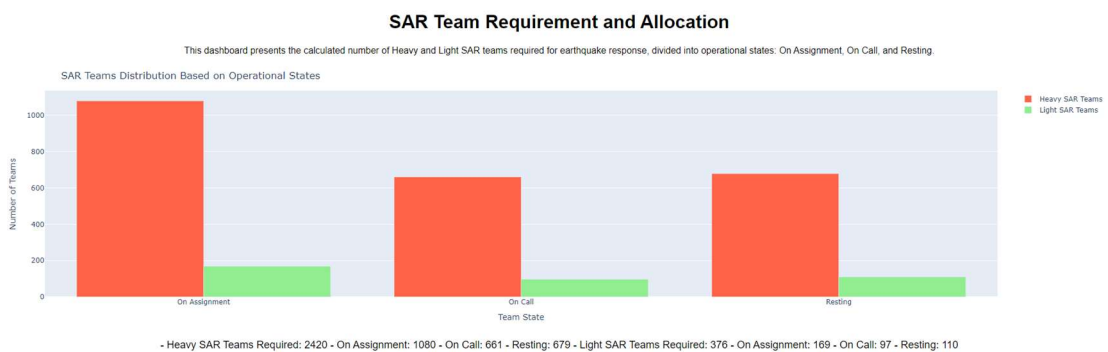


Figure 6.1: SAR operations management

The SRDT also excels in estimating the number and location of individuals trapped under debris, a critical component of search and rescue operations. By leveraging data on building damage classifications (e.g., Complete or Extensive Damage), occupancy patterns, and demographic distributions, the system provides precise estimations of

trapped individuals. This functionality not only enhances the allocation of search and rescue resources but also enables targeted interventions that maximize the likelihood of saving lives.

Another pivotal application of the SRDT is its analysis of emergency muster sites, which are essential for evacuating and temporarily sheltering affected populations. The system evaluates the capacity and accessibility of these sites, identifying areas where overcrowding may occur due to limited space. By prioritizing such locations for additional support or rerouting evacuees to alternative shelters, the SRDT minimizes risks associated with overcrowding and ensures safer conditions for evacuees.

In addition to addressing human impact, the SRDT provides a comprehensive assessment of infrastructure and utilities within the affected area. By identifying damaged or inaccessible roads, bridges, and utility networks, the system supports the efficient planning of logistics for emergency response teams and the distribution of essential supplies. The inclusion of underground utility networks, such as natural gas and water pipelines, further enables the identification of potential secondary hazards, such as gas leaks or water contamination, which can be mitigated promptly to prevent further harm.

The DSS embedded within the SRDT also facilitates enhanced communication and coordination among stakeholders. By offering a unified interface for emergency managers, first responders, and government officials, the system enables the sharing of critical information, visualization of dynamic scenarios, and streamlined coordination of response activities. Real-time updates on rescue operations, casualty numbers, and resource availability ensure that decisions are based on the latest information, fostering a cohesive and efficient response strategy.

The strategic implications of integrating decision-support functionalities into the SRDT are significant. By combining predictive modeling, spatial analysis, and real-time monitoring, the system accelerates decision-making processes while minimizing human and material losses during seismic disasters. As demonstrated in the Kocaeli case study, the SRDT provides a powerful tool for building resilience and enhancing the safety and well-being of affected populations. Its potential applications extend beyond the immediate context, offering a model for disaster preparedness and response in other seismically vulnerable regions.

6.2. Comparison with Traditional Earthquake Management Techniques

The adoption of advanced systems, such as the Seismic Risk Digital Twin (SRDT), marks a significant departure from traditional earthquake management approaches. Traditional methods, while effective to an extent, often rely on static risk assessments, generalized resource allocation, and manual coordination during emergencies. In contrast, digital twin technologies integrate real-time data, dynamic modeling, and advanced analytics, providing a comprehensive and adaptive framework for managing seismic risks.

Traditional earthquake management techniques typically involve pre-disaster planning based on historical data and static risk maps. These approaches offer a generalized understanding of seismic hazards but often lack the granularity needed for precise decision-making during an event. For example, conventional methods may categorize areas by broad risk zones without considering detailed building vulnerabilities or demographic distributions. This limits their ability to prioritize specific structures or populations during emergency response operations.

