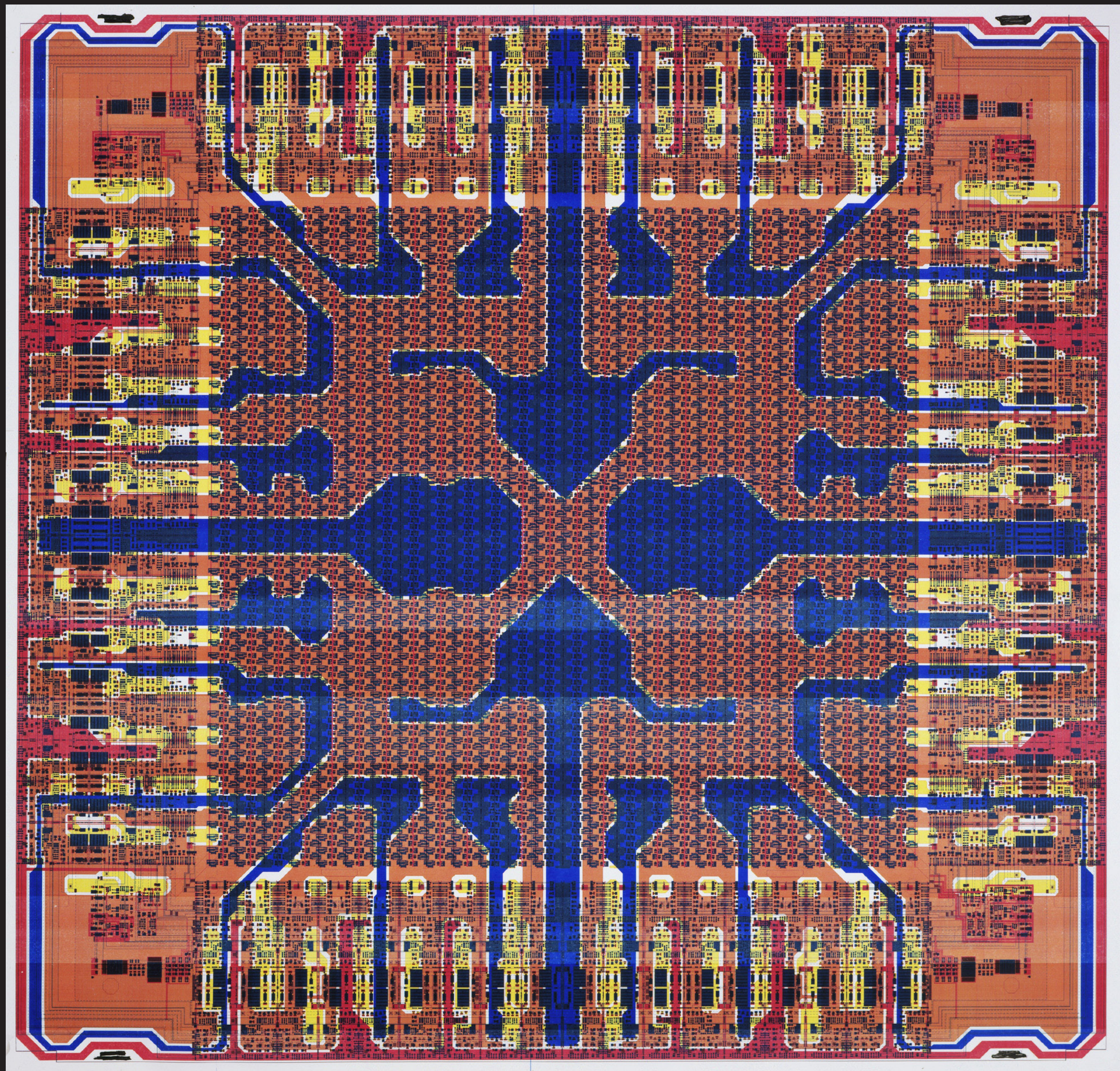
Architectural Pipeline

An experiment
into the role of
topological graphs
in the early stages of
architectural design
in the era of
machine learning

Tarique Ali



[1]

Chapter Zero

Ambivalence Relation

Architectural Intelligence in the age of AI

Why look at AI in architecture ? And why technology matters ?

Although often discussed among architects and students alike, it is not a coincidence that the field of Architecture and Construction is perceived outdated in its use of technological advancements compared to other professional fields. While architecture has become a point of departure to the argument of whether it is an art form or a public utilitarian service,[1] it is safe to go beyond these pedantic arguments to point out that neither of the two opposing sides have had the time to look at the process of producing architecture in itself. And this means ways in which architects can work smarter and not harder, each time, on every project. Meanwhile the field of artificial intelligence seems to be integrated in people's everyday lives more than ever, take for example the way your email clients are able to segregate spam from your primary mails.

