Step 2 - Final Report

Easy Automation of Complex Decision Making

Team ID : 43

Inter IIT Tech Meet 11.0

COGNITIVE GARAGE

Contents

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Understanding Problem Statement

In today's technologically advanced world, we collect a great deal of information and use it to automate a variety of processes. A domain expert's decision-making process is automated by **Cognitive Garage** using the data. A domain expert will assist us in determining the nodal values and network topology in order to construct a knowledge model based on the fundamentals of **Bayesian networks**. They can enter the parameters established by preliminary tests and feed them into the model to obtain a predictive or probabilistic score (specific to the problem we intend to solve) and receive a comprehensive, error-free, and quick understanding of the issue. Instead of attempting to replace people's ability to reason, this created technology assists individuals in validating their opinions and making sound decisions.

An illustration of the fundamental overview of the necessary model, taking into account information flow and automation space, is shown in the flowchart figure below.

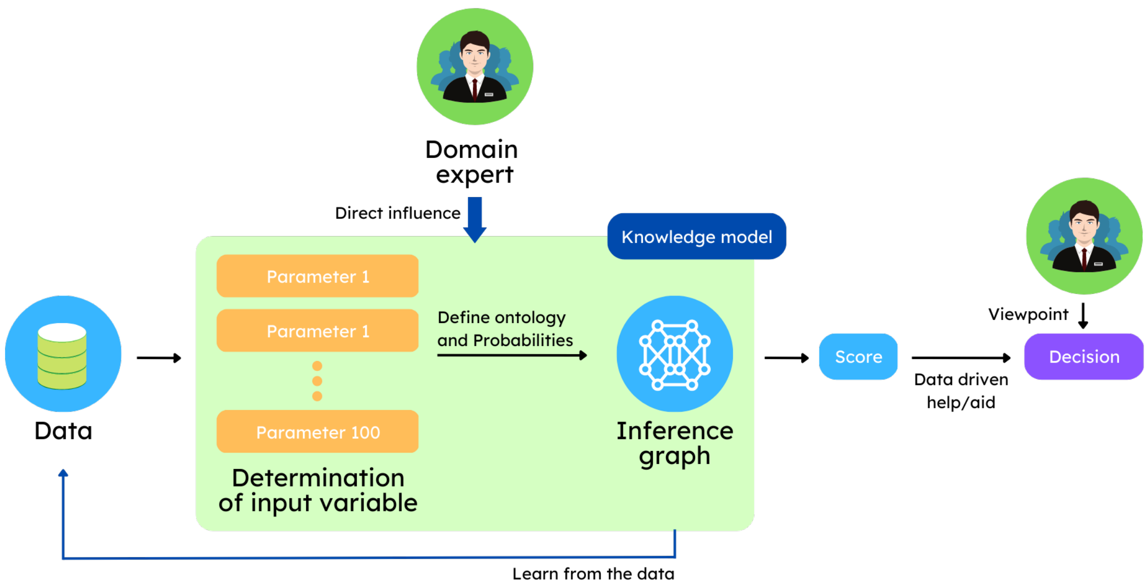


Figure 1.1: Flowchart of Problem Statement

2

Selected Use Case

Automated Risk Assessment for Infrastructure Auditing

There are now over **100 million structures** in India, and many more are being built all the time. Safety inspections are carried out at many points, including before, during, and after construction. The post-construction realm of safety auditing and risk assessment is performed in two stages: immediately after the building is built and periodically. These safety assessments are based on various characteristics and necessitate analysis by various subject matter experts. The typical results are only a subjective description of the required repairs and retrofits. Additionally, conducting non-destructive tests to find various problems is exceedingly expensive and time-consuming.

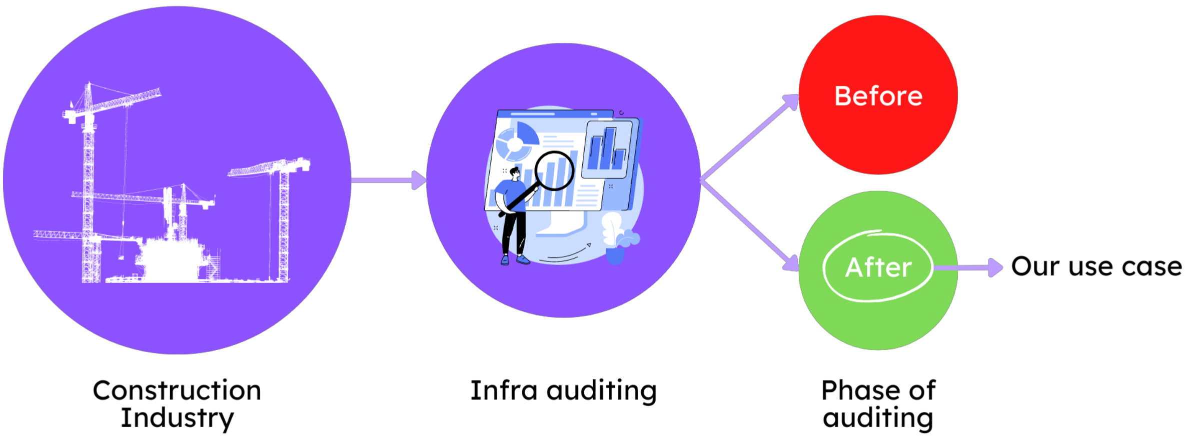


Figure 2.1: Outline of our use case

Our model will contain several parameters with integrated inputs from the building's historical data, its characteristics, outside influences, and the outcomes of the visual inspection undertaken. Based on how they are interrelated, the program will then take these inputs and produce a risk score for the building. It will then give a probable list of tests that should be conducted to pinpoint the problem if and when required. Our model would also tell the urgency of the situation.

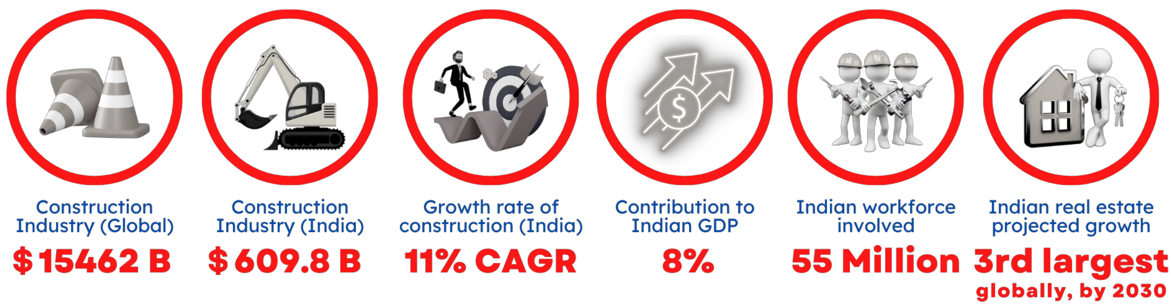
This would speed up decisions regarding the numerous repairs and retro fittings needed while also making the auditing process more effective, convenient, and cost-effective.

3

Industry Analysis

3.1. Construction Industry - An Overview

The India construction market size was valued at **$609.8 billion** in 2021 and is expected to achieve an AAGR of more than 6% during 2023-2026 while the global construction market grew from $14503.87 billion in 2022 to **$15461.84** billion in 2023 at a compound annual growth rate (CAGR) of 6.6%. According to data from the Ministry of Statistics and Programme Implementation, the construction sector in India accounted for around **8% of the country's GDP in 2020.**



The workforce involved in the real estate and construction domain in FY21 was roughly **55 million** (4% of the Indian population). Indian real estate holds immense significance in the Indian economy with the sector being the third largest employer after agriculture and manufacturing. According to a joint report by the real estate body NAREDCO and KPMG, India's real estate and construction sector are projected to be the **3rd largest globally by 2030.** The Indian construction industry is one of the fastest-growing in the world, with an estimated compound annual growth rate of 11% between 2020 and 2025. The construction industry is a major source of employment in India, providing jobs to millions of workers, including unskilled labor, skilled labor, and professionals such as architects and engineers.

3.2. Auditing/Inspection/Risk-assessment of Infrastructures

Infrastructure auditing and inspection consist of analytical and monitoring tools that assist in analyzing the health of the infrastructure. The technology incorporates the collection and evaluation of meaningful data associated with the infrastructure. It basically inspects relative data and information about the infrastructure. Infrastructure inspection covers aging bridges, highways, buildings, dams, pylons, tunnels, and other structures that are essential for safety. Infrastructure control systems can increase safety and productivity. The structural auditing sector in India is an important component of the broader construction and infrastructure industry, as it helps ensure buildings' safety and structural integrity. Structural auditors are *trained professionals* who specialize in evaluating building structures' stability, safety, and performance and can provide recommendations for repairs and improvements as needed. Indian Infrastructure Inspection industry is about **$104.5 Million***. At the same time, the Global Infrastructure Inspection market was valued at **$2.09 billion** in 2021 and is expected to reach **$3.78 billion** by 2029, registering a CAGR of **7.70%** during the forecast period of 2022-2029.

3.3. Current Industrial Model

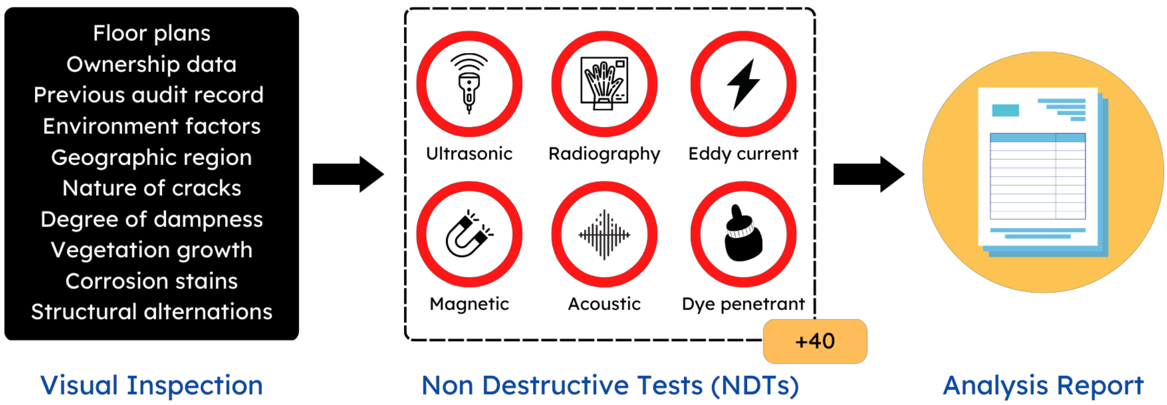


Figure 3.1: Current procedure in Infrastructural Auditing process

An auditor at the building site follows a three-step procedure as follows:

3.3.1. Visual Inspection

Before the site visit for the visual inspection, the auditor collects all the relevant data about the target building like floor plans, ownership data, previous audit records, environmental condition, geographic region, etc. to gain a knowledge base regarding the structure. With all this necessary data, the auditor visits the site and notes down all the important indicators of the building's damages with pictures. Data regarding the nature of cracks (length, position, depth, angle), degree of dampness, presence of vegetation growth, corrosion stains, and structural alterations are recorded. Columns beams are subjected to tapping by fibre hammer **(Delams)** to understand the hollowness. After this data collection procedure, the auditor works on this data and tries to infer from using stress maps and tries to dial down to the root cause of the problem and further suggest the required NDTs for additional data. The detailed report submitted by the auditor also contains a judgment regarding whether the building is safe or does it need immediate reconstruction/evacuation.

3.3.2. Non Destructive Testing

Non-destructive Testing systems are the method of testing in which properties of material or condition of the material is determined without harming or making changes in the object. This way of testing allows us to test the material or member without losing its utility.

- **Ultrasonic Testing:**
  Ultrasonic NDT is the process of transmitting high-frequency sound waves into a material in order to identify changes in the material's properties.
- **Radiography Testing:**
  Radiography NDT is the act of using gamma- or X-radiation on materials to identify imperfections.
- **Eddy Current (Electromagnetic) Testing:**
  Eddy Current NDT is a type of electromagnetic testing that uses measurements of the strength of electrical currents (also called eddy currents) in a magnetic field surrounding a material in order to make determinations about the material, which may include the locations of defects.
- **Magnetic Particle Inspection:**
  Magnetic Particle NDT identifies imperfections in a material by examining disruptions in the flow of the magnetic field within the material.
- **Acoustic Emission Testing:**
  Acoustic Emission NDT uses acoustic emissions to identify possible defects and imperfections in a material.
- **Dye Penetrant Testing:**
  Dye Penetrant NDT (also called Liquid Penetrant Testing) refers to using a liquid to coat a material and then looking for breaks in the fluid to identify imperfections.

3.3.3. Structural Audit Report

The auditor prepares a detailed report of the building, which would include an initial description of the building's structure, including its age, materials used, construction methods, nearby topology and soil structure of the adjacent area of inspection. This is done after the auditor has finished the visual inspection and Non-Destructive Testing (NDT) (if necessary as per the auditor's discretion). He must also include his examination of the building's foundation, including its kind and state, as well as any problems that may be compromising the building's stability, such as atypical vegetal growth, soil erosion, nearby deep excavations, etc. The evaluation of the building's walls is added after, and at this point, he can point out any cracks, bulges, or other indications of structural stress. The analysis of the roof and any indications of leakage or structural problems with the roof framing follow. The study of the building's windows and doors is presented at the end, and he shall highlight any issues with the frames and seals that might be causing air or water infiltration.