In contrast, the SRDT enables a more detailed and dynamic assessment of seismic risks. By integrating real-time ground motion data and predictive models, the SRDT provides a localized understanding of seismic impacts at the building level. It incorporates variables such as construction year, structural type, and occupancy to estimate damage and casualty numbers with high precision. This level of detail allows for targeted interventions, optimizing the allocation of search and rescue resources and minimizing response times.

Coordination challenges are another limitation of traditional earthquake management. Manual communication and reliance on disparate systems often hinder effective collaboration among emergency response teams and stakeholders. Traditional approaches may struggle with the real-time synchronization of data, leading to delays in decision-making and resource deployment. The SRDT addresses these issues by serving as a centralized platform for data integration and communication. It provides a unified interface for sharing information, visualizing scenarios, and coordinating response efforts, thus enhancing operational efficiency.

Resource management is another area where traditional techniques fall short. In many cases, resource allocation is based on pre-established contingency plans that may not reflect the actual conditions of a disaster. For instance, the distribution of emergency supplies or the selection of muster sites may be misaligned with the most affected areas. The SRDT mitigates this by analyzing real-time data on damage and population distribution to ensure that resources are directed to the areas of greatest need. It also evaluates the capacity and suitability of muster sites, identifying potential overcrowding issues and recommending alternative solutions.

Furthermore, traditional methods often overlook the potential of predictive modeling for preemptive decision-making. While historical data remains a cornerstone of risk assessment, it does not account for evolving urban environments or infrastructure changes. The SRDT incorporates predictive simulations, allowing for scenario testing and impact forecasting. This proactive approach supports strategic planning and helps mitigate the risks associated with rapidly changing urban landscapes.

While traditional earthquake management techniques have been instrumental in establishing foundational disaster response protocols, they are limited by their static nature and lack of integration. The SRDT offers a transformative approach by combining real-time data, predictive modeling, and centralized coordination to enhance the accuracy, efficiency, and adaptability of seismic risk management. This comparison highlights the potential of digital twin technologies to address the shortcomings of traditional methods, paving the way for more resilient and effective disaster management systems.

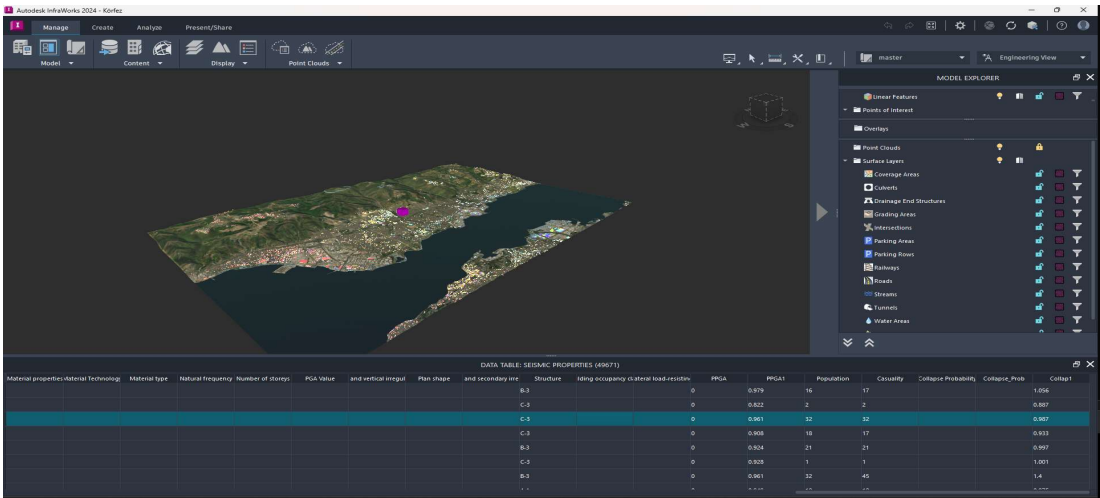


Figure 6.2: General overview of models situation and needs analysis

7. RESULTS AND DISCUSSION

7.1. Implications for Smart Disaster Management

Traditional seismic risk management tools often struggle with integrating multidisciplinary data, accounting for uncertainties in seismic activity, and adapting to rapid urbanization. Furthermore, reliance on historical earthquake records and deterministic models can limit their ability to predict or mitigate emerging risks effectively. Limitations in incorporating socio-economic and environmental factors, such as population growth, informal settlements, and climate-induced changes, further exacerbate these challenges.

