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SYSTEM ANALYSIS AND DESIGN OF A SEISMIC DAMAGE ESTIMATION WEB PLATFORM USING MODEL-BASED ENGINEERING

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Predicting seismic damage is crucial in seismic engineering for constructing resilient buildings and enabling effective emergency responses. Traditional dynamic models for damage index estimation are complex and time-consuming, typically requiring specialized users. However, this process can be optimized and simplified using machine learning models, making it accessible to both engineers and non-specialized users. This paper proposes a formal system analysis procedure to determine the functional requirements and optimal architecture for a web platform that estimates building damage using machine learning, based on building parameters and seismic motion. The analysis identifies user profiles and adapts requirements to satisfy a wide range of users.

Keywords: system analysis, model-based system enrgineering, SysML, web application, damage index

1. Introduction

Accurate estimation of seismic damage in structures is a crucial component of earthquake engineering, serving as a foundation for designing resilient buildings and infrastructure. The potential consequences of earthquakes—ranging from structural failure to economic losses and loss of life—necessitate a thorough understanding of how various structures respond to seismic forces. Seismic damage estimation provides essential insights into the behavior of structures during earthquakes, enabling engineers and researchers

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to predict potential failure modes and assess the effectiveness of design strategies. By identifying vulnerable elements within a structure, this process informs the development of targeted retrofitting and reinforcement measures, thereby enhancing structural resilience.

Furthermore, seismic damage estimation is integral to the formulation of building codes and standards. It supports the creation of regulations that ensure new constructions are capable of withstanding seismic events, while also guiding the assessment and upgrading of existing structures. This proactive approach not only mitigates the risk of catastrophic failure but also contributes to public safety and economic stability. In addition to its role in engineering and design, seismic damage estimation is critical for disaster management and policy-making. It enables the quantification of potential economic losses, informing the allocation of resources for emergency preparedness and post-disaster recovery. The data generated from these estimations also play a significant role in the insurance industry, aiding in the assessment of seismic risk and the pricing of policies.

Damage assessment is a topic of significant interest among researchers, and the scientific literature is rich with important papers in this field. In one important recent paper [1] the authors proposed a regional-scale time history analysis method for evaluating seismic damage risk, addressing gaps in existing assessment techniques. The method included automated modeling, response calculation, and 3-D visualization, alongside a calculation method for building damage degrees (DD). The method's accuracy was validated using real earthquake damage data from 192 buildings affected by the Ludian Earthquake, providing a valuable tool for accurate seismic damage assessment and risk mitigation. In another recent paper [2], the authors assessed the seismic vulnerability of structures in high seismic zones using fragility curves derived from the HAZUS method. They applied a performance-based design to evaluate building capacity against seismic events in Padang. By calculating damage probability through a lognormal distribution, the study reveals a significant vulnerability to collapse, highlighting the importance of accurate seismic assessments to prevent structural failures during earthquakes. In [3] the authors proposed a rapid seismic-damage assessment method using deep learning and spectrum-compatible data augmentation. They addressed the challenge of limited strong ground motion data by using continuous wavelet transform (CWT) to generate augmented strong-motion data. This data was then applied to deep-learning algorithms for predicting building damage on a regional scale. The method was tested through case studies and compared to traditional data-augmentation approaches. Results showed that the proposed method reduces dispersion in seismic responses and improves prediction accuracy, achieving 87.4% accuracy with a processing time under 1 second. In another important paper [4], the authors developed a numerical model database for typical regular reinforced concrete (RC) frame structures to improve seismic damage simulation in large cities. Unlike existing models, which are based solely on structural theories and design codes, the models in their were calibrated using refined numerical models to enhance accuracy. The study includes the impact of reinforcement corrosion and construction year on structural performance. The accuracy of the models was validated by comparing them with refined models and real RC frame buildings. Furthermore in [5] the authors tackled the challenge of correlating changes in a structure's dynamic properties with specific damage levels for effective structural health monitoring (SHM). They applied a methodology using numerical analyses to assess damage based on SHM data. The study focused on 3D models of reinforced concrete buildings designed to non-seismic standards in the Mediterranean region. By conducting non-linear dynamic analyses and modal analyses, they captured variations in dynamic properties due to seismic events. The study assessed the probability of frequency changes at different damage levels, offering insights into damage detection and assessment.