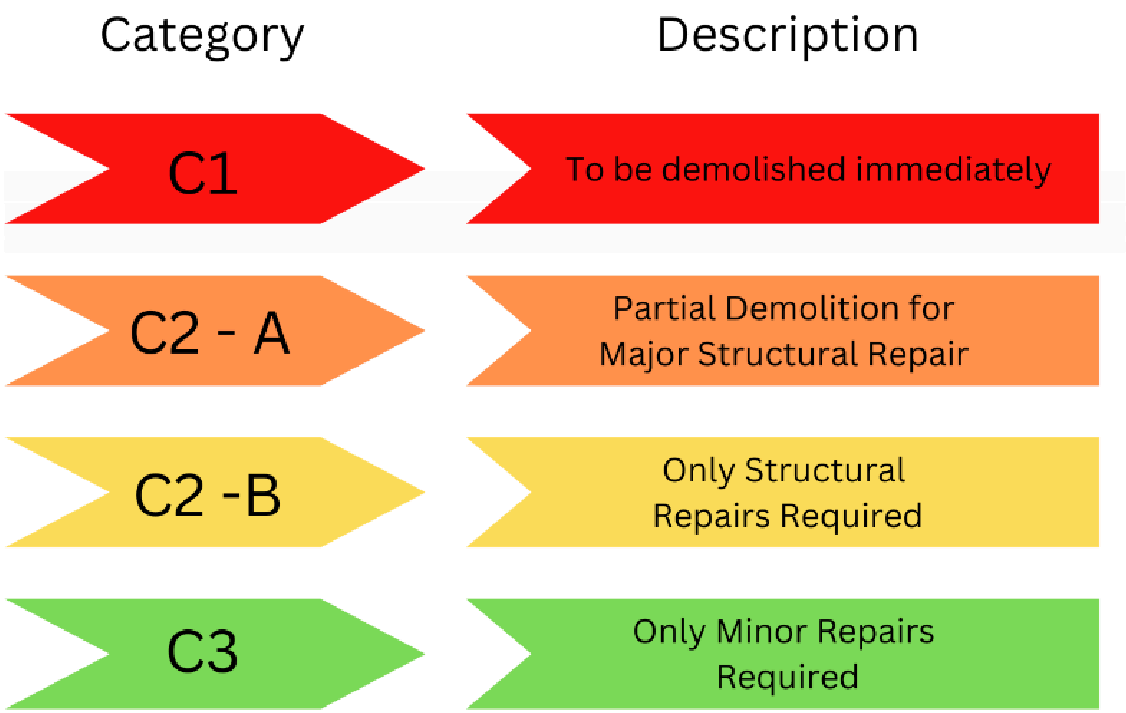


Figure 3.2: Standards laid down by Brihanmumbai Municipal Corporation

Using the information gathered during the building inspection, the auditor **categorises** the building based on the standards laid down by the Municipal corporation. This Structural audit report is also sent to the Municipal corporation for records so that it is aware of the building's category in order to determine if it can be repaired or if it needs to be evacuated so that it can be demolished.

4

Where Do We Fit In?

4.1. Automation - A need in risk assessment analysis

With the number of construction failure cases increasing worldwide, periodic building audits and inspections are gaining pace and focus. The current process of building inspection is entirely manual and mainly includes two steps:

- Visual Inspection
- Non Destructive Tests (NDTs)

This process takes place in a systematic order; the inspector (usually a civil engineer) first analyzes the current state of the building and makes a subjective report of the possible defects and damages. Based on this report, the domain expert tries to judge the possible reasons for the damage and further suggests some NDTs. This is where the redundancy and error show up. The NDTs suggested are sometimes based on the **personal bias** of the inspector and often lead to waste of time and resources by offering some non-required tests. There are also various cases of **malicious practices** taken up by the inspector to suggest additional tests to increase the bill.

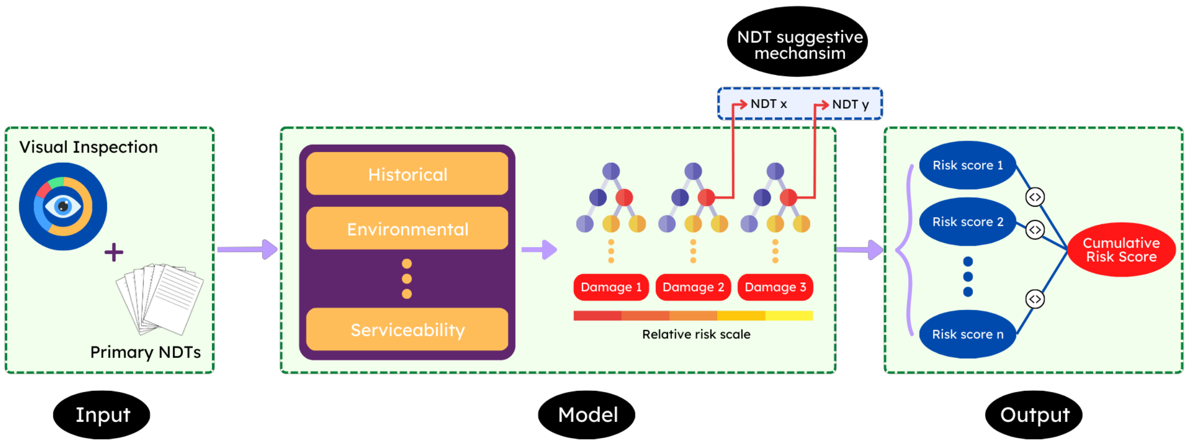


Figure 4.1: Proposed pipeline for automation of decision-making process

We plan to step in here and help automate this process by building a knowledge model which would help provide a list of NDTs required for the building based on the inputs fed into the model by the inspector. The model would calculate risk scores in various buckets of damages defined in the model. Whenever this risk score shall be greater than the safety limit, some more tests and NDTs shall be suggested to further pinpoint the exact problem and eliminate any redundant tests. Along with this, the model shall also provide a cumulative risk score for the building conveying the urgency with which the tests should be conducted and depicting the functionality and habitability of the building.

4.2. Fit of Bayesian Networks

Many problems occur in creating such an automated decision model, considering that historical data on risks and failures are usually scarce, confidential, and often not available until several years after a failure event. These factors make assessing and using knowledge on risks in such a use case complicated.

Therefore most of the conventional methods fail to provide reliable support for risk assessment as they evaluate risks independently and incomprehensibly. Even the more comprehensive methods like failure mode and effects analysis, hazard analysis, top-level event tree, fault tree analysis, etc., struggle to deal with the epistemic uncertainty of risks caused by incomplete information, which is quite common in the case of construction risks.

Therefore this demands an alternate approach such that expert judgment about the risk factors associated with critical risks is incorporated to bridge the gaps in the available historical data. This deems **Bayesian Belief Networks (BBNs)** approach the most potent to help analyze the information on new risk factors and the causal relations between them.

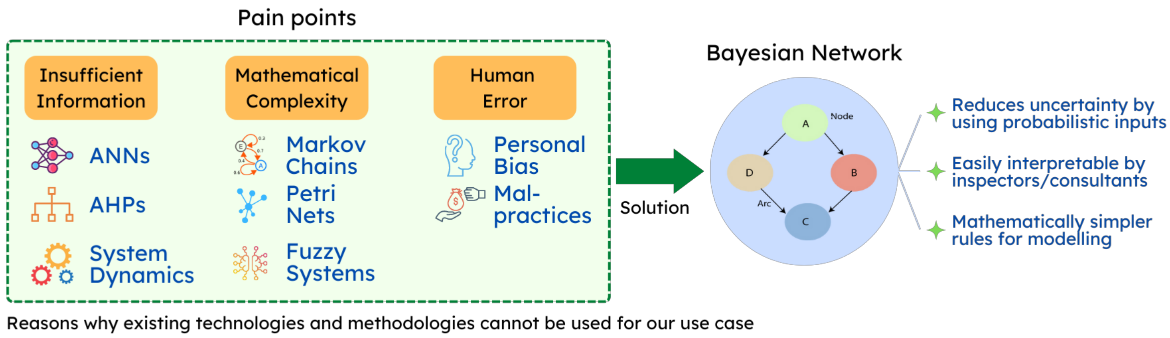


Figure 4.2: Why BNs provide best fit solutions for Infrastructural auditing/inspection

Though there are other methods for representing risks, such as Markov Chains, Petri Nets, Artificial Neural Networks (ANNs), the Analytical Hierarchy Process (AHP), Systems Dynamics, and Fuzzy Systems, but some of these (notably Markov Chains and Petri Nets) are too complicated to be used by common inspectors. Others, such as ANNs, the AHP, and Systems Dynamics, require a lot of data that is usually unavailable for construction risks.

Also, whilst Fuzzy Systems modeling is a realistic alternative to the BBN approach, the latter makes use of mathematically sounder and simpler rules for drawing inferences to execute efficient analysis and provide information on the most critical factors risk measures should focus on.

5

Domain Expert's input

35 years experience

Rajat Pandey
Senior Technical Consultant, Larsen & Toubro Construction

The government mainly mandates the auditing or inspection portion of India's widely fragmented construction sector. Depending on the project's scope, contractors and builders take this idea seriously, although the owner usually decides whether to have the structures inspected for health. Owners are currently primarily led by responsible auditors in making entirely manual decisions.

17 years experience

Kamlesh Dhandha
Internal Audit Manager

A qualified and accredited civil engineer carries out periodic audits and inspections of buildings, with a concentration on high-rise and relatively ancient structures. The audit procedure requires a lot of time and subjectivity. It heavily depends on the bias of the auditor, necessitating the use of an automated decision-making model that would assist in standardizing and unifying these judgments and building assessments.

16 years experience

Rashmi Khamkar
Structural Auditor, Civil Engineer and Partner, M/s Rigvil Consultants

In the future, structural auditing automation will be a disruptive technology. Innovative approaches such as sensor technology and drone-based laser systems could automate not only visual inspection but also provide reliable data on building components that could not be manually accessed otherwise.

19 years experience

Sudib Kumar Mishra
Associate Professor, Department of Civil Engineering

While considering an RCC structure, main focus should be put on the frames of the building as they would bear the maximum load during an earthquake. Special considerations should be given to the columns of the structure as their failure would lead to a catastrophic collapse of the building.

6

Proposed Knowledge Model

6.1. Overview

The visual examination and primary Non-Destructive Tests (NDT) occur during the structural audit. The domain expert enters the data they obtain into our knowledge model, which runs and analyses several factors with their corelation and co-dependence. It performs the appropriate probabilistic calculations and determines which secondary NDTs (often expensive) should be pursued. Such tests ought to be conducted in a priority or sequential sequence. The output of our model, which is produced by combining the positives and negatives of the data, will also include potential infrastructure issues and their predicted risk scores. The engineer will be able to prioritize his tests and take the necessary action with this aid.

Data Sources and interpretations by Domain Experts

We analyzed numerous structural audit reports to try and understand the whole process behind structural auditing. Further, we attempted to identify the different parameters the visual inspector records in their audit report and the format in which they are inputted. Based on this, we tried to divide all the input parameters into a few buckets to obtain different damage bucket lists to identify the exact problem associated with the building. Then we analyzed the process the domain expert takes to develop the implications from these input parameters in consultancy with the domain expert. With the collaboration of the two, we came up with the approximate probabilities to denote the extent to which the parameters affect the overall damage profile of the building.
Sample Audit Report

6.2. Unfolding the Structure

6.2.1. Input Parameters

Here we have listed the parameters that will be taken as input by the concerned authority that is auditing the building.

Historical Parameters

The history of the building plays a very important role in determining its strength and condition during auditing.

1. **Age**
   Input Format: Age of the infrastructure.
   Description: The age of the building plays one of the most significant roles in determining its strength and weaknesses.

2. **Rating of land history**
   Input Format: Subjective rating of the land's historical condition.
   Description: The land's history affects the strength of the foundation of the infrastructure. If the land is fragile, it, in turn, makes the foundation prone to faults and defections.

3. **Last Renovation Age**
   Input Format: Age of the last renovation of the infrastructure, if any.
   Description: The study and the age of the last renovation of the building directly co-relates the condition of the building.

4. **Score of the last audit**
   Input Format: Rating of the last audit/inspection from 1 to 10 and 0 if no audit has been done.
   Description: The rating and score of the last audit can be a very crucial factor in recognizing the weak and strong points and make the process faster.

Structural Parameters
In structural, we are first looking at the overall features of the building and its surrounding conditions. After that, we will be looking at singular storeys of the building, whose risk scores will be combined with the risk score obtained from the serviceability model, giving us the risk score of the given storey. The Structural test shall be divided into 2 parts:

- **Overall Structure**

  Here we consider the conditions that will directly affect the overall structure of the building, for example, the seismic zone in which the building lies, the foundation which has been given to the building, the present soil conditions etc. These data are either already available from the building plan made by the civil engineer at the time of construction, obtained through experiments or from the city administration.

  1. **Hanging or Floating Columns**
     Input Format: Height, Number of columns, and Strength of each Column.
     Description: The floating column is a vertical member which rests on a beam and doesn't have a foundation. But such a column cannot be implemented easily to construct practically since the true columns below the termination level are not constructed with care and hence finally cause failure.

  2. **Geometry**
     - **Division of building in sections, presence of elevators, or staircase**
       Input Format: A binary answer (Yes/No) that indicates the presence or absence of sections, elevators or staircase.

If the above answer is yes, then we check for the presence of seismic joints, inputting the width of the seismic joint and the relative stiffness.
Description: If the building is divided into sections, and has a staircase and/or elevators on the side, then seismic joints should be installed as they allow large multi-directional movements of structures to avoid collisions and ensure the durability of the structures.

- **Design**
  Input Format: Length, the Radius of Curvature and Shape in the plan.
  Description: Buildings with regular shapes often perform better in earthquakes because they are more resistant to the lateral forces generated by seismic waves. On the other hand, curved buildings can concentrate the force of the earthquake at certain points, making them more vulnerable to damage.

