Climate-aware Resilience for Sustainable Critical and Interdependent Infrastructure Systems enhanced by emerging Digital Technologies

Massive Open Online Course:
Resilience, Sustainability & Digitalisation in Critical Infrastructure

This project has received funding from the Horizon Europe Programme under the Marie Skłodowska-Curie Staff Exchanges Action (GA no. 101086413). Co-funded by the UK Research & Innovation, and the Swiss State Secretariat for Education, Research & Innovation.

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Lecture 5

Massive Open Online Course

Resilience, Sustainability & Digitalisation in Critical Infrastructure

Digital technologies

Jelena Ninic
Associate Professor in Digital Engineering
University of Birmingham
J.Ninic@bham.ac.uk

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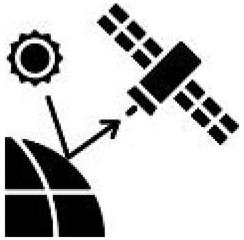
Lecture 5 Outcomes

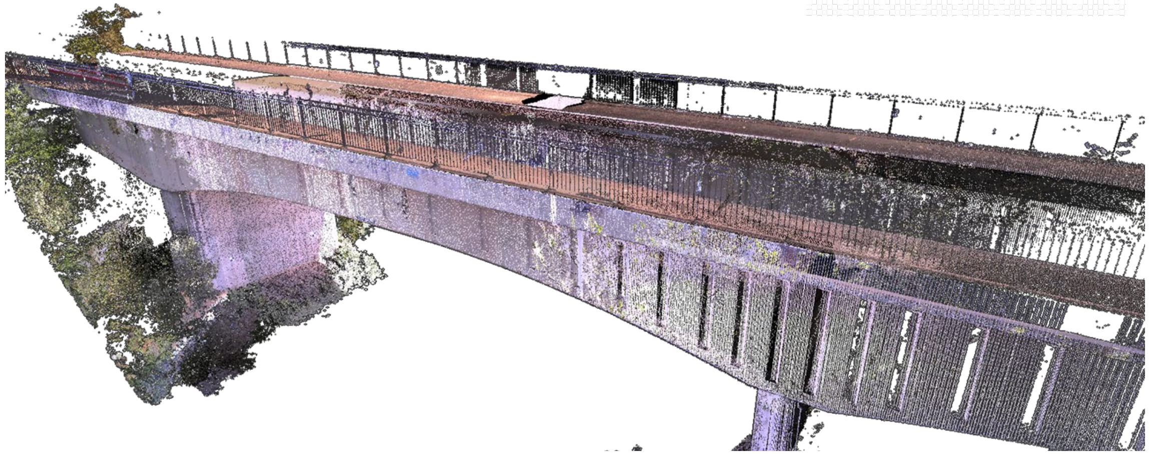
- Understand how digital technologies are employed in monitoring and inspection of infrastructure.
- Learn about the classes of digital technologies and understand the scope of their application.
- Understand how machine learning and computer vision can be employed to transform the way we design, construct and maintain our structures
- Learn what are Building Information Modelling and Digital Twins and their application for digital modelling of infrastructure.

ACTIVITY 1: Types of Digital Technologies and Data (DT & Data)

- What is digital engineering?
- What is the value of data?
- Type of theologies for monitoring & assessment







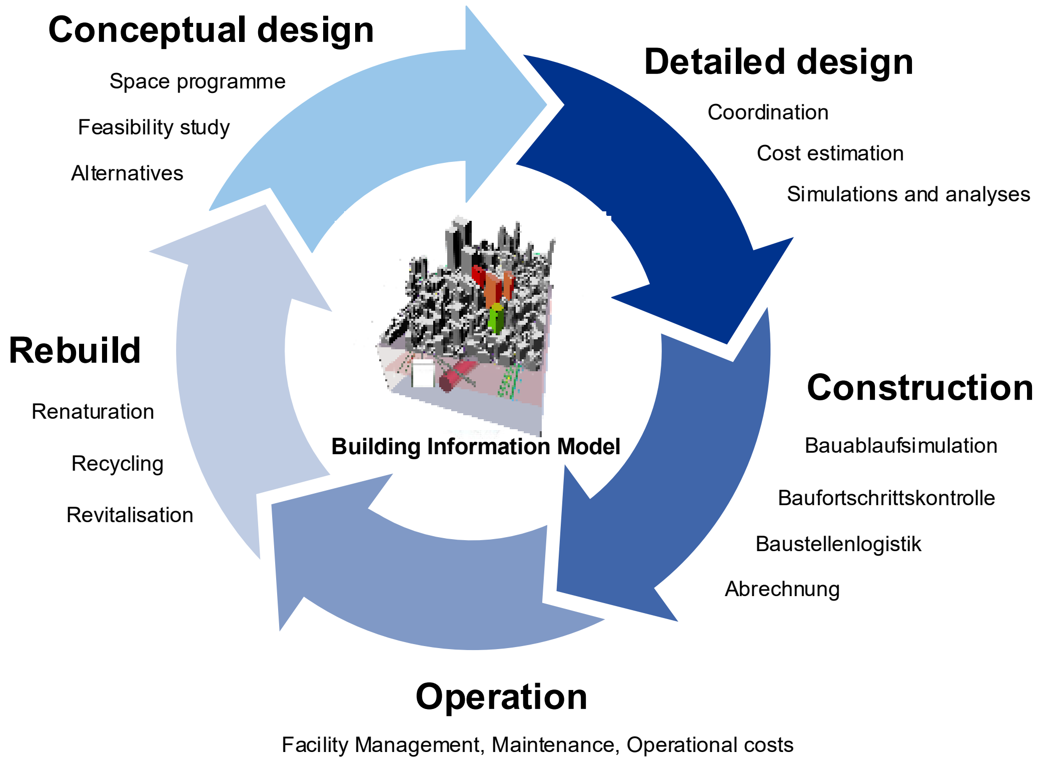
DT & Data: Digitalisation of infrastructure

Digital Engineering is the construction of digital (computer) models that represent characteristics of a complex product or system.

It involves application of digital technologies, processes, and methodologies over the lifecycle of infrastructure assets.

It leverages digital tools, software, and data-driven approaches to improve efficiency, accuracy, and collaboration.

Digital technologies include: Building Information Modelling (BIM), computer-aided design (CAD), virtual and augmented reality, data analytics, advanced simulation and visualization techniques.



DT & Data: Digitalisation of infrastructure

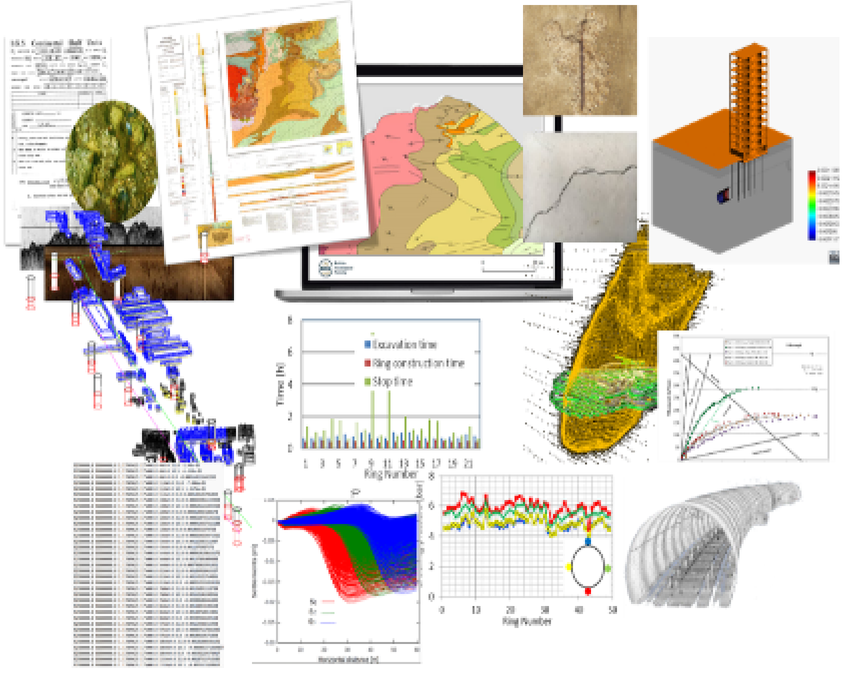
The key aspects of digitalisation for structures and infrastructure include:

- **Modelling and Visualization** to understand the design and spatial relationships.
- **Collaboration and Coordination** among multidisciplinary teams through shared digital platforms and real-time data exchange.
- **Data Integration and Analysis** by integrating various data sources, including sensor data, geospatial information, and historical records.
- **Simulation and Analysis** to assess the structural integrity, energy efficiency, and environmental impact.
- **Construction and Asset Management** using automated machinery, drones for surveying and monitoring, and real-time progress tracking, as well as digital asset management systems for efficient maintenance, operation, and asset lifecycle management.

DT & Data: Value of data

All data driven processes depend on both quality and quantity of data.

- **Quality** of the data will drive the accuracy and reliability of outcomes. High-quality data is accurate, complete, relevant, and up-to-date.
- Large **Quantity** of data will enhance the robustness and validity, statistical significance, and better identification of patterns and correlations.
- **Data collection and acquisition** processes must be suitable. This involves defining data requirements, selecting appropriate data sources, employing accurate measurement techniques, and utilizing reliable data collection tools or sensors



DT & Data: Type of theologies for monitoring & assessment

Several types of digital technologies commonly used for the assessment of infrastructure.

Remote Sensing provide high-resolution imagery and data about infrastructure assets. Assessment of large-scale projects, monitoring changes, and identifying potential issues.

Geographic Information Systems (GIS) combines spatial data with attribute information to create digital maps. Applications: visualization, analysis, and management of infrastructure data, aiding in asset inventory, condition assessment, and planning.

Non-Destructive Testing (NDT) techniques employ digital technologies to assess the condition of infrastructure components without causing damage. Applications: ultrasonic testing, infrared thermography, ground-penetrating radar, and magnetic particle inspection

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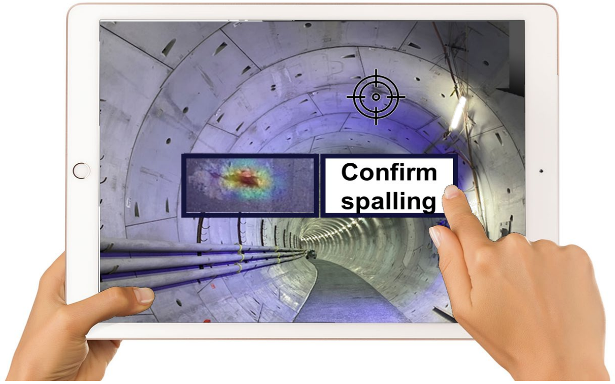
DT & Data: Type of theologies for monitoring & assessment

Structural Health Monitoring (SHM) systems use sensors to continuously monitor structures. SHM detects anomalies, predicts failures, and optimizes maintenance.

The Internet of Things (IoT) connects devices with sensors and embedded processing, providing real-time data, enabling continuous monitoring and condition-based maintenance.

Mobile applications for infrastructure assessment streamline data collection and reporting. Inspectors use apps to capture photos, record measurements, and input data.



DT & Data: Remote sensing

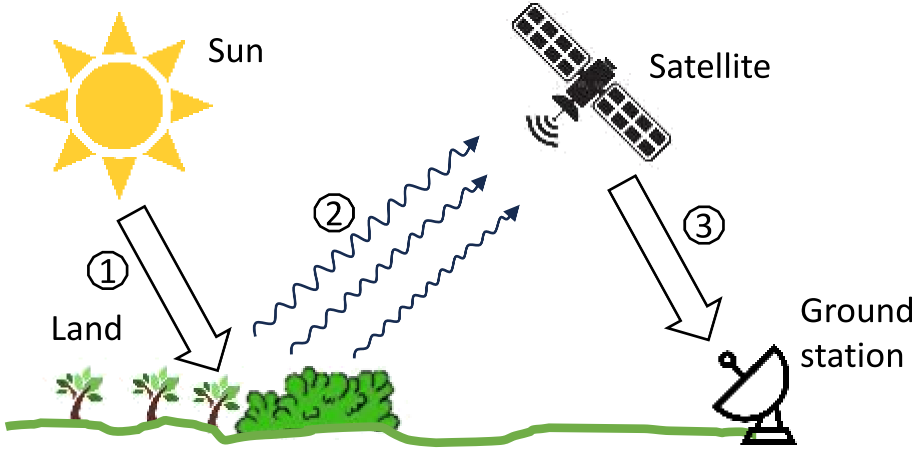
Remote sensing is the acquisition of information about an object without making physical contact. It allows to capture, visualize, and analyse objects.

It uses satellite- or aircraft-based sensor technologies to detect and classify objects on Earth

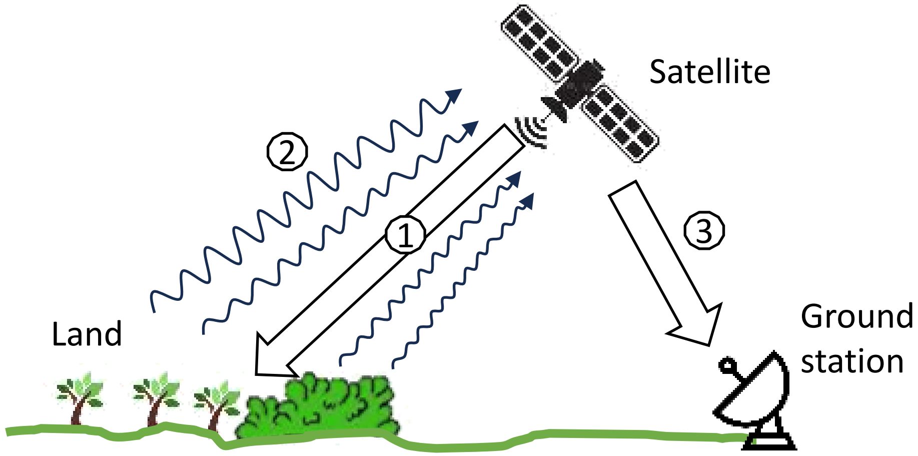
There are two types of technologies

- "passive" remote sensing when the reflection of sunlight is detected by the sensor (e.g. optical, thermal and infrared)
- "active" remote sensing when a signal is emitted by source to the object and its reflection detected by the sensor (e.g. LiDAR, InSAR), and

Passive remote sensing



Active remote sensing



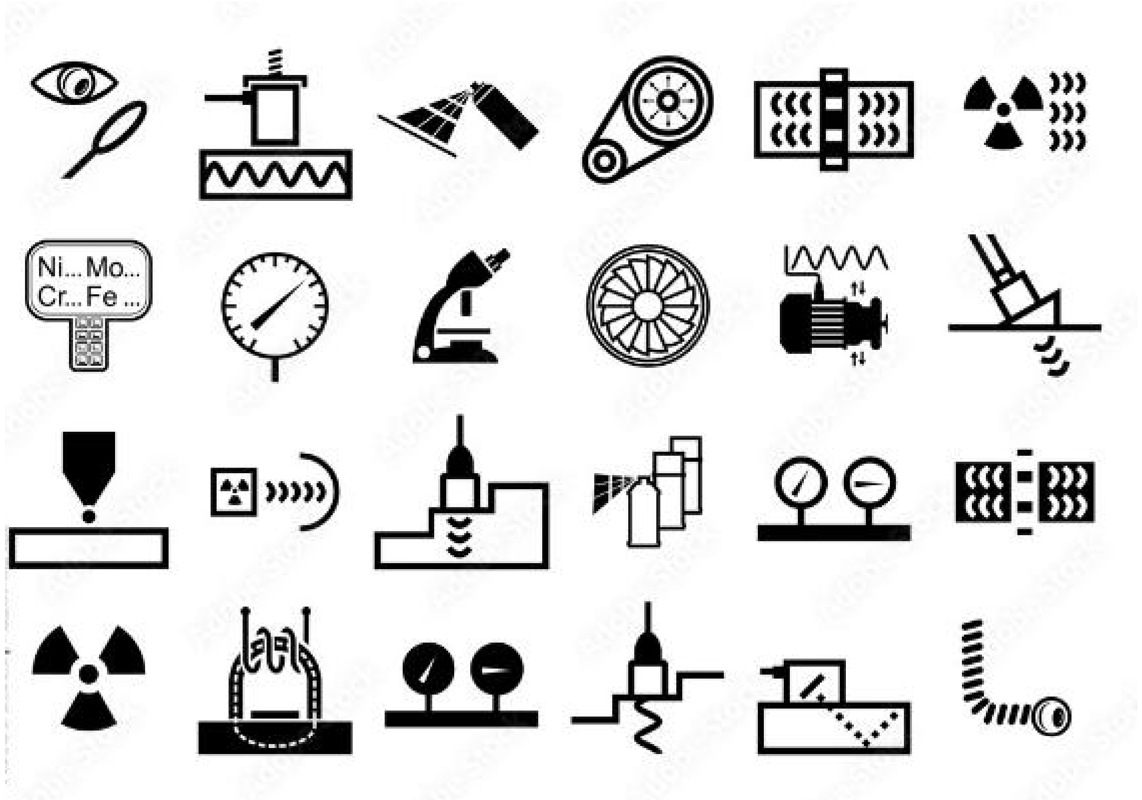
DT & Data: Geographic Information Systems (GIS)

- GIS is a framework for gathering, managing, analyzing and visualizing data
- GIS reveals deeper insights into data, such as patterns, relationships, and situations—helping users make smarter decisions
- GIS Includes
  - Maps,
  - data,
  - analysis,
  - applications

DT & Data: Non-Destructive Testing (NDT)

Non-destructive testing (NDT) is a set of techniques used to assess and evaluate the performance of structures without causing any damage to the infrastructure itself. It is essential for detecting defects, flaws, and potential issues in infrastructure.

Some common NDT methods used for infrastructure condition monitoring include: Ground Penetrating radar, ultrasonic testing, radiography, electromagnetic, magnetic and acoustic testing, etc.



DT & Data: Non-Destructive Testing (NDT)

Ground Penetrating Radar (GPR) utilizes radar pulses to investigate the subsurface condition of materials or spaces, to detect voids, presence of discontinuities, etc.

Ultrasonic NDT (UT) -using high-frequency sound waves to identify changes in properties.

Radiography NDT (RT) - using gamma- or X-radiation on materials to identify imperfections.

Eddy Current NDT (ET) - electromagnetic testing that uses measurements of the strength of electrical currents in a magnetic field surrounding a material to assess the condition.

Magnetic Particle NDT (MT) - identifying imperfections in a material by examining disruptions in the flow of the magnetic field.

Acoustic Emission NDT (AE) - using acoustic emissions to identify possible defects

Dye Penetrant NDT (PT) - detects surface defects in non-porous materials by applying a liquid penetrant and developer to highlight flaws.

DT & Data: Structural Health Monitoring (SHM)

- SHM involves using sensors, data acquisition systems, and analysis techniques to continuously monitor the condition and performance of infrastructure assets.
- It is used to detect changes or anomalies in the structures' behaviour, providing early warnings of potential issues providing the decision-making support.
- SHM of infrastructure Involves following tasks:
  - Sensor deployment and data acquisition
  - Data analysis and interpretation
  - Condition assessment and remaining life estimation
  - Predictive Maintenance
  - Long-term performance evaluation

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DT & Data: Internet of Things

The Internet of Things (IoT) refers to the integration of various smart devices, sensors, and communication technologies to collect and exchange data in real-time.

IoT enables infrastructure elements, such as, bridges, roads, water systems, and energy grids, to be connected and monitored digitally, providing valuable insights into their performance, condition, and usage.

Sensors and devices are deployed strategically throughout the infrastructure to measure parameters such as temperature, humidity, vibration, strain, pressure, flow rates.

The key components of IoT are:

- Sensors and devices for data collection
- Communication networks to transmit data from sensors to the central platform (e.g Wi-Fi)
- A central platform or dashboard collects and integrates data from different sensors
- Data analytics and cloud computing
- Decision support systems

DT & Data: Internet of Things

- **The Internet of Things (IoT**) will provide new streams of input data, from different monitoring systems during contraction/operation
- This data will also feed back into design
- Digital construction will extend beyond the boundaries of project sites, linking BIM models to City Information Modelling (CIM) or “Smart City” systems.

DT & Data: IoT vs SHM

The main difference between IoT and SHM is in their scope and focus:

Scope:

IoT for infrastructure monitoring is a broader concept that encompasses the integration of various smart devices and sensors into different types of infrastructure elements

SHM is a specialized subset of infrastructure monitoring that specifically targets the structural integrity and health of civil engineering structures. I.e. the scope of SHM is on the structural aspects of the infrastructure.

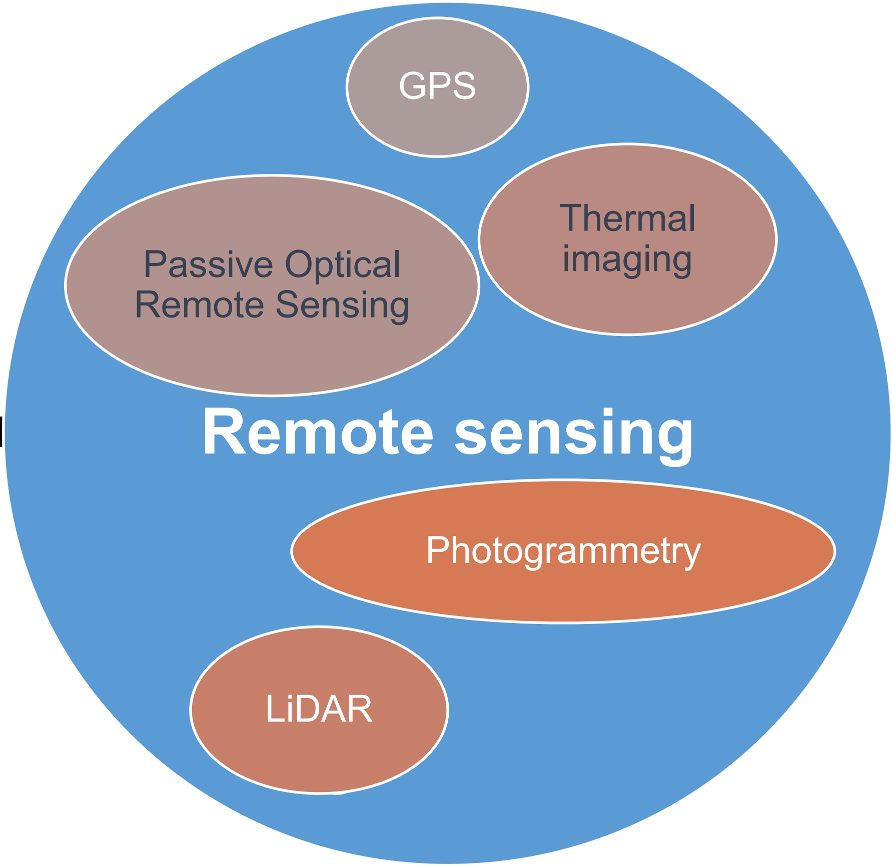
Focus:

The primary focus of IoT for infrastructure monitoring is to gather real-time data from various sensors deployed throughout the infrastructure to provide insights into its overall performance, condition, and usage. The main focus of SHM is to continuously monitor and assess the structural condition of a specific asset or component.

DT & Data: Remote sensing

Based on the data acquisition method, remote sensing technologies for infrastructure assessment can be classified into the following categories:

- **Optical Remote Sensing**: *Aerial Photography, Satellite Imagery, Multispectral, Hyperspectral and Panchromatic Imaging*
- **Synthetic Aperture Radar (SAR):** *SAR Imaging* emitting microwave signals and measuring the reflected signals; and *Interferometric SAR (InSAR)* measuring surface deformation by combining multiple SAR images.
- **LiDAR (Light Detection and Ranging):** *Airborne LiDAR* emitting laser pulses and measuring the time it takes for the pulses to return after reflecting off and *Terrestrial Ground-based LiDAR* systems capture detailed 3D data
- **Thermal and Infrared Sensing**: *Thermal Imaging* for capturing thermal energy emitted by objects to detect heat anomalies, energy loss, and temperature patterns; and *Infrared (IR) Thermography* capturing infrared radiation to identify heat signatures, insulation issues, and electrical problems.