The web platform developed in this paper estimates structural damage induced by earthquake excitation using the well-established Park-Ang Damage Index [6], which has been refined in subsequent research [7]. This index offers a robust and widely accepted method for quantifying damage to structural elements, providing a reliable assessment of seismic impacts on structural integrity. The platform leverages data from a large number of nonlinear dynamic analyses, utilizing a numerically efficient methodology previously developed by the authors [8, 9, 10]. Building on our previous work [11], which introduced non-linear machine learning algorithms for damage index estimation, this paper extends the analysis to propose these algorithms for broader public use via a web platform. We formally define the requirements for this platform, addressing the needs of both experienced and non-experienced users, and conclude with an architecture that guides implementation, mitigating the risks of developing an inaccessible or ineffective tool.

2. Relevant Research Initiatives in the Field

In recent years, researchers have explored various approaches to simplify the dynamic methods used to estimate damage indices. These approaches frequently utilize machine learning algorithms, which have emerged as powerful tools for providing accurate predictions in an efficient manner. Consequently, researchers and governing institutions have made significant contributions both in terms of datasets and software tools.

At the international level, the Global Earthquake Model Foundation has been developing tools and datasets for seismic hazard and risk assessment, with a key focus on the OpenQuake platform. OpenQuake is an open-source software capable of integrating machine learning models to predict the seismic performance of buildings and infrastructure. By standardizing seismic risk assessment methodologies globally, GEM initiatives facilitate the development of resilient infrastructure in earthquake-prone regions. Another notable platform is the Prompt Assessment of Global Earthquakes for Response (PAGER) system developed by the USGS, which estimates the impact of earthquakes globally. PAGER provides information on the impact of significant earthquakes worldwide, informing emergency response authorities, governments, aid agencies, and the media about the potential disaster's extent. It rapidly assesses earthquake impact by comparing the population exposed at each intensity level using economic and human loss models based on previous earthquakes in various countries or regions.

Another example is the SimCenter platform, under development at the University of California, Berkeley, which offers state-of-the-art computational modeling and simulation tools, user support, and educational materials for the natural hazards engineering research community. The goal is to enhance the national capability to simulate the impact of natural hazards on structures, utility networks, and communities. Additionally, the center enables leaders to make better-informed decisions regarding the necessity and effectiveness of potential mitigation strategies. It employs machine learning to improve modeling and simulation using data from experimental tests, field investigations, and previous simulations.

The Next Generation Attenuation (NGA) project, an ongoing research initiative at the Pacific Earthquake Engineering Research Center, contributes to the development of predictive models for seismic motion attenuation. This project integrates precise models that can estimate structural responses in various seismic scenarios.

Although the aforementioned research initiatives significantly advance hazard impact estimation, they often operate with large-scale data without providing specific analyses for certain types of buildings. In this context, investigating solutions that focus on estimating the damage index considering specific building-level characteristics would be valuable. Moreover, given the complexity of the parameters involved in both building and earthquake software modeling, exploring an approach for developing a platform suitable for both specialists and non-specialists in the construction field would be beneficial. Such a platform would engage a broader audience, fostering a deeper connection between people and the residential building construction domain.

A web platform would also represent a useful tool from a software perspective [12, 13, 14]. Web-based tools have become increasingly popular for interfacing various complex applications [15, 16], dedicated to both specialized and non-specialized users. However, in the research domain of structural analysis, to the best of our knowledge, the availability of such tools is either limited or confined to private institutions, making them inaccessible to the public.

A useful approach for desging such a web platform, given its novel character, is system analysis through the model-based system engineering (MBSE)

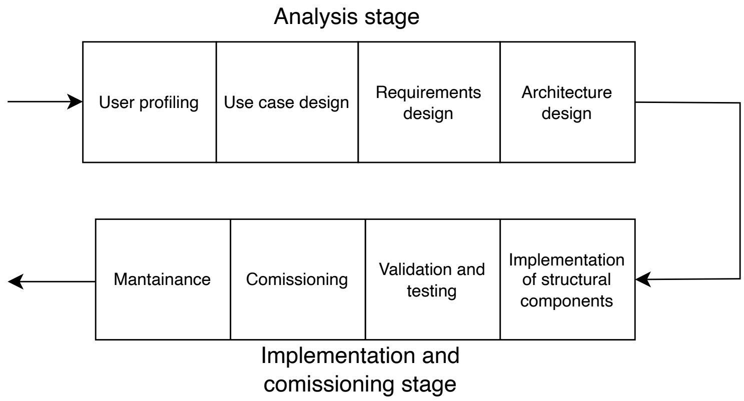

FIGURE 1. System design proposed method

formalism. This formal analysis involves developing diagram models that enable a robust, maintainable formulation of the system requirements and architecture. The foundation for this formalism is defined in reference works such as [17] and [18]. The diagrams used in this formalism, designed under the *SysML* standard, facilitate a more in-depth analysis of the connection between the system user and the informational system itself, regardless of the complexity [19].