- **Setbacks**
  Input Format: A binary answer (Yes/No) that indicates the presence or absence of setbacks.
  If Yes, a further 3 parameters; Height at which setback begins, Storey at which setback begins and Percentage change in area are to be entered.
  Description: It is the sudden irregularity in the area of the successive floors. In the case of building models with a setback at the bottom stories, the structure's capacity is more affected compared to the building models with a setback at the upper levels.

- **Seismic Zone Properties**

1. **Seismic Coefficient**
   Input Format: The Seismic Coefficient.
   Description: The seismic coefficient represents the maximum horizontal equivalent acceleration expected in a slip potential failure wedge. Depending on the seismic zone in which the building lies, it increases the value of the load according to which all the building members are designed.
2. **Peak Ground Acceleration**
   Input Format: can be taken up from the IS Code 1893.
   Description: Depends on the seismic zone.
3. **Exact Location**
   - **Soil Characteristics**
     Input Format: Cohesion, Angle of internal friction, Unit weight of soil.
     Description: The soil's geotechnical test determines whether it is still stable enough to support the load of the building and the constituting load. Soil with low cohesivity and shear strength is not suitable enough to take the load of the soil.
   - **Slope**
     It is the steepness of the plot. For a particular region, A building should not be constructed after a particular angle of slope

(a) **Foundation Characteristics**

* ⋆ **Cut In**
  Input Format: Cut in ratio.
  Description: It is the ratio in which land is cut for the foundation.
* ⋆ **Foundation Type**
  Input Format: We would require the Shape of the foundation; square, circular or rectangular; width of the foundation; depth of the foundation, angle of internal friction, and angle of resultant load.
  Description: Here, on the basis of the given inputs, we will calculate the Meyerhof's shape, depth and inclination factors which, when combines with Terzaghi's bearing capacity factors, will give ultimate bearing capacity for our foundation.
* ⋆ **Earthquake Base Isolation**
  Input Format: Rollers, Flexible pads, Fixed base (no base isolation given)
  Description: It is the separation given to the foundation of the building from the soil to lessen the earthquake's impact. The type of base isolation depends on the soil's cohesion and the building's height. For e.g. Roller base isolation is best for low to medium-rise buildings on hard soil

- $\boxed{\textbf{Load}}$

1. **Dead Load**
   Input Format: Weight will be put in by the auditor, considering the weight of the building and other non-variable loads on the basis of the building design and visual inspection.
   Description: Load that remains relatively constant over time. i.e. Just the weight of the structure.
2. **Live Load**
   Input Format: Weight will be put in by the auditor, considering the weight of the building and other variable loads on the basis of the building design and visual inspection.
   Description: Load that is not constant but changes over time.

Internal Building Characteristics: In this, we look at the structural members of a particular floor of the building, i.e., columns, columns-beam joints, beams, walls and many more. From the building plan, we see if the quality and design of the members are suitable for the load that those members are bearing. We also see if further measures like horizontal bands and vertical reinforcements have been made available. Please note that the flow of load happens from the floors to the beams and walls and then to the columns; from the perspective of an earthquake, the columns of the building should be the strongest member to prevent the outright collapse of the building.

- $\boxed{\textbf{Walls}}$

  Structures that define an area in construction, carry a load, provide security, shelter, soundproofing, or are decorative.
  Input Format:

  1. **Material Used**
     - **Masonry**
       Input Format: Compressive Strength.
       Description: A structure with brick, stone, or similar material, often laid in and bound together by mortar. Walls usually don't contribute much to the earthquake resistance design and are applicable mainly for demarcating separate rooms. They do share the horizontal earthquake load with the columns but only up to a certain extent. When it fails, cracks appear on the walls.

- $\boxed{\textbf{Openings}}$

  An open space. Any opening in the wall should not be located near the corners, as it will disrupt the transfer of load from the walls and beams to the columns. For a similar reason, the size of the opening shouldn't be excessively large as it will cause a discontinuity in the load flow path.
  Input Format:

  1. **Windows**
     Location: Distance from load-bearing beams and columns.
     Size: Dimensions.
  2. **Doors**
     Locations: Distance from load-bearing beams and columns.
     Size: Dimensions.

- $\boxed{\textbf{Reinforcement}}$

  Bars, wires, strands, fibres, or other slender elements that are embedded in a matrix such that they act together to resist forces.
  1. **Horizontal Bands**
     These are concrete or wooden bands which are installed in the buildings. Based on the need and their location, there are four different kinds of horizontal bands. If the bands are present, we also confirm if the given mandate is satisfied or not - The Indian Standards IS:4326-1993 and IS:13828 (1993) provide sizes and details of the bands. When wooden bands are used, the cross-section of runners is to be at least 75mm×38mm and of spacers at least 50mm×30mm. When RC bands are used, the minimum thickness is 75mm, and at least two bars of 8mm diameter are required, tied across with steel links of at least 6mm diameter at a spacing of 150 mm centres.

     - **Lintel Band**
       Input Format: A binary answer (Yes/No) indicating the presence of the band; if yes, then the strength of the material, mandate satisfaction (yes/no)
       Description: The lintel band ties the walls together and creates a support for walls loaded in a weak direction from walls loaded in a

strong direction. This band also reduces the unsupported height of the walls and thereby improves their stability in the weak direction. The lintel band is the most important of all and needs to be provided in almost all buildings

- **Roof Band**
  Input Format: A binary answer (Yes/No) indicating the presence of the band; if yes, then the strength of the material, mandate satisfaction (yes/no)
  Description: In buildings with flat reinforced concrete or reinforced brick roofs, the roof band is not required because the roof slab also plays the role of a band.
- **Plinth Band**
  Input Format: A binary answer (Yes/No) indicating the presence of the band; if yes, then the strength of the material, mandate satisfaction (yes/no)
  Description: Plinth bands are primarily used when there is concern about the uneven settlement of foundation soil.

- **Columns**

  Vertical load-bearing members that primarily support axial compressive loads. Columns that are required to resist earthquake forces must be designed to prevent shear failure by a skilful selection of reinforcement.

  1. **Amount and Distribution of Steel Input Format:** Composition, Strength, and Elasticity (sourced from the Indian Ductile Code)
  2. **Size**
     Width of the column: The Indian Ductile Detailing Code IS:13920-1993 requires columns to be at least 300mm wide. A column width of up to 200mm is allowed if the unsupported length is less than 4m and the beam length is less than 5m.
  3. **Material Properties**
     - **Grades of Steel Bar**
     - **Concrete**
  4. **Strength:** Can be determined by rebound hammer test
  5. **Closed Ties:** Closely spaced horizontal closed ties help in three ways, namely:
     (a) they carry the horizontal shear forces induced by earthquakes and thereby resist diagonal shear cracks,
     (b) they hold together the vertical bars and prevent them from excessively bending outwards (in technical terms, this bending phenomenon is called buckling), and
     (c) they contain the concrete in the column within the closed loops.

- **Beams**

  A beam is a structural element that primarily resists loads applied laterally to the beam's axis. Here the following quantities will be decided on the basis of the loads calculated earlier, and then the strength and the appropriate shape and size will be compared to the actual values. Please note that the IS 456 - 2000 will be used for these calculations.

1. **Amount and Distribution of Steel Input Format:** Composition, Strength, and Elasticity (sourced from the Indian Ductile Code)
2. **Size Input Format:** Dimensions
3. **Material Properties:**
   - **Steel bar**
     Input Format: Grade of Steel
   - **Concrete**
     Input Format: Composition, Strength, Durability, Porosity, Density, Impact Resistance
4. **Stirrup Mandates Input Format:** Diameter, Angle of the bend of ends, spacing. Following mandates must be satisfied. The user would have to give a yes or no answer. The Indian Standard IS13920-1993 prescribes the following requirements related to stirrups in reinforced concrete beams:
   - The diameter of the stirrup must be at least 6mm; in beams more than 5m long, it must be at least 8mm.
   - The maximum spacing of stirrups is less than half the depth of the beam.

   Description: Stirrups are installed vertically and diagonally, and it is done to prevent shear failure as cracks in beams mostly occur diagonally. Stirrups in RC beams help in three ways, namely (i) they carry the vertical shear force and thereby resist diagonal shear cracks (Figure 2b), (ii) they protect the concrete from bulging outwards due to flexure, and (iii) they prevent the buckling of the compressed longitudinal bars due to flexure.

- **Beam-Column Joints**

  In RC buildings, portions of columns that are common to beams at their intersections are called beam-column joints. Since their constituent materials have limited strengths, the joints have limited force-carrying capacity. Joints are severely damaged when forces larger than these are applied during earthquakes. Repairing damaged joints is difficult, so damage must be avoided. Thus, beam-column joints must be designed to resist earthquake effects.

  1. **Width of the Column**
     Input Format: Dimensions
     Description: If the column cross-sectional size is insufficient, the concrete in the joint develops diagonal cracks. Diagonal cracking crushing of concrete in joint regions should be prevented to ensure good earthquake performance of RC frame buildings. Using large column sizes is the most effective way of achieving this.

Serviceability Parameters
In serviceability, we check whether the building is in working condition and habitable. We analyze the building for the presence of various damages and some visual observations which might be the indication of some further internal damage to the building. This extent of damage is then formulated with regard to the different buckets under Serviceability as a damage score for each bucket. If the limit of serviceability is exceeded for any bucket, then the structure is

deemed to be unfit for use. The serviceability test shall also be divided into 2 parts:

1. **External Inspection:** A basic measurement of the various buckets and the corresponding parameters shall be made for the exterior part of the buildings.
2. **Internal Inspection:** For measurements in the internal part of the building, if multi-storey, the building shall be further divided into Underground, Ground floor, Middle part, and Top floor. Then each of these floors shall further be divided into DPC(Damp Proof Course), Floor, ceiling, and Wall. The wall shall also be further divided into window and non-window regions. The building auditor then shall input these parameters according to the above-mentioned specifications in the respective buckets, and the model shall output a cumulative risk score for each bucket.

The parameters for serviceability are listed below:

- **Dampness**

  Control of the measure of the dampness for any building is of essential importance considering the fact the dampness in the building can lead to a large number of consequences such as corrosion in the beams or column rods, mold/vegetation growth(due to moisture), weakening of plaster(especially lime plaster), efflorescence(resulting in disintegration of bricks, stones, tiles, etc., and consequent reduction in strength). Therefore having the knowledge of dampness measures is of utmost importance.

  1. **Moisture-meter**
     Input Format: Gives the value of the dampness as a score
     Description: Offers many preset characteristic curves based on alternative material densities. This digital moisture device gives quick and accurate moisture measurements without causing any damage to the test material.

  2. **Extent of dampness**
     Input Format: A binary answer (Yes/No) with Yes further dialing down as an external source or internal source(like water pipes)
     Description: If the source of dampness is easily identifiable (i.e., like the wall with dampness has water pipes going through it/ is exposed to the external environment).

  3. **Level of building/Floor**
     Input Format: Inputs the floor value (1,2,3,....,n)
     Description: The lower part of the building is usually more exposed to moisture than the remaining building.

  4. **Water table level**
     Input Format: Water table depth (in meters)
     Description: Higher water table depth leads to more humidity which can actively cause dampness.

  5. **Kind of Bricks**
     Input Format: Binary: Porus bricks or not
     Description: Porous bricks used in construction is a permanent source of dampness.

- **Cracks**

  Cracks in the building structure are one of the most common building damage analysis parameters, but the presence of cracks often has may non-linear impacts on the condition of the building. The angle of the crack, its measurements, the presence of dampness in proximity, its location, etc. often signify fault in entirely different parts of the buildings. Cracks could be signs of creeping effect in the building, overloading of some structural parts like beams, columns, etc. Therefore correct inference from these crack parameters serves to be a vital part of structural auditing.

  1. **Crack Measurement**
     Input Format: Measurements of the crack including its length, width, depth(in meters), and angle of inclination to the vertical.
     Description: Usually vertical cracks are more dangerous than shear. While horizontally aligned cracks are the least harmful. In terms of measurements of the crack, the larger cracks obviously imply more severe structural damage.
  2. **Crack Concurrency**
     Input Format: A binary answer (Yes/No) for checking the crack on one side of the wall is further replicated and extended to the other side. Further extending the case of crack concurrency on the basis of 2 parameters:
     - Checking whether the crack concurrency is between 2 sides of an internal wall or whether one side is facing the external environment.
     - Checking if the crack concurrency is inter-storey(between rooms on different floors) or instra-storey (between different rooms on the same level).

     Description: Concurrent cracks further dial up the severity of the problem, with concurrent with the external wall being even more serious as it leads to the internal structure of the building being exposed to the environment. Here is the kind of crack concurrency refers to:
     - Inter-storey crack concurrency implies problems in columns
     - Intra-storey crack concurrency implies problems in beams
  3. **Crack Proximal Frequency**
     Input Format: A binary answer (k/0) stating whether there are multiple(k number) parallel cracks or a single crack.
     Description: It was concluded with the help of a domain expert's advice that multiple parallel cracks serve to be less harmful than one single crack. As multiple parallel cracks usually imply the load is divided between the rods, while a single crack usually implies a severe load-bearing failure of one particular rod.
  4. **Proximity to Dampness**
     Input Format: A binary answer (Yes/No) for checking if there is any dampness close to the cracks.
     Description: The dampness along with the crack could lead to the failure of concrete and thereby may lead to corrosion and weakening of rods.
  5. **Proximity to Mold/vegetation**
     Input Format: A binary answer (Yes/No) for checking if there is any

proximal vegetation/mold growth near the cracks.
Description: The mold/vegetation growth near the crack could imply the presence of moisture which could further lead to the failure of concrete and thereby may lead to corrosion and weakening of rods.