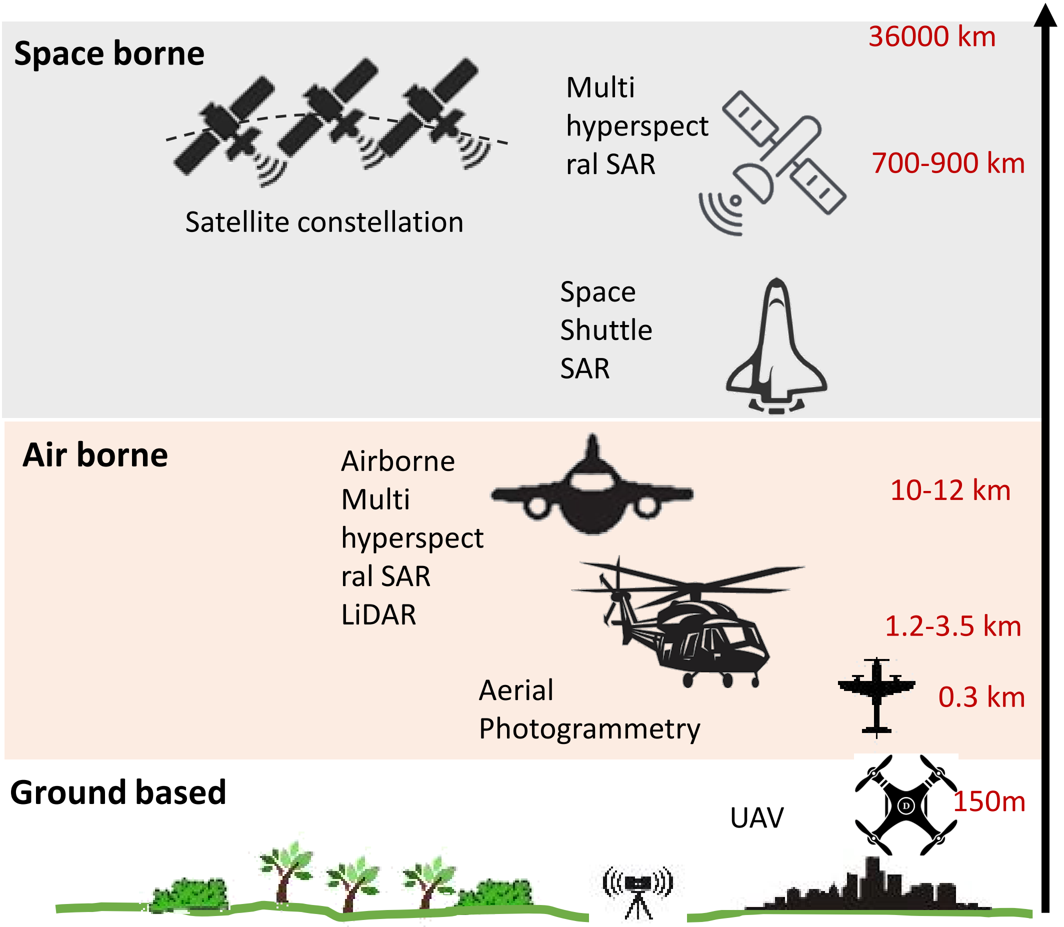
DT & Data: Remote sensing

Remote sensing technologies and their altitudes

Satellite Imagery:

- Low Earth Orbit (LEO) satellites: (160-2,000 km).
- Synthetic Aperture Radar (SAR) (200-2,000 km).

- **Unmanned Aerial Vehicles (UAVs) :(10-150 m).**
- **LiDAR:**
  - Airborne LiDAR: (200-5,000 m).
  - Terrestrial (Ground-based) LiDAR operate at close proximity to the infrastructure being monitored.
- **Infrared (IR) and Thermal** Imaging can be used on satellites, aircraft, or ground-based platforms, and their altitude depends on the specific platform and application.



DT & Data: Optical Remote Sensing

Optical Remote Sensing technologies include:

Aerial Photography, obtained from manned aircraft or unmanned aerial vehicles (UAVs), offers high-resolution images that enable detailed visual inspection and assessment of infrastructure.

High-Resolution Satellite Imagery, provides a bird's-eye view of infrastructure assets

Multispectral and Hyperspectral Imaging (MSI & HSI) capture images in various spectral bands, including visible, near-infrared, and sometimes additional spectral ranges.

Panchromatic and High-Resolution Imagery capture detailed grayscale or colour images with high spatial resolution.

DT & Data: Photogrammetry

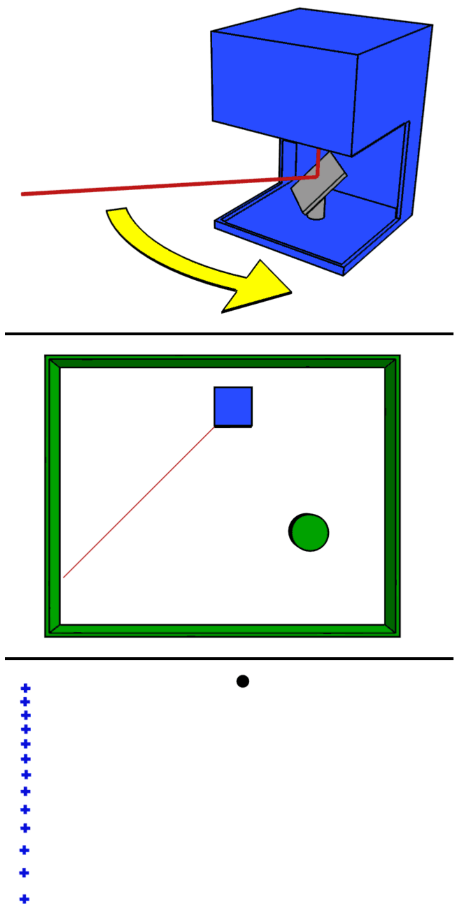
Photogrammetry is a technique within optical remote sensing that focuses on the measurement and extraction of accurate geometric information from overlapping images. It involves the analysis of photographs or digital images to determine the shape, position, size, and other spatial properties of objects.

Photogrammetry utilizes the principles of triangulation and stereo vision to reconstruct the 3D geometry of objects from multiple images taken from different positions or angles.

While **Optical Remote Sensing** encompasses a broader range of technologies for data acquisition **Photogrammetry** focuses specifically on the geometric analysis and measurement of objects and surfaces using optical images.

DT & Data: LiDAR

- LiDAR (Light Detection and Ranging) operates by emitting laser light pulses and precisely timing how long they take to return after bouncing off the ground. It also measures the intensity of these reflections.
- LiDAR employs oscillating mirrors to emit laser pulses in multiple directions, creating a "sheet" of light. By measuring the timing and intensity of the returning pulses, it can gather data on objects such as terrain and structures.
- Other important features of LiDAR are:
  - high-precision satellite positioning system (GNSS
  - inertial measurement unit (IMU) high-accuracy sensors to determine the orientation of the LIDAR sensor in space



DT & Data: LiDAR

LiDAR systems:

- **Airborne LiDAR** systems are mounted on aircraft or helicopters to collect data over large areas.
- **Terrestrial LiDAR** systems are ground-based and capture data by scanning the environment from a stationary or mobile position.
- **Mobile LiDARs** are typically mounted on vehicles, such as cars to capture data while driving along road networks and is combined with other positioning technologies, such as GPS to accurately georeferenced acquisition of data.
- **UAV-based LiDAR** sensors can be mounted on unmanned aerial vehicles (UAVs).

DT & Data: LiDAR vs Photogrammetry

LiDAR	Photogrammetry
Based on laser technology and the measurement of rebounding light points.	Employs an aligned series of digital images that overlap, as well as location data associated with pixels.
Produces high-density point clouds with precise distance measurements.	Generates 3D models, but its accuracy and point density depend on the quality of the images, camera calibration, and the number of overlapping images.
Signals can penetrate vegetation and other obstructions, making it suitable for mapping terrain and structures beneath dense vegetation canopies.	Relies on visible images and cannot penetrate obstacles.
Can be expensive to acquire and operate, especially for high-density data collection.	More cost-effective option, especially when utilizing existing aerial imagery or UAVs.

DT & Data: Challenges

The primary source of infrastructure condition data comes from visual inspections. Visual inspections are subjective, variable and non-reproducible. Some of the specific issues are:

- photographic evidence recorded and presented in an unsystematic manner
- difficulty in comparing photographs from successive inspections and hence comparing defect condition over time
- variation in practice between regional inspection teams
- inconsistent reliability of defect instance identification by inspectors
- a large range of possible defect types, which correlates with inaccurate defect classification

DT & Data: Digital inspection of structures

Automated inspection framework consists of two main steps:

Utilizing optical sensing theologies for remote automated data acquisition;

→

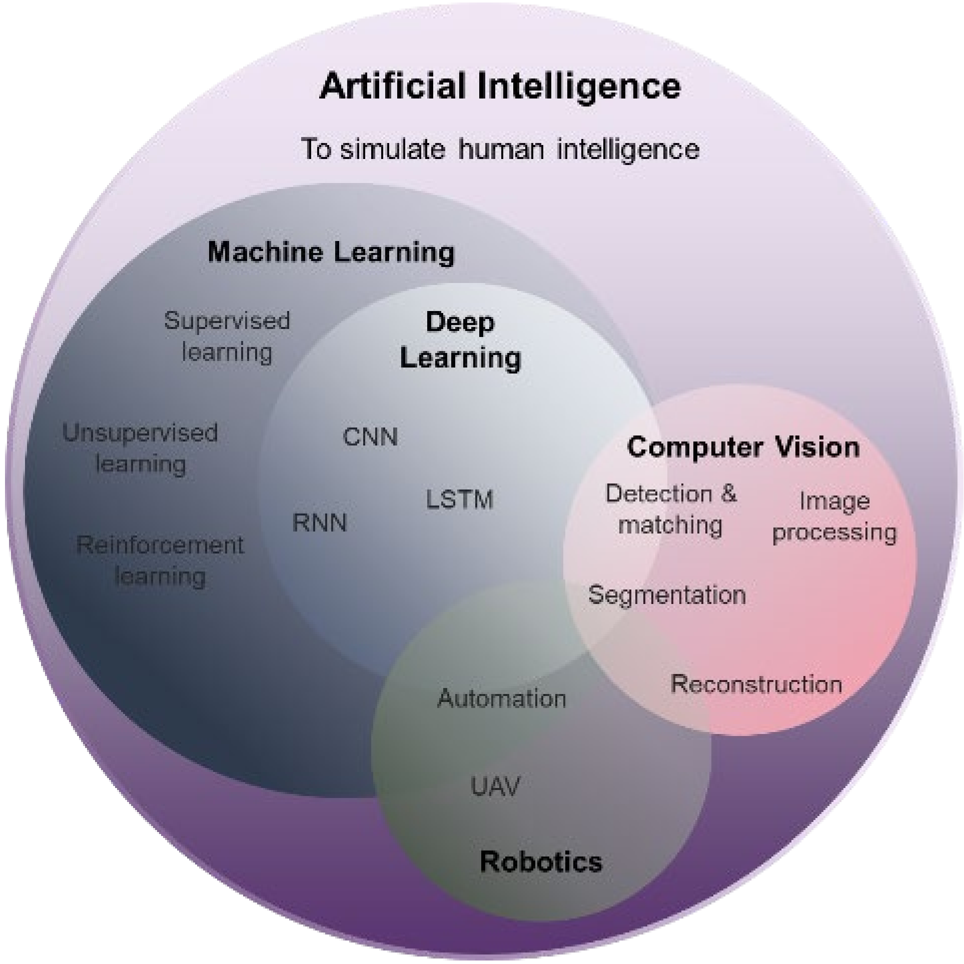
Data processing and inspection using AI techniques

→

Created digital models to continuously store, manage and analyze collected data

DT & Data: Methods for digital assessment of structures

- Artificial intelligence
  - Computer Vison
  - Machine leering
  - Robotics
- Building information Modelling
- IoT

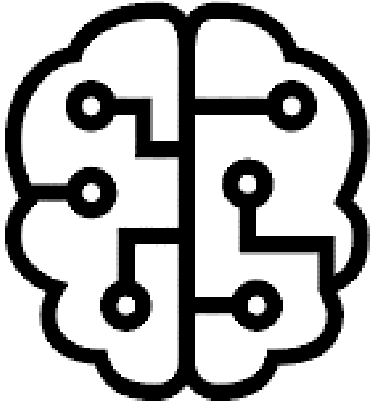


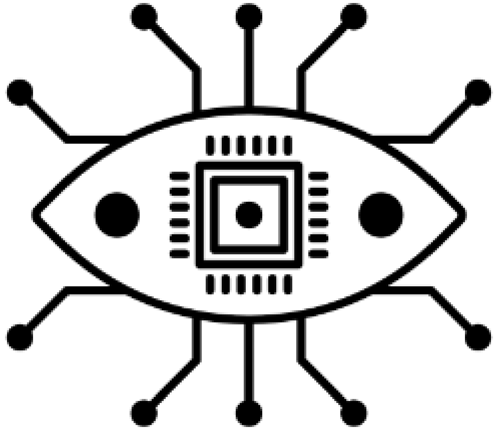
Reflection:

- How has digitalization transformed the design, construction, and operation of infrastructure?
- What are the different classes of digital technologies based on their application scope?
- What are the most commonly used remote sensing technologies for data acquisition?
- What are the major challenges in assessing structural conditions based on acquired data?

ACTIVITY 2: Machine learning and Computer Vision (ML&CV)

- What is machine learning, and how is it applied in infrastructure lifecycle?
- What is Computer Vision and how is it applied for infrastructure inspections?

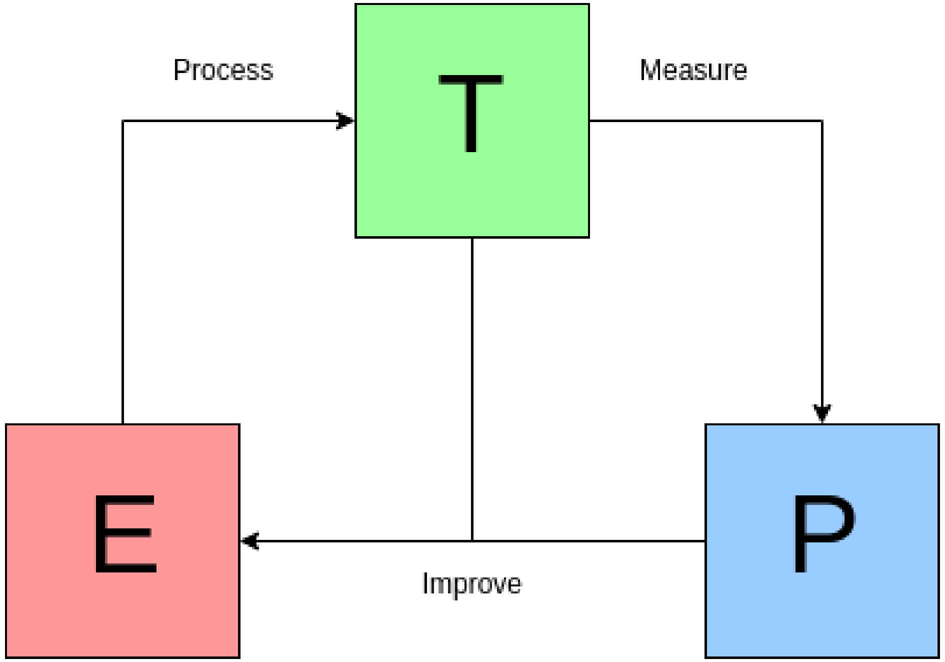




ML&CV: Machine learning

“field of study that gives computers the ability to learn without being explicitly programmed” (Samuel, 1959) (Samuel, 1959)

“a computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.”



ML&CV: Machine learning

There are generally three types of machine learning:

(1) supervised learning, → Labelled data

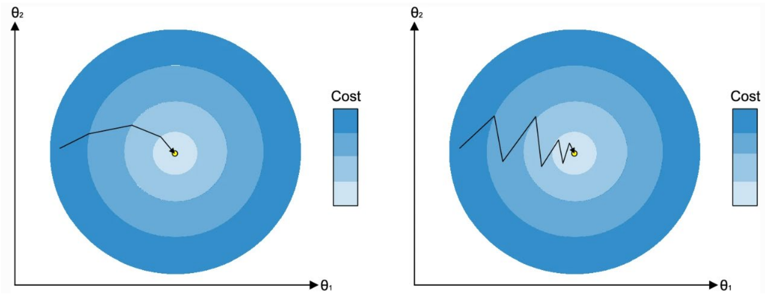
(2) unsupervised learning, and → Unlabelled data

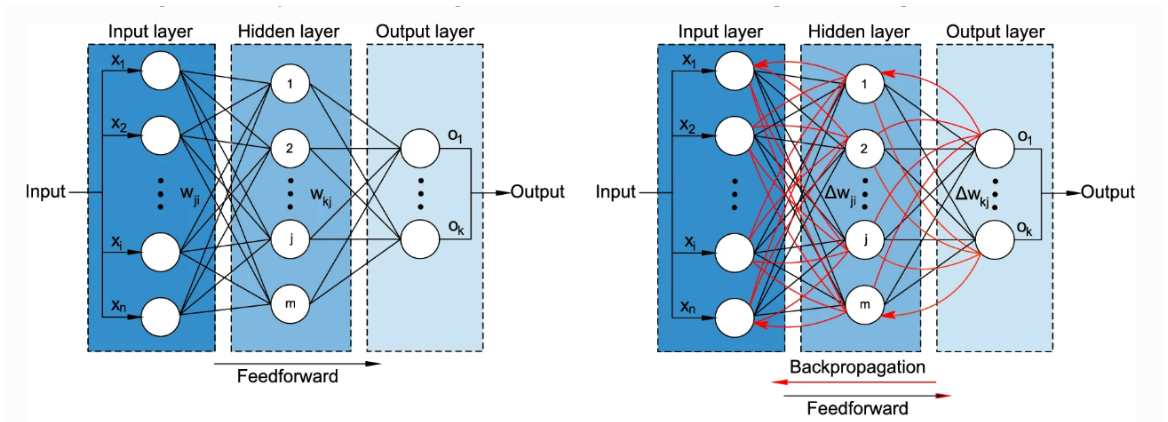
(3) semi-supervised learning → Labelled data, Unlabelled data

ML&CV: Types of ML algorithms

Some supervised learning algorithms:

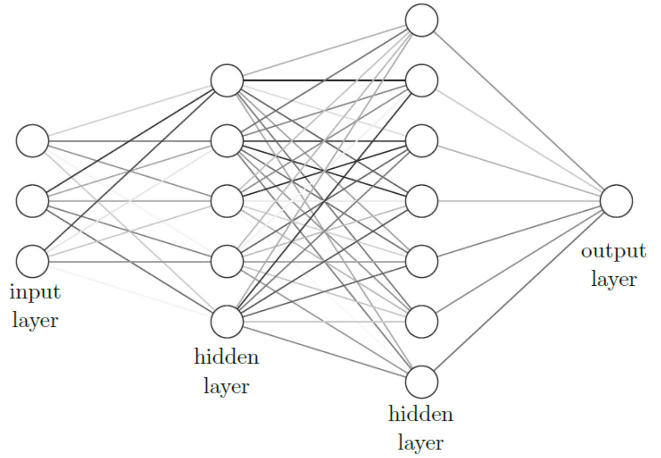
- Linear & Polynomial Regression
- Support Vector Machine
- k-Nearest Neighbours
- Decision Trees
- Neural Networks
- Random Forest
- Gaussian Processes





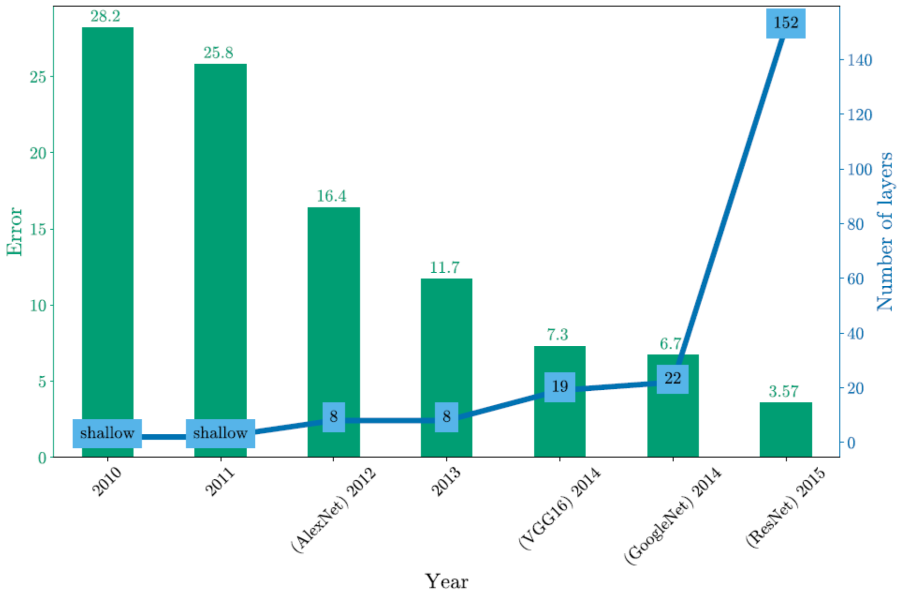
ML&CV: Types of ML algorithms

Deep neural network is a hierarchical organisation of more than one non-linear hidden layer, where the output of the previous layer serves as the input to the following layer



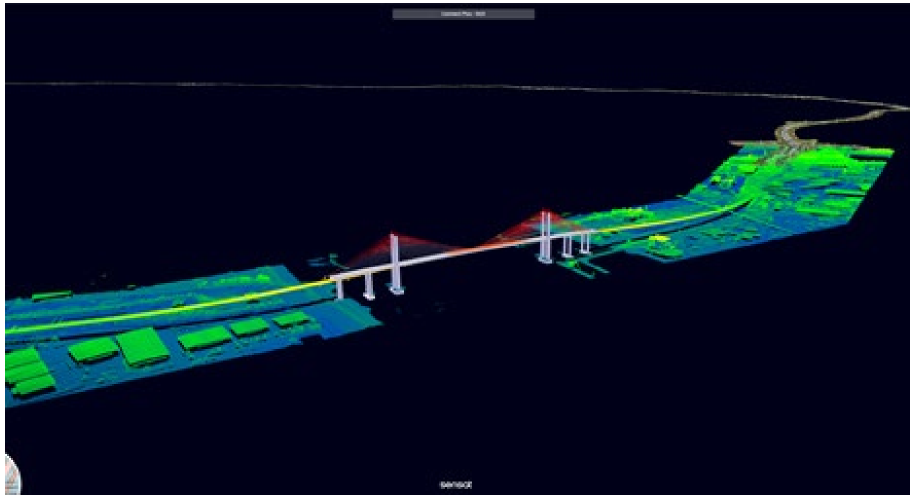
Deep learning has developed over the past decade in conjunction with several factors

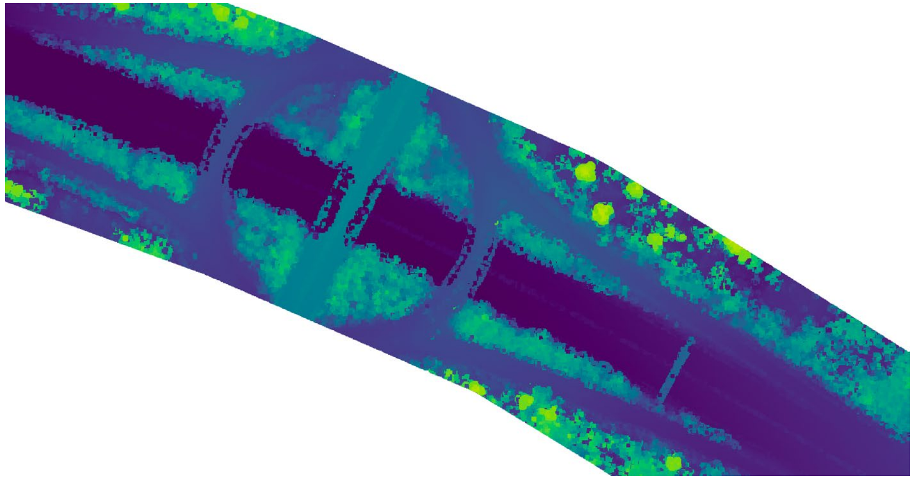
- hardware development (GPU computing in particular),
- algorithm improvements
- and the availability of large training datasets.



ML&CV: Infrastructure data sets

- Topology (LIDAR),
- Network models (GIS)
- BIM models (design teams)
- Sensor data (e.g, traffic, weather)
- Condition from a Pavement Management System

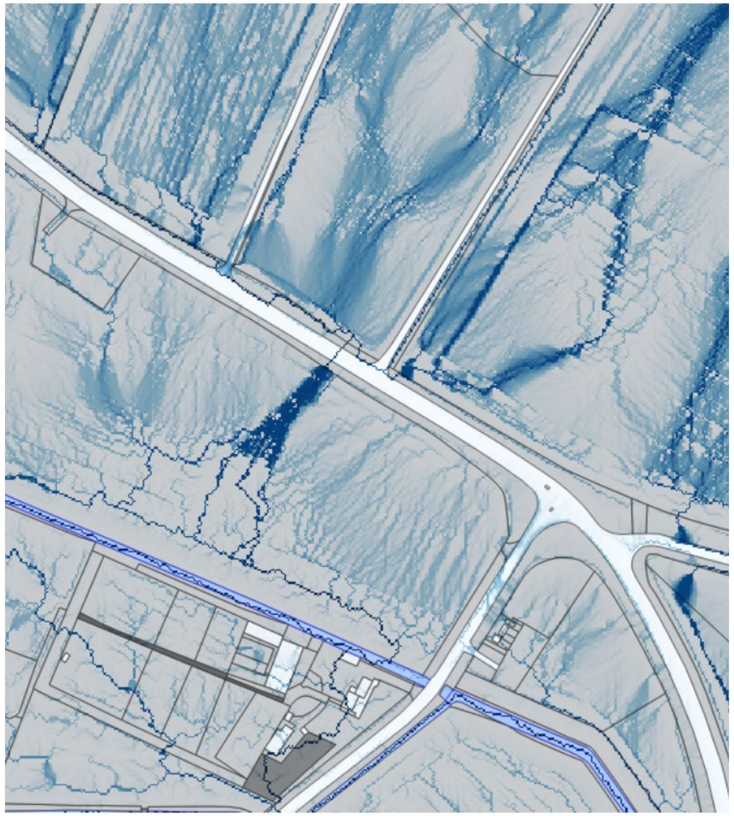




To create a single view of the asset portfolio – reduce costs, improve service.