3. Proposed method and formal analysis

The system analysis was based on a structured method that ensures a clear and detailed understanding of the necessary steps for developing a web platform integrating machine learning models. This method involves identifying user profiles, defining requirements, and designing the system architecture, followed by implementation, testing, and maintenance [17]. The diagram below illustrates these essential stages of the life cycle of such a system:

Consequently, the stages presented in Fig. 1 refer to:

- **Determining user profiles** - This first stage of the life cycle involves accurately identifying the actors who interact with the information system to be implemented. The user profile should outline the type of interaction, whether these users are the primary beneficiaries of the system or require a certain level of training to be able to interact with the system.
- **Identifying use cases** - This stage focuses on outlining the interactions between users and the system. Use case diagrams can be used for actual modeling of the use cases, or sequence diagrams can be employed to add a temporal dimension to the interaction representation [20].
- **Determining functional requirements** - This critical stage for system analysis highlights the main functionalities of the system, related to the needs of the beneficiaries. Functional requirements should express what the system does to facilitate user-system interactions defined previously in the use cases [21].

- **Designing an architecture** - This stage involves defining a system architecture that outlines how the system implements the proposed functional requirements. The architecture highlights potential technologies used and how they interact with each other.
- **Actual implementation** - This stage immediately follows system analysis and aims at the actual implementation of the system based on the proposed architecture.
- **Testing and validation** - At this stage, the functionalities of the system are tested and validated in various scenarios. The goal is to ensure that the system meets all the requirements set out in the design phase [21].
- **Commissioning and maintenance** - This stage includes both the commissioning of the system and its continuous adaptation according to new user needs or legislative or business changes that may require system adaptation.

3.1. Profiling users that interact with the damage estimation platform

In the initial stage of system analysis, we need to outline the user profiles of the system. This step can be based on knowledge of the process, past experiences in implementing similar processes, or even interviews with the people directly involved in operating the respective process.

Users must be categorized into two main groups [18]:

- End users - interact with the system without requiring specialized training; can be considered beneficiaries of the system's capabilities.
- System users - have extended rights over system usage, but also need specialized training to interact with it.

For the web platform estimating the degradation index, we can consider four types of users as follows:

- ***Non-specialist* end user** - This type of user includes individuals who, although having a low level of knowledge in structural engineering, are interested in using the platform.
  This user should be able to enter basic data about buildings into the platform, such as: number of floors, building height, and plan dimensions. As a result of interacting with the web platform, this type of user will obtain adequate estimates to provide an overview of the potential structural degradations of the analyzed building, considering the limitations imposed by the types of data entered.
  Regarding the configuration of a degradation index estimation experiment, this user will use a default estimation model and will have the option to choose from a series of pre-defined accelerograms in the platform.
  This category may include, for example, real estate agents or insurance agents.

- ***Intermediate level* end user** - This category includes users who have a relatively advanced level of training in civil engineering. These users can provide the application with additional parameters, such as the dimensions of structural elements (columns, beams), modulus of elasticity, or the type of building (regular or irregular).
  In configuring simulation experiments, these users can select both an estimation model and the desired accelerogram.
  As a result of interacting with the system, these users would typically obtain a more accurate degradation index estimate.
- ***Specialist* end user** - This category includes users with specialized training in civil engineering. These users need to provide the platform with all the specific parameters (number of storeys, storey hieght, building height, column section width, column section height, uniform distributed load, first natural period of vibration, second natural period of vibration, third natural period of vibration, the maximum number of formed plastic hinges, divided by the total number of plastic hinges defined, hysteretic energy divided by the input seismic energy, concrete Young Modulus, maximum base shear on X direction, maximum base shear on Y direction, the maximum number of formed plastic hinges, beams bending capacity, column bending capacity on X direction, column bending capacity on Y direction, the bay dimension, beam section height, the number of span, the number of bays, beam section width) of a building required for estimating the index with machine lerning algorithms.
  They also have the ability to define new accelerograms in the system, which they can use later in various simulation experiments. Similar to intermediate users, these users can choose an estimation model and the desired accelerogram.
  Regarding the estimation of the degradation index, these users will obtain the highest level of precision in conducting simulation experiments.
- ***Administrator* system user** - Users in this category have extended capabilities of using the application, including rights to manage and configure the platform.
  In configuring a simulation experiment, these users, in addition to the capabilities of specialist users, can introduce new estimation algorithms and calibrate algorithms already defined in the platform.
  Concerning the administration function, these users can create, modify, or delete users and can extract specific reports with all simulation experiments executed in the platform.