6. **Presence of Redness**
   Input Format: A binary answer (Yes/No) for checking if there is any redness or formation of rust.
   Description: Redness/presence of rust is a direct identification of the presence of internal corrosion.

7. **Location of Cracks**
   Input Format: Tristate input showing the location of cracks into columns, beams, and slabs.
   Description: The different locations of the cracks could imply the varying level of seriousness of the crack with column cracks being the most severe, followed by beams and the least severe being slabs.

8. **Measurement Type of crack near the window frame**
   Input Format: The measurements(length, width, depth and angle) with the type of crack(triangular, shear, vertical).
   Description: Usually in building older than 30-40 years, the presence of triangular cracks near the window frame implies the building is creeping and the load system of the building failing. While the other parameter of the cracks remains the same as above.

- **Vibration**

  In general, a building faces multiple sources of vibration. These sources of vibration can be broadly divided into external and internal sources. The external sources usually contain sources like vibration due to external construction, rail lines, etc., while the internal sources of vibration are mainly constituted by the presence of machinery in the rooms.
  The analysis of the amount of vibration and the vibration-bearing capacity of the building is critical, as low vibration-bearing capacity can cause many problems with the building, such as concrete defects, an increase in cracks, joint weakening, and so on. When a building is constantly exposed to high vibration rates, the damage can happen more quickly. This means that the building will need constant repairs and safety measures.

  1. **Floor number**
     Input Format: A numeric input of the floor on which the deflection is being checked.
     Description: The floor number helps to determine the extent of vibration in the building. Lower floor numbers are more exposed to external vibrations (i.e. vibrations from the surroundings) while higher floor numbers are more prone to vibration from the machinery.

  2. **Internal Vibration Source**
     Input Format: Frequency of vibration due to constant internal factors like machinery and movement inside the building.
     Description: Buildings with less concrete strength or weaken columns can be vulnerable to internal vibrations. These vibrations can also cause further weakening of structure and expansion of existing cracks.

3. **External Vibration Source**
   Input Format: Frequency of vibration due to external reasons like average traffic in the neighborhood, other buildings, or construction sites in the area.
   Description: External vibration can lead to an increase in the settlement of the building and weaken the column strength, and in some cases, cause external cracks and deflection.

- **Deflection**

  Deflection is a very common problem that occurs in multistory buildings with concrete floors/decks. It is mainly associated with the bending of joists, trusses, and rafters associated with overloaded structures. Various interior building effects result from deflection movement. Typically, deflection causes unsightly cracks in the drywall along the inside corners where the wall meets the ceiling. Over time, deflection can worsen causing visual concerns, additional maintenance costs, and structural problems. Therefore check of deflection values is important to help avoid unrepairable damage in the building.

  Interior Building

  1. **Floors number**
     Input Format: A numeric input of the floor on which the deflection is being checked.
     Description: The floor number helps define the degree of seriousness of the deflection. A lower level floor would be having the load of the entire building, therefore adding to the weight of the deflection measure.
  2. **Horizontal Angle Measurement**
     Input Format: Angle Type(Horizontal or Vertical) and measurement (degrees)
     Description: Greater the deflection angle, the more severe the load imbalance of the building. Usually, vertical deflections are more severe and destructive as compared to horizontal deflections.
  3. **Moment of Inertia**
     Input Format: Value of the moment of inertia
     Description: Greater moment of inertia implies lesser deflection in the building; therefore, this measure helps us find what extent of deflection the building can sustain.

  Exterior Building

  1. **Number of floors**
     Input Format: A numeric input of the number of floors in the building.
     Description: The number of floors helps define the seriousness of the deflection, with an increasing number of floors adding to the weight of the degree of deflection
  2. **Horizontal Angle Measurement**
     Input Format: Angle Type(Horizontal or Vertical) and measurement(degrees)
     Description: Greater the deflection angle, the more severe the load imbalance of the building. Usually, vertical deflections are more severe and destructive as compared to horizontal deflections.

3. **Physical Characteristics of the building**
   Input Format: Measurement of physical factors like moisture, elasticity, temperature, and strength, type of material.
   Description: These parameters help directly define the extent of deflections the building will be able to sustain.

- **Settlement**

  Settlement in a building refers to the downward displacement of the structure due to various factors such as soil consolidation, loss of soil support, or changes in load-bearing capacity. In extreme cases, settlement can cause cracks in the walls and foundation, misaligning doors and windows, and even structural collapse. It can also damage utility lines and fixtures within the building.

  1. **Level of building/Floor**
     Input Format: Inputs the floor value
     Description: In a multi-story building, the lower floors may experience more settlement than the upper floors due to the increased weight of the structure and the greater amount of soil deformation caused by the load. This can lead to a noticeable misalignment of doors and windows on the lower floors. However, in certain cases, the upper floors may experience greater settlement if the soil conditions are particularly weak.
  2. **Water table**
     Input Format: Water table depth, can be measured with the help of hygrometer and tensiometer.
     Description: When the water table rises, the soil absorbs more moisture, causing it to expand and apply more pressure on the foundation. This increased pressure can cause the foundation to sink and result in settlement. Similarly, if the water table drops, the soil can shrink and create voids below the foundation, which can cause the foundation to settle.
  3. **Soil's average vibration**
     Input Format: Value measured by using Seismic instruments, such as geophones, seismographs and Dynamic Cone Penetrometer
     Description: Vibrations can cause soil liquefaction, which is a process where soil loses its strength and stiffness, resulting in the failure of structures.
  4. **Neighbourhood condition of construction**
     Input Format: Subjective rating based on the discretion of the auditor
     Description: The nearby condition may affect the strength of the building because of the excavation of land and soil.
  5. **Type of soil**
     Input Format: Subjective Rating of soil which can be identified through visual inspection and other penetration tests like DCP.
     Description: Soil type can influence the compressibility of the soil; soils with high compressibilities, such as clay soils, can result in significant settlement under load. Soil type can also influence the shear strength of the soil. Soils with low shear strength, such as loose sand or silt, can result in settling or sliding of the soil.

6. **Grade of soil**
   Input Format: The value of grade of soil can be identified through visual inspection and other penetration tests like DCP
   Description: The grade of soil can also impact the drainage characteristics of the soil, Soils with poor drainages, such as clays, can retain water and become more susceptible to liquefaction and settlement under seismic loads.

7. **Width: Depth ratio of foundation (W:D ratio)**
   Input Format: Measure the width of the foundation at its widest point. Measure the depth of the foundation from the surface of the ground to the bottom of the foundation and calculate the ratio.
   Description:A larger W:D ratio generally results in a more stable foundation, reducing the pressure on the soil and reducing the potential for settlement.

Environmental Parameters
Any infrastructure is impacted by its surroundings in a variety of ways. The environment of any infrastructure is made up of a number of elements, including temperature, humidity, etc. Studies have demonstrated that factors including soil type and sulphate attacks can affect the stability and integrity of the construction. Thus, it is crucial to research and gauge the potential effects of the environment on an infrastructure.

- **Displacement of structure**

  The displacement is the distance from the original position of a point to its final location on the deformed model. Such displacement of the complete structure can cause severe damage to the structure

  1. **Sinking**
     Input Format: Soil Conditions (Soil Moisture Content, Specific Gravity, Dry Density, Proctor Compaction, Atterberg Limits), Extent of sinking
     Description: Sinking foundation is a problem that occurs in case of improperly laid foundations which is the result of careless consideration of the soil type. The problems are very crucial and have to be solved as soon as they are detected to prevent the structure from further damage.

  2. **Shifting**
     Input Format: Soil Conditions (Soil Moisture Content, Specific Gravity, Dry Density, Proctor Compaction, Atterberg Limits), Extent of shifting
     Description: The foundation and hence the entire structure might get displaced laterally because of environmental factors, impacting the integrity of the structure

  3. **Settling**
     Input Format: Soil Conditions (Soil Moisture Content, Specific Gravity, Dry Density, Proctor Compaction, Atterberg Limits), Extent of shifting
     Description: Settlement of the foundation soil is a vertical displacement of the soil surface caused by the workload of the building. While the settlement of the foundation structure is considered normal and acceptable to a certain extent, it might have severe impacts in the long run.

- **Temperature Fluctuations**

  Cold

  1. **Surface spalling:**
     Input Format: Depth of spalling, diameter of spalling
     Description: Spalling is the breakaway of the concrete surface, which often extends to the top layers of reinforcing steel. If left unchecked then spalling will tend to accelerate and spread so that, eventually, the structure could bome unstable. Diligent maintenance is therefore of great importance and legislation places a duty of care on owners to ensure that structures are not hazardous to users.
  2. **Internal cracking**
     Input Format: Length, depth, width and location of the crack
     Description: Internal cracks are formed at the solidification front just below the solidus temperature and they are related to the reduced ductility in Area

  Heat

  1. **Strength**
     Input Format: Compressive strength measured using the rebound hammer test.
     Description: The strength of the material used can be compromised due to exposure to heat, and the resulting expansion and compression of the material.
  2. **Surface Finish**
     Input Format: Lay(direction of texture), Surface roughness, waviness.
     Description: Surface finish, also known as surface texture or surface topography, is the nature of a surface. On exposure to heat, the surface finish can get damaged.
  3. **Cracking**
     Input Format: Length, depth, width, location of crack
     Description: Thermal cracks appear when the restraint results in tensile stresses that exceed the in-place concrete tensile strength. Cracking due to temperature can occur in concrete members that are not considered mass concrete.
  4. **Mold**
     Input Format: Extent of the spread of mold
     Description: It grows indoors when mold spores land on surfaces that are wet, and they can grow anywhere in the building when moisture is present.

- **Signs of Biological Degeradation**

  1. **Plants**
     Input Format: Types of plants(as per soil parameters), no. of plants of each type
     Description: The extension of the roots of a plant and how it bind the soil impacts the soil's binding quality and strength to hold the building

2. **Tree**
   Input Format: Types of trees(as per soil parameters), no. of trees of each type
   Description: The extension of the roots of a plant and how it bind the soil impacts the soil's binding quality and strength to hold the building
3. **Termites**
   Input Format: Extent of spread of termite
   Description: Termites can damage the internal structure of the building causing severe damage.
4. **Mold**
   Input Format: Extent of the spread of mold
   Description: It grows indoors when mold spores land on surfaces that are wet, and they can grow anywhere in the building when moisture is present.

- **Humidity**

1. **Mold**
   Input Format: visual inspections, air and surface sampling, and moisture measurements.
   Description: Mold can cause the deterioration to build materials such as drywall, flooring, and insulation. Mold growth can also lead to the warping or buckling of floorboards and walls.
2. **Average humidity of the area**
   Input Format: measured using a hygrometer
   Description: High humidity levels can also cause building materials to deteriorate more quickly, such as warping, rotting of wood and corrosion of metal components.
3. **Musty smell**
   Input Format: Existence of Musty smell (Yes or No)
   Description: Subjective, Can experience through nose
4. **Damping**
   Input Format: Measured using techniques such as experimental modal analysis (EMA) or frequency response analysis (FRA).
   Description:affects the structural integrity of the building by causing corrosion and weakness of concrete.

- **Corrosion**

Corrosion is the deterioration of a material as a result of its interaction with its surroundings

1. **Stress corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: Stress corrosion occurs when a material exists in a relatively inert environment but corrodes due to applied stress.
2. **Intergranular corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: This is a corrosion type that attacks the boundaries of the metal crystallites, as opposed to attacking the surface of the metal.
3. **Corrosion Fatigue**
   Input Format: Extent, Location (in beam or column or slab)

Description: It is the mechanical degradation of a material under the joint action of corrosion and cyclic loading.

4. **Atmospheric corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: Atmospheric corrosion is an electrochemical process whereby thin films of water are deposited on a metallic surface leading to wet corrosion.
5. **Erosion corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: The gradual wearing away of a metal surface by a combination of both corrosion and abrasion from an impinging water stream, such that the higher the velocity of the impinging stream, the greater the rate of erosion-corrosion.
6. **Selective corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: Selective corrosion occurs in alloys where one of the component metals is de-alloyed by the corrosive environment.
7. **Uniform corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: The attack of the entire metal corrosive environment resulting in uniform metal loss from the exposed surface.
8. **Pitting corrosion**
   Input Format: Extent, Location (in beam or column or slab)
   Description: A type of corrosion that attacks a local area of the metal and eventually leads to the formation of holes in the metal

- **Sulphate Attack**

  The reaction between sulfate ions in the pore solution of concrete and constituents in the concrete that result in formation of new reaction products with a relatively large molar volume.

1. **Pushing wall outwards**
   Input Format: Outward displacement of the wall from original position
   Description: Pushing the wall outwards can cause further stress on the affected areas and potentially lead to more cracking or collapse
2. **Lateral movement of bricks**
   Input Format: Lateral displacement of bricks
   Description: The lateral movement of individual bricks can cause misalignment of the brickwork, which can put additional stress on the mortar holding the bricks in place.
3. **Stepped diagonal cracks on external wall**
   Input Format: Size of crack, extent of crack
   Description: Stepped diagonal cracks weaken the wall and reduce its load-bearing capacity, which can increase the risk of collapse in the event of a natural disaster such as an earthquake.
4. **Heaving and cracking**
   Input Format: Length of heave/crack, extent of heave/crack, depth of heave/crack
   Description: Heaving and cracking can allow water to penetrate the

building, leading to further damage and potential health hazards if mould or mildew develops

5. **Lumpiness and doming**
   Input Format: Extent of lumps, size of lumps
   Description: Lumpiness and doming can cause additional stress on the building's foundation and structure, leading to further cracking and instability.

6. **White salt deposits**
   Input Format: Spread of white salt
   Description: The presence of white salt deposits can indicate that the building is suffering from long-term moisture exposure, which causes the building's structure to deteriorate, leading to cracking, warping, and decay of the building materials.