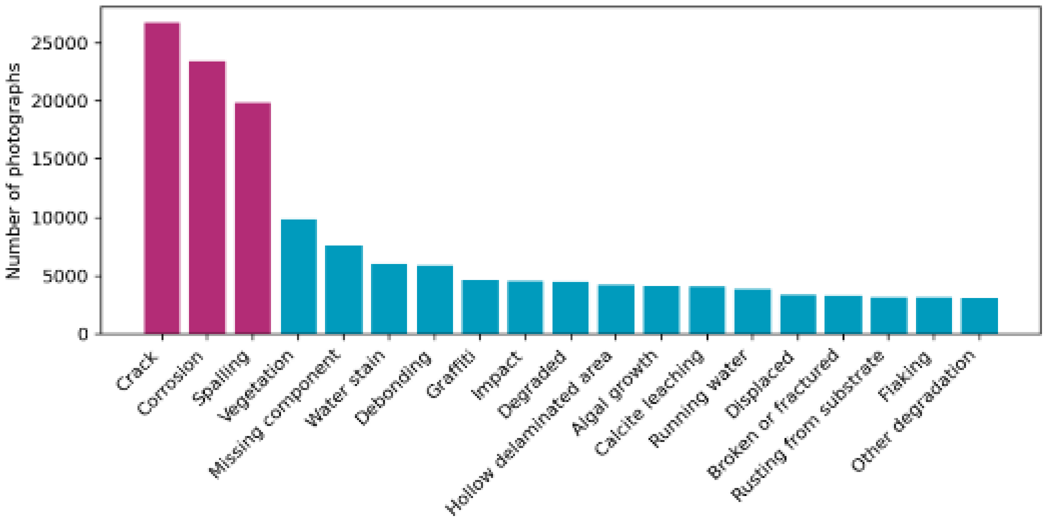
ML&CV: Infrastructure data sets

- LiDAR derived roughness
- Detailed drainage from LIDAR topological model



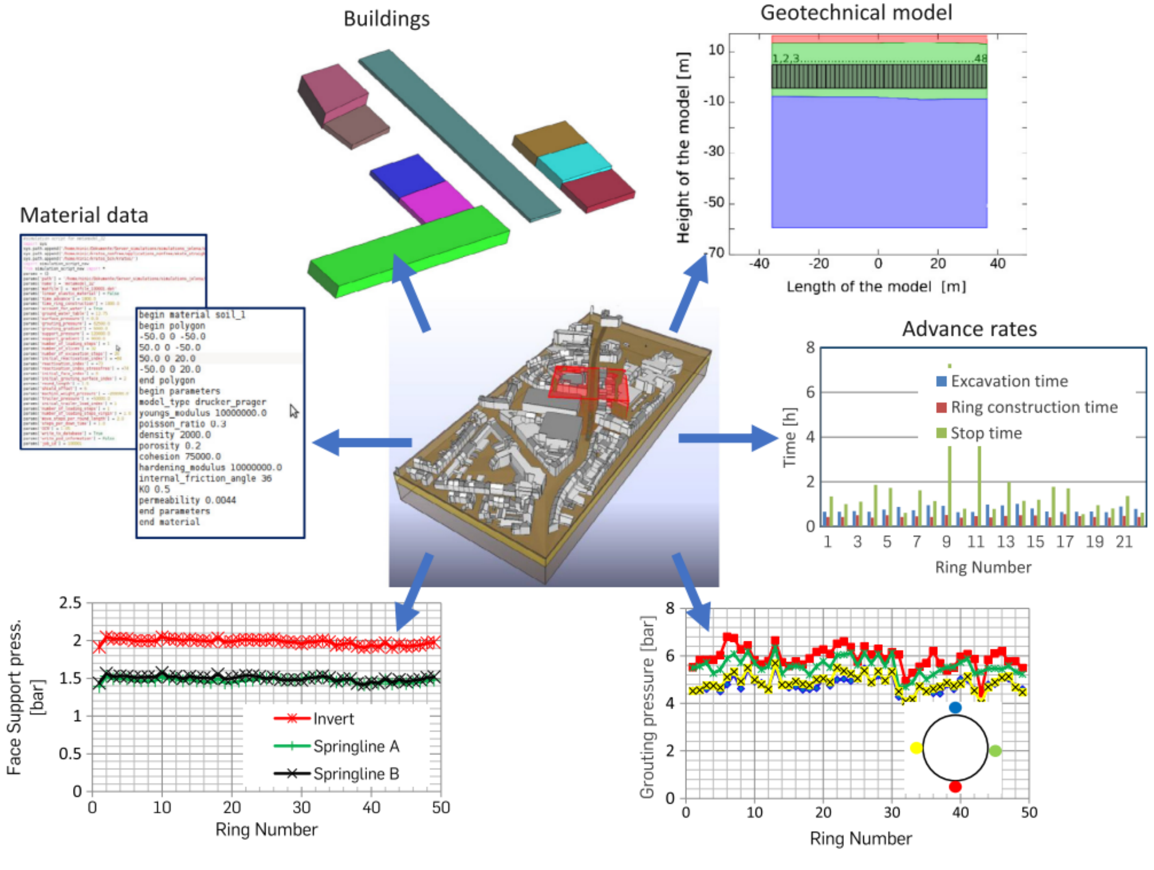
ML&CV: Infrastructure data sets

- Asset management systems can be another valuable source of data.
- The asset management database provides a source of images and condition assessment
- 200K defect photographs (40GB) were collected
- Each photo is tagged with one of a total of 161 possible defect types
- Three super-classes (crack, corrosion and spalling) for classification are created



ML&CV: ML tasks and the data

- For complex infrastructure projects like tunnelling a diverse sources of data are collected over the project lifecycle
- During the design phase the data sources are geological, geotechnical and design data
- During the contraction operational parameters are recorded as well as monitoring of the tunnelling induced displacements
- Operational data can include inspection reports with condition assessment and images



Face support and grouting pressure measurements

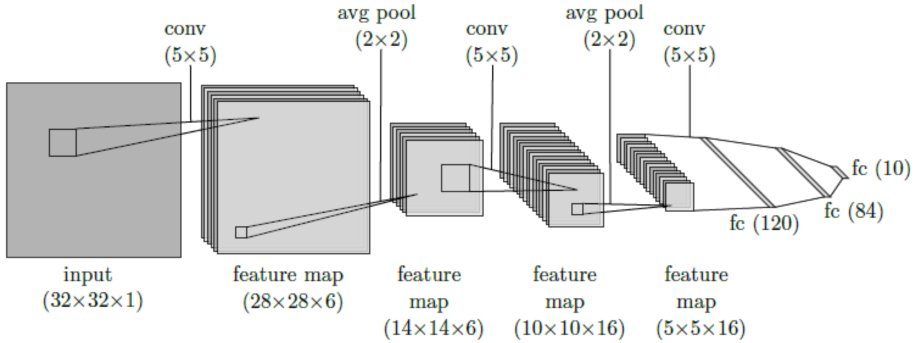
ML&CV: ML tasks and the data

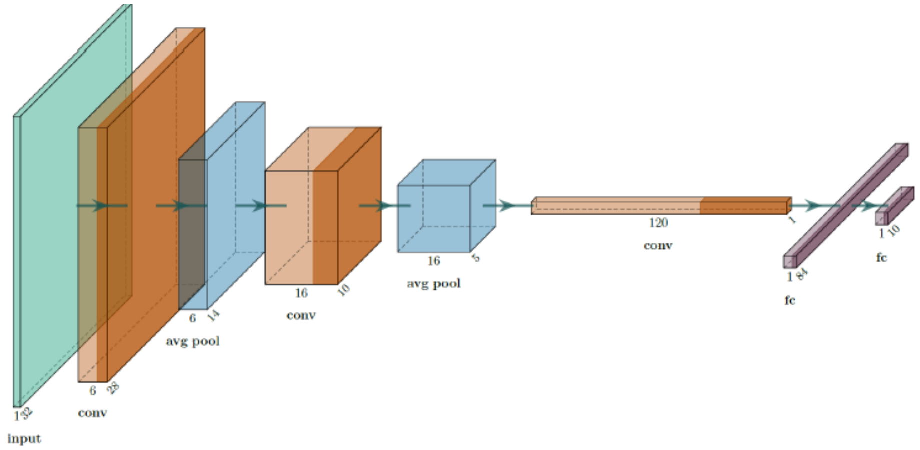
- **Detection** of defects, damages, and anomalies in infrastructure elements
- **Analyse sensor data** collected from infrastructure assets in real-time to identify patterns of degradation, estimate remaining life, and predict failures.
- **Predict the maintenance needs** of infrastructure based on historical data and monitoring
- **Object detection and segmentation** form image and video data to identify and classify various components, defects, and changes.
- **Process LiDAR data** for 3D modelling and assessment of infrastructure.
- **Assessment of the environmental impact** of infrastructure projects by analysing data on factors like air quality, noise levels, and ecological changes.
- **Material characterization** and analysis to determine material properties & detect defects.
- **Assessment of the risk and resilience** to natural disasters & climate change.

ML&CV: ML algorithms for image processing

Convolutional Neural Networks (CNNs) are currently dominating computer vision research. CNNs can be traced back to the early LeNet architecture.

- Visualising stacks of feature map channels is intuitive, however this representation becomes cumbersome for more complex networks.
- Extruded squares representation is a widely adopted convention
- Three fully connected (fc) layers in (left) is equivalent to the last convolutional (conv) layer in (right).



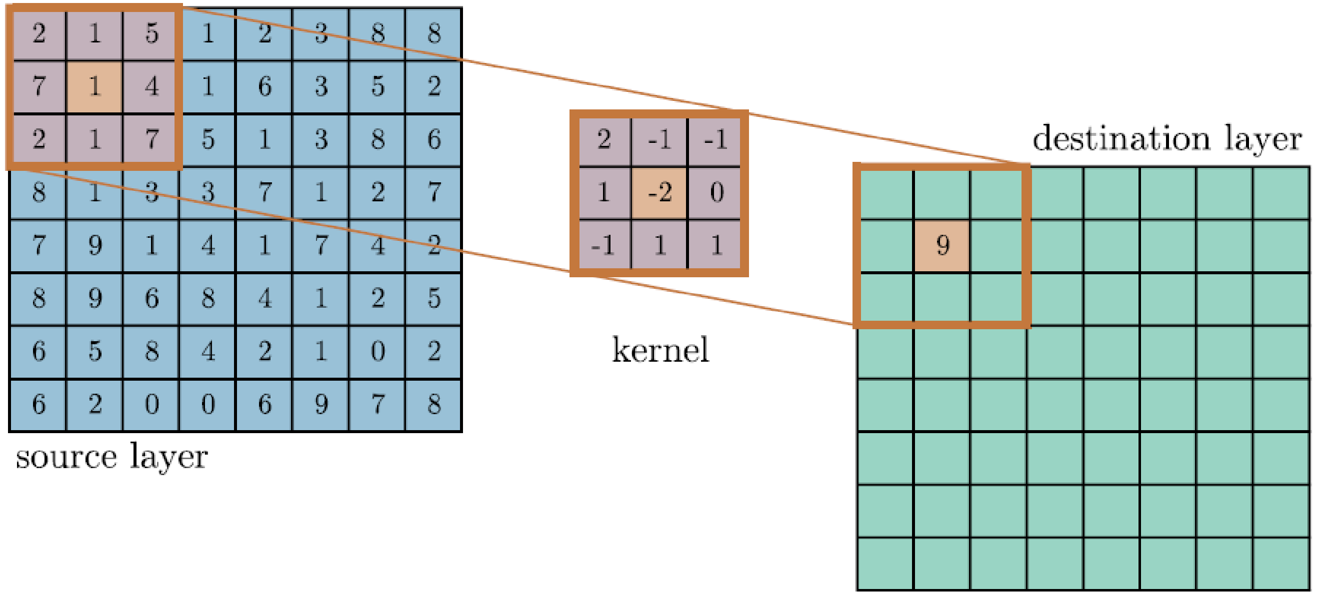


ML&CV: CNN- convolution

- Convolution marked a step change in neural networks as it made the jump from tabular to image data computationally viable. The convolution operation applies a kernel to every pixel position in the source layer
- The output of convolution is the sum of element-wise multiplication of two matrices, and this is passed on to the corresponding pixel position in the destination layer

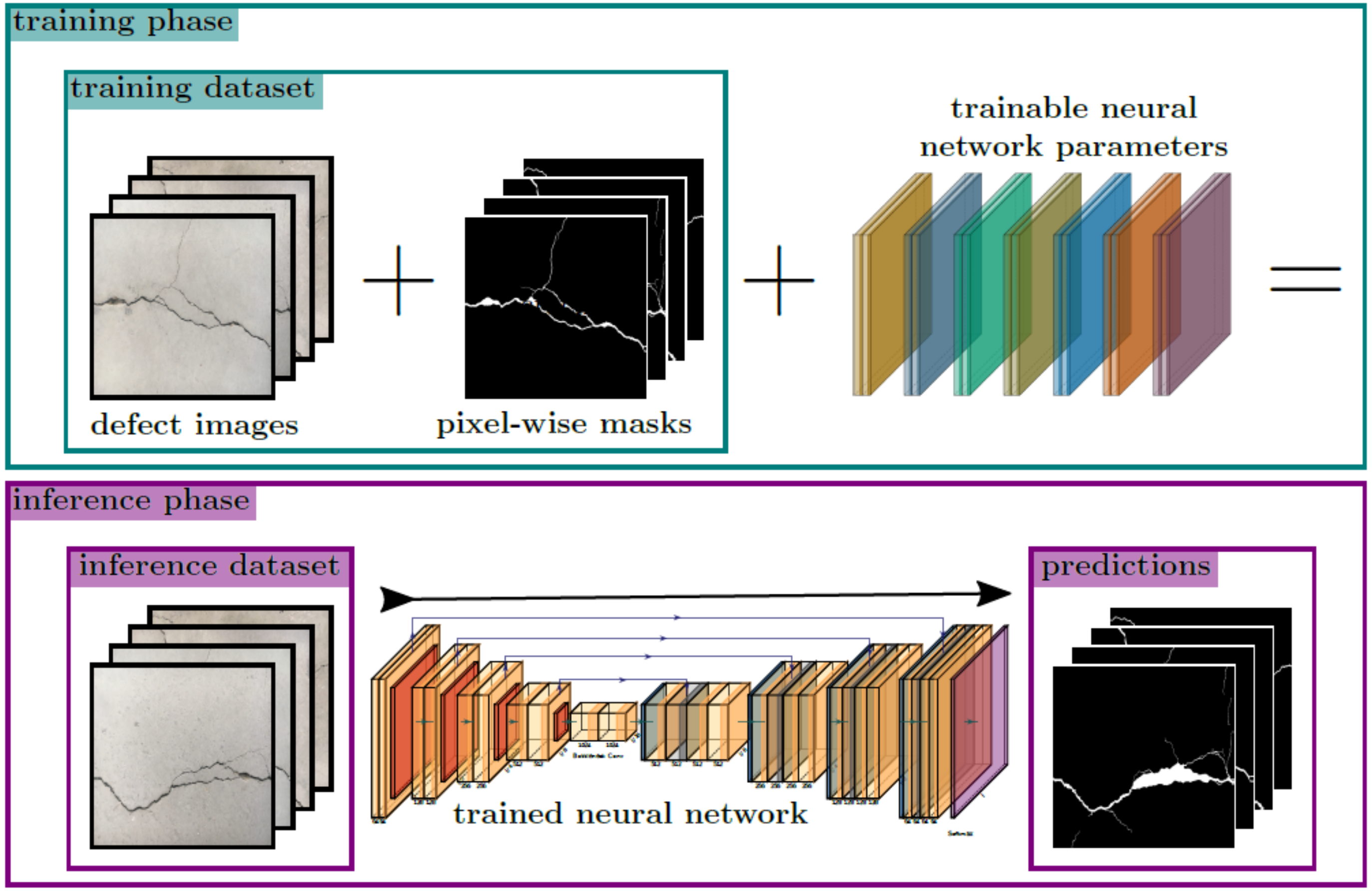
$$y_n = \sigma_n(\boldsymbol{w}_n^{\mathrm{T}} \boldsymbol{x}_n + \boldsymbol{b}_n)$$

$$y_n = \sigma_n(\mathrm{W}_n * \boldsymbol{x}_n + \boldsymbol{b}_n)$$



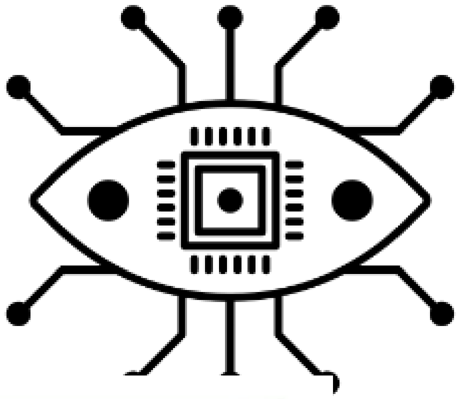
ML&CV: ML tasks and the images

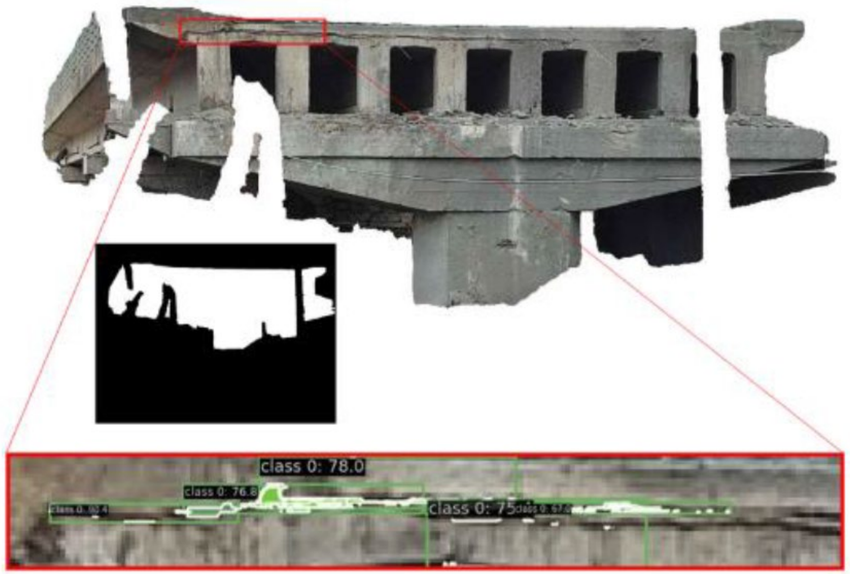
- A fully supervised learning for defect image classification based on label images.
- Concrete crack image semantic segmentation under the fully supervised learning

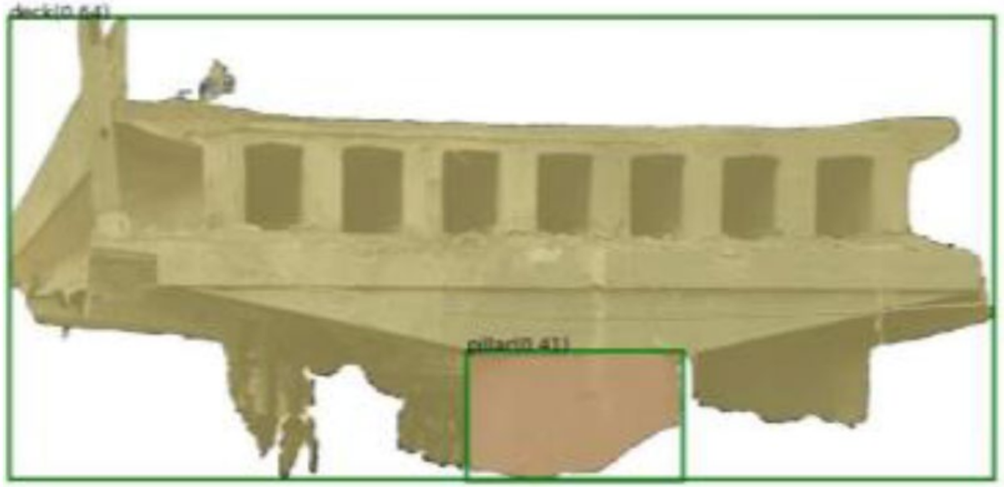


ML&CV: What is Computer vision?

Computer vision is an interdisciplinary scientific field concerned with the automatic extraction of useful information from image data in order to understand or represent the underlying physical world, either qualitatively or quantitatively.

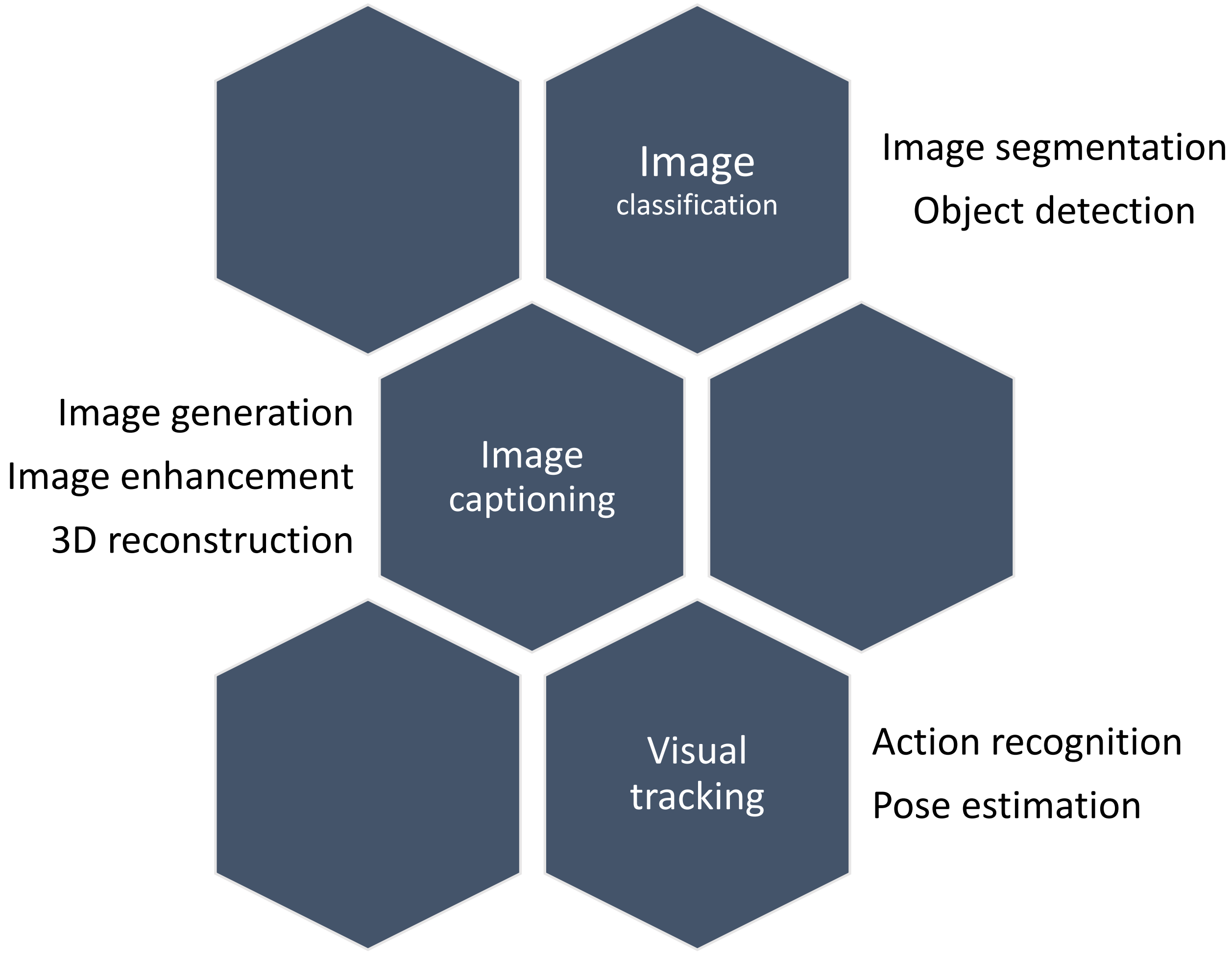






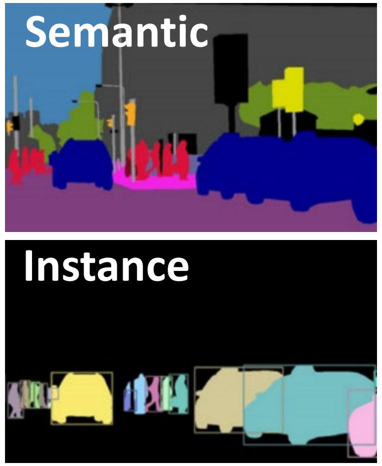
ML&CV: Computer vison tasks and methods

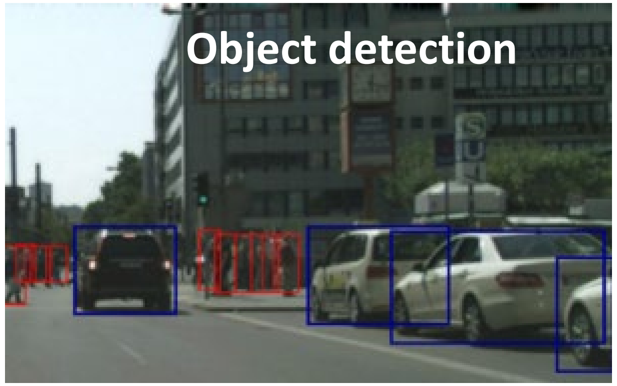
- **CV tasks** refer to the specific objectives or goals that computer vision techniques aim to achieve in the context of infrastructure inspection. These tasks are designed to extract meaningful information from visual data and enable automated analysis and understanding
- **CV methods** refer to the specific techniques and algorithms used to accomplish the computer vision tasks. These methods can vary based on the type of data available, the complexity of the structures, and the specific inspection requirements.