This serves as a reminder that, currently, the potential of varying software skills for each individual task might not be realized unless we learn to understand and translate the process of designing itself, to a more computational way of thinking and see where a situationally fitting tool needs to exist to make the tasks simpler. Or at the least be discussed collectively by scholars, practitioners and students to see where it can best fit to solve problems that we hesitate to question in this day to day process of 'producing' architecture.

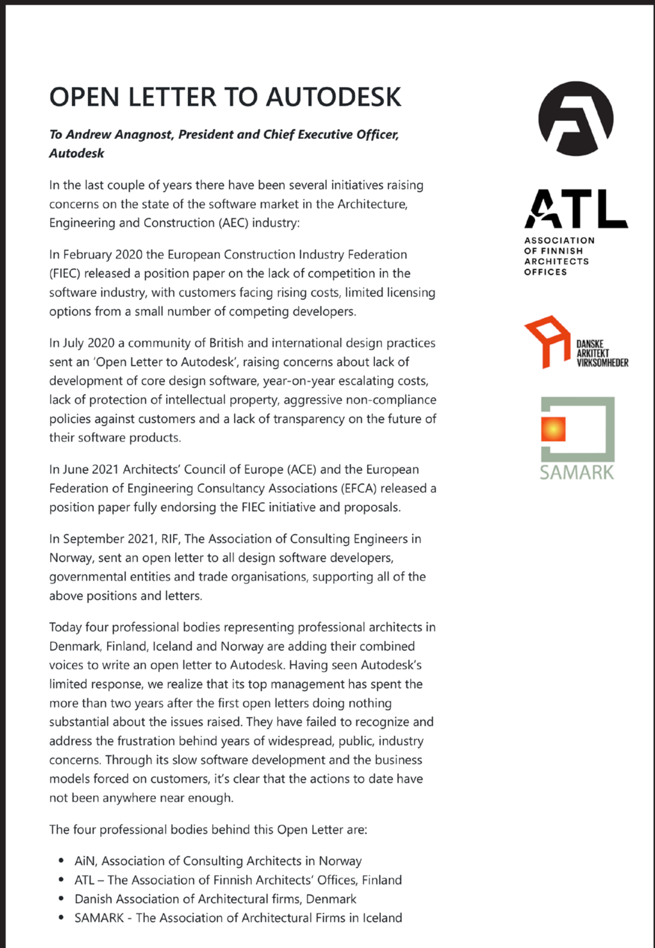
Current landscape of architectural technologies

In response to the 2022 Nordic Open letter towards Autodesk, Iain Godwin, a former senior partner at Foster + Partners, explained how graduates are not taught to think critically about technologies nor to understand the vital economic frameworks of these tools in the process followed by designers.

In its core, the 'open letter to autodesk' signed by over 300 companies and counting, specifically addressed Autodesk's BIM platform, Revit, because of its lack of innovation and shortcomings in providing the right tools to aid the workflow that the designers of this generation need; Whilst charging a hefty price which the signees would rather have spent elsewhere to fill the resulting gap in the necessary tools. This brings us to the point of needing to try and democratise the tools of designing which in turn democratises the process of designing and its heavy reliance on tools from the likes of Autodesk that looks at customer expansion over innovation and the needs of its existing userbase .[2]

1
Hosey, L. (2015, November 2). Why Architecture isn't Art (And Shouldn't be). Huffpost. *https://www.huffpost.com/entry/why-architecture-isnt-art-and-shouldnt-be_b_8447388?utm_medium=website&utm_source=archdaily.com*

2
Robledo, A. F. (2022, October 20). The Revit Open Letter Through the Lens of QWERTY-Nomics. architosh. *https://architosh.com/2022/10/the-revit-open-letter-through-the-lens-of-qwerty-nomics/2/*



OPEN LETTER TO AUTODESK

To Andrew Anagnost, President and Chief Executive Officer, Autodesk

In the last couple of years there have been several initiatives raising concerns on the state of the software market in the Architecture, Engineering and Construction (AEC) industry:

In February 2020 the European Construction Industry Federation (FIEC) released a position paper on the lack of competition in the software industry, with customers facing rising costs, limited licensing options from a small number of competing developers.