3.2. Defining Use Cases

With the user categories already defined, the next step is to define the use cases. As mentioned in the previous section, a use case defines an interaction of a user type with the system, forming the basis for defining functional requirements.

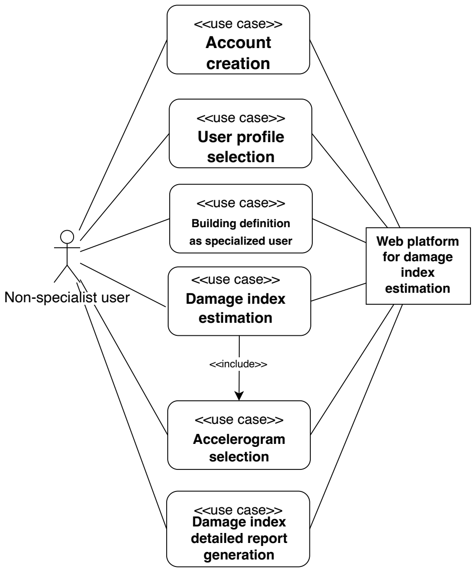

FIGURE 2. *Non-specialist* end user

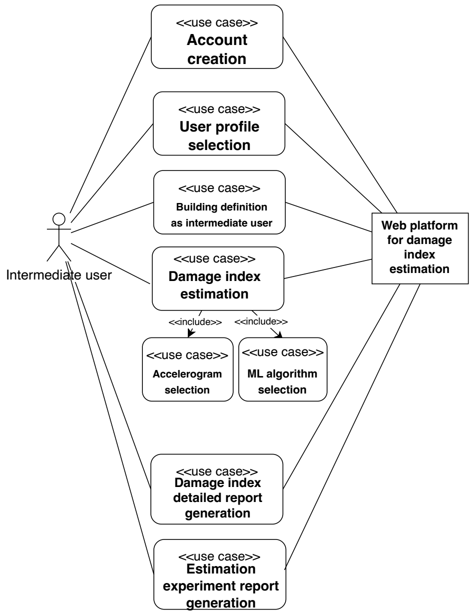

FIGURE 3. *Intermediate* end user

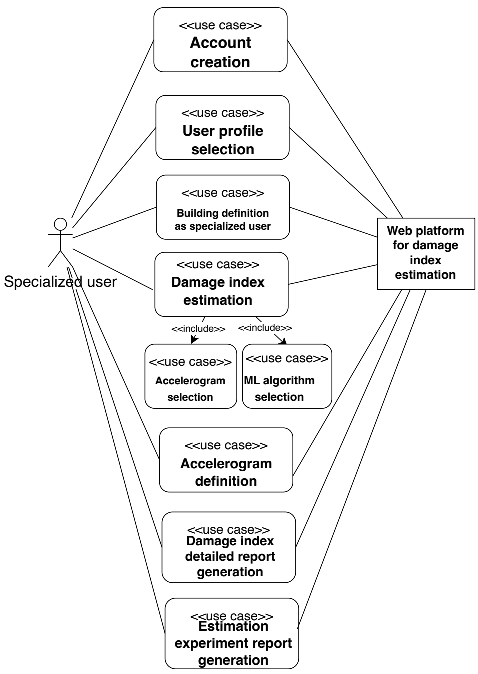

FIGURE 4. *Specialist* end user

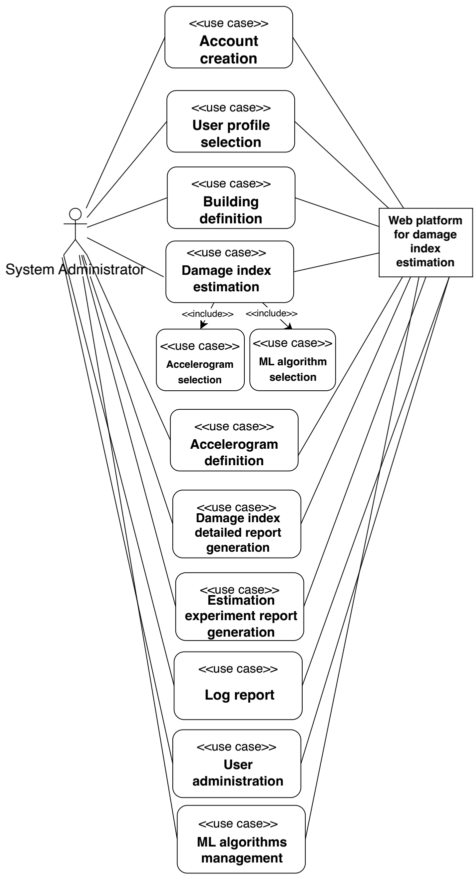

FIGURE 5. *Administrator* end user

FIGURE 6. Use case diagrams for the end users and system users of the platform

In Fig. 6, we can analyze the use case diagrams for the end users and system users of the platform. These diagrams reflect a relatively simple pattern of user interaction with the system. This pattern is highlighted by the fact that in each interaction, there is only one human actor involved. This aspect is particularly useful as it indicates, from an early stage of system analysis, that the system can be implemented on a relatively simplistic architecture.

Moreover, we observe that there are three main stages using the platform for estimating the degradation index. These stages are:

- Choosing the user type
- Configuring a simulation experiment in a manner appropriate to the involved user
- Generating the results of a simulation experiment in a form suitable to the involved user

This procedural sequence implies analyzing user-system interaction from a temporal perspective. To further highlight this temporal dimension, sequence diagrams have been developed.

Given the complexity of each interaction and the subset of similar capabilities that can be identified among user categories, we can analyze the sequence diagrams for the experienced user (Fig. 7). Both sequence diagrams and use case diagrams were developed based on the *SysML* standard [19].

Before analyzing the sequence diagrams, it is important to mention that each sequence diagram corresponds to a use case defined by a unique identifier. For example, the Create Account use case is identified by the synthetic key *UC1*.

Conceptually, sequence diagrams describe the interactions of users with the system as a whole, without going into specific details that involve certain additional functional or non-functional constraints. Thus, relative to the main stages defined earlier, we can highlight the following classification:

- Use cases UC1, UC2, and especially UC3 are associated with choosing the user type
- Use cases UC4, UC5, UC7 are associated with configuring and executing the simulation experiment
- Use case UC6 is associated with the reporting stage

The temporal dimension attributed to the sequence diagrams provides an important detail regarding the existing conditions in the application. Specifically, sub-processes that are conditioned by the execution of other sub-processes can be identified. For example, entering building data is conditioned by selecting a user type, as the functionality of entering data will be influenced by the restrictions associated with each user category. Another relevant example is the use case associated with executing a simulation experiment, as this execution involves a configuration stage where the user needs to enter building data.