ML&CV: Computer vison tasks

- Image acquisition (general CV methods)
- Pre-processing (restoration, contrast enhancement, noise reduction)
- Segmentation (thresholding, edge detection, region growing, clustering)
- Feature extraction (features related to colour, texture, shape, motion)
- Object recognition (classification of materials objects share locations)
- Object analysis





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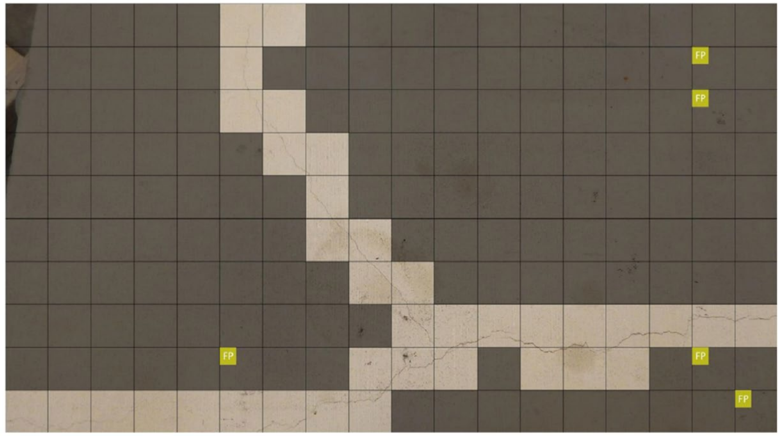
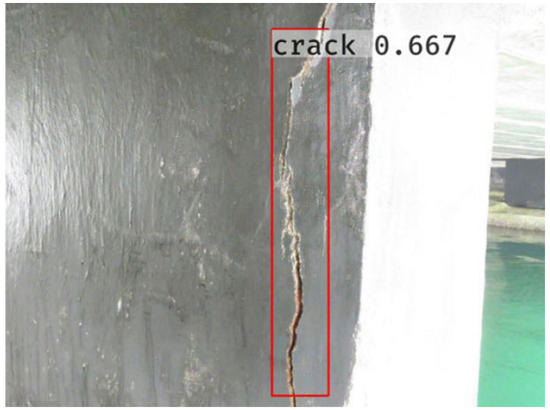
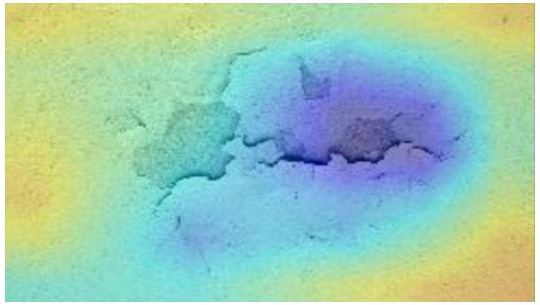
ML&CV: Computer vison tasks

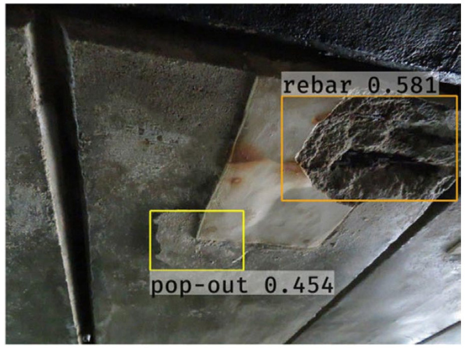
Image classification


Patch-wise classification



Object localisation - box


Object localisation - heatmap

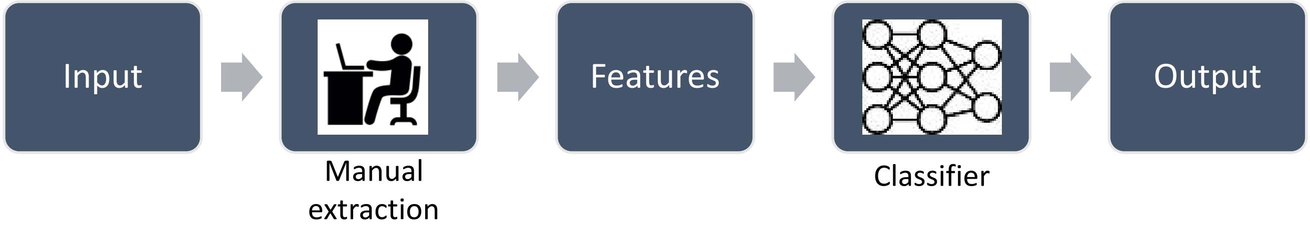


Object detection

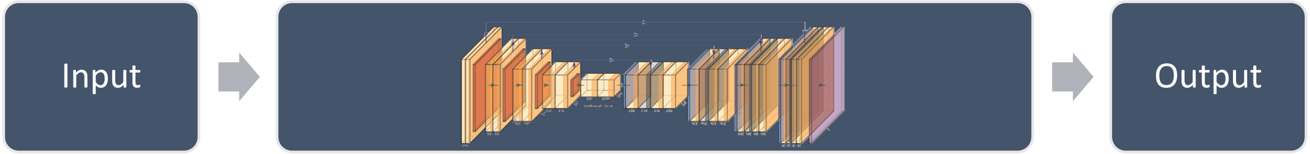

Semantic segmentation

ML&CV: CV methods before and now

Traditional CV workflow



Deep Learning workflow



Crack detection in concrete structures and pavements	Patch-based	Machine learning (SVM, Random forest) Deep learning (CNN)
	Pixel-based	General image processing • Edge detection • Filter-based method • Thresholding Deep learning (FCN, CDN)
Spalling detection in concrete structures		General image processing (Entropy-based thresholding) Machine learning Deep learning
Delamination detection		General image processing IRT and HD cameras on vehicles and UAVs Machine learning
Crack propagation monitoring		Tracking-based methods (DIC, Full field optical flow)
Critical region of interest (ROI) detection		3D Reconstruction Deep learning
Local structural assessment via 3D reconstruction		3D Reconstruction

ML&CV: Computer vision methods

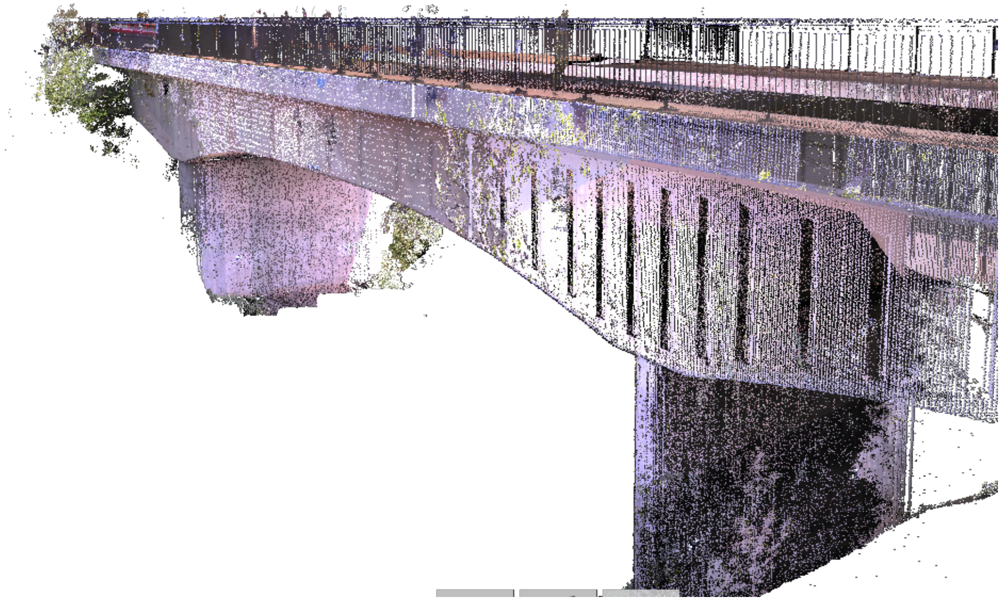
- **Image filtering** using methods such as Gaussian, Sobel, or Canny filters, to enhance edges, remove noise, and highlight relevant features in the images.
- **Image registration** by aligning multiple images or frames to account for differences in perspective or movement.
- **Feature detection and matching** to identify key points or features in images, such as corners or edges, and matching these features across multiple images to detect structural changes or movement.
- **Object detection and tracking** to locate and track specific objects or defects in images or videos.
- **Structural feature extraction**, to detect features, such as beams, columns, or joints, from images for further analysis and assessment.
- **Segmentation** for dividing the images into regions to isolate and analyze specific parts.
- **Texture analysis** of structures to detect surface anomalies or signs of wear and tear.

ML&CV: CV for 3D reconstraction

Computer vision for 3D reconstruction is a set of techniques and algorithms that aim to create three-dimensional models of objects or scenes using multiple 2D images as input. This process is also known as "structure-from-motion" or "multi-view stereo.“

3D reconstruction from 2D images typically involves the following steps:

1. Feature Extraction
2. Feature Matching
3. Camera Pose Estimation
4. Triangulation
5. Bundle Adjustment
6. Surface Reconstruction

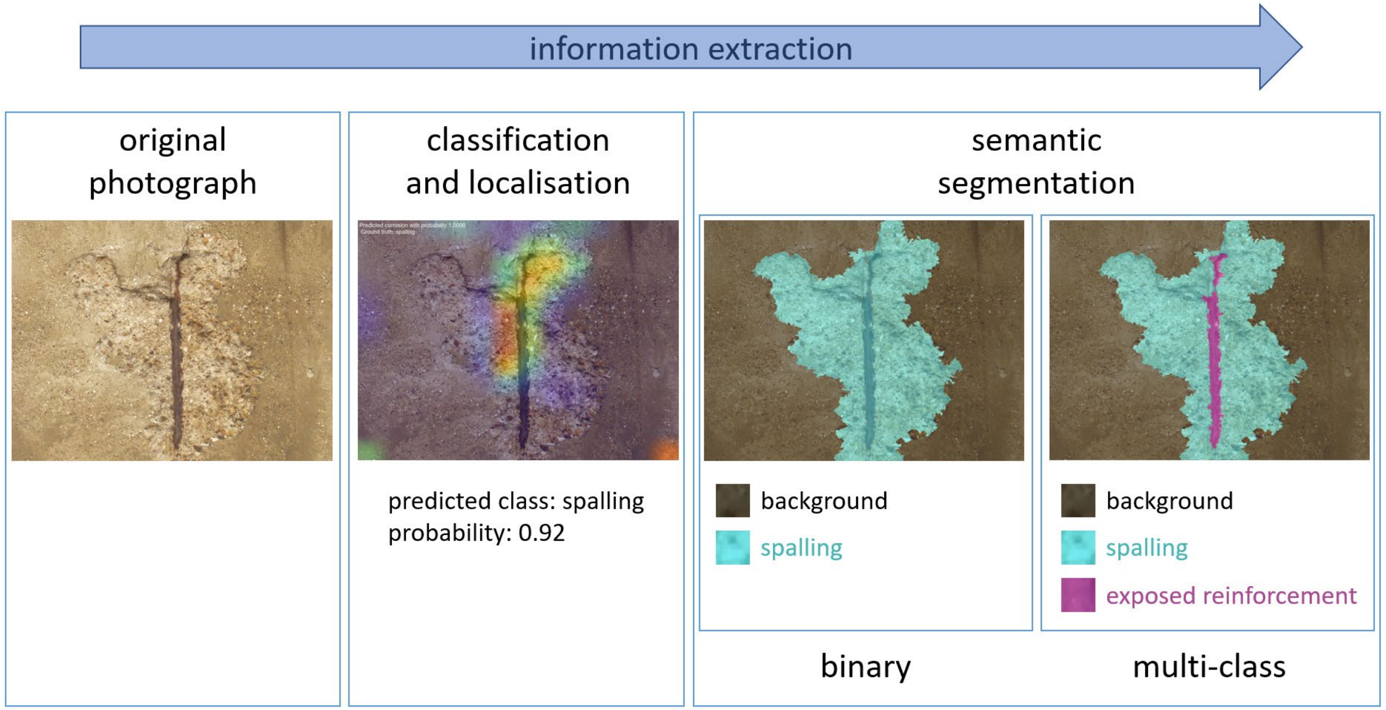


ML&CV: CV for detection of condition

Use of image processing and machine learning techniques to analyse visual data and identify various defects, damages, or anomalies on structures.

This problem can be decomposed into three main parts

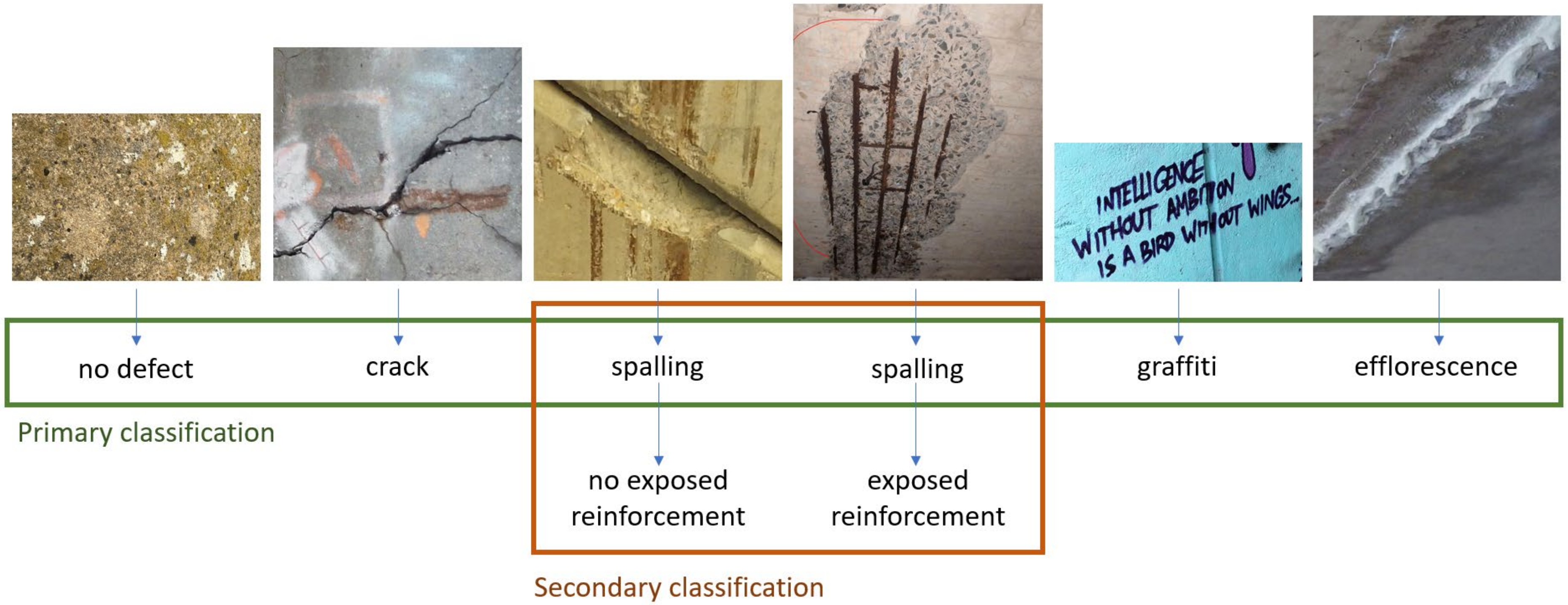
- defect classification,
- quantifying defect extent, and
- tracking defect propagation



ML&CV: CV for detection of condition - classification

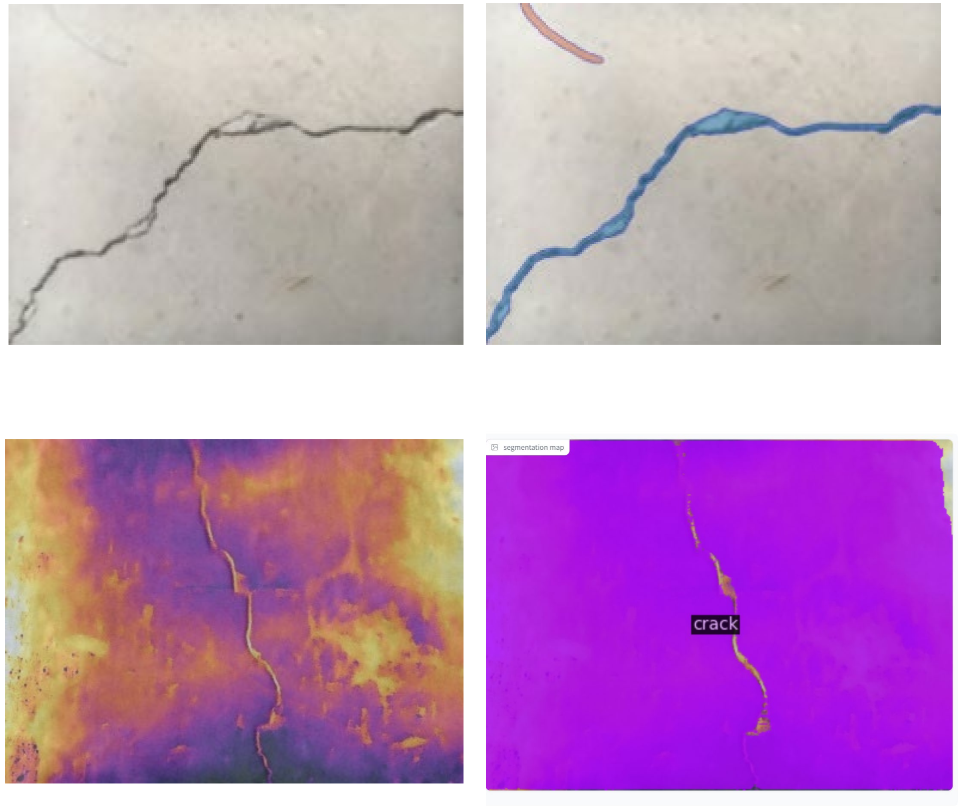
Under the of defect classification, we include computer vision tasks:

- image classification
- object detection
- and meta-learning



ML&CV: CV for detection of condition - segmentation

- Semantic segmentation is a complex computer vision task (compared with image classification and object detection)
- Semantic segmentation is the act of classifying each pixel in an image into one of a fixed number of classes. The result is a segmented image in which each segment is assigned a certain class.
- When applied to damage detection, the precise location and shape of the damage can be delineated.



ML&CV: CV for component recognition

Structural component recognition is a process of detecting, localizing, and classifying characteristic parts of a structure, which is expected to be a key step toward the automated inspection of civil infrastructure

It is expected to be a building block of autonomous navigation and data collection algorithms for robotic platforms

- Heuristic methods (hand-crafted image filters & heuristics)
- 3D point-cloud data recognition
- Deep learning-based recognition

ML&CV: CV for recognition of components and condition

- Segment Anything Model, SAM, trained on existing largest image segmentation dataset.
- Large vision models shows great performance in computer vision tasks, it is worth combining such advanced method with the field of Structural Health Monitoring (SHM), which significantly enhance the resilience of the structural system.

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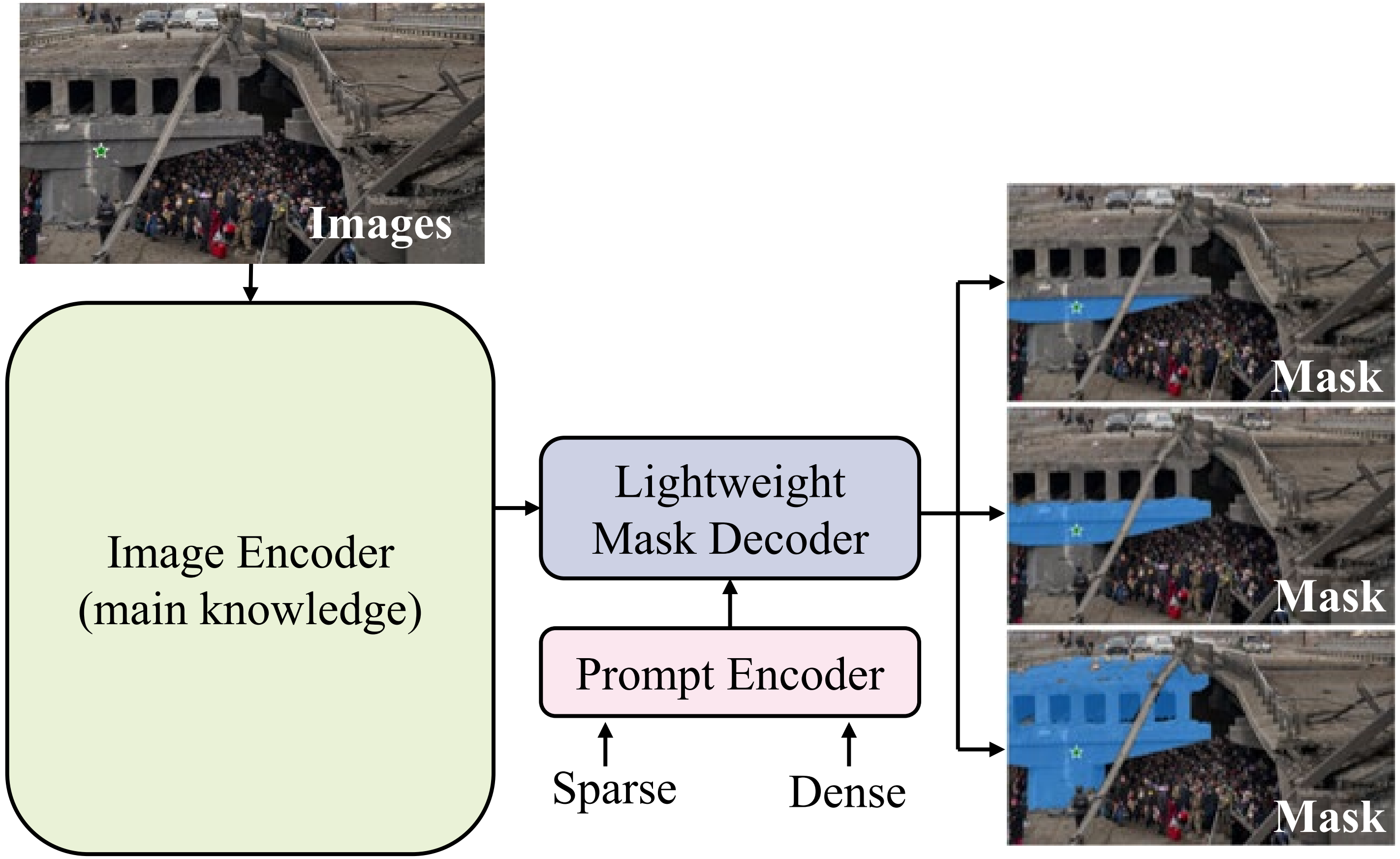
ML&CV: CV for recognition of components and condition

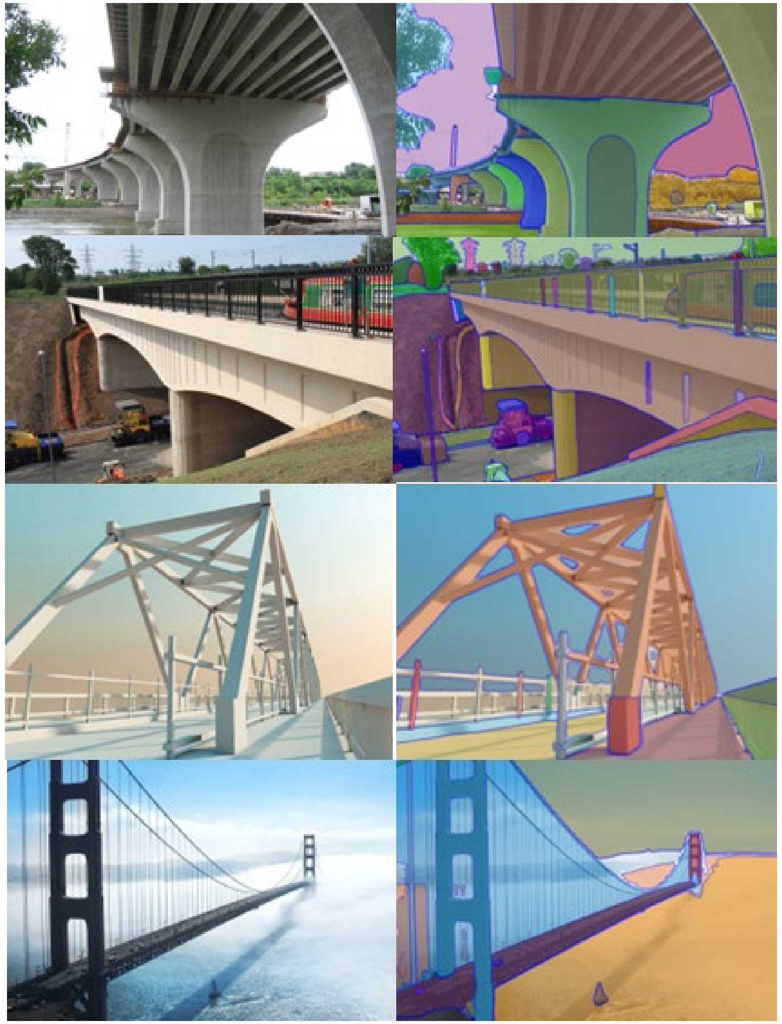
Basic architecture of the Segment Anything Model (Kirillov et al., 2023)

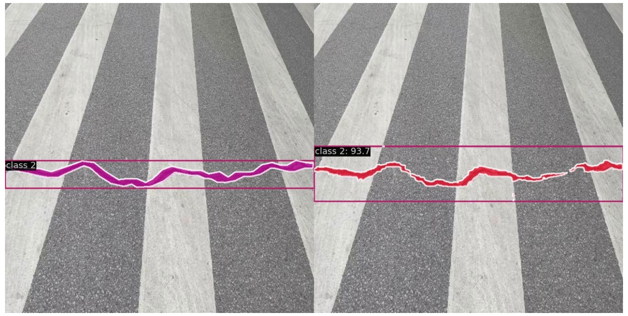
1. Only for segmentation
2. Only for common objects (dataset not including defects)
3. No sematic information
4. Require prompts

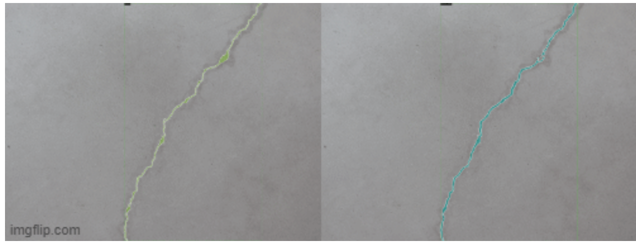


ML&CV: CV for recognition of components and condition

- SAM can detect bridge components by segmenting images, identifying and classifying structural parts for detailed analysis and maintenance.
- SAM detects bridge conditions by segmenting images, highlighting areas of wear or damage, and providing detailed assessments for maintenance.