As technological advancements and novel data sources become more accessible, the gaps in traditional approaches are increasingly apparent. This necessitates a critical evaluation of their shortcomings and an exploration of innovative solutions that can enhance their efficacy. By understanding the challenges of traditional tools, seismic risk management can evolve to meet the demands of complex, interconnected systems and build resilience against future earthquakes.

7.1.1. Data Gaps and Quality

One of the prominent and recurring challenges is the presence of data gaps. The complexity and uncertainty inherent in seismic risk management necessitate robust methodologies to handle imprecise data, as demonstrated by the use of fuzzy set theory to manage uncertainties in risk parameters, which enhances the reliability of risk models [7]. These gaps refer to the inadequacies and limitations in the data available for understanding, assessing, and managing seismic risk. Data gaps can impede the development of accurate hazard assessments, vulnerability analyses, and risk mitigation strategies [288].

Historical data gaps are a common issue. This deficiency in historical data makes it challenging to accurately assess the frequency and severity of seismic hazards. Geological and geophysical data are essential for comprehending the subsurface structure and identifying active fault lines. However, data gaps in these areas can hinder hazard assessment and source characterization. Additionally, monitoring

networks, which provide real-time data from seismic and GPS stations, might be limited in some regions. Data related to environmental factors, such as groundwater levels and soil characteristics, as well as climate data that may influence seismic activity, are sometimes insufficient. Information about the construction materials, design, and vulnerabilities of buildings and infrastructure may be incomplete, making it difficult to assess their susceptibility to seismic forces. Accurate population data, including the distribution of vulnerable populations, is crucial for emergency planning and response but can be outdated or incomplete in some areas. Socioeconomic data, such as income levels, access to healthcare, and social vulnerability factors, may not be readily available or may lack granularity. Furthermore, satellite and remote sensing data used for monitoring ground movements and surface deformations can have gaps due to cloud cover or limitations in imaging frequency.

The consequences of data gaps are far-reaching and impactful. Insufficient data can lead to inaccuracies in hazard assessments, vulnerability analyses, and risk models, potentially underestimating or overestimating seismic risk. Incomplete or low-quality data can lead to overestimation or underestimation of seismic hazards, as seen in the comparison of local and national datasets for seismic loss estimates in Montreal, where the national model overestimated losses by up to 30% compared to the local model [289]. The lack of data can introduce uncertainty in the design and implementation of mitigation strategies, making it challenging to prioritize risk reduction efforts effectively. Incomplete data can hinder emergency planning and preparedness efforts, leading to inadequate response strategies. Data gaps, such as those caused by short-term aftershock incompleteness, can bias analyses and necessitate reconstruction techniques like Singular Spectrum Analysis to fill these gaps more reliably than traditional interpolation methods [290], [291]. Policy formulation and governance frameworks may face challenges due to incomplete or outdated data, affecting the ability to enact and enforce regulations related to seismic risk management. Moreover, data gaps can limit efforts to raise public awareness and educate communities about seismic risks and preparedness measures.

To address these data gaps, several strategies and approaches can be employed. Investing in data collection and monitoring networks, including seismic and geophysical instruments, remote sensing technologies, and population surveys, can help fill data gaps and enhance the quality of available data [292]. Encouraging

collaboration between government agencies, research institutions, and international organizations can facilitate data sharing and improve data quality. Leveraging advanced technologies such as satellite imaging, machine learning, and artificial intelligence can help extrapolate and interpolate data in regions with limited data availability. Effective risk communication plays a vital role in helping stakeholders and the public understand the limitations of available data and the implications for risk management. Addressing data gaps is crucial for enhancing the accuracy and effectiveness of seismic risk management strategies, and DTs and data integration can play a significant role in mitigating data gaps by providing a comprehensive and dynamic view of the physical and social environment, aiding in hazard assessment and risk analysis.

The proposed modeling framework integrates multi-source data to address the spatial and temporal gaps inherent in seismic risk management. By combining data from diverse sources, including monitoring networks, satellite imaging, and remote sensing technologies, the framework enhances the comprehensiveness and resolution of datasets. This multi-source integration ensures a more accurate representation of geological, environmental, and socio-economic variables, which are critical for reliable hazard assessment and risk modeling.