In July 2020 a community of British and international design practices sent an 'Open Letter to Autodesk', raising concerns about lack of development of core design software, year-on-year escalating costs, lack of protection of intellectual property, aggressive non-compliance policies against customers and a lack of transparency on the future of their software products.

In June 2021 Architects' Council of Europe (ACE) and the European Federation of Engineering Consultancy Associations (EFCA) released a position paper fully endorsing the FIEC initiative and proposals.

In September 2021, RIF, The Association of Consulting Engineers in Norway, sent an open letter to all design software developers, governmental entities and trade organisations, supporting all of the above positions and letters.

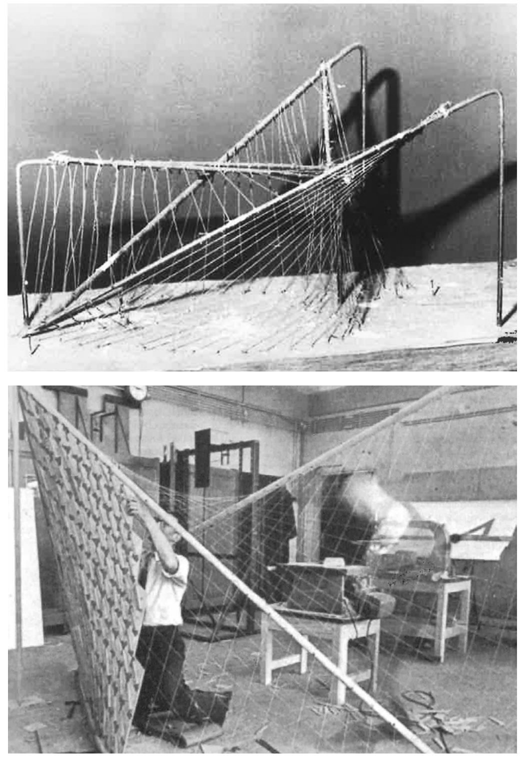
Today four professional bodies representing professional architects in Denmark, Finland, Iceland and Norway are adding their combined voices to write an open letter to Autodesk. Having seen Autodesk's limited response, we realize that its top management has spent the more than two years after the first open letters doing nothing substantial about the issues raised. They have failed to recognize and address the frustration behind years of widespread, public, industry concerns. Through its slow software development and the business models forced on customers, it's clear that the actions to date have not been anywhere near enough.

The four professional bodies behind this Open Letter are:

- AiN, Association of Consulting Architects in Norway
- ATL – The Association of Finnish Architects' Offices, Finland
- Danish Association of Architectural firms, Denmark
- SAMARK - The Association of Architectural Firms in Iceland

[A]

These democratic new tools can ideally come into play in various stages of the design process. For instance, in the early conceptual stage, Andrew Witt explains about the existence of 'scientific sourcebooks' in his article titled 'Grayboxing' in the journal 'Log 43', shows us two instances during the high modernism of the 1950s and 60s where architects would adopt both the language and forms from these scientific sourcebooks as tools for design.



[B]

Firstly, with crystallographic structures made of lattice packing and cells and secondly from complex mathematical surfaces and forms.[3] This new way of designing, relying on what one can term as blackboxes for the field of design, soon became something more tangible and interoperable between design, art and science. The ways of thinking and talking about the architectural forms were adopted from these fields, way beyond just the inspiration for the forms themselves.[4] And in later stages of design, this cross between disciplines comes into play when a quantitative assessment of the earlier qualitative decision making is required.

3
Oubrerie, J. (1999, August). Architecture before Geometry, or the Primacy of Imagination. Assemblage, 39, 94-105. *https://www.jstor.org/stable/3171261*

4
Witt, A. (2018). Grayboxing. Log, (43), 69-77. *https://www.jstor.org/stable/26588482*

This brief research is motivated by the observation that the application of artificial intelligence in architecture has been mostly limited to generating visually striking renders using diffusion models such as Midjourney.

Leading to a misconception of what it means to 'create architecture' using AI. Therefore, the goal was to explore an alternative way in which AI could be utilized in a more substantive manner by designers and architects, without the need for overtly highlighting the involvement of AI in the process.