ML&CV: Vision based automatic inspection of structures

Example of application of CV methods for inspection and analysis of bridges

- LiDAR or UAV-based image acquisition
- Object detection
- Object grouping and model recontraction
- Condition detection

Image acquisition
- LiDAR
- UAVs
- Preprocessing

Model training
- Semantic segmentation
- Multi-label

Damage detection
- Component detection
- Damage detection

ML&CV: CV for defect propagation

Digital photographs collected during visual bridge inspections are typically taken from different angles. Without pixel-wise correspondence between images, it is not possible to quantify and compare defect extent in an automated and objective manner

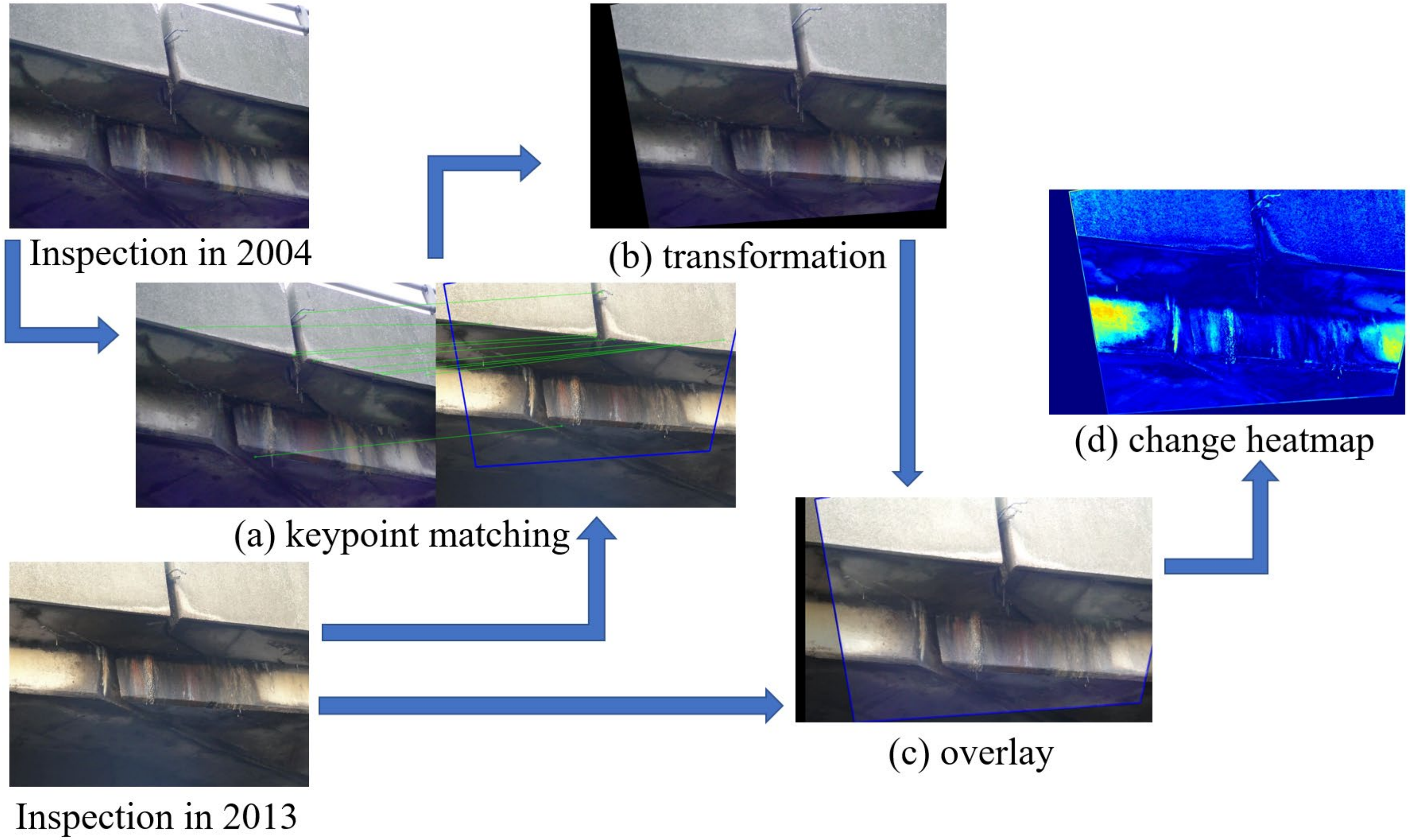
Change detection algorithms compare images taken at different times to identify and highlight differences or changes in the structure's appearance.

Use of CV image registration algorithm to identify matching key points across the pair of images.

RANdom SAmple Consensus (RANSAC) to discard outliers from the set of matched key points.

ML&CV: CV for defect propagation

- Keypoints matching
- Transformation
- Overlay, and
- Change heatmap



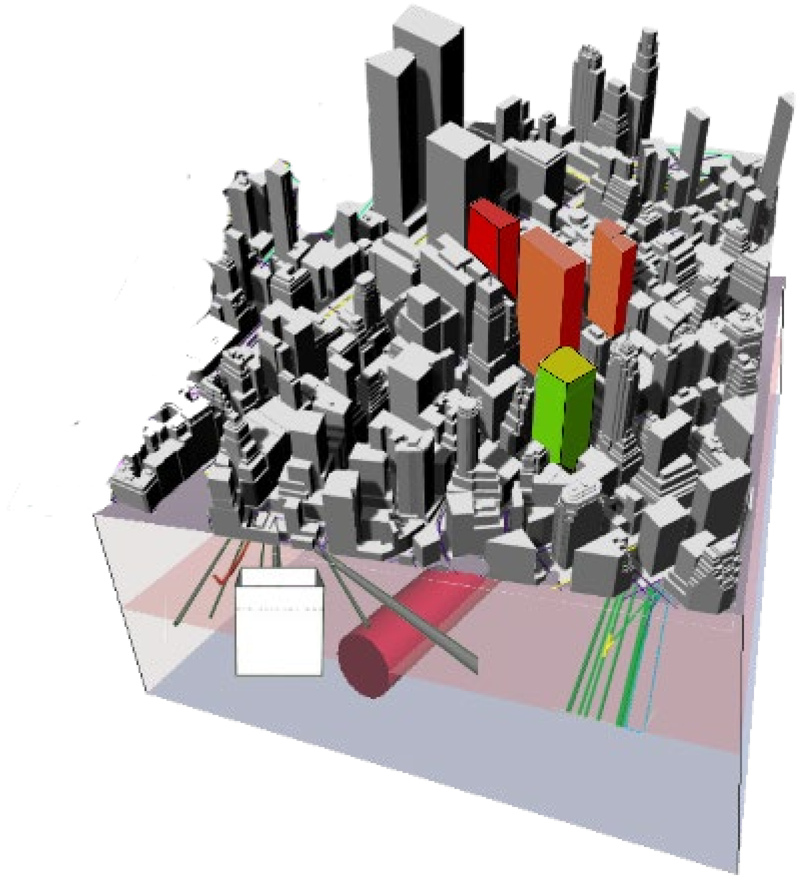
Put your face here

Reflection:

- What is machine learning, and how are its algorithms classified?
- What are the most common applications of machine learning in infrastructure assessment?
- What is computer vision, and how does it support infrastructure maintenance?
- What has been your experience with these technologies?
- After this lecture, consider how you might apply these technologies to solve tasks in your future work.

ACTIVITY 3: Building Information Modelling and Digital Twins

- What is Building Information Modeling (BIM) and Digital Twins (DTs)?
- What are the current trends in BIM and DT developments within infrastructure engineering?



BIM & DT: Definitions

Building Information Modelling:

"the **process** of **designing, constructing or operating** a building or infrastructure asset using **electronic** object-oriented **information**" (BS EN ISO 19650-2: 2018)

"a **digital** representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for **information** about a facility forming a reliable basis for decisions during its **lifecycle**; defined as existing from earliest conception to demolition." (NBIMS-US™)

BIM & DT: Definitions

- **Building** is the verb '*to build*' rather than the noun 'a building'.

It is therefore relevant to any asset of the built environment (e.g. tunnel, a road).

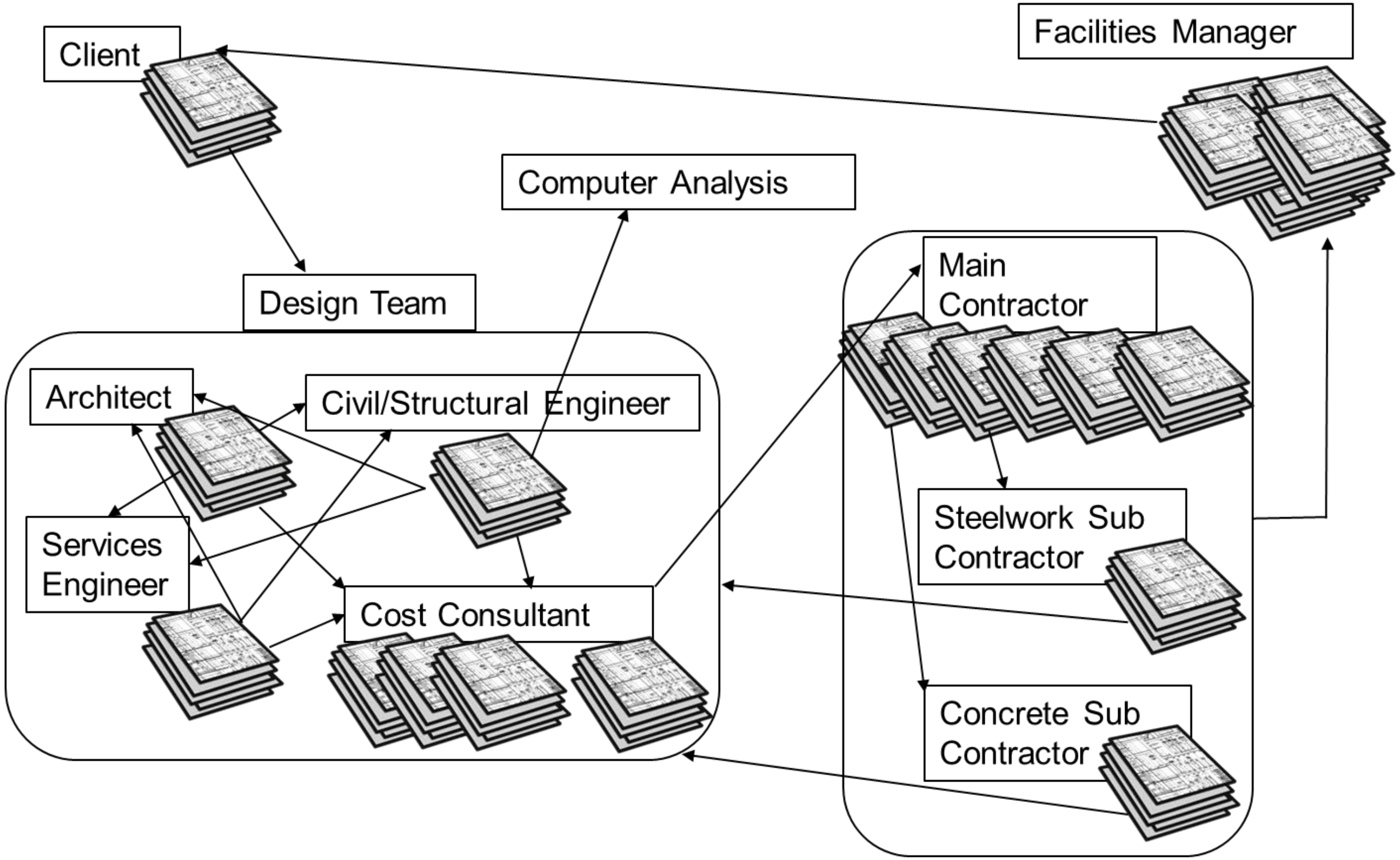
- **Information** (or more specifically 'the sharing of structured information') is the fundamental concept of BIM.

This includes both *geometric* and *non-geometric information* (such as time, cost, fire-rating etc.).

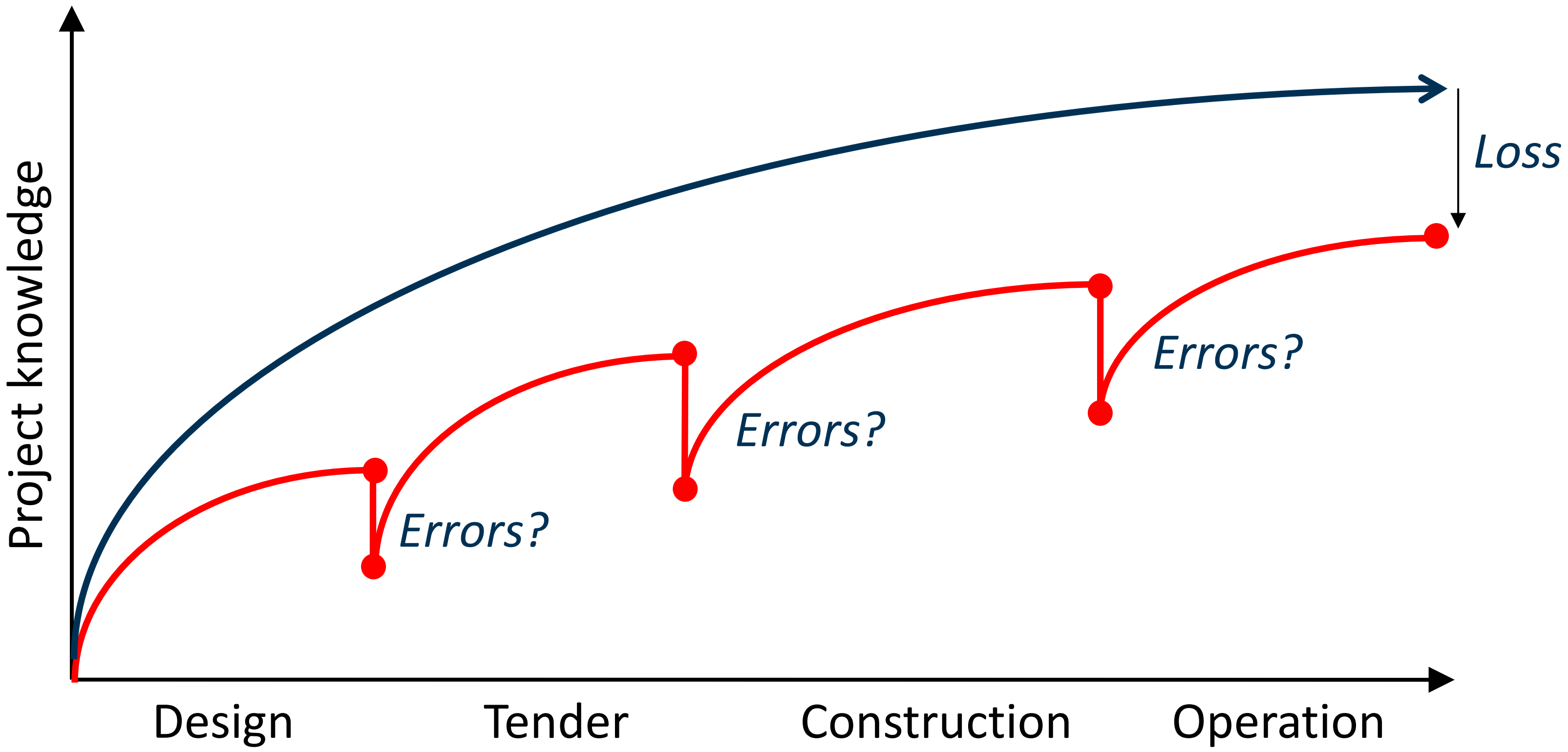
- **Modelling** refers to the '*representation of a system or process*' rather than a '3-dimensional representation of a person or thing'.

Though there can be no doubt that geometric representation is important, we must be able to simulate the various facets of <u>the design</u> of an asset (structural, architectural, building services etc.), <u>the construction</u> of the asset, and <u>the operation</u> of the asset.

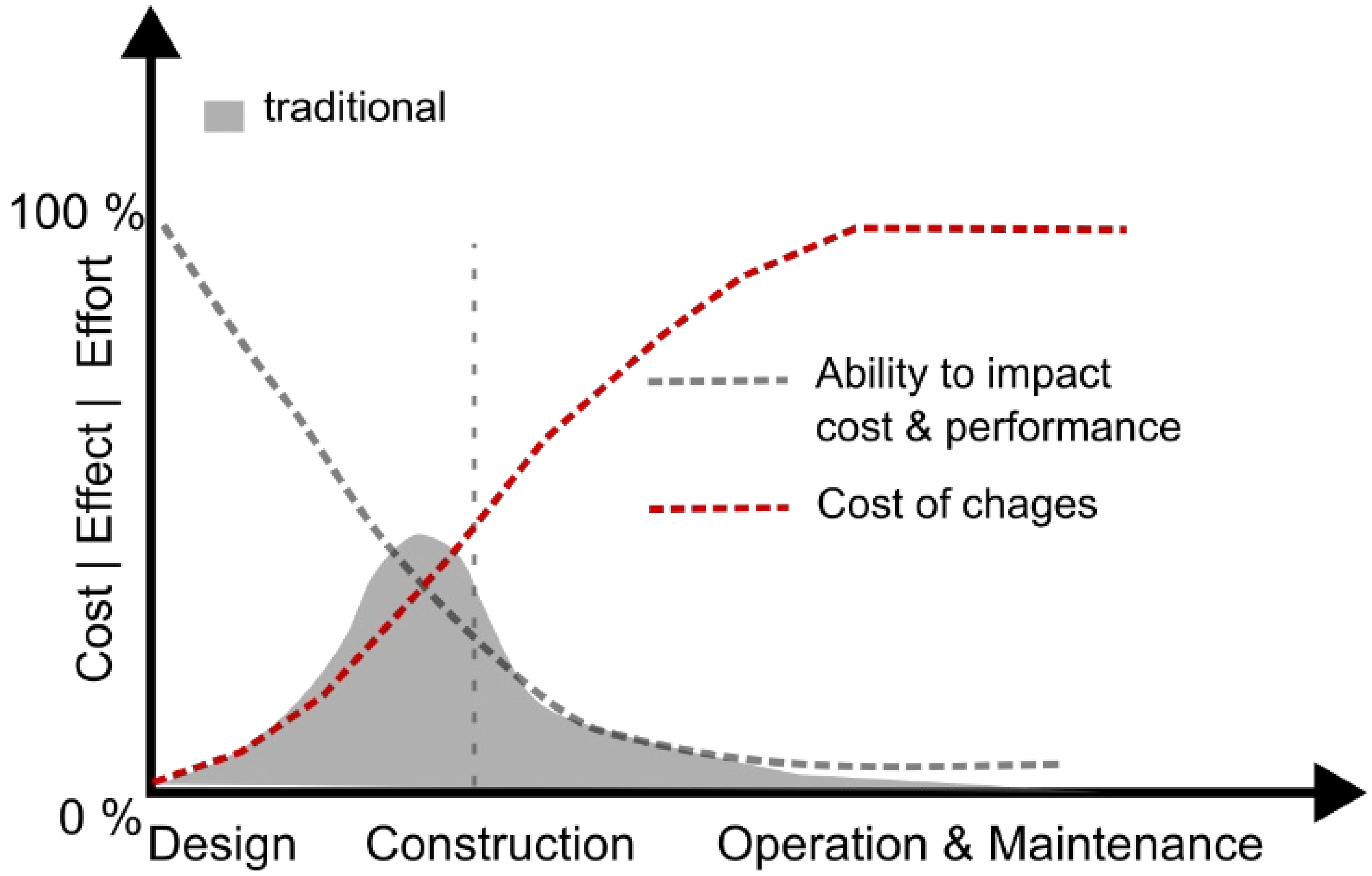
BIM & DT: Traditional processes in construction project