Advanced analytical techniques form the backbone of the framework, enabling it to manage imprecise and incomplete datasets effectively. For instance, the incorporation of fuzzy set theory allows for the quantification of uncertainties in risk parameters, while machine learning algorithms facilitate the identification of patterns and relationships within fragmented data. Additionally, Singular Spectrum Analysis (SSA) is employed to reconstruct incomplete datasets, providing a robust alternative to traditional interpolation methods. These techniques collectively mitigate the biases introduced by data gaps and enhance the precision of risk estimates.

The integration of digital twin technology represents a transformative aspect of the framework. Digital twins create dynamic, virtual replicas of both physical systems and social environments, offering a holistic perspective on seismic risk. By continuously incorporating real-time data, these digital models enable the simulation and analysis of complex scenarios, improving the accuracy of hazard assessments and the effectiveness of response strategies. This approach ensures that decision-making

processes are informed by the most up-to-date and comprehensive information available.

Collaboration among stakeholders is a critical component of the framework's design. By fostering partnerships between government agencies, research institutions, and international organizations, the framework promotes data sharing and standardization, addressing inconsistencies in data quality and accessibility. This collaborative approach not only enhances the robustness of the datasets used but also facilitates the development of harmonized risk mitigation strategies.

Finally, the framework emphasizes the importance of transparent and effective risk communication. By clearly articulating the limitations and uncertainties associated with available data, it ensures that stakeholders—including policymakers, emergency planners, and the public—are equipped to make informed decisions. This transparency builds trust and fosters a shared understanding of the challenges and opportunities inherent in seismic risk management.

Through these comprehensive and innovative solutions, the modeling framework significantly advances the field of seismic risk management. It addresses critical data gaps, enhances the accuracy of risk assessments, and supports the development of effective, adaptive mitigation strategies.

By addressing data gaps and quality problems, our modeling framework ensures greater accuracy and reliability in seismic hazard assessments, vulnerability analyses, and risk mitigation strategies. It supports the prioritization of risk reduction efforts, improves emergency planning, and strengthens governance frameworks. Furthermore, the integration of advanced technologies ensures scalability and adaptability, making the framework a powerful tool for dynamic and effective seismic risk management.

7.1.2. Public Awareness and Education

The significance of public awareness and education in seismic risk management cannot be overstated, as they play a crucial role in enhancing the resilience of communities and individuals when confronted with seismic events [293]. These components play a crucial role in equipping society with the knowledge and comprehension required to address earthquake threats.

To begin with, the dissemination of information and educational initiatives within the public sphere contribute to an enhanced understanding of the potential hazards associated with seismic events, so helping citizens to develop a more profound awareness of their gravity. The aforementioned consciousness has the potential to operate as a stimulant for a more proactive stance towards readiness, instilling a sense of duty towards one's personal safety as well as the protection of their community. In addition, towns with higher levels of education possess greater capabilities to successfully address earthquakes, rebound from their consequences, and provide assistance to their constituents throughout and following the occurrence, thus augmenting the overall resilience of the community.

The dissemination of information and the promotion of knowledge among the general public are crucial in effectively managing and reducing panic levels in the event of earthquakes [294]. Individuals who possess knowledge and understanding of safety protocols and the correct responses to seismic events are more inclined to remain composed and less susceptible to experiencing panic. On the contrary, individuals tend to exhibit a propensity for composed reactions, thereby alleviating the disorder and anxiety that may intensify the consequences of an earthquake. The level of readiness is contingent upon persons possessing knowledge of appropriate actions to take in the event of an earthquake, as well as strict adherence to evacuation protocols.

However, there are various obstacles that hinder the smooth transmission of public knowledge and education on seismic risk management. In some geographical areas, there exists a notable deficiency in knowledge pertaining to the risks associated with earthquakes, whereby the general population tends to underestimate the possible consequences of seismic occurrences. Promoting community engagement and cultivating active participation in earthquake preparedness and response endeavors also presents significant hurdles.

In order to effectively tackle these difficulties, it is imperative to adopt a comprehensive and multidimensional approach. Education initiatives, which encompass comprehensive information regarding earthquake dangers, safety protocols, and preparedness measures, have the potential to significantly enhance public knowledge. The inclusion of earthquake preparation into school curricula guarantees that children and young adults receive comprehensive education regarding the potential hazards associated with seismic events from an early stage of their

academic journey. The utilization of diverse media platforms, including radio, television, social media, and mobile applications, plays a pivotal role in the distribution of earthquake-related information and updates. The involvement of community leaders, religious figures, and local authorities in the dissemination of earthquake awareness and education has the potential to mobilize community engagement. The implementation of earthquake drills and simulations serves to acquaint the general population with reaction protocols and behaviors, so fostering a state of preparedness.