6.2.2. Correlations and Inter-dependencies

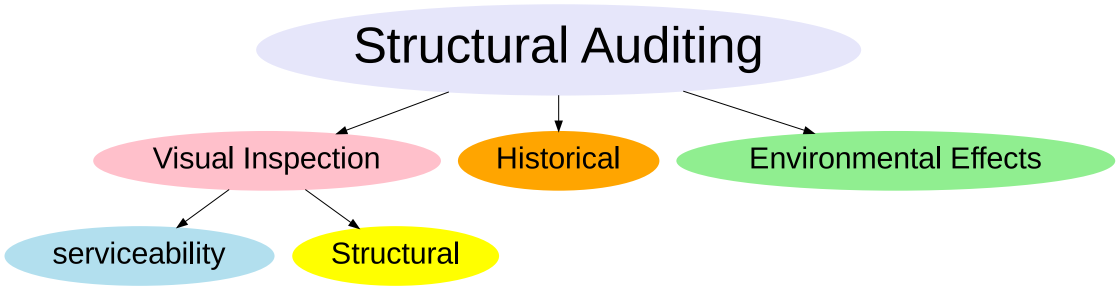


Figure 6.1: Basic overview of dependencies and correlations

Structural component of Knowledge model

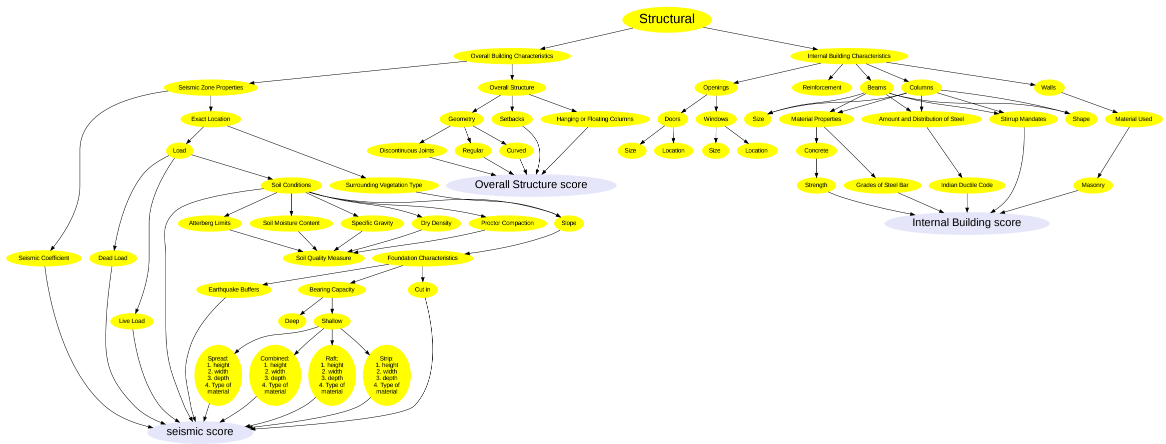


Figure 6.2: Structural component of model with its inter-dependencies

Historical component of Knowledge model

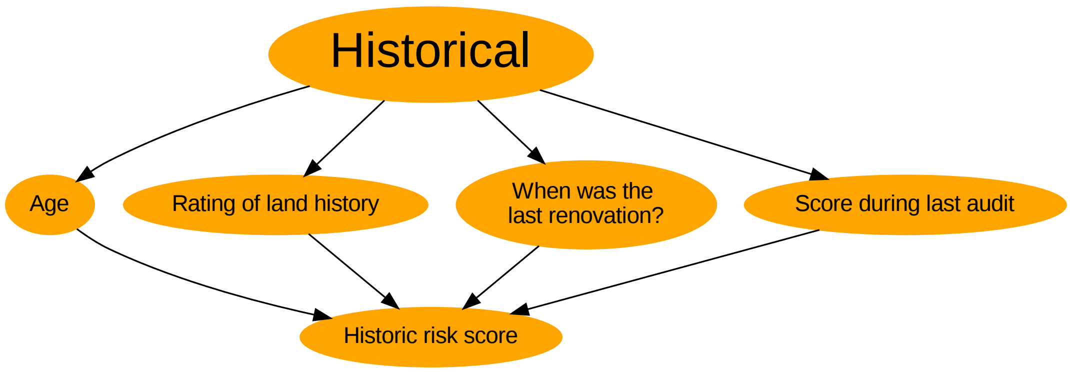


Figure 6.3: Historical component of model with its inter-dependencies

Serviceability component of Knowledge model

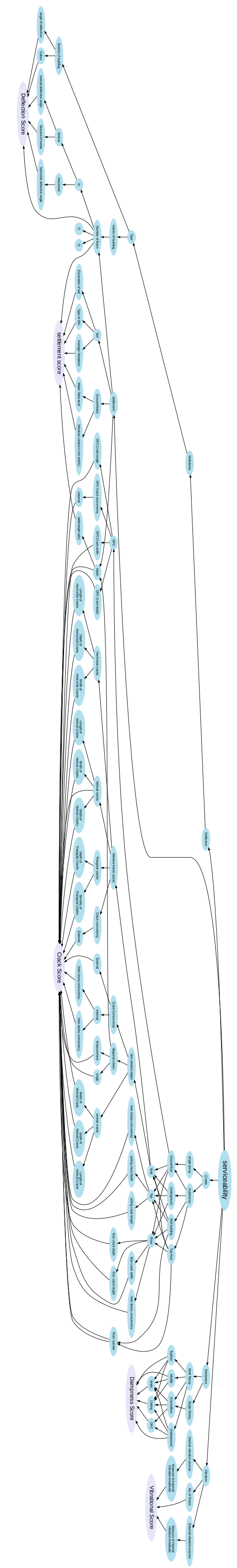


Figure 6.4: Serviceability component of model with its inter-dependencies

Environmental component of Knowledge model

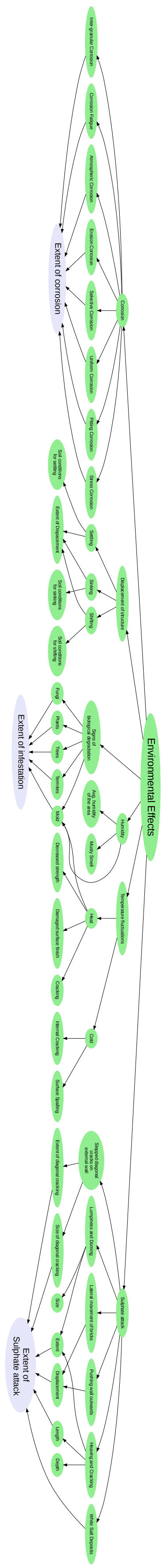
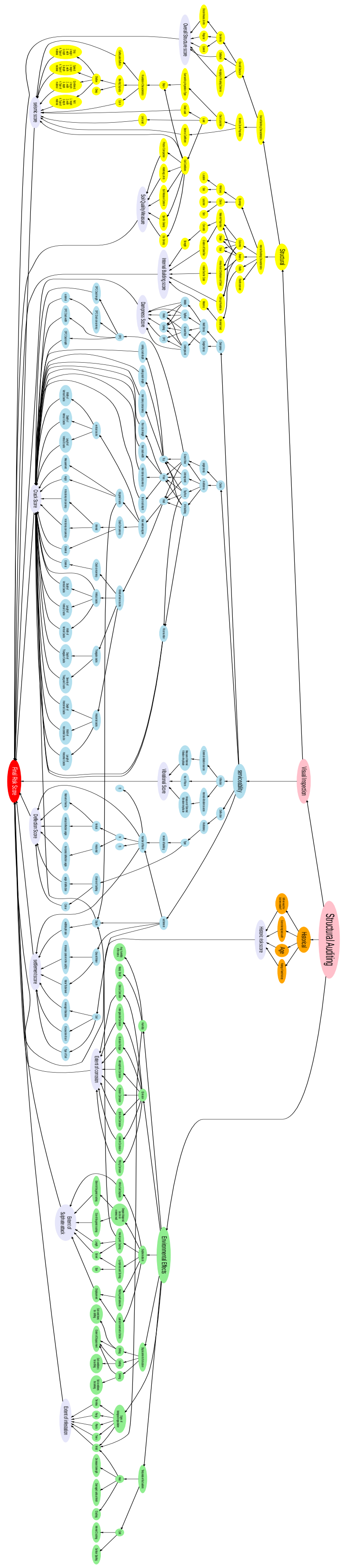
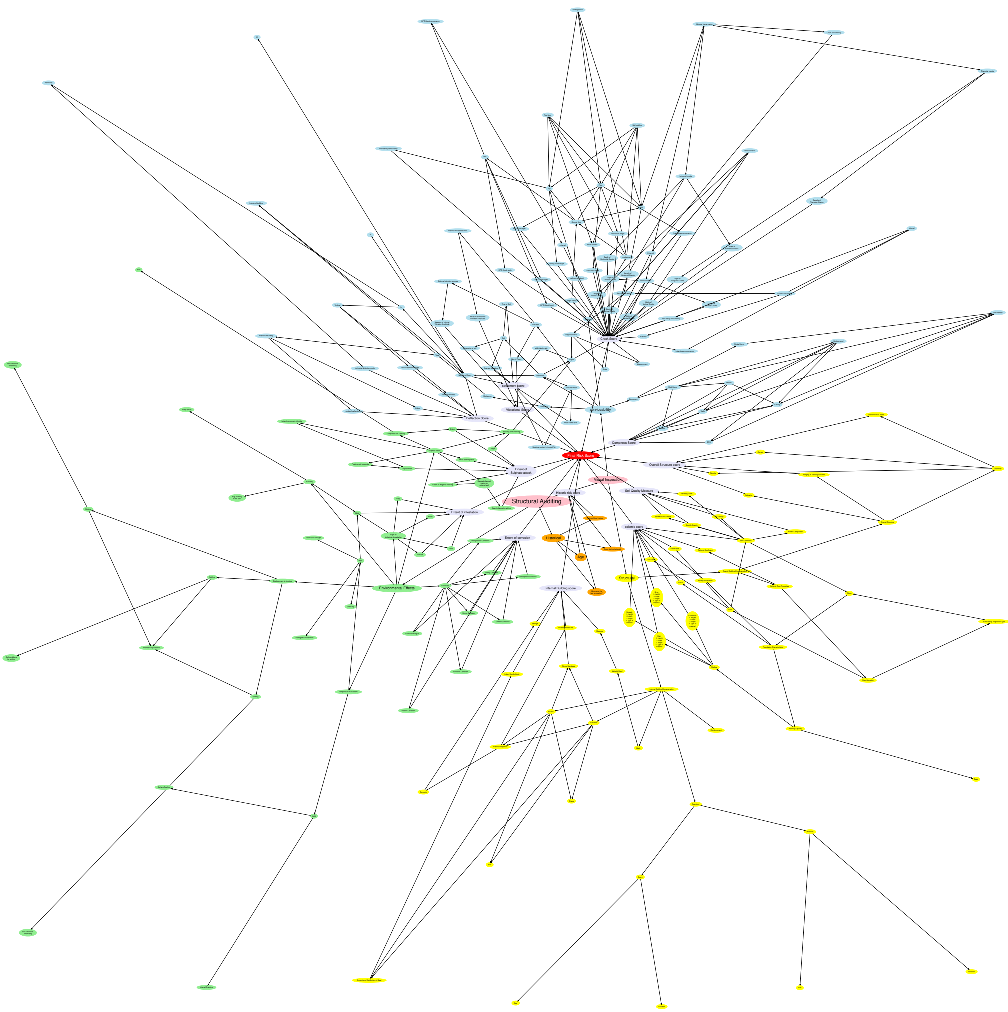


Figure 6.5: Environmental component of model with its inter-dependencies

Panoramic view at the proposed knowledge model



Exploded view of the proposed knowledge model



Part of Model	**Link**	**Description**
Overall Structure	Link	The structural auditing process is divided into three steps namely historical, environmental parameters and visual inspection. The visual inspection is further divided into serviceability and structural parameters.
Serviceability	Link	The serviceability tree of the graph is further classified into cracks, dampness, settlement, vibration and deflection. The respective risk scores are then used to calculate serviceability risk score.
Structural	Link	The structural tree of the graph is classified into extent of displacement, seismic score, internal building and overall structure.The respective risk scores are then used to calculate structural risk score.
Environmental	Link	The environment subsection of the tree is classified into extent of corrosion, extent of sulphate attack, extent of infestation, soil quality measure. The respective risk scores are then used to calculate environment tree risk score.
Historical	Link	The historical subsection of the tree is classified into age, rating of land history, when was the last renovation, score during last audit. The respective risk scores are then used to calculate the historic tree risk score.
Full Knowledge Model	Link	It is the combination of all the buckets, including the final risk score (weighted sum of bucket risk scores). More of it is already covered extensively in the previous section

6.2.3. The Link: Output to Decision

At the end of the model, we receive multiple risk scores, namely bucket risk scores - structural, serviceability, environmental, historical and the final risk score. The bucket risk score indicates the severity of the individual parameters, while the overall score determines the current risk level of the building as a whole. The next step is to determine the urgency of repairs from the recommended thresholds and conduct detailed Non-Destructive Tests to investigate the issues further.