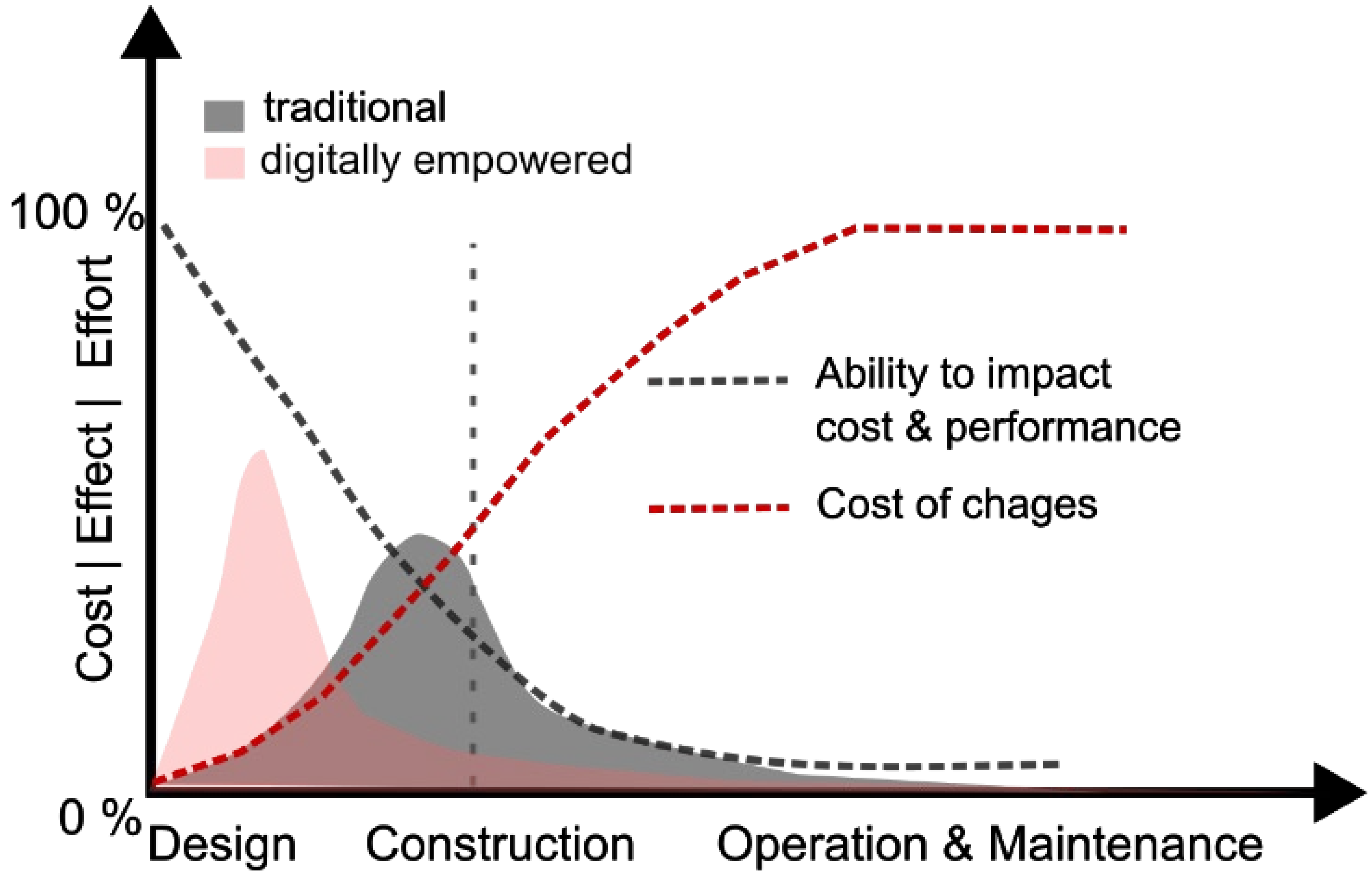
BIM & DT: Information loss due to interruption in information flow



BIM & DT: Traditional workflow



BIM & DT: BIM workflow (MacLeamy Curve)



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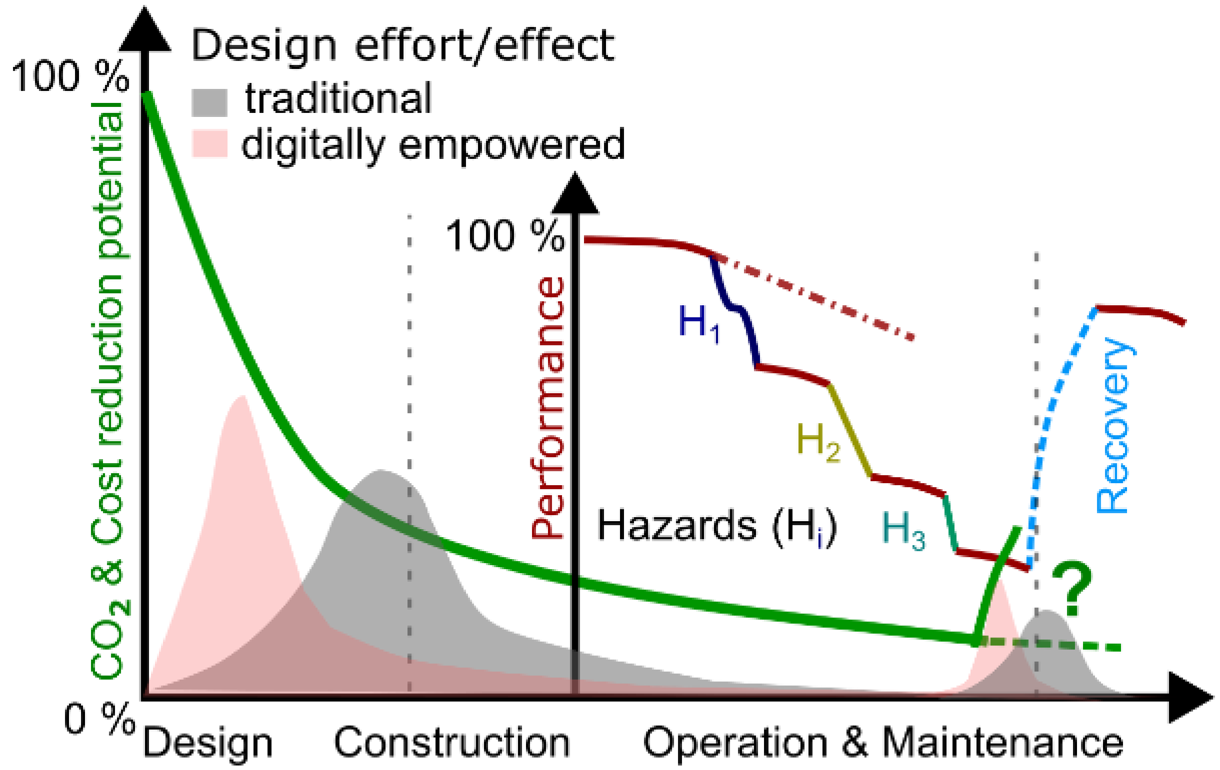
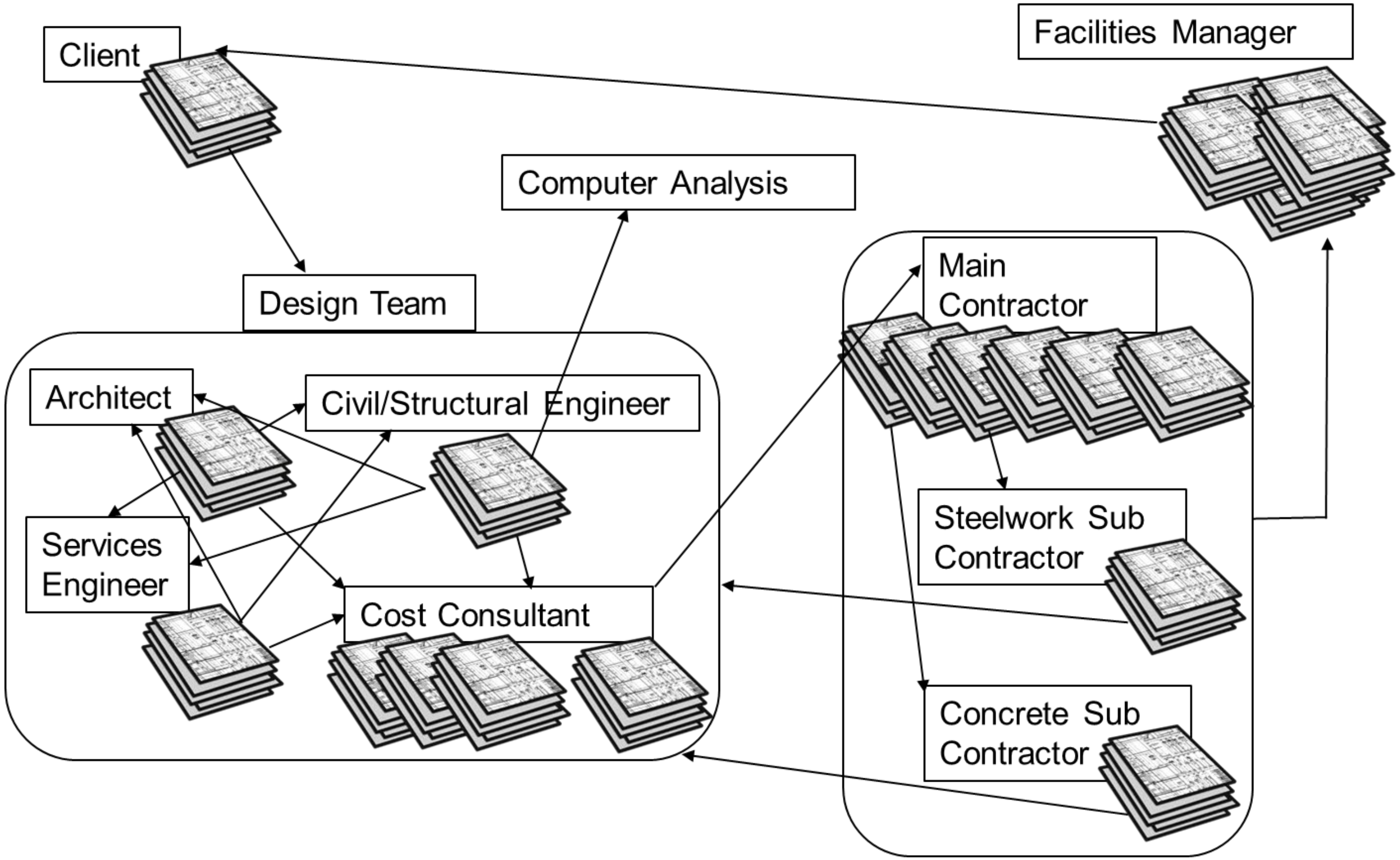
BIM & DT: Recovery of infrastructure

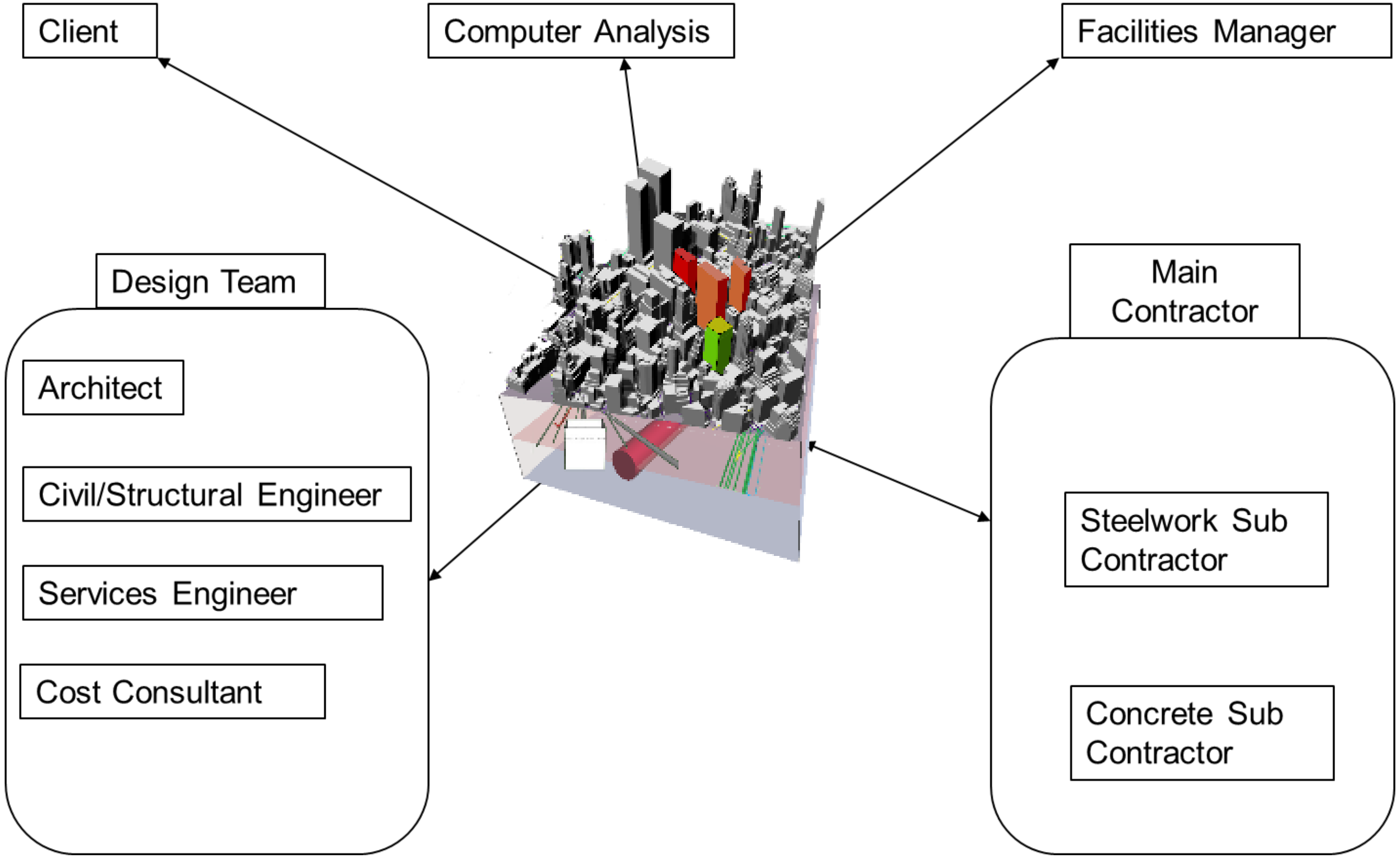


- Cost reduction
- CO2 reduction
- Easy exploration of scenarios in early design phase
- Exploration of scenarios to resilience on human and naturally induced hazards
- Reactive or proactive?
- Adaptation or recovery?

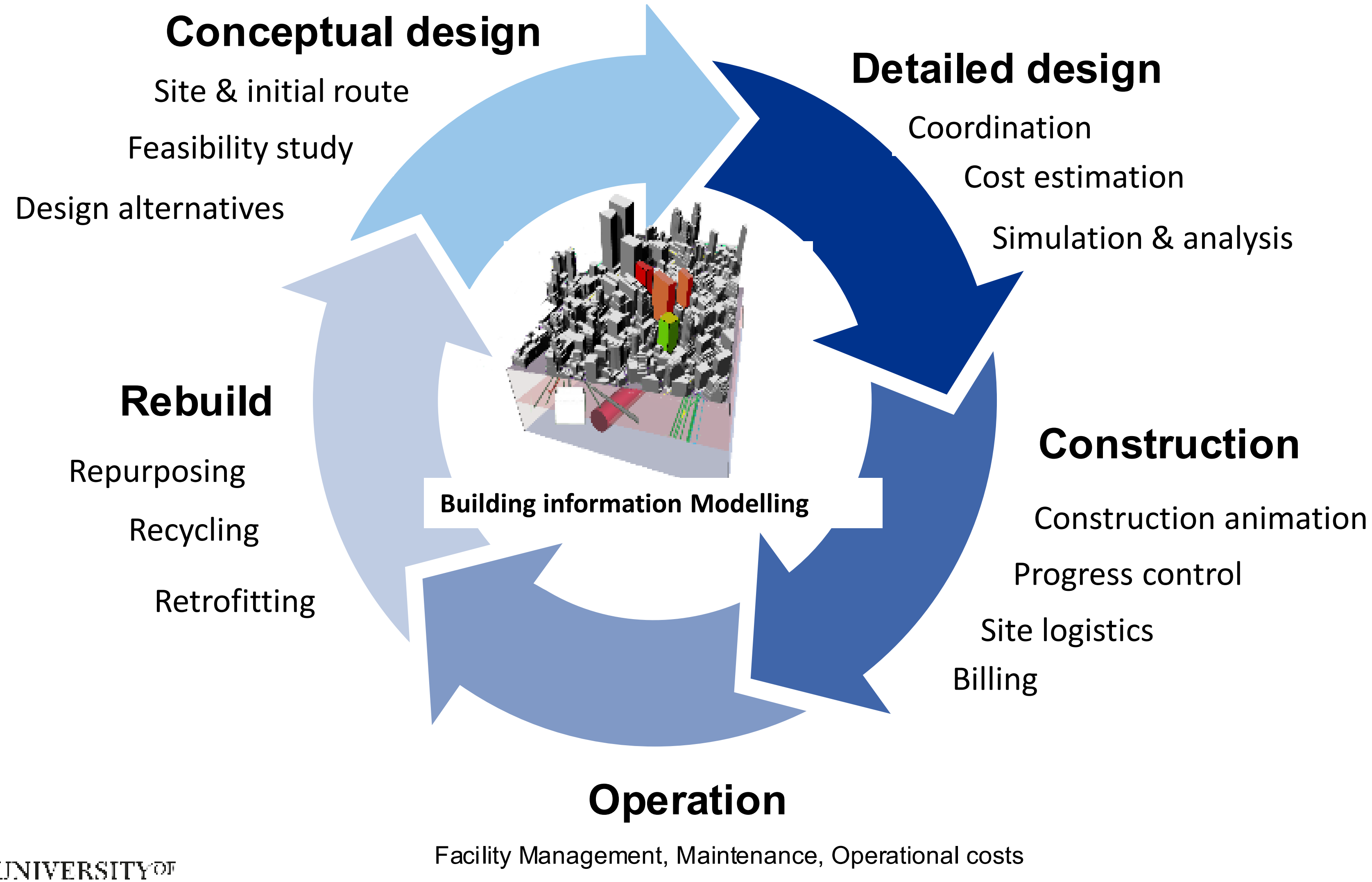
BIM & DT: Traditional processes in construction project



BIM & DT: Collaborative project development



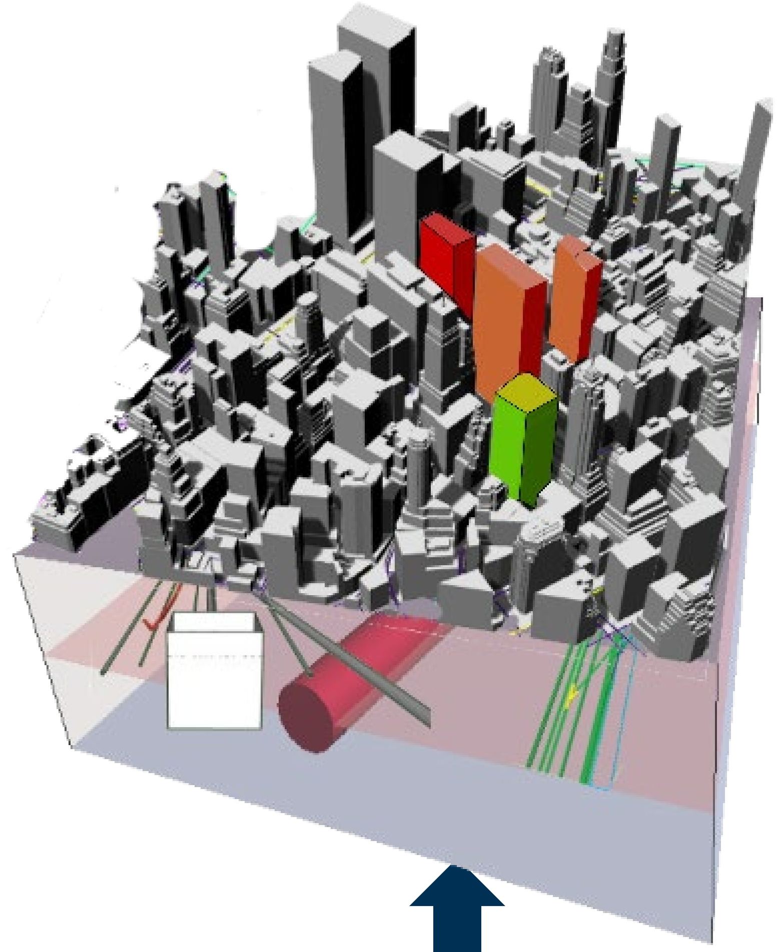
BIM & DT: A lifecycle process



BIM & DT: The Information Model

Graphical Data

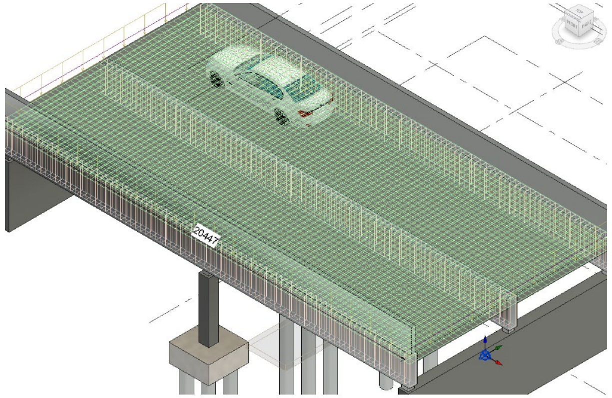
Non-Graphical Data



Documents

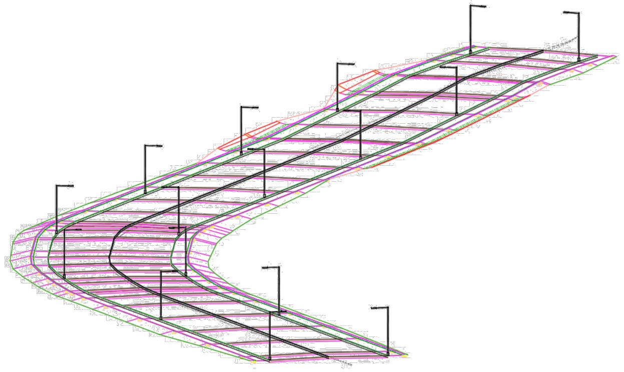
BIM & DT: The Information Model

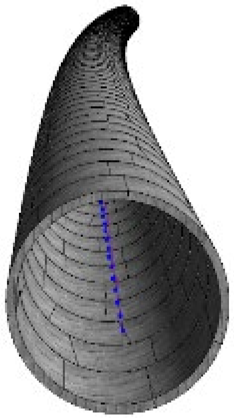
1. Graphical Data



Geometric modelling

- *What shape does an infrastructure component have?*
- *What volume, surface area is associated with it?*
- *Does it collide with other components?*



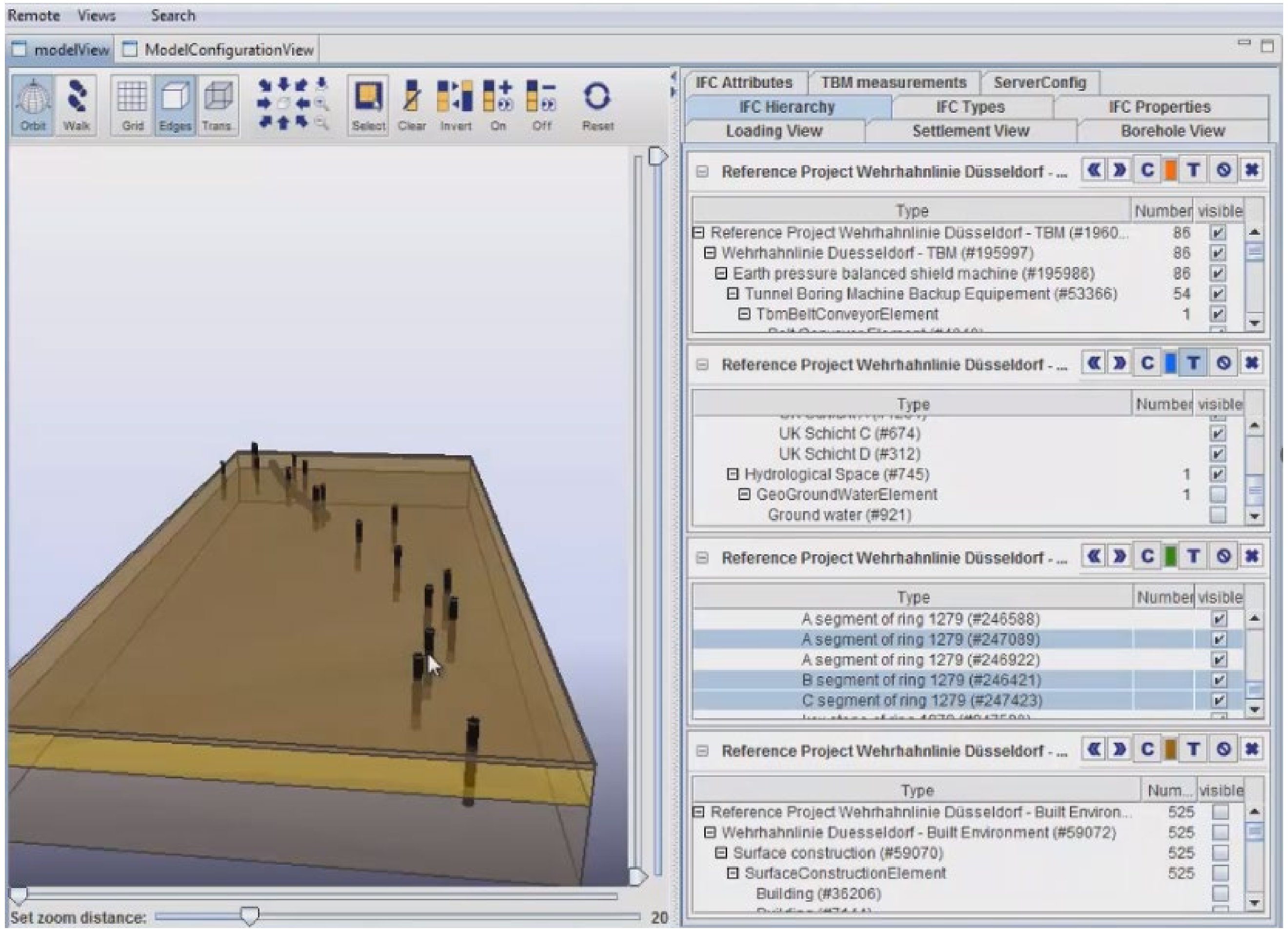


BIM & DT: The Information Model

2. Non-Graphical Data

Semantic modelling

- *What is the type of the component?*
- *What are its properties, such as material?*
- *What are its relations to other components?*