The implementation of robust public awareness and education initiatives can greatly augment a community's capacity to effectively address and rebound from seismic occurrences. Digital tools and technologies, such as interactive simulations and mobile applications, play a crucial role in educating the general people and delivering up-to-date information in the event of earthquakes. These tools contribute significantly to enhancing society's ability to withstand seismic threats and increase overall resilience.

7.1.3. Policy and Governance

The establishment of robust policies and governance frameworks provide the necessary legal and regulatory mechanisms to facilitate earthquake planning and response efforts. Nevertheless, there are certain obstacles that need to be addressed in order to successfully establish and implement these regulations, as well as ensure their effectiveness in mitigating seismic risk. The aforementioned obstacles necessitate a more thorough analysis in the domain of policy and governance pertaining to seismic risk management.

The importance of policy and governance is in their function of establishing norms and standards pertaining to development, land utilization, and preparedness for emergencies. The implementation of these standards is crucial in order to effectively reduce seismic risk and guarantee the durability and adaptability of populations and infrastructure located in regions prone to earthquakes. The allocation of resources is a crucial function of governance structures, as it ensures that sufficient money is designated for the purpose of properly addressing seismic hazards through mitigation, readiness, response, and recovery initiatives. Moreover, the establishment of efficient governance frameworks plays a crucial role in promoting the coordination and communication between various entities, including agencies, organizations, and

stakeholders involved in the management of seismic risks. This, in turn, enhances the ability to respond cohesively to earthquake events. Policies and governance structures establish a framework by which governments and organizations may be held responsible for their efforts in mitigating seismic risk and their actions in reaction to earthquake events.

Nevertheless, the field of policy and governance in seismic risk management is faced with numerous obstacles. Certain locations face challenges due to the lack of comprehensive rules and regulations that effectively address seismic risk. This includes crucial aspects such as building codes, land use planning, and emergency response methods. Insufficient enforcement of policies, despite their existence, can result in non-compliance, hence increasing the levels of seismic risk. The institutional framework might exhibit fragmentation, as many agencies and groups assume distinct responsibilities pertaining to different aspects of seismic risk management, hence impeding coordination efforts. In some geographical areas, there is a scarcity of technical and administrative expertise, which poses obstacles to the progress and successful execution of policies and governance structures. The formulation and enforcement of comprehensive seismic risk management strategies may face obstacles due to political interests, economic constraints, and conflicting agendas. Engaging local communities and stakeholders in the process of policy creation and governance decisions presents an additional significant obstacle.

To effectively tackle these policy and governance difficulties, it is imperative to adopt a comprehensive approach. This entails the formulation of comprehensive and empirically supported rules and regulations pertaining to seismic risk management, encompassing construction codes, land-use planning, and zoning. The primary objective of capacity building initiatives is to augment the technical and administrative competence of both governmental and non-governmental entities. This is done with the intention of facilitating the efficient execution and enforcement of policies. The implementation of coordination structures that facilitate the collaboration of diverse stakeholders, governmental entities, and organizations engaged in the management of seismic risks promotes a unified and synchronized approach. The inclusion of the public in the creation and decision-making processes of policies serves to ensure their local relevance and promote widespread support. It is imperative to advocate for political dedication in prioritizing seismic risk management and allocating resources

towards risk reduction. Effective management of trans-boundary seismic risks can be achieved through collaboration with international organizations and neighboring countries.

7.1.4. Technological Limitations

Technological limitations refer to the obstacles related to the accessibility and efficacy of technology employed in the field of seismic risk management. Although technology has the potential to greatly improve risk assessment, early warning systems, and response tactics, there are various challenges that hinder its complete utilization.

The creation and operation of early warning systems heavily depend on technological advancements, enabling the timely delivery of vital signals prior to the arrival of seismic waves in densely populated regions. Cutting-edge technology, encompassing a range of sophisticated tools such as sensors, satellites, and modeling software, assumes a crucial role in the gathering and examination of data for the purpose of hazard evaluation and continuous surveillance. Furthermore, the utilization of technology facilitates expeditious communication and the swift transmission of information both during and in the aftermath of an earthquake. This capability greatly enhances the ability to respond promptly and coordinate effectively among various parties involved.

Nevertheless, the environment of technological restrictions presents a multitude of obstacles.