Threshold Score	Description
0.75 - 1.00	Acute Structural Damage, needing immediate repair and reconstruction and NDTs are suggested to find the main damaging section
0.50 - 0.75	Moderate Structural Damage, further needing NDTs to dial down to the exact problem, need some repair measures
0.25 - 0.50	Minute Structural issues, with regulatory maintenance measures required
0.00 - 0.25	The building is in good condition and doesn't need any specific preventive/repair measures

6.3. From Bayesian POV

Bayes Theorem

The mathematical formula, Bayes' Theorem, can be used to calculate conditional probability. The possibility of a result depending on the likelihood that a comparable outcome has already occurred is known as conditional probability. The Bayes theorem offers a mechanism to update the probability for current predictions or hypotheses in light of new or additional data. The mathematical expression for Bayes' theorem is given by:

$$P(B|A) = \frac{P(A|B) \times P(B)}{P(A)}$$

Here

- $P(A|B)$ = the probability of event A occurring, given event B has occurred
- $P(B|A)$ = the probability of event B occurring, given event A has occurred
- $P(A)$ = the probability of event A
- $P(B)$ = the probability of event B

In our problem statement, the conditions are **dynamic** (concerning time, the conditional values may be altered, or there might be an addition of new nodes or a deletion of existing nodes), and the network adapts to the change. In this approach, the probabilities in our network are flexible and dynamic, and the judgment of the domain expert considers this shift.

Bayesian Belief Networks (or BBNs)

A building's or infrastructure's risk assessment comprises several factors structured from top to bottom, as explained in section 6.2.2. Due to the network's intricacy and the interconnectedness of diverse components, some inspection elements may not be immediately inferable by human cognition. The risk score presented (as indicated in section 6.2.3) at output consists of two dependable levels; the first layer suggests the severity of the problem at the sub-component level (inside the structural, environmental, etc. buckets), and the second layer is a weighted total of all the risk scores. While the first layer conveys the intensity and enables the auditor to take further action as needed, the second layer still fails to support its meaning when seen in the context of the entire structure. Here comes the concept of going back to the genuine trouble spots that significantly impact the risk score and providing the auditor with few direct answers as to where the issue is, what part of it is more problematic, and what other elements are raising the risk.

Integration of BBNs in our knowledge model

The entire structural auditing procedure has been separated into ***n*** buckets. The domain expert must enter the various parameters for each bucket, and the Bayesian network will generate a risk score for each bucket. Then, a cumulative risk score representing the current condition of the building will be generated.

- **Bucket Risk Score**

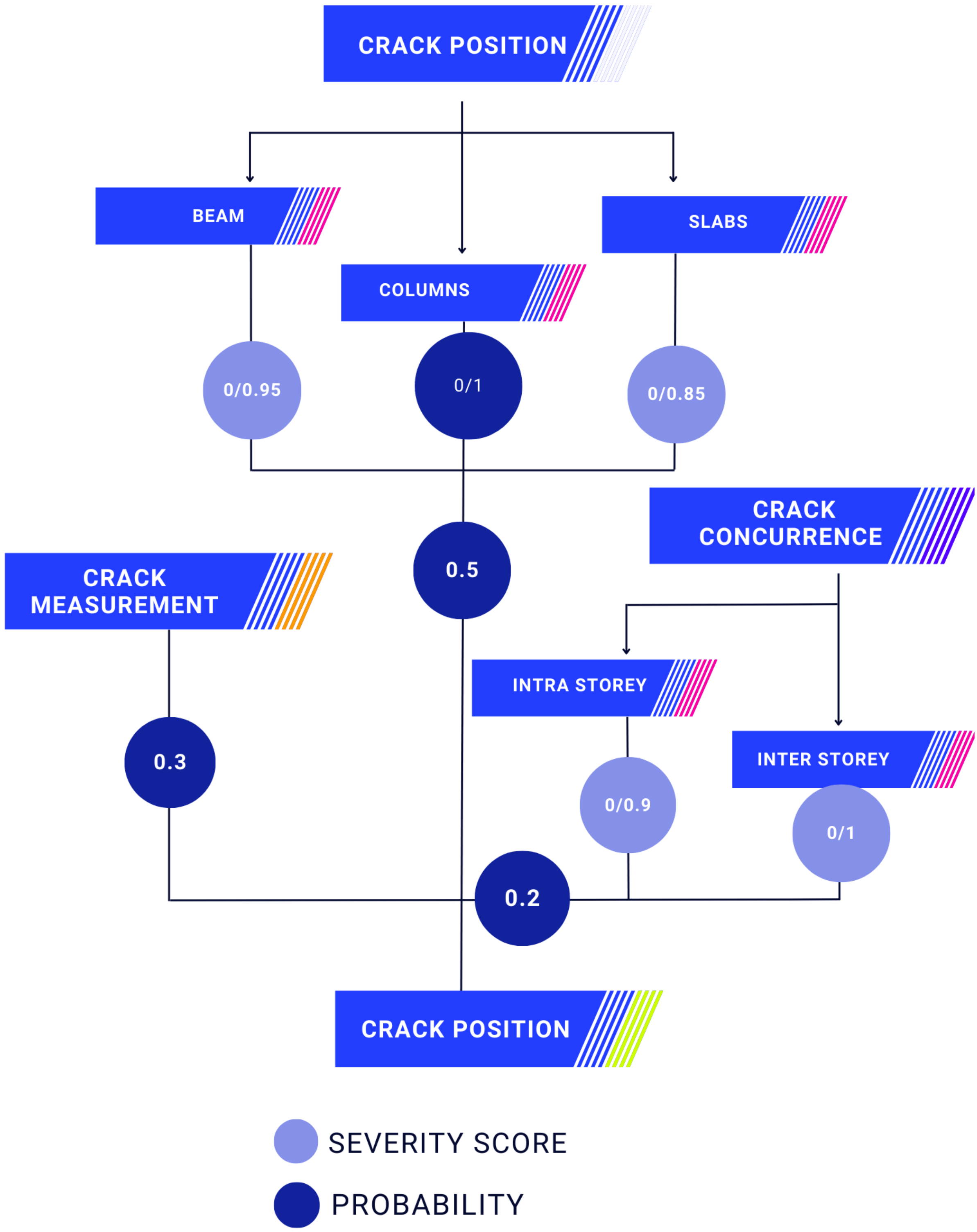
  The various parameters inputted into the model by the structural auditor shall be converted into a quantifiable measure, i.e., a parameter score ranging from 0 to 1, with 1 indicating that the damaging parameter is in critical and severe condition and 0 indicating the absence of that particular damage indicator. Assuming all parameters to be independent of each other, the parameter's score is then multiplied by the probability factor, i.e. the probability of the parameter's influence on the damage bucket.

$$
\begin{aligned}
p_{bucket_{(j)}} = \sum_{i=1}^{k} \alpha_{ij} \cdot p_{ij} \\
& where \ \sum_{i=1}^{k} p_{ij} = 1 \ and \ k = number\ of\ parameters\ in\ bucket_{(j)} \\
& \alpha_{ij}, p_{ij} \in (0,1) \\
& \alpha_{ij} : Parameter\ Severity\ Score\ (Deterministic) \\
& p_{ij} = P(bucket_{(j)} \mid (parameter_i \cap (\overline{\cup\, parameter_l}))),\ \forall\ l \in (0,k) \backslash \{i\}
\end{aligned}
\tag{6.1}
$$

Example: Crack Score

The domain expert will be inputting the various parameters into the model in the crack sub-section of the serviceability bucket. Depending on the parameters set by input, a parameter score shall be calculated (lying between 0 and 1), and then these parameter scores shall be multiplied by the probabilities with which they affect the Crack Score. The corresponding parameter scores and probabilities are mentioned in the infographic.

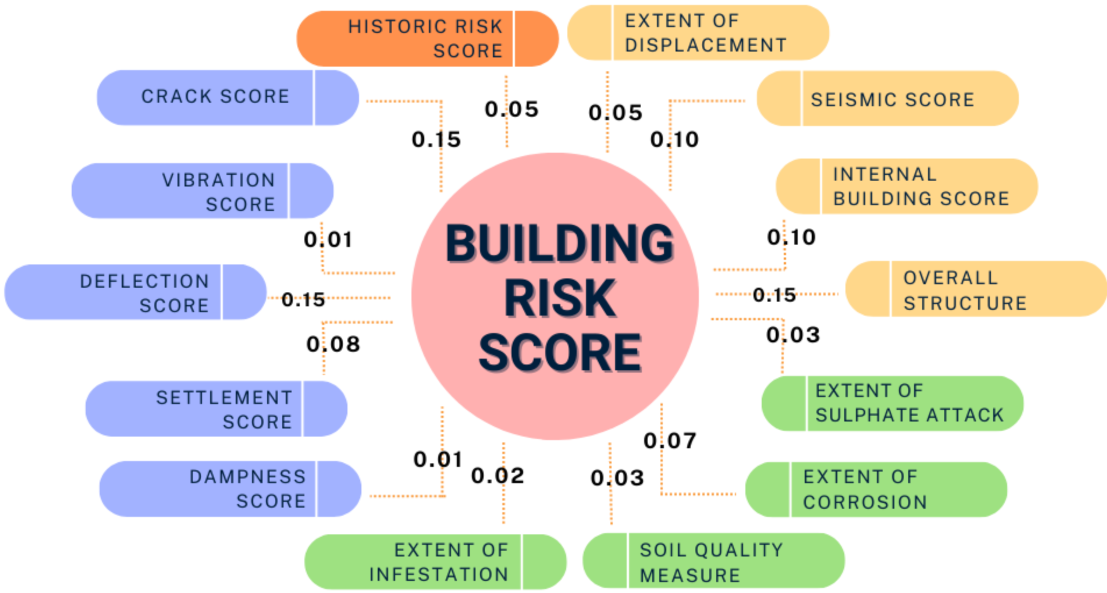
$$P(crack \mid risk) = \frac{P(risk \mid crack)(crack)}{\sum_i P(risk \mid F_i)(F_i)}$$



- **Cumulative Risk Score**
  For calculating the overall risk score for the building, weights shall be assigned to each bucket with regards to the degree to which it affects the overall risk report of the building. These weights shall then be multiplied by the risk score of each bucket and the corresponding summation of this final bucket score multiplied by their weight gives the final risk score of the building signifying the usability and habitability of the building, while also helping understand the seriousness with which the preventive and repair

measures shall be executed. The corresponding weights are mentioned in the figure below.

$$\begin{aligned} &Cumulative\ Risk\ Score = \sum_{j=1}^{n} w_j \cdot p_{bucket_{(j)}} \\ &where\ \sum_{j=1}^{n} w_j = 1\ and\ n = number\ of\ buckets \\ &w_j, p_{bucket_{(j)}} \in (0,1) \\ &w_j : weight\ for\ individual\ bucket's\ risk\ score \end{aligned} \tag{6.2}$$



6.4. Illustrative Example

An auditor is going to analyze an IT Company's 10-storey office building with two basement levels (used for parking) situated in a busy urban area in Bangalore. The auditor would conduct a visual inspection of the building and feed the inspection's findings into our model. Based on this data, our model would predict risk scores of multiple sections and factors related to the building and suggest tests if required. This model will help in easy analysis using visual inspection of a structural audit.

The data is derived from historical data available for the building, the environmental factors, visual inspection, and results of the primary NDTs.
Note: The risk scores have been evaluated on a scale of 1-10 in the example for easy understanding.

1. **Historical data and its interpretation:**
   The building is 15 years old. The land history is rated at 8.5 out of 10, which suggests that it was appropriate for the construction to a great extent. The model also considers data from previous safety audits/inspections and any renovations done prior to the current audit. It was found that no safety audit was conducted previously, and no renovation has taken place.

   Cumulative risk score and interpretation: The model gives a historical risk score of **7/10**. This was given considering the age of the building and the fact that no previous audits and renovations were done, suggesting the possibility of damages and defects.

2. **Environmental effects and their interpretation:**

   - **Displacement of structure:**

     The structure was found to have settled by 3 inches. No sinking and slight shifting were reported. The soil was one of the governing factors for settlement. The soil was found to be laterite with 18% moisture content, a specific gravity of 3.5, and a dry density of 1800 kg/m^3. The proctor compaction and atterberg limits were also tested and found.

     Output and interpretation: **Risk score- 2/10**. All the parameters were in the desired range, indicating that settlement did not occur because of the soil conditions.

   - **Temperature Fluctuations:**

     Surface spalling due to colder weather conditions was not found. Internal cracks were observed. Moreover, based on higher temperature conditions, which might have resulted from heat generation from machinery, the strength of the building material, as per the rebound hammer test, was found to be 22N/mm^2. The surface roughness and waviness were measured when the surface finish was observed. As mentioned above, cracks were observed. Molds were also visible in some places.

     Output and interpretation: **Risk score- 5/10.** As surface spalling was not observed, it was concluded that the internal cracks did not result from the cold weather conditions. Based on the rebound hammer test, the strength of the building materials was found to be fair but degrading. As for the surface finish, the lay and waviness were in the permissible range, but the surface roughness was found to be slightly problematic.

   - **Biological Conditions:**

     In the biological conditions, the model takes the input of the trees and plant level in the surrounding of the building to understand its effect on the structure. The auditor did not record them; hence, the rating was taken as 0. The extent of Termite spread was recorded and rated

6/10. Molds were also observed.

Output and interpretation: **Risk score- 3.5/10**. The spread of termites was found to be troubling, and the growth of molds indicated the presence of moisture.

- **Humidity:**

  The average humidity in Bangalore was found to be 71%. The auditor observed a musty smell inside the building. Dampness in the walls and concrete was also recorded and studied in detail in serviceability parameters.

  Output and interpretation: **Risk score- 6/10**. The presence of moisture in concrete and high humidity indicated problems in the building's integrity and stability.

- **Corrosion:**

  Corrosion tears were conducted on various columns. Testing on one such column revealed stress corrosion values to be 6 on a scale of 10, and intergranular corrosion to be one, and so on for the other types of corrosion.

  Output and interpretation: **Risk score- 9/10**. Stress corrosion was above the permissible range, while the other corrosion levels were within the permissible range. This indicated that the columns were unable to bear the total load of the building.