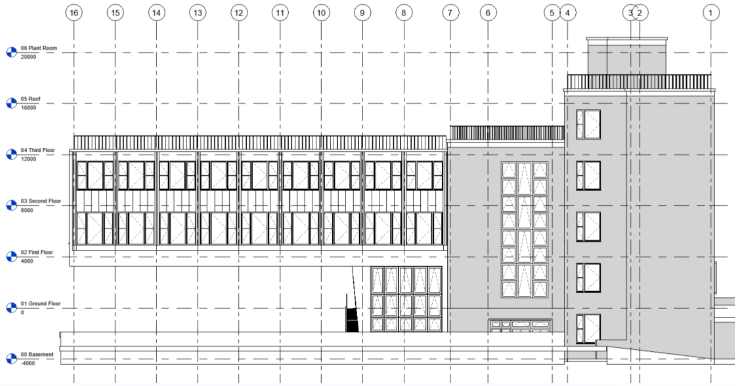


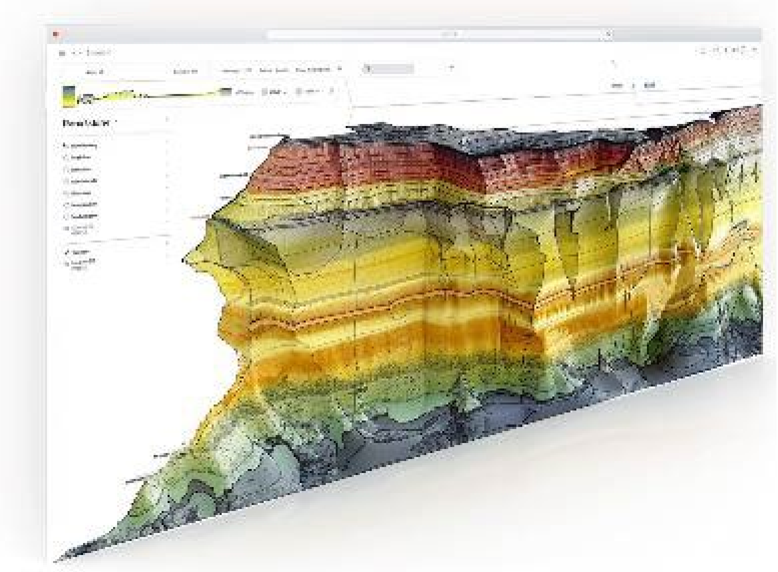
BIM & DT: The Information Model

3. Documents

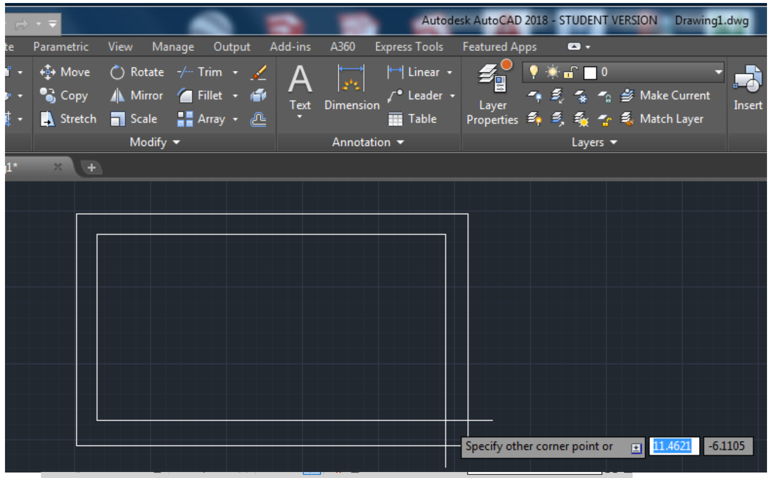
‘Static’ in PDF format

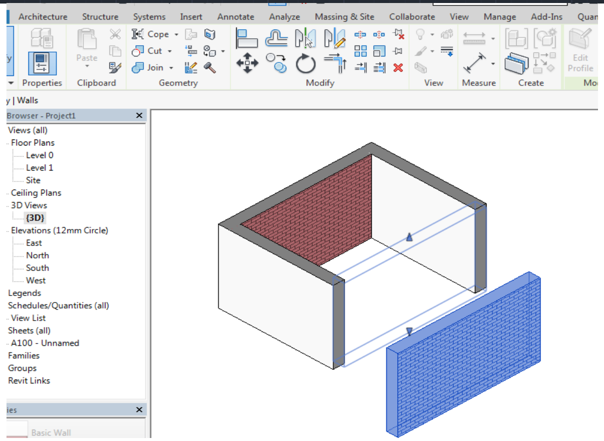
- *Specifications*
- *Reports*
- *Historical Record Drawings*

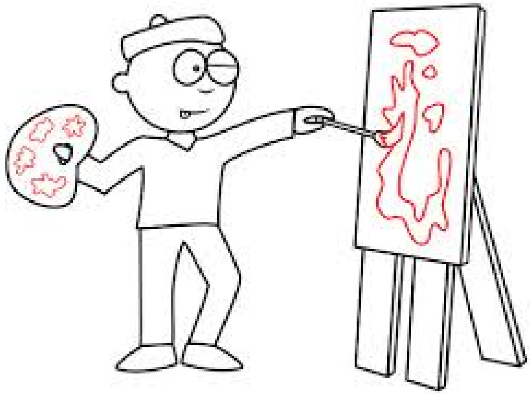




BIM & DT: Producing an Information Model







BIM & DT: BIM Objects

A BIM object is a combination of many things:

- **Geometry** representing the objects physical characteristics

- Material **properties** such as stiffness, density, cohesion

- **Visualisation data** giving the object a recognisable appearance

- **Functional data** such as detection zones that enables the object to be positioned correctly

BIM & DT: Object-Based Parametric Modelling:

Each object class has parameters (variables)

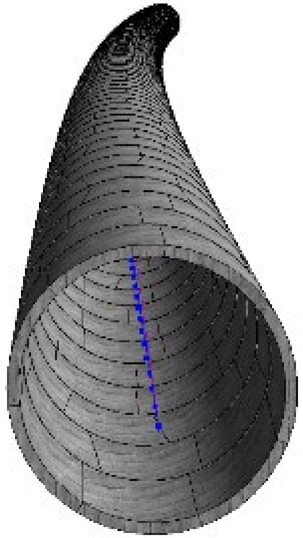
In parametric design the designer defines **instances** of objects within the model.

The **parameters** (or variables) which position object instances include distance, angles, and rules like ‘attached to’, ‘parallel to’ or ‘distance from’

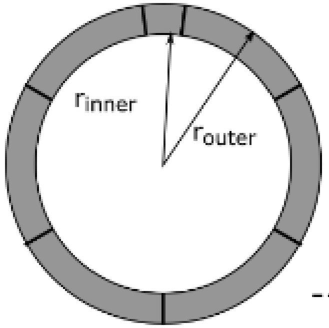
On parameter change → **automatic update** of dependent parameters

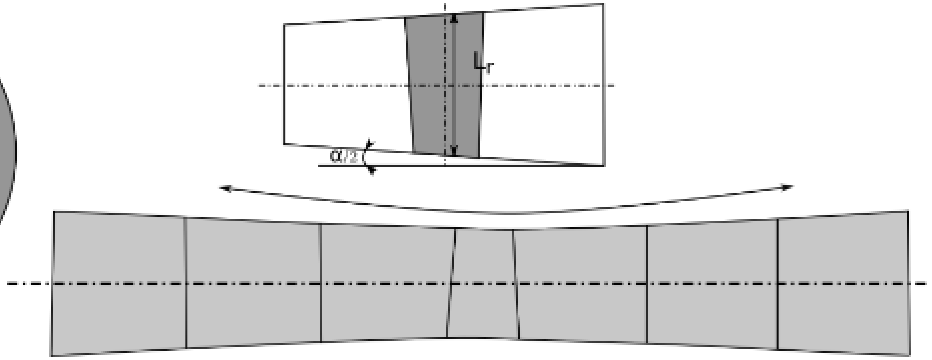
BIM & DT: Example of parametric object modelling

Segmental tunnel lining



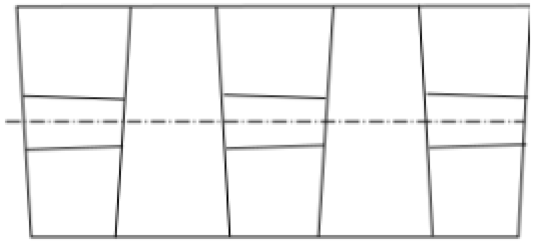
Universal lining ring geometry



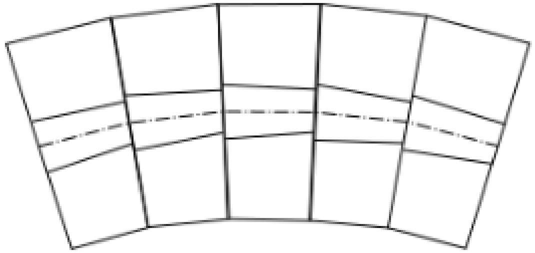


Tapered geometry!

a) Straight alignment



b) Curved alignment



BIM & DT: What is BIM not?

- Models that contain 3D data only and no (or few) object attributes
- Models with no support of behavior (models that cannot adjust when changes are added because they do not use parametric modelling)
- Models that are composed of multiple 2D CAD reference files that must be combined to define the building
- Models that allow changes to dimensions in one view that are not automatically reflected in other views

BIM & DT: Lonely BIM vs Federated models

You could build a BIM model in software (e.g. Autodesk) on your own and generate 2D drawings from it.

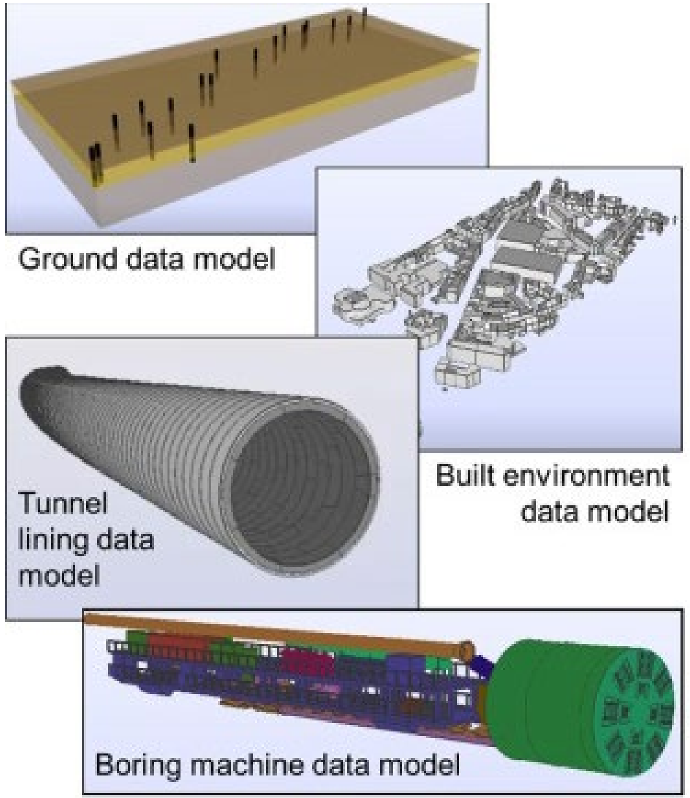
Some companies do this. This Level 1 BIM, sometimes called 'LonelyBIM'.

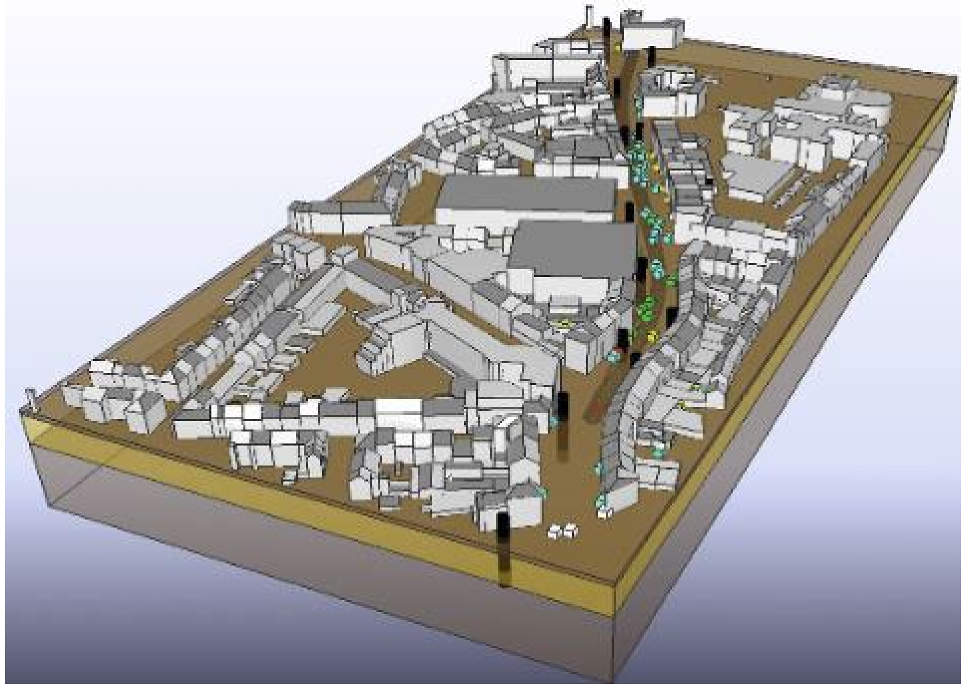
Very useful way to analysis a building and generate drawings but not in the true spirit of BIM.

The real benefit is when all disciplines can produce a 'Federated Model', Level 2 BIM.

BIM & DT: Federated model

Is a combined/merged Building Information Model that has been compiled by amalgamating several different models into one.





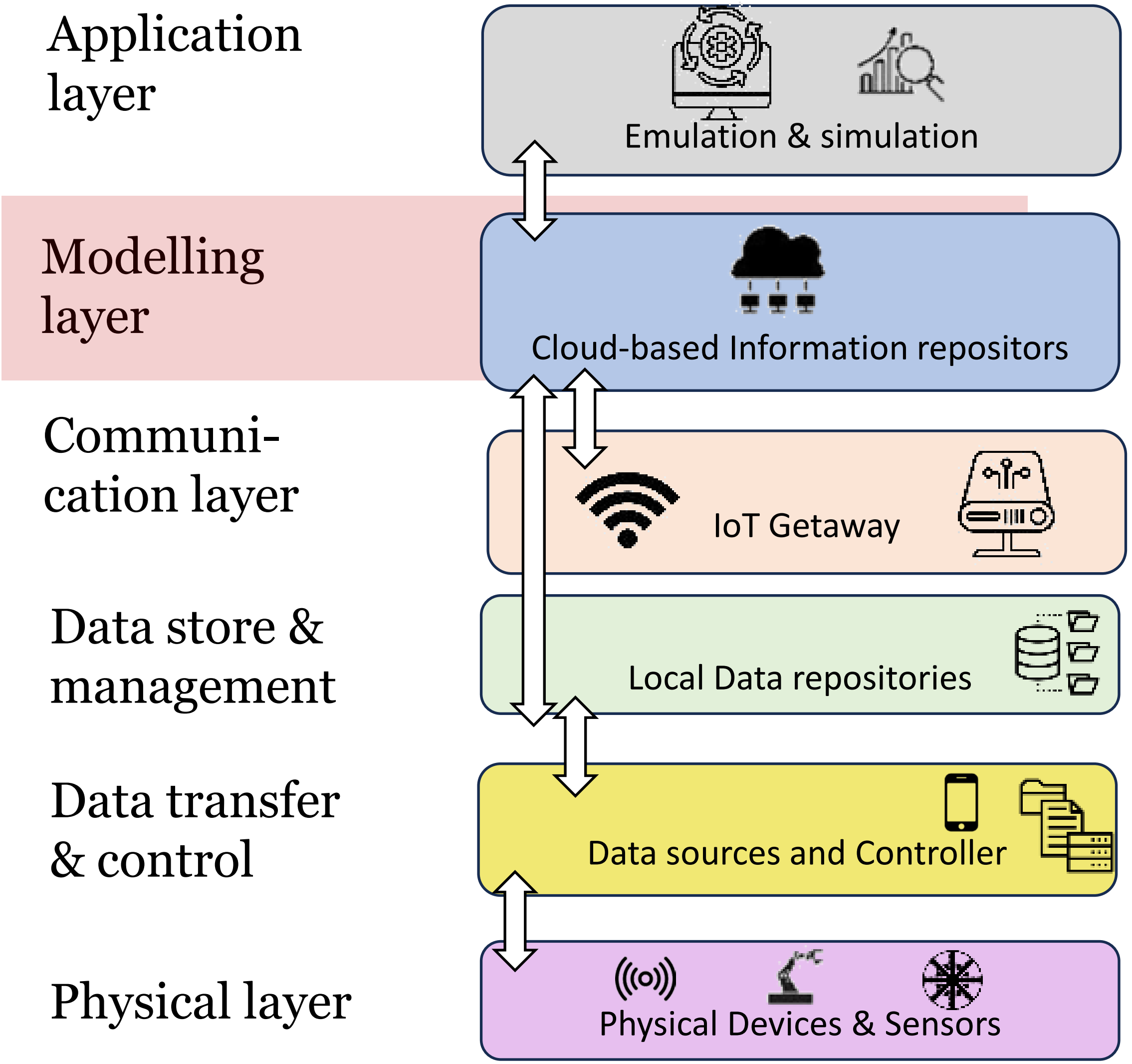
BIM & DT: What is Digital Twin?

- “a Digital Twin is an exact digital replica of a construction project or asset” (Wiki)
- But DTs are **virtual replicas** of real-world physical products or **systems**. DTs integrate data with 3D digital model representation, Machine Learning (ML), AI and Data Science to **create living transdisciplinary simulations that update and change in real-time** with changes of the physical counterpart **over the whole lifecycle.** They are then employed for optimising processes, supporting decision making, virtual control, and analysis.

BIM and DTs

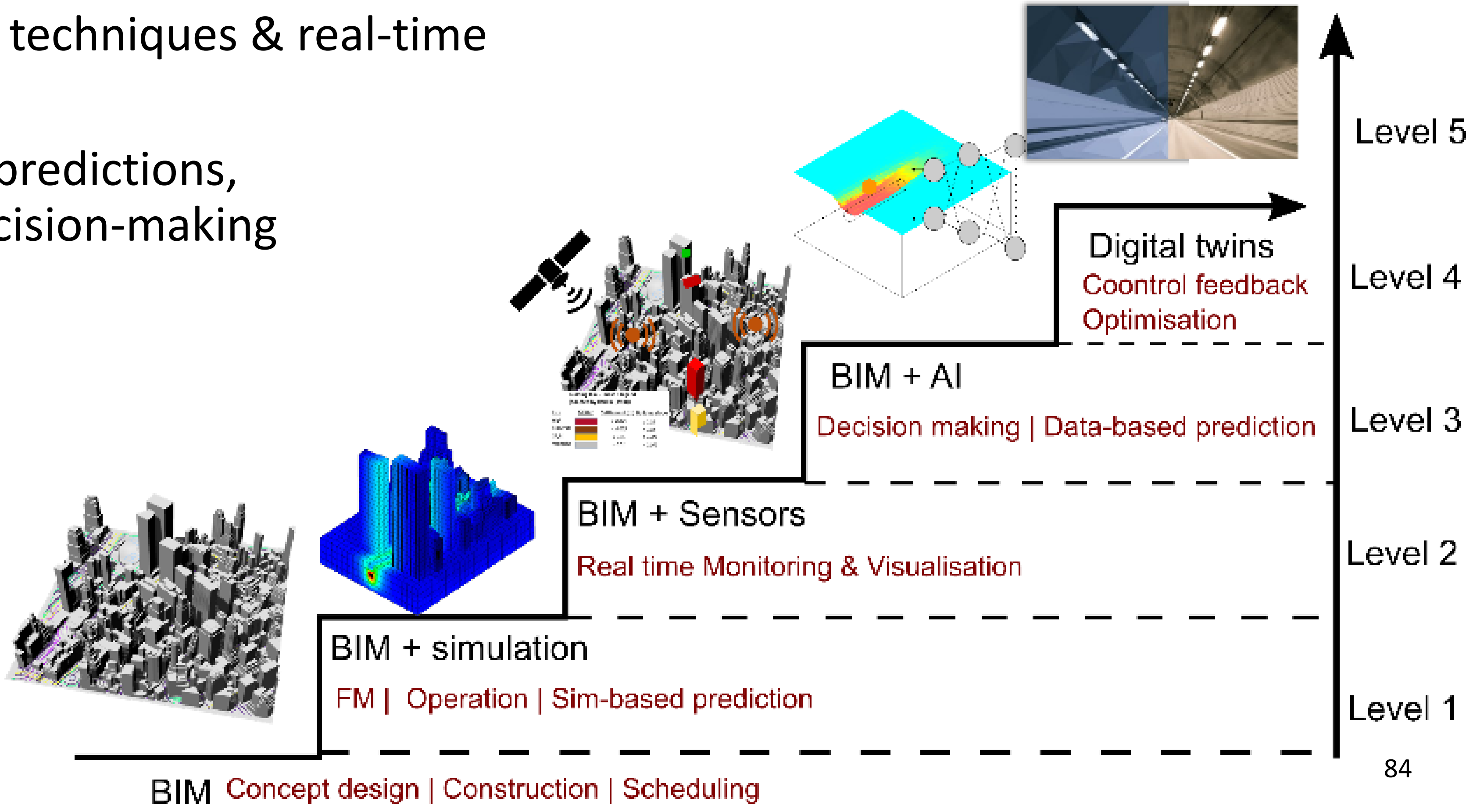
- In general DTs consist of:
  - Physical layer
  - Data transfer, store, management and communicating layer
  - Modelling layer
  - Application layer

- BIM can be
  - subset of DT (model)
  - Or a way to achieve DT



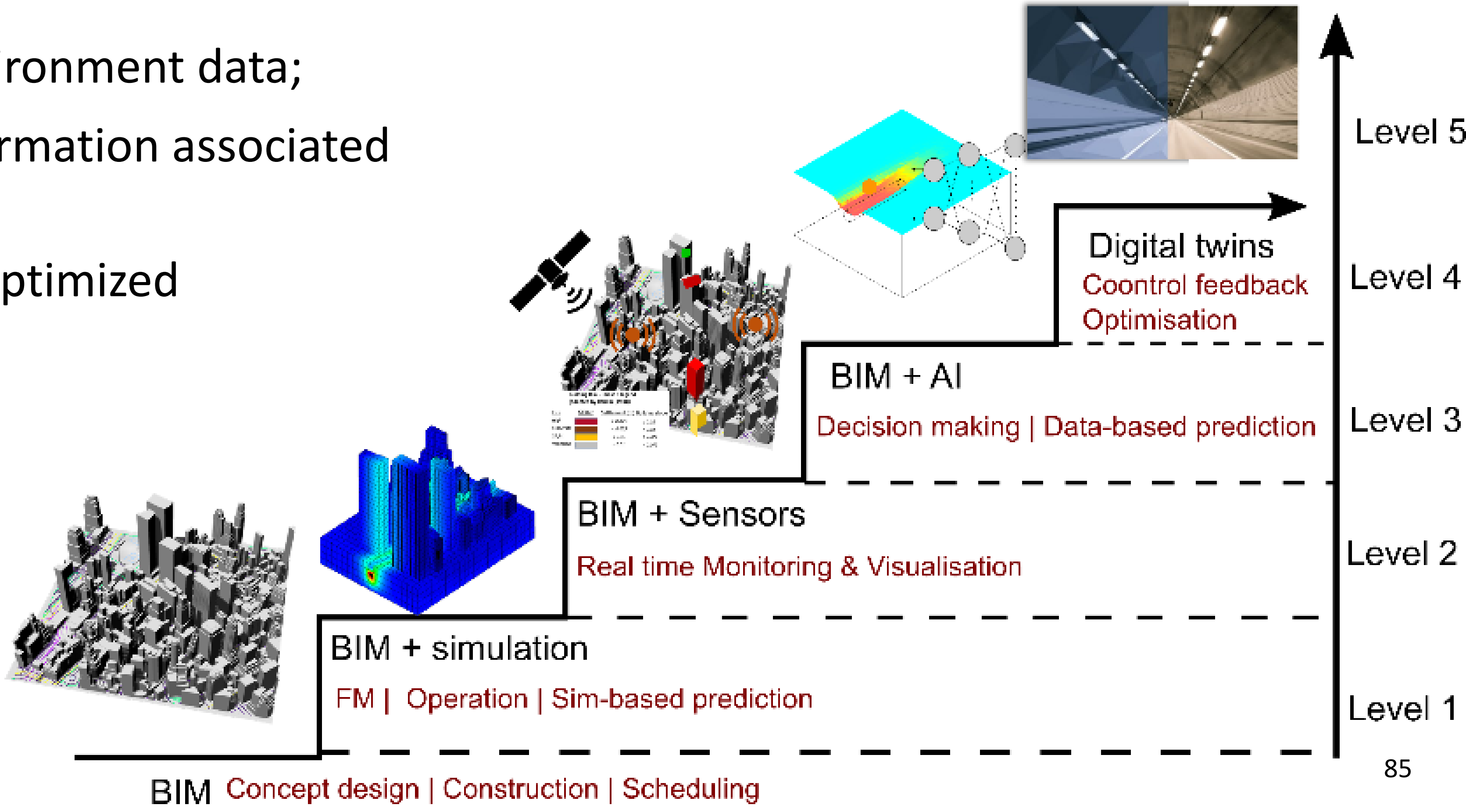
BIM & DT: BIM to Digital twins

- Level 1: A static 3D visualization tool
- Level 2 : BIM-supported simulations based on static project information;
- Level 3: Integration of BIM and IoT techniques & real-time sensor data
- Level 4: Associated with real-time predictions, by incorporating algorithms for decision-making
- Level 5: Digital Twin



BIM & DT: BIM to Digital twins

- Level 1-4 enables intelligent feedback control system to automatically take actions based on optimized results and control strategies;
- Visualization of real-time built environment data;
- Predictions based on dynamic information associated with real-time data sensing;
- Automatic control feedback with optimized management strategies.