- **Resource Constraints:** The availability of limited financial resources might hinder the implementation and upkeep of sophisticated technologies, especially in regions that have restricted budgets and resources.
- The presence of insufficient infrastructure, including inconsistent power and communication networks, might hinder the efficacy of technology in early warning systems and response efforts.
- The challenges associated with data quality and availability arise from the presence of data gaps and concerns over the accuracy and reliability of data utilized in technical applications, such as hazard assessment and modeling.

- The achievement of interoperability, which refers to the ability of diverse technologies and systems to effectively collaborate and exchange data, is a persistent obstacle in the pursuit of a comprehensive seismic risk management strategy.
- The importance of accessibility lies in its role in facilitating the successful adoption and utility of technology among many stakeholders, such as the public and local authorities. It is crucial to ensure that technology is accessible and user-friendly to a wide range of individuals in order to achieve this objective.
- In the digital era, the protection of technological systems against cyber-attacks and the maintenance of data security have emerged as significant problems, necessitating the implementation of strong cybersecurity protocols.
- The development of technical ability among individuals and organizations is of paramount importance in ensuring the efficient operation and maintenance of technologies for the management of seismic risks.

Mitigating these technological constraints necessitates a comprehensive and multidimensional strategy.

- The mobilization of resources, particularly financial resources, is a crucial aspect in the allocation of funds towards the advancement and implementation of vital technologies for the purpose of managing seismic risks.
- Infrastructure Development: In order to address deficiencies in infrastructure, it is important to undertake expansion initiatives that involve enhancing communication networks and ensuring the availability of dependable power sources. These efforts are crucial for facilitating the effective operation of technology.
- The assurance of data quality and the promotion of data standardization play crucial roles in addressing technical issues and enhancing interoperability in technological applications.
- Training and capacity building are crucial components in enabling individuals and organizations to successfully harness technology for the purpose of managing seismic risks.

- The support of research and development has a critical role in developing technological capabilities, namely in the areas of early warning, hazard assessment, and response.

The mitigation of technological limits is of utmost importance in order to fully use the capabilities of technology in the field of seismic risk management. Digital twins and advanced modeling software are essential in mitigating these constraints by offering a holistic perspective of the physical surroundings and facilitating the evaluation of potential hazards and risk modeling. Consequently, they play a crucial role in enhancing the efficacy of seismic risk management systems.

7.1.5. Resource Constraints

Resource constraints play a crucial role in the management of seismic risks, comprising constraints in financial, material, and human resources that might hinder the formulation and implementation of effective solutions for risk management. The limitations possess extensive ramifications, impacting various aspects of seismic risk management, including hazard assessment, preparedness, response, and recovery endeavors.

Sufficient resources play a crucial role in facilitating the execution of mitigation strategies, including the retrofitting of structures, fortification of vital infrastructure, and strategic land use planning aimed at minimizing seismic hazards. Furthermore, the availability of resources plays a crucial role in determining the ability to facilitate recovery endeavors, such as the restoration or rebuilding of infrastructure, the provision of humanitarian assistance, and aid to impacted communities.

However, a multitude of issues emerge within the context of resource limitations.

- The presence of funding shortages is a substantial obstacle, impacting the accessibility of resources necessary for implementing risk reduction and preparedness initiatives. Insufficient allocation of financial resources might pose substantial obstacles to the effective implementation of seismic risk control initiatives.
- The execution of good risk management techniques may be hindered by a lack of adequately qualified individuals and technical knowledge. The scope of

resources expands beyond financial factors to embrace the human capabilities necessary for the management of risks.

- The allocation of resources might provide a hindrance to investments in infrastructure enhancements that seek to enhance the resilience of buildings and key systems against seismic impacts. This constraint presents difficulties in the context of long-term risk mitigation.
- Public investment goals play a crucial role in determining the distribution of resources, and in some cases, may prioritize alternative expenditures over the management of seismic risks. Resource restrictions can arise as a result of this, impeding proactive measures to reduce risks.
- The presence of economic uncertainty on a global scale can exacerbate the challenges associated with resource allocation for risk management initiatives, as economic downturns or crises at both national and international levels can restrict the availability of resources. This, in turn, adds complexity to the process of allocating scarce resources.

In order to effectively manage limited resources, it is imperative to adopt a comprehensive and multidimensional strategy.