- **Sulphate attack:**

  The walls were not found to be pushing outwards. There was no lateral movement of bricks. Average sized lumps were found at an extent level of 7/10. While the white salt deposits were rated at 7.5 on 10. As mentioned above, cracks were observed.

  Output and interpretation: **Risk score- 8/10**. All the above factors indicate that due to additional stresses on the building structure, the building was getting damaged, and the white salt deposits were causing decay in the building materials. It was also noted that the lumps could have been a reason for the cracks.

Cumulative risk score and interpretation: The total risk score of the building based on environmental factors was found to be **5.5/10**, indicating that environmental effects can be a reason for the cracks and further damage to the building's structure, majorly because of the stress corrosion, heating effects of the machinery and formation of lumps.

3. **Serviceability parameters based on visual inspection and primary NDTs**

   - **Dampness:**

     A dampness check was done on every floor of the building, and it was found that the lowest basement had a dampness rating of 8.5 and mostly because of external conditions like the water table. The dampness rating for the upper basement and the ground floor was around 8. The second floor to the sixth floor had a constant dampness rating of 6. The seventh floor had a sudden rise with a rating of 9. The eighth and the ninth floor had a rating of 8.

     Output and interpretation: **Risk score- 8.5/10**. While the dampness level was high on the lowest and highest floors, as expected, due to external factors like groundwater, moisture in the soil, and water collection in the ground and terrace. The sudden increase in the 7th floor indicated leakage in the water line of the building, and it raised concerns and could be a possible reason for cracks and molds.

   - **Cracks:**

     A total of 131 cracks with varying parameters and dimensions were observed. Each crack's location, orientation, and concurrency were noted and fed into the model. The average risk rating of cracks was 7, with the peak on the 6th floor with a rating of 9. The auditor also noted the proximal frequency of the cracks to check if the load was distributed, and most of the walls had multiple cracks, which were less severe. Closeness to the moisture was also recorded and the average rating was 6, with the highest on the seventh floor at 9.5. The level of redness was also highest on the 7th floor.

     Output and interpretation: **Risk Score- 9/10**. Since cracks are usually multiple in a single wall, it was less severe than the single cracks noticed. The highest number of cracks was on the 6th, making it one of the weakest. Proximity to dampness was highest in the seventh, making it more prone to corrosion and indicating that the dampness is concerning.

   - **Vibration:**

     The frequency of vibrations on each floor was measured, and it was found to be the highest on the ground floor, with a casual decrease till the 5th floor and a sudden peak at the 6th floor.

     Output and interpretation: **Risk score- 7/10**. The high frequency on the ground floor was attributed to heavy traffic in the surroundings, the nearby construction site, and the presence of the company servers on the same floor. The high vibrational frequency on the 6th floor was concerning. The possible reasons could be the high number of cracks and the moisture seepage from the 7th to the 6th floor, which might have resulted in the weakening of columns or beams on that floor.

- **Deflection:**

  The deflection of the building was measured both internally and externally, including the internal deflection of each floor. In the internal inspection, both horizontal and vertical deflections were recorded, and in the vertical deflection moment of inertia was also noted. There was no horizontal deflection seen on any floor. There was a vertical 1-degree internal deflection on the 6th and 7th floors. MOI was also in the acceptable range, with a slight fluctuation on the 6th and 7th floors. The total external deflection was found to be around 2 degrees.

  Output and interpretation: **Risk Score- 8/10**. The overall external deflection was found to be concerning and could be one of the most probable reasons for the settling of 3 inches of the building. The internal vertical deflection only on the 6th and 7th floor could mainly be because of the weakening of the concrete due to dampness and cracks.

- **Settlement:**

  As observed before, there was a 3-inch settling of the building. The model considered a number of floors, which in this case was 10 + 2 levels of the basement, to understand the load on the ground. The water table, as checked above, was noted as 16m. Average soil vibration of 167Hz was noted. Neighborhood condition was found to be as discussed above, with the addition of soil excavation rated 8/10 due to closeness with other buildings. The type of soil was as recorded above. The width to Depth ratio of the foundation was found to be 0.625.

  Output and interpretation: **Risk Score-7/10**. It is highly likely that the settlement resulted from higher soil vibration frequencies, the total load of the building, and added excavation of soil. The width-to-depth ratio of the foundation was found to be appropriate.

Cumulative risk score and interpretation: Total risk score due to serviceability parameters was found to be **8/10**. Dampness and cracks in the building were found to be significant contributors to the serviceability risk. All the risk score and parameters indicated that the 6th and 7th floor is damaged and need instant repair.

4. **Structural parameters based on visual inspection and primary NDTs:**

   - **Overall building characteristics:**

     - *OVERALL STRUCTURE:* Height was 110 feet, and floating columns were used and rated a 9/10 on average, with the lowest around the 7th and 8th floor. Elevators and emergency staircases were present in the building, and their relative stiffness was recorded and rated at 8.4/10. It was a regular-shaped building. Building setbacks were not present.

Output and interpretation: **Risk score- 4/10**. The overall structure was found to be in okay condition with no major defects.

- *SEISMIC ZONE PROPERTIES:* The seismic coefficient was found to be 0.1 as the building lies in Earthquake Zone II. The average live load of the building was found to be 5kN/m^2. The surrounding vegetation type was assessed and rated at 9.5/10. Foundation characteristics were recorded. The bearing capacity of the building was found to be okay, with a rating of 7/10.

  Output and interpretation: **Risk score- 2/10**. The building has no significant damage because of its seismic zone properties, as it is in a less earthquake-prone area. If an earthquake hits the building, the foundation will most likely survive.

- *SOIL QUALITY MEASURE:* The soil was found to be laterite soil with 18% moisture content, a specific gravity of 3.5, and a dry density of 1800 kg/m^3. The proctor compaction and atterberg limits were also tested and found.

  Output and interpretation: **Risk score- 2.5/10**. The building has no significant risk because of the surrounding soil conditions.

- **Internal building characteristics:**

  The total number of doors and windows were counted and their location was noted. The total no. of openings was 400. Columns and beams were analyzed, and the material quality was rated at 6.5/10. The shape and size of the columns and beams were as per the building codes. Slight deterioration was noted on floors 7,8,9. Stirrup Mandates were followed in the beams. The wall material was analyzed and was given an average rating of 7, with the lowest rating on the 3rd and 8th floors.

  Output and interpretation: **Risk score- 6.5/10**. The internal structure of the building was acceptable except for wall conditions on the 3rd and 8th floors, possibly because of high vibration and load on lower floors and dampness and cracks on higher floors. Columns and beams were in average condition and could be defective in upcoming years. Beams on higher floors were slightly lousy, primarily because of cracks, dampness, and other parameters mentioned in the above interpretations.

Cumulative risk score and interpretation: Total risk score due to structural parameters was found to be **5/10**. The structural integrity of the foundation had an average risk score. Wall material on the higher floors is needed to be renovated in general. 3rd floor's material needs to be adequately analyzed. The soil quality of the site is in good condition.

***Final risk score and suggestions* - 6.2/10**. Foundation strength in the lower floors needs to be checked further. The 6th and 7th floors are at very high risk and must be renovated within 6 months. Cracks throughout the building should be checked and fixed. There is a possible leakage on the 7th floor, which needs to be fixed immediately. Further measures need to be taken to ensure such leakages don't occur again. Better heat isolation is required on the ground floor.

7

Business Study

7.1. Feasibility Analysis

7.1.1. Technical Feasibility

The proposed model is technically workable. Given that Cognitive Garage offers a chatbot for simple feasibility, the intended consumers of this model can use it without much difficulty. Users would feel more confident using the model because it would be developed with assistance from domain experts. Additionally, as India's infrastructure and inspection sectors are currently predominately manual, such automation would be advantageous and appealing to decision-makers and stakeholders.

7.1.2. Economic Feasibility

While the need for such safety checks is increasing daily, reports suggest that a huge majority of safety inspectors will retire or exit the profession. Providing an automated model to assess safety will attract decision-makers in such a situation. They are highly likely to support the model financially.

7.1.3. Legal Feasibility

As per the Model Bye-law no. 77, it is mandatory to conduct a structural audit every 5 years for any building aged between 15-30 years and every 3 years for any building aged more than 30 years. Many such mandates are slowly coming into picture in India, and our model would make it more feasible to conduct these audits timely and without any redundant delays.

7.1.4. Organizational Feasibility

A complete team needs to be set up to deal with the technical and the business domain in the long run. Apart from that, the domain experts will have to be consulted to develop the knowledge model completely and to ensure accurate results since this is a field with a negligible scope of error.

7.2. Go-to-market Strategy

7.2.1. Data Collection/Extraction

Currently, auditing is a time and cost-intensive activity conducted at a superficial level. The procedure is rife with bias and even misconduct. The process is also not very exhaustive or frequent. This causes an increase in expenditures and efforts when the issue is discovered later. Early identification and resolution of a problem can result in substantial cost savings. The status quo in the industry is a three-step process consisting of **Visual Inspections**, **Non-destructive Testing (NDTs)**, and an **Analysis Report**.

Since NDTs are relatively costly and time consuming, we propose reducing the number of NDTs performed on a structure. This will be achievable by utilizing data from Visual Inspections, building history, and input from domain experts. Highlights of our model will comprise of:

- Propose which NDTs *must be conducted and where*, thereby conserving time, money, and manpower
- Offered for sale to Infrastructure Auditing companies and/or contractors
- We recommend selling the model as a **one-time purchase** basis

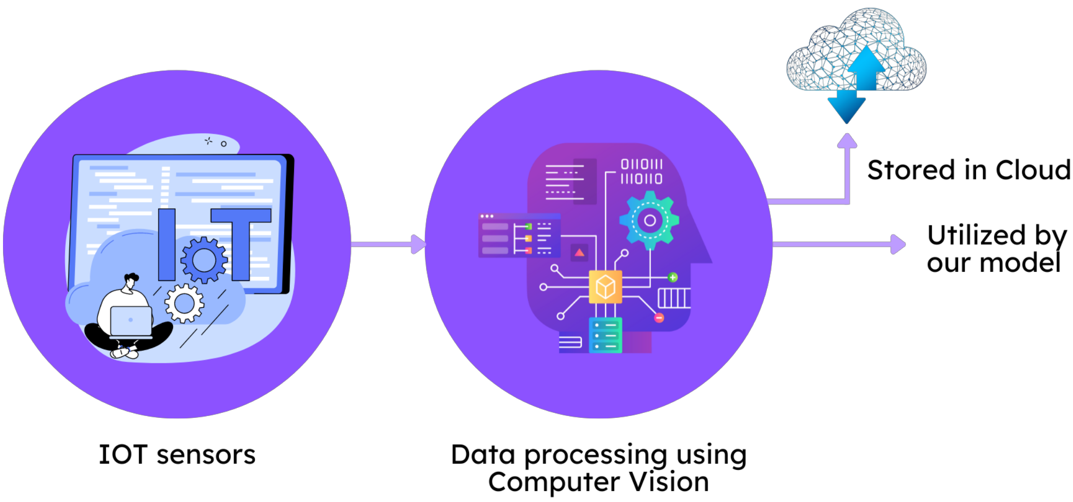


Figure 7.1: Integration of IOT sensors and Computer Vision to automate data collection

7.2.2. Integrating IOT With Our Proposed Model

As the Internet of Things (IoT) technology becomes more readily available, we present a futuristic solution for Structural Audits. We can replace the visual Inspection with various Computer Vision technologies and integrate them with data from various IoT sensors capable of detecting specific flaws. This information will be kept in the cloud and can be utilized to train the model based on the risk scores obtained, the model can also help in emergency situations to come up with spontaneous results in the absence of Structural Auditors.
This model will be offered to Contractors on a 10-year subscription basis.

7.3. Targeted Users

- **Residential Sector**- Structural engineers and Building inspectors might not be able to visit every area of the building or they can have limitations while using their equipment for audits. The structural engineers might also not be able to easily detect some hidden defects to structural parts. It is also challenging to determine with accuracy the precise impact of numerous corrosive and degrading chemicals on diverse structural parts.
- **Commercial Sector**- Due to the need for valuation of several different commercial structures like Office spaces, Airports etc, these Hazard as-

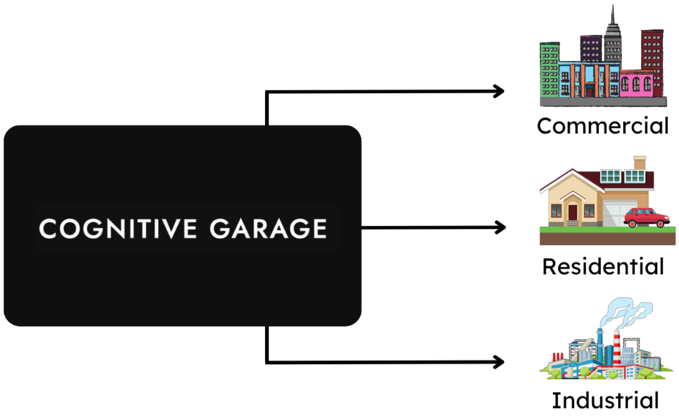


Figure 7.2: B2B model for Cognitive Garage

sessment specialists appointed by Insurance companies are under pressure to assess the risk factor of various buildings in a short period of time, This model can help them ease this process by providing a quantitative risk score according to which the company can charge premium.

- **Industrial Sector**- This model can be used to assess the risk factor at different industrial structures like mines, power plants, petroleum industries, etcetra.

  As an illustration When an earthquake occurs, it is imperative to immediately assess the nearby buildings to determine whether they are habitable so that people can be evacuated in accordance with the situation. Regions located on top of fault lines or in the space between two plates are particularly susceptible to long-lasting prolonged earthquakes. Since the availability of a structural auditor or any other domain expert may not be possible during these crucial times, our model can be extremely valuable.