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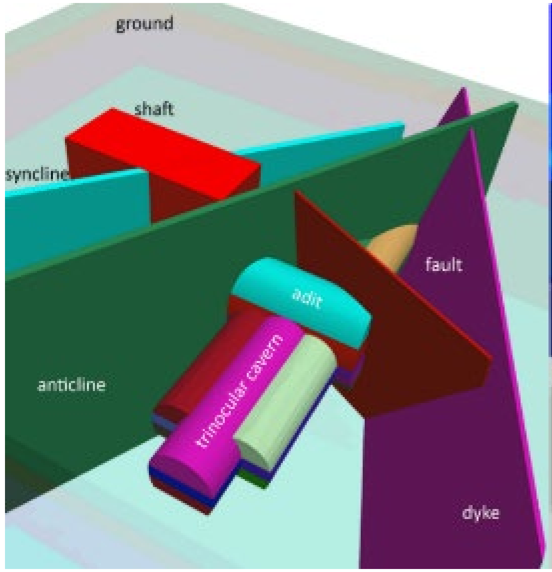
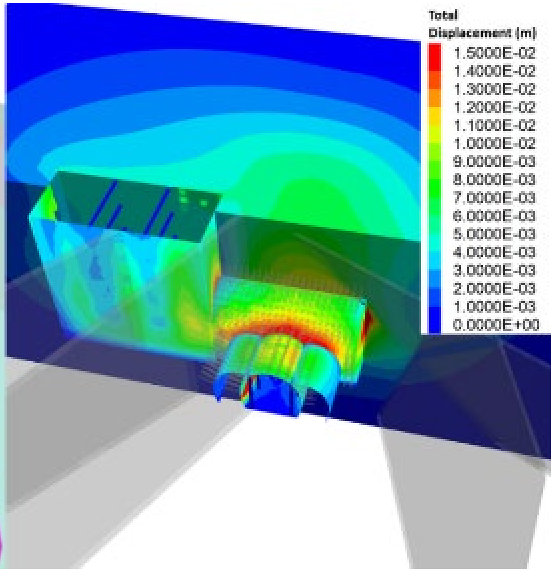
BIM & DT: Applications

- Integration with numerical modelling
- Sustainability assessment
- Digital twin prototypes

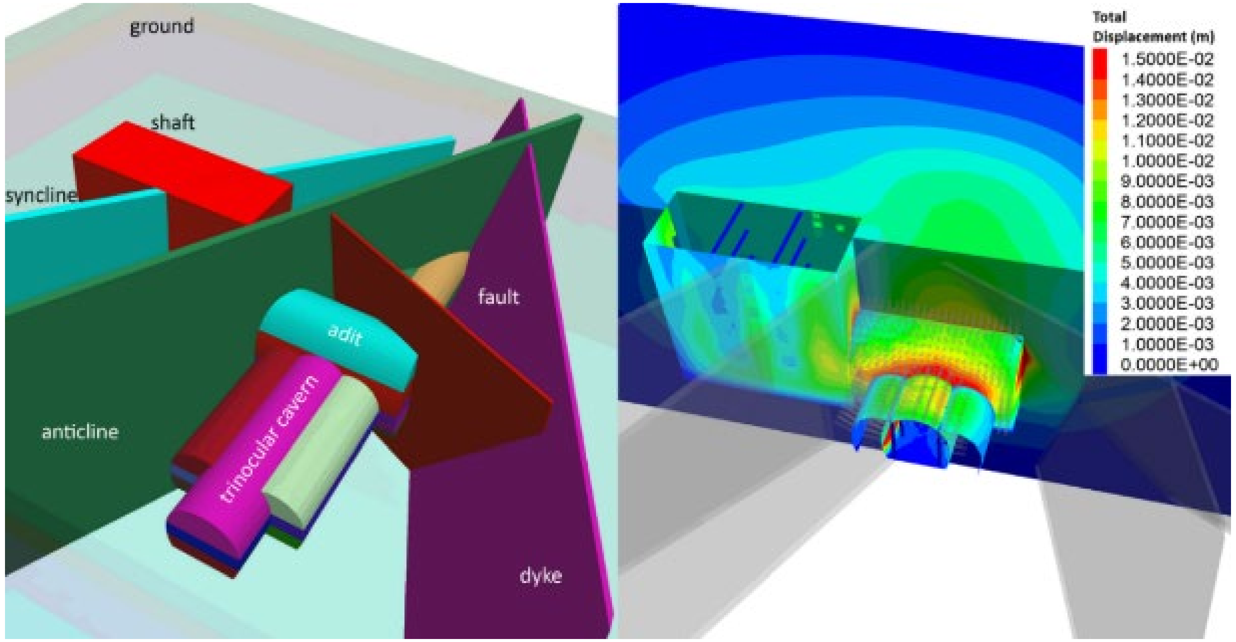




BIM & DT: Integration with numerical modelling

Design-to-design use case has numerous challenges:

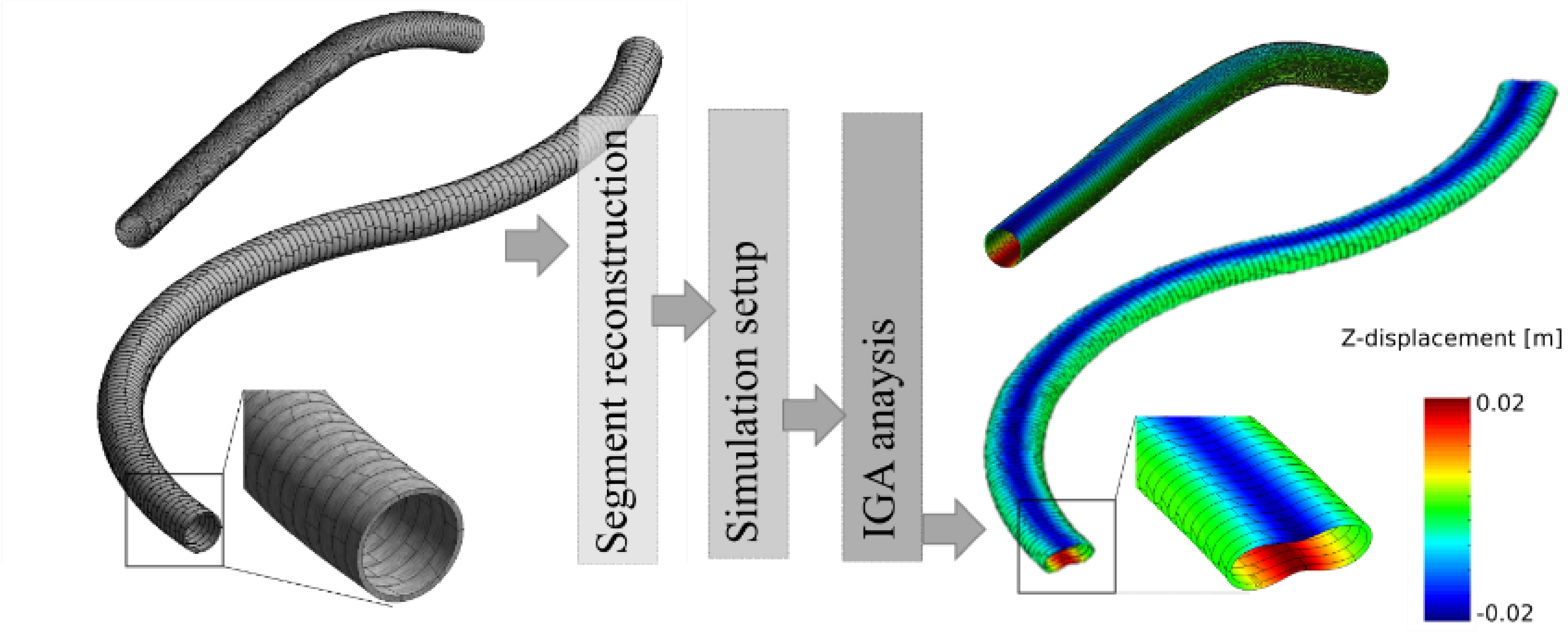
- Numerical software doesn’t have standardised formats for geometry
- Boundary conditions must be applied
- Mesh generation
- Postprocessing

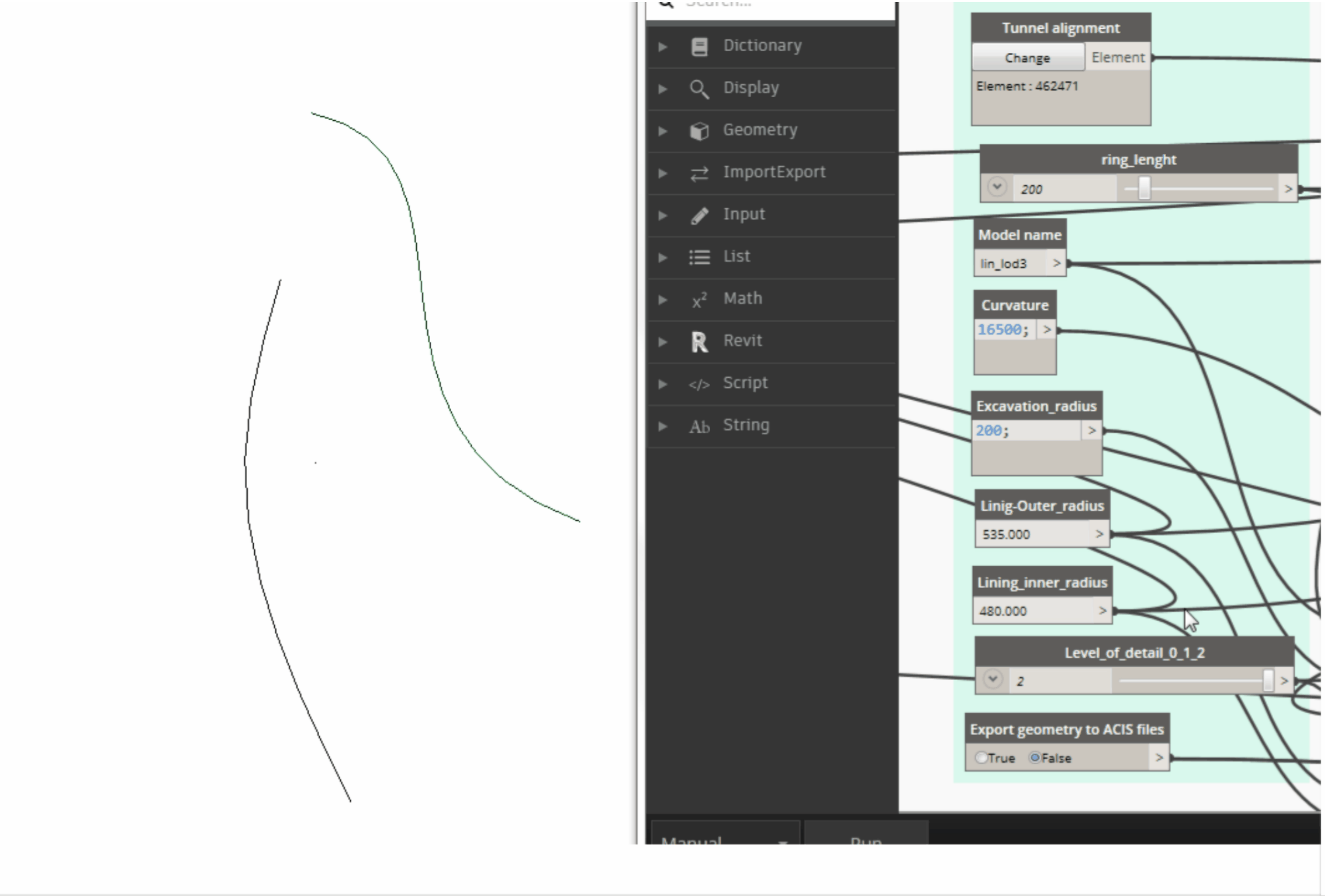


BIM & DT: Integration with numerical modelling

Opportunities:

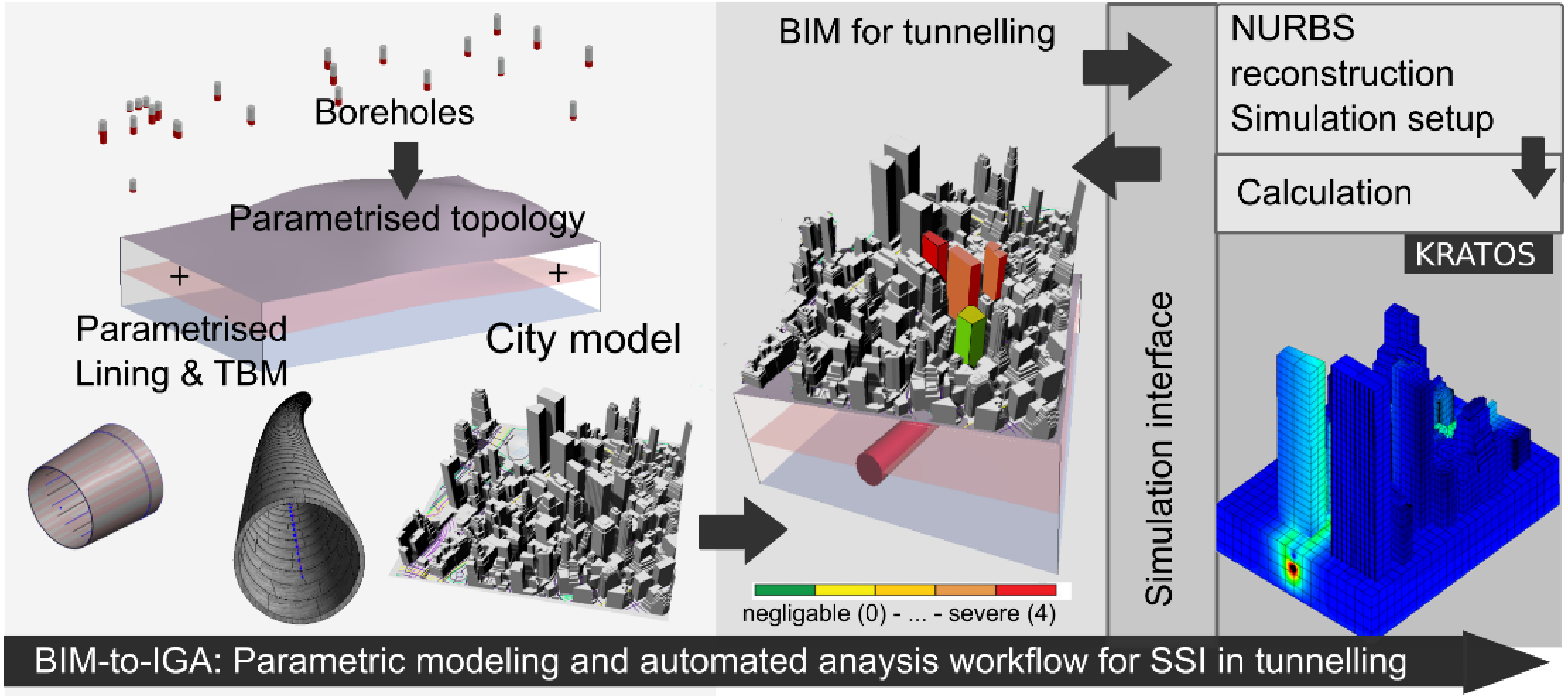
- To adopt interoperability principles
- To go for open-source platforms with advanced methods: IGA, CutFEM



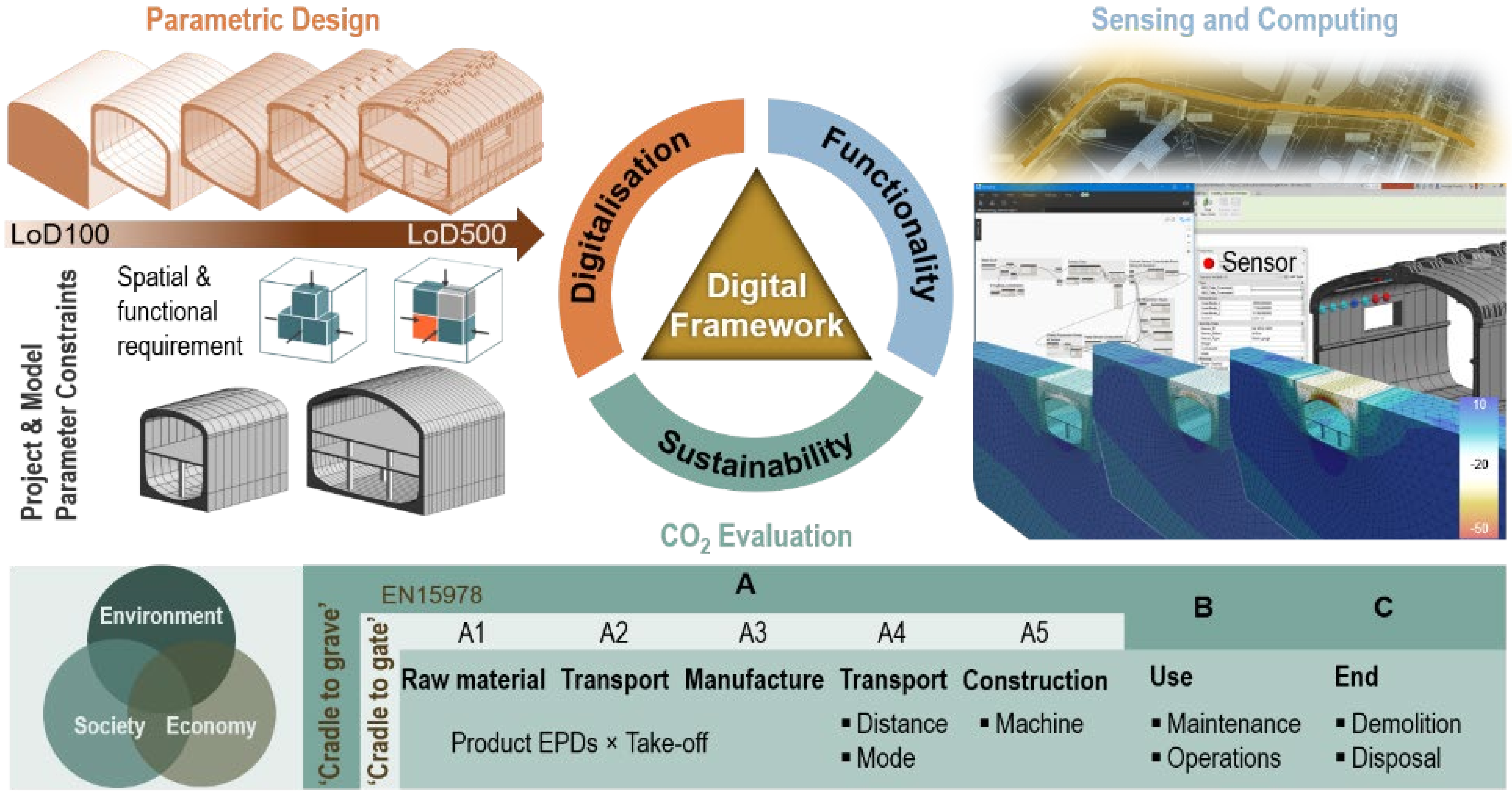


Link for the gif

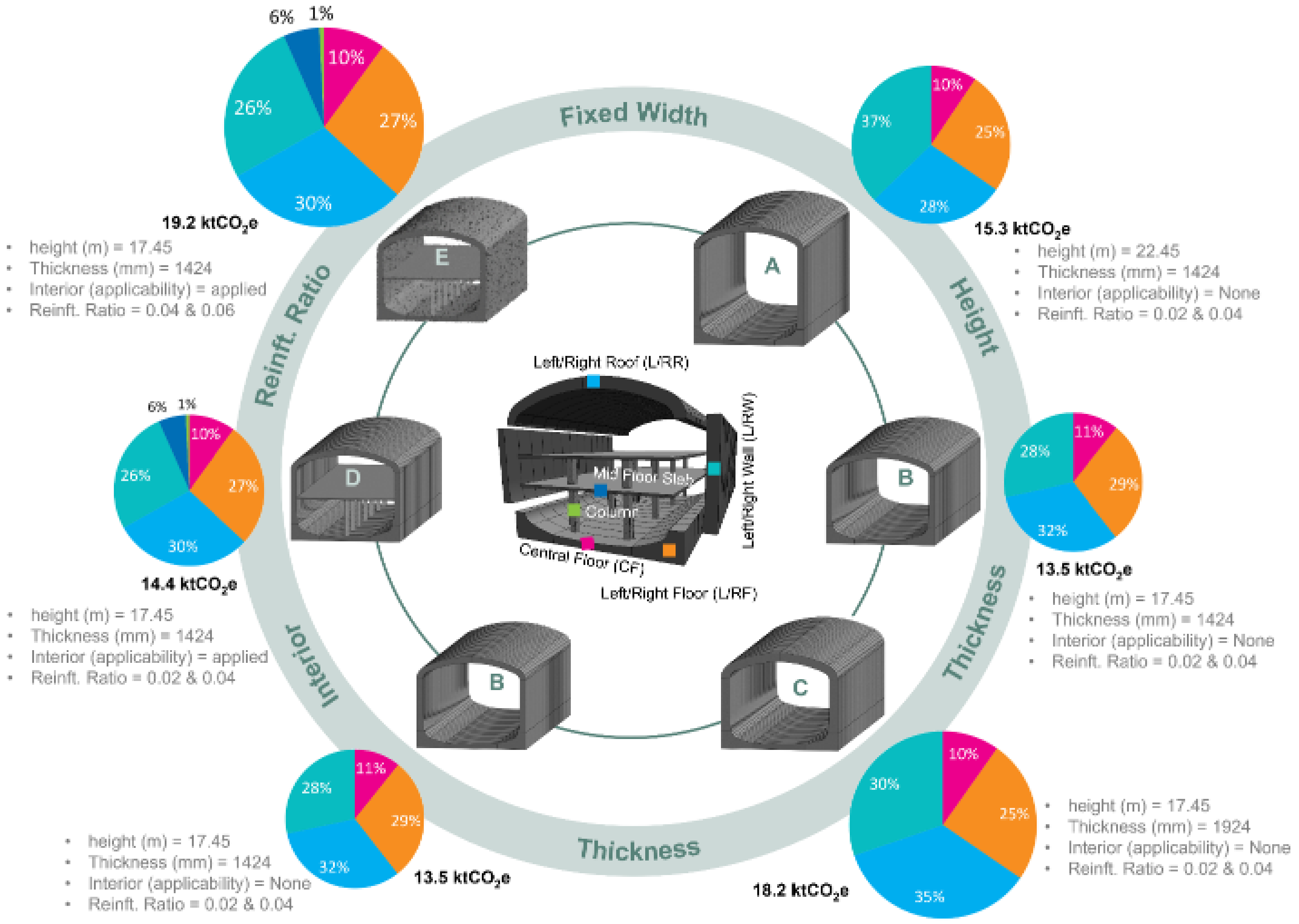
BIM & DT: Integration with numerical modelling



BIM & DT: Multi-LoD BIM for accessing carbon emission



BIM & DT: Multi-LoD BIM for accessing carbon emission



- Sustainability assessment with automatic exploration of scenarios
- Total embodied carbon and proportionate contributions by components of five parametric models

Reflection:

- What is Building Information Modeling (BIM)?
- How do BIM and Digital Twins relate to each other?
- What are the current trends in BIM and Digital Twin developments within infrastructure engineering?
- What has been your experience with using BIM?
- Reflect on how you could leverage BIM and Digital Twins to advance your future work.