- The process of resource mobilization involves the acquisition of financing from many channels, such as government budgets, international aid, and public-private partnerships. This stage is of utmost importance in order to obtain the required resources for effectively supporting risk reduction initiatives.
- Capacity building is a crucial process that involves enhancing the technical and administrative capabilities of governmental agencies, companies, and individuals engaged in seismic risk management. This process is essential in order to address and overcome limitations in resources.
- Risk finance involves the establishment and advancement of mechanisms aimed at managing and mitigating risks, such as insurance and catastrophe bonds. These mechanisms provide avenues for consolidating resources to facilitate the process of recovery and reconstruction following seismic disasters.

- Resource allocation strategies refer to the methods and approaches used to distribute and assign resources in an efficient and effective manner. These strategies are employed in various contexts, such as business organizations. The implementation of techniques aimed at prioritizing the allocation of resources for seismic risk management, taking into consideration both the potential impact and likelihood of earthquakes, is of utmost importance in order to assure the appropriate direction of resources.
- Advocacy and Awareness: The act of advocating for the significance of seismic risk management and fostering awareness among policymakers and the general public play a crucial role in mobilizing the requisite resources for endeavors aimed at reducing risk.
- Efficient resource utilization is a critical factor in risk management, since it involves ensuring the effective use of available resources, optimizing resource allocation, and eliminating waste.

Effectively handling resource limitations is crucial in ensuring that communities are sufficiently prepared to mitigate and respond to seismic disasters. Digital twins play a significant part in this undertaking by providing data-driven insights on areas of high vulnerability and the efficacy of risk mitigation measures. Consequently, they assist in the optimization of resource allocation.

7.2. Challenges and Limitations

The integration of **CIM** and **DT** technologies into earthquake management holds immense potential. However, the process is fraught with several challenges and limitations that must be addressed for successful implementation. These challenges span technical, operational, financial, and institutional domains, each contributing to the complexity of adopting these advanced technologies.

From a technical perspective, ensuring the quality and availability of data is a primary challenge. Accurate CIM and DT models rely on comprehensive, up-to-date datasets from various sources. However, gaps in data or outdated information can significantly reduce the reliability of simulations and analyses. Moreover, integrating data from diverse sources such as GIS, population databases, and seismic monitoring systems is often complicated by differences in formats and standards. Additionally, modeling

large cities with highly detailed 3D data demands substantial computational resources, posing scalability issues. Real-time updates for DTs, essential during disasters, require a robust IoT and sensor network infrastructure, which may not be fully established in many regions.

Operational challenges further complicate the adoption of these technologies. Developing and utilizing CIM and DT systems demand specialized skills and expertise, which may not be readily available in some organizations or regions. Effective deployment also requires seamless coordination among multiple stakeholders, including government agencies, private sectors, and academic institutions. This coordination is particularly challenging in the chaotic and unpredictable environment of a disaster, where rapid decision-making and data interpretation are critical.

Financial constraints pose another significant barrier. The initial costs of developing CIM and DT frameworks are high, involving investments in advanced software, hardware, and skilled personnel. Even after implementation, maintaining and updating these systems requires ongoing financial resources, which may be difficult to secure, particularly for cities with limited budgets or competing priorities.

Institutional limitations also play a crucial role. The lack of clear policies and regulatory frameworks for the adoption of CIM and DT technologies can hinder progress. Data privacy and security concerns are heightened in the context of these systems, as they often involve managing large volumes of sensitive data. Ensuring robust safeguards to address these concerns is critical but can be resource-intensive. Additionally, resistance to change from stakeholders accustomed to traditional methods of disaster management can slow the adoption of these innovative approaches.

Finally, physical and environmental constraints add another layer of complexity. The resilience of the infrastructure supporting CIM and DT systems, such as communication networks and servers, is crucial, especially during disasters. However, ensuring their functionality in adverse conditions is a challenge. Furthermore, the inherent unpredictability of earthquake events, including cascading failures and unforeseen secondary hazards, limits the precision and reliability of even the most advanced models.

Addressing these challenges will require a combination of technical innovation, capacity-building efforts, collaborative governance, and sustainable investment strategies. By overcoming these limitations, the transformative potential of CIM and Digital Twin technologies to enhance urban resilience in the face of seismic hazards can be fully realized.