7.4. Scalability

7.4.1. Future Scope in the Industry

Construction is one of India's most competitive industries, as was stated before in the industry study analysis, with a compound annual growth rate of 10% by 2027. According to the **Economic Survey Of India**, The target for capital expenditure in 2022-23 (BE) was increased sharply by 35.4% from Rupees 5.5 lakh crore in the previous year (2021-22) to Rupees 7.5 lakh crore, of which approximately **67%** has been spent from April to December 2022

Despite global uncertainty, foreign investors have a bullish outlook for the Indian markets. With infrastructure-related operations accounting for nearly 13% of the **$81.72 billion** in total FDI inflows during the financial year, the nation also had its highest-ever total FDI inflows in 2021–22.

7.4.2. Government Regulations and Reforms

According to an S&P analysis, India's infrastructure severely impedes economic progress. To close the present infrastructure gap, it estimates $1.5 trillion in infrastructure investments over the following ten years. The Indian government decided to focus more of its emphasis on the infrastructure industry as a result of all of these imminent circumstances. The government launched numerous housing reforms, such as the "**Pradhan Mantri Awas Yojana - Housing for All**" the "S**mart Cities Mission**" etc., where it intends to not only improve the

Indian infrastructure but also to offer 20 million homes for the urban poor population. In 2020, the multilateral Asian Development Bank (ADB) committed to investing **$100 million** in the government-sponsored National Investment and Infrastructure Fund (NIIF) in order to create a resilient and sustainable India. The housing industry's need for structural auditing will rise as a result of all these reasons.

With time, the government would launch mandates to ensure that structural inspections are conducted more regularly and strictly. And with that, our model will come into more use.

7.4.3. Natural Disasters

Earthquakes wreak havoc on the entire population of the region, killing and leaving people homeless in their wake. The recent earthquake of magnitude 7.8 that hit Turkey and Syria is a prime example of possible destruction. Our model can be used to analyse the surviving building in the region hit by the earthquake to assess if it is still habitable; if not, people can be evacuated in due time before it collapses. Our methodology would be especially useful as quick decisions are required to be taken by the authorities to prevent casualties brought by the earthquake aftermath.

The current Joshimath incident has also had everyone concerned. Even though reports of soil sinking in the Joshimath region date back to the 1970s, little action was taken until lately. Earthquakes and similar ground subsidence events are occurring frequently around the nation. A model like ours would guarantee that such issues are handled promptly in the future. Our methodology would offer a simpler and more efficient method for carrying out timely safety audits. This would result in the early detection of such circumstances, which would ultimately aid in their management as and when necessary. As more people become aware of these catastrophes, plans will be created to cope with them more effectively. Our model will then be even more useful as a result.

8

User Guide

The entire structural audit process can be divided into **two main parts**:

- Analysis of past audits, building history, climatic and environmental conditions in the building's region, etc.
- On-site visit and collection of various input parameters (external and internal structure audit).

The structural auditor must collect all of these parameters and enter them into the model according to their respective buckets. Then, the model will output the risk score for these buckets based on the values set by the structural auditor using his past experiences; if any of these risk scores are above the threshold level, some non-destructive tests **(NDTs)** will be **recommended** to pinpoint the exact cause and extent of the problem. Following this, the model shall also output the total **cumulative risk score** of the building, indicating the severity of the risk and enabling us to determine the habitability and usability of the structure.

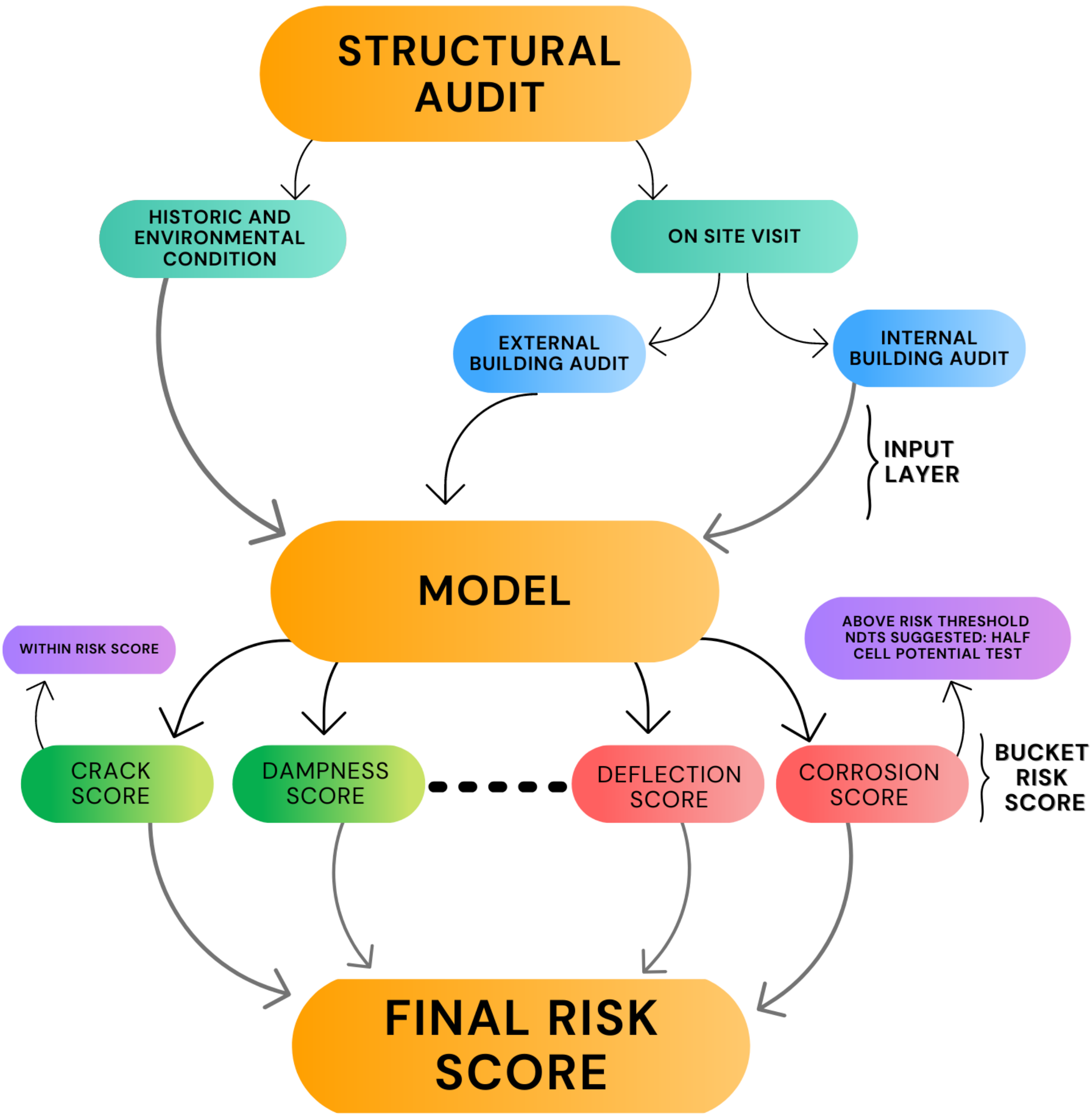


Figure 8.1: User Guide for Structural Auditing

9

Case Studies

The use of Bayesian networks in the construction sector is relatively new, despite their ubiquitous use in anomaly detection and other diagnostic domains. However, There have been numerous risk assessment models that have made use of similar technology. We provide two unique case studies in this part that demonstrate how automation is applied in the infrastructure sector.

- **Case Study 1**: Uncertainty in Building Inspection and Diagnosis: A Probabilistic Model Quantification

  Although uncertainty is widespread in building inspection, it cannot be easily measured. According to this article, Bayesian networks can be used by auditors to measure this uncertainty. Additionally, it aids in the identification of faults and their root causes. The usage of Bayesian networks is also encouraged in the article because it enables the creation of coherent probabilistic representations. It confirms that these models can give auditors and inspectors better information. This would eventually result in alternatives for maintenance and repair that are superior.

- **Case Study 2**: A modelling approach based on Bayesian networks for dam risk analysis

  The decision-making process becomes significantly more complex when evaluating the safety of dams due to the involvement of several unclear, diverse, and interconnected risk factors. The bayesian network created with the aid of the expertise of domain experts has been improved in this article using machine learning methods like **"Peter-Clark (PC)"**.Here, the risk of dam failure is predicted using a four-step process that involves assigning probabilities to several parameters. The model had an **84%** accuracy when tested with an extensive dataset of dams given by the Association of State Dam Safety Officials **(ASDSO).**

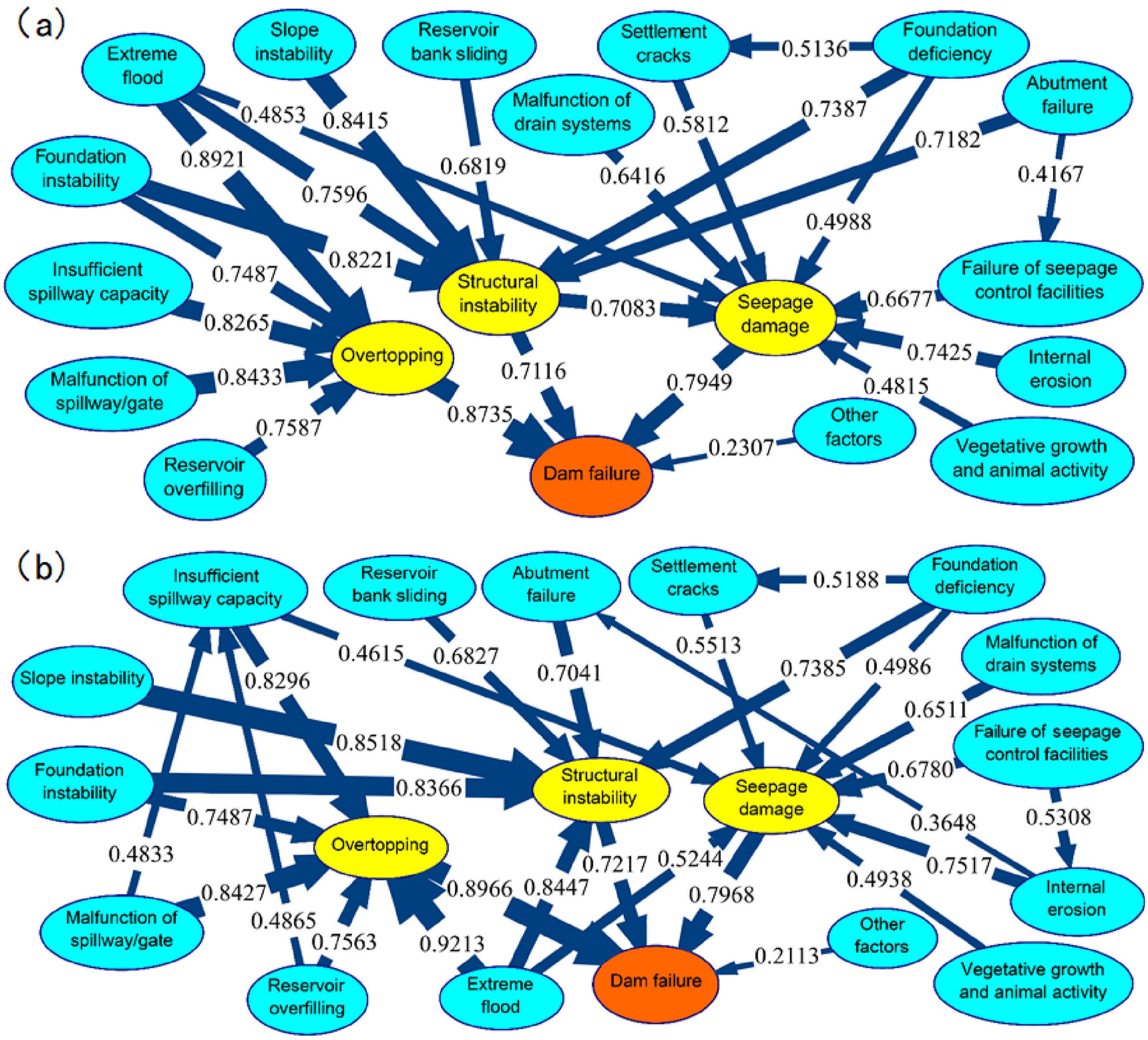


Figure 9.1: Use of Bayesian Networks for Dam Risk Analysis

10

Conclusion

Bayesian networks are among the most useful and indispensable graphical models for decision-making under uncertainty and sophisticated complex reasoning. Bayesian networks have been utilised extensively in anomaly detection, healthcare, and bioinformatics. The construction industry, and auditing in particular, is one of the few sectors that still employs a conventional business model. However, substantial research is being conducted to implement **cutting-edge technologies** in this industry as well. We anticipate that the use of Bayesian networks to develop a knowledge model in this field will prove to be a breakthrough technology.

Although India is one of the world's fastest-growing economies, its booming economic development is **hampered** by a lack of infrastructure capable of supporting the needs of a growing population. To close the current deficit, the government has developed important programmes and reforms and is investing heavily in infrastructure (approximately **35%** of GDP).

In the future, structural auditors will be in **high demand** not only because of the growing demand for infrastructure induced by rapid urbanisation but also due to a series of poor and unplanned construction in the past. A knowledge model that may aid in automating this process would be of tremendous use for Immediate, Rapid, and Objective Analysis. It would not only ease the **immense burden** currently encountered by Structural Auditors and Hazard Analysts, but also shall indefintely be very instrumental when making **impromptu decisions** in emergency situations in the absence of a domain expert.

11

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