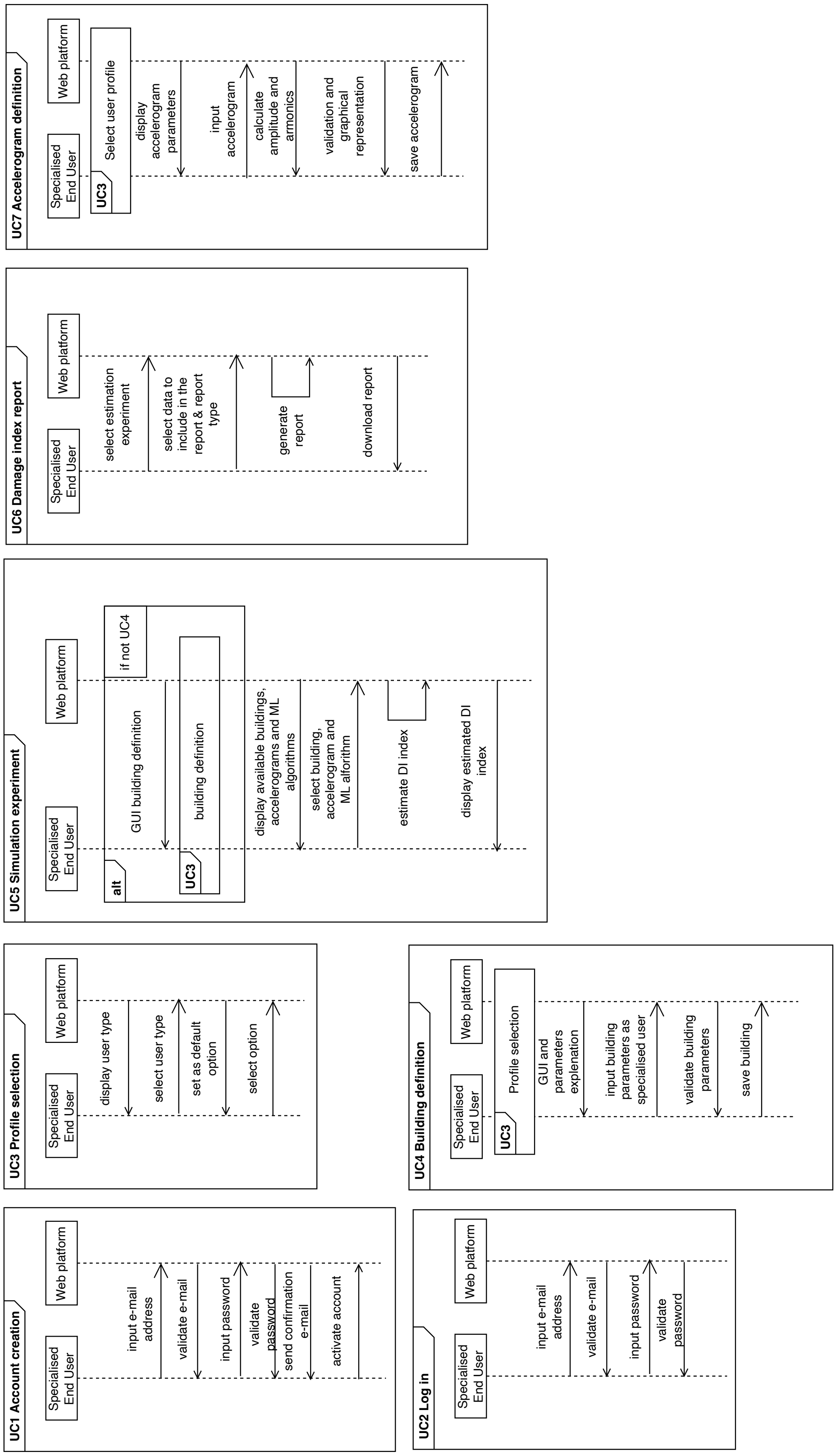

FIGURE 7. Sequence diagram for the *specialised* end user

3.3. Developing Functional Requirements

Based on the use cases, functional and non-functional requirements have been developed to concretely express what the platform must do in relation to user needs.

Since the requirements are a consequence of the use cases, they are presented in a structured manner with respect to each use case. Fig. 8 presents the functional requirements diagram, designed using the SysML standard. Fig. 8 depicts all functional requirements developed, depending on the user profile. Given that there are many common requirements among end-users, one can notice the predominance of the green color associated with the typical end-user profile. Additionally, it is important to note that most of the requirements are linked through two relationship types:

- **Derivation relationship** - signifying that one child requirement is derived from another parent requirement.
- **Composition relationship** - enforcing that a parent requirement is satisfied only when all the child requirements are satisfied.

By analyzing the requirements, we can observe, for example regarding the building generation requirements, that there are certain validation mechanisms that can be implemented through a software component of the platform, as well as certain storage capabilities that the platform must have. For instance, the platform must allow a user to enter data associated with multiple buildings, which is associated with the need for the platform to store the data entered by the user.

In another case, for example the requirements related to the estimation experiment, the requirements defined here describe how the system must represent information in interaction with the user so that the user can configure a simulation experiment in an accessible way. These requirements aim to provide relevant information to the user when choosing a building, proposing an accelerogram, or a machine learning algorithm. Also, the system must be able to provide detailed explanations regarding the index estimation, adapted to the type of user involved in the interaction.

The administrator represents a system user that has complete flexibility when using the web platform. He can also use the platform for damage index estimation, but also has a user-management component. He also has different reporting tools available, while also being the only user profile who can manage machine learning models inside the system, given the sensible nature of these algorithms.