8. CONCLUSION

The study and implementation of the Seismic Risk Digital Twin (SRDT) in the Kocaeli region have demonstrated the transformative potential of digital twin technologies in advancing earthquake management practices. By integrating a wide range of data sources, including geospatial, structural, demographic, and real-time sensor data, the SRDT offers a comprehensive and dynamic platform for understanding and mitigating seismic risks. Its capabilities extend across all phases of disaster management, from preparedness and mitigation to emergency response and recovery, establishing it as a crucial tool for enhancing urban resilience.

Key findings from the study emphasize the advantages of the SRDT over traditional earthquake management techniques. The system's ability to dynamically assess building vulnerabilities, predict damage and casualties, and identify high-risk areas ensures that resources and response efforts are allocated with precision. Unlike conventional methods, which rely on static risk maps and generalized contingency plans, the SRDT provides a real-time, data-driven framework that adapts to evolving disaster scenarios. This adaptability not only reduces response times but also minimizes human and material losses during seismic events.

The SRDT also excels in improving coordination and decision-making during emergencies. By serving as a centralized platform for data integration, it facilitates effective communication among stakeholders, including emergency managers, government agencies, and first responders. The system's predictive modeling capabilities further enable preemptive planning and scenario testing, ensuring that cities are better prepared for future seismic events. Additionally, the evaluation of critical infrastructure, such as emergency muster sites and utility networks, underscores the SRDT's role in ensuring the safety and well-being of affected populations.

While the development and implementation of the SRDT highlight significant advancements in seismic risk management, this study also underscores the importance of continued research and refinement. Challenges such as ensuring data accuracy, integrating diverse data types, and addressing ethical considerations related to data privacy must be carefully managed. Moreover, the scalability of the SRDT to other

regions with varying urban and seismic characteristics presents an opportunity for future exploration.

In conclusion, the Kocaeli SRDT represents a paradigm shift in how seismic risks are managed in urban environments. By combining real-time data, predictive analytics, and centralized decision-support tools, the SRDT enhances the efficiency and effectiveness of earthquake management systems. Its success in the Kocaeli region provides a valuable blueprint for other seismically active areas, emphasizing the need for innovative, technology-driven approaches to disaster management. As cities continue to grow and face increasingly complex risks, the integration of digital twin technologies will be essential in building resilient and sustainable urban communities.



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BIOGRAPHY

Mustafa KORKMAZ earned a B.Sc. in Environmental Engineering from Atatürk University in 2005, followed by a B.Sc. in Civil Engineering from the same institution in 2006. In pursuit of further academic development, he completed his M.Sc. in Civil Engineering at Iğdır University in 2018. After graduation from university, Mustafa worked as a project controls engineer for 12 years, contributing to various high-profile projects, including petroleum refineries, hospitals, and residential developments. He then transitioned to academia and currently serves as a research assistant at Iğdır University. Mustafa is married and a proud father of three children, managing his professional and personal life with commitment and enthusiasm.



PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

[1] Korkmaz, M.; Zulfikar, A.C.; Demirkesen, S. Leveraging Digital Twins as a Common Operating Picture for Disaster Management: Case of Seismic Hazards. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 430.



APPENDICES

APPENDIX-A: Construction Unit Costs per Square Meter for Different Building Types and Classes in Turkey

Class	Group	Cost (TL/m ²)	Description
I. Class	A	1,450	Simple structures: farm shelters, covered resting areas, simple barns, soft plastic greenhouses, etc.
	B	2,100	Glass greenhouses, water tanks, basic commercial depots, simple animal shelters, etc.
II. Class	A	3,500	Towers, retaining walls, boathouses, etc.
	B	5,250	Small workshops, community parks, prefabricated agricultural buildings, etc.
	C	7,750	Hangars, single-story industrial structures, etc.
III. Class	A	12,250	Sports complexes, three-story residential/commercial buildings, small shopping centers, etc.
	B	14,400	Schools, health clinics, restaurants, mid-sized residential buildings, etc.
IV. Class	A	15,300	Administrative offices, thermal facilities, shopping malls, etc.
	B	17,400	Research centers, large health facilities, high-end residential structures, etc.
	C	18,700	Ministry offices, high-rise residential buildings, luxury hotels, etc.
V. Class	A	21,300	Broadcasting stations, skyscrapers, diplomatic residences, etc.
	B	22,250	Hospitals, scientific research centers, airports, etc.
	C	24,300	Five-star hotels, museums, library complexes, etc.
	D	26,800	Opera houses, theaters, historical restorations, etc.