Overall, the proposed functional requirements focus primarily on outlining a service deeply oriented towards the human user and their experience in the process of estimating the degradation index. This aspect comes as a consequence of the fact that civil engineering concepts can be relatively complex for non-specialized users, which is why the platform must offer a friendly and useful environment to the target audience, regardless of their level of training.

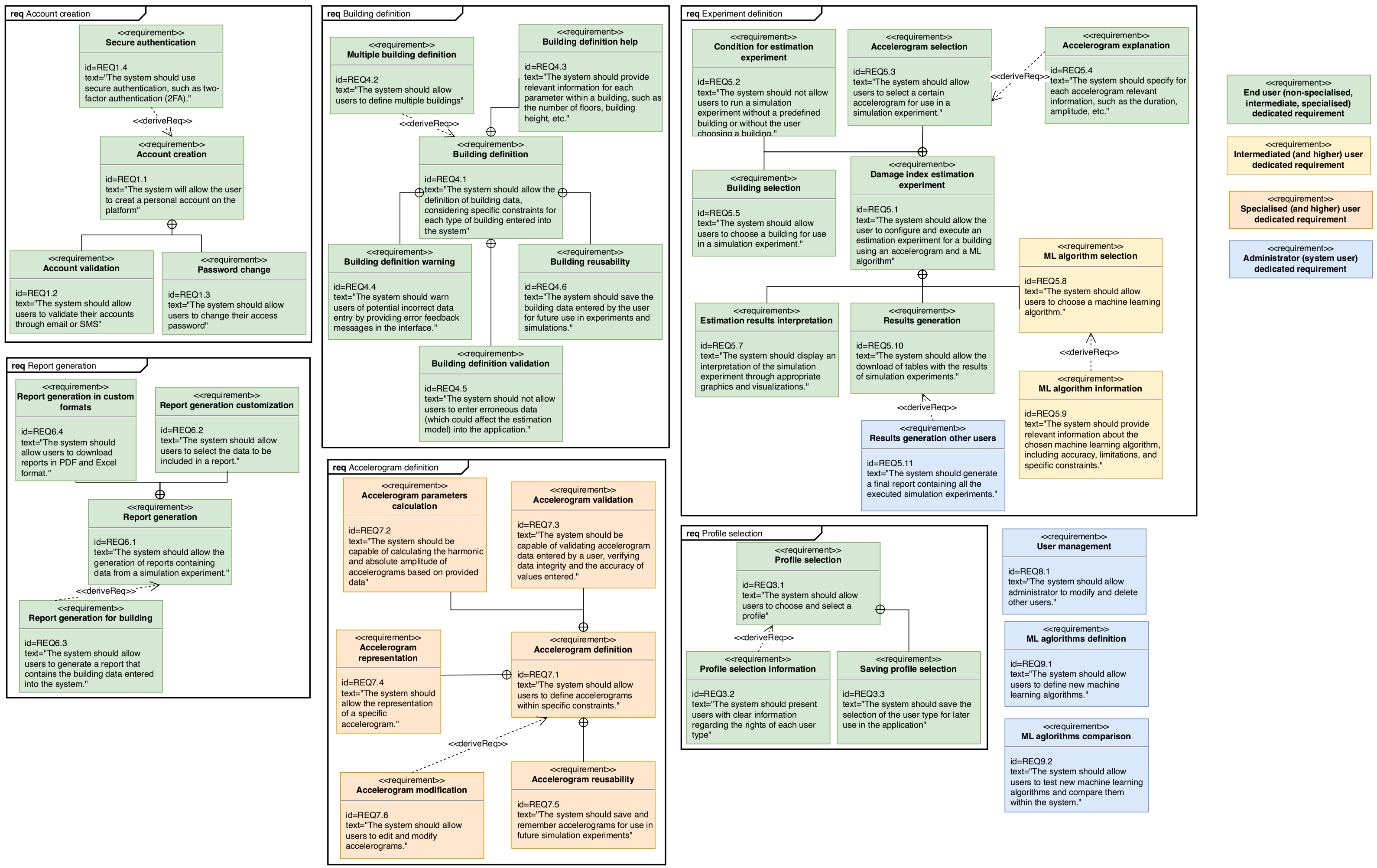

Figure 8. Requirements diagram and associated legend, depending on the user profile

3.4. Platform Architecture for Degradation Index Estimation

Finally, based on the functional requirements, the architecture described in Fig. 9 was proposed.

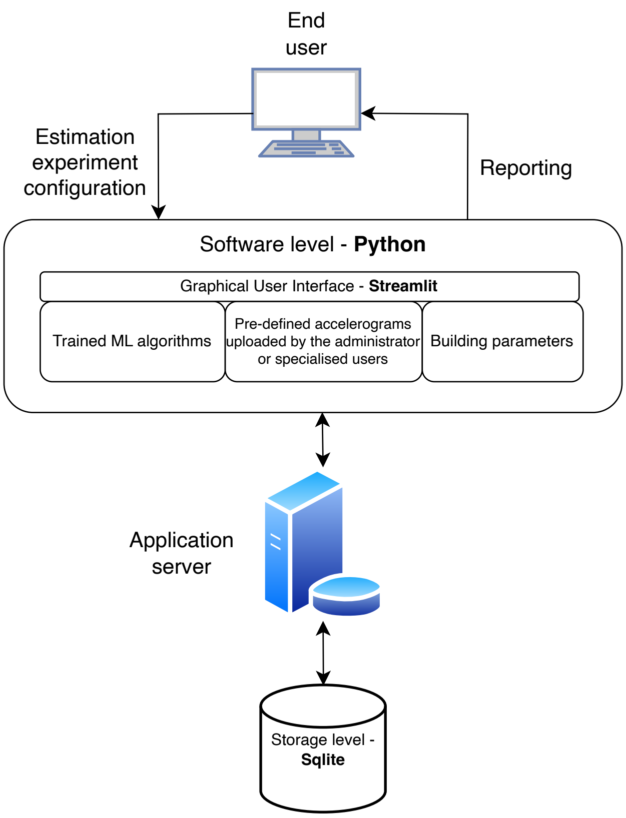

FIGURE 9. Proposed architecture for the degradation index estimation platform

From a hardware perspective, the platform for estimating the degradation index operates on a single server. This server allows storing estimation experiments and user data in a *Sqlite* database, considering the estimated volume of experiments and the number of users involved.

At the software level, the interaction between the database and the end user will be realized through an application developed in Python. This application enables both the development of an intuitive interface based on the *Streamlit* framework and the integration with the already implemented module containing pre-trained machine-learning algorithms.

The central point of this architecture is the user interface developed, as mentioned earlier, in the *Streamlit* framework. This technology was specifically chosen to offer the user an intuitive environment through which they can use the machine learning algorithms. The framework can provide alerts, notifications, allow user authentication under certain conditions, and include graphical or tabular representations for reporting. Being an open-source framework and able to cover numerous functional and non-functional requirements defined earlier, this development framework is more than suitable for implementing the user interface.

4. Conclusions

In conclusion, the paper presents a system analysis conducted for developing a web platform for estimating the seismic degradation index of buildings. We went through the fundamental stages of the software product life cycle, including determining user profiles, identifying use cases, and developing functional and non-functional requirements. Through this analysis, we were able to outline the needs and expectations of end users and design an architecture that efficiently meets these requirements. The system analysis was essential to define the platform's functional requirements and establish the optimal architecture to guide subsequent implementation.

An important contribution of the paper is related to identifying and classifying users into four main categories: non-specialist end users, intermediate end users, specialist end users, and system administrator users and adapting the system analysis principles to design adequate requirements in the context depicted by these user profiles. Each user category has specific needs and interactions with the system, leading to the definition of detailed requirements for each use case.

Additionally, use case and sequence diagrams were developed to illustrate the interactions between users and the system in a clear and structured manner. The functional and non-functional requirements were presented using the SysML standard, highlighting the requirements associated with different use cases. These requirements ensure that the platform will meet all necessary functionalities to provide users with an optimal experience and facilitate the process of estimating the seismic degradation index.

Finally, the proposed architecture represents another important contribution. By using the system analysis approach, a robust architecture was determined, mitigating the risk of implementing a system that is inadequate for its targeted end-users.

Future work will involve the actual implementation of the proposed architecture, followed by testing and validating the system to ensure that all functional and non-functional requirements are met. Successful implementation of this platform will significantly contribute to improving the seismic resilience of buildings, offering a valuable tool for engineers and companies in designing safer and more resilient structures.

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