Architects often seek inspiration from other projects of similar typologies before reaching conclusions. However, the challenge arises when attempting to

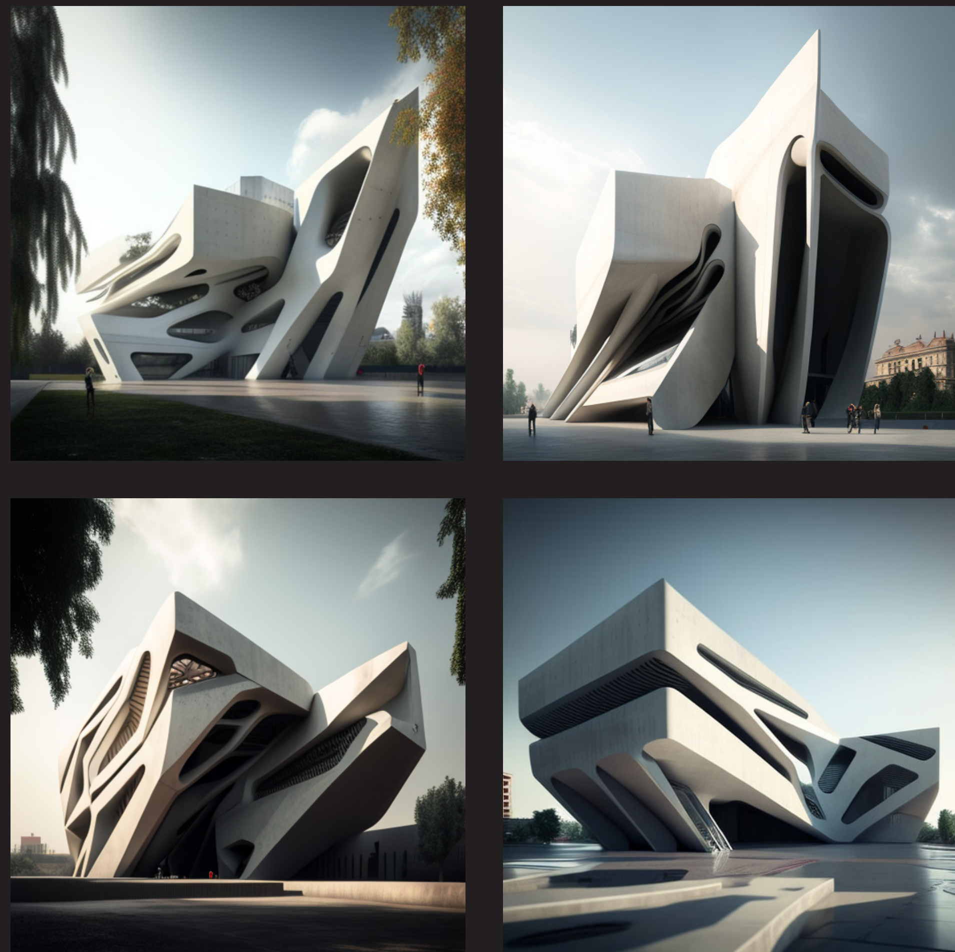
consume multiple projects,
as the sheer volume
makes it difficult to
digest their
spatial organization and
extract valuable insights
for decision-making.

This aids in becoming the point of departure for this research in looking at a way to extract information of architectural floor plans without the visual burden that they possess in their conclusive form.

[**A**]
Front page of the Nordic open letter PDF to Autodesk, as seen on *https://the-nordic-letter.com/*

[**B**]
Iannis Xenakis and Le Corbusier's Philips Pavilion for the 1958 World's Fair, utilising mathematical models as their source of inspiration for design. *Brussels, Belgium, c.1958. Photograph. Fondation Le Corbusier / ADAGP*

[**C**]
Midjourney render generated with the prompt *'design for a museum building right next to the MAXXI museum by Zaha Hadid in Rome, which features ai explaning art and architecture within its spaces, 4k'*



[**C**]

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LISTA DE PLANTAS
LEGENDA
EDIFÍCIO SEDE BANCO SAFRA – SÃO PAULO
BURLE MARX & CIA LTDA
ROBERTO BURLE MARX
PROJETO
P8

[2]

Graphical Depiction of Floorplans

Intro to graphical representation of plans

While the scope of this research is not necessarily to define what the best ‘graph’ based representation of floor plans are, it is imperative to look at the theory behind how we tend to better understand floor plans beyond their varied drawings and representational techniques. Architects primarily conceive spatial design with graphical representations such as bubble diagrams, to conceive spatial arrangements and also through architectural drawings, a more concretized form of the design; Surmising that the predecessor plays a more crucial role in dictating the eventual outcome of the design.

It is imperative though to state that the above use of the term ‘graphical representation’ was in its most basic sense of graphics as a ‘drawing’ rather than the mathematical ‘graph’ where in, objects placed in a certain structure are in some way related to one another. And more specifically in ‘graph theory’, introduced by Leonhard Euler in his resolution of the famous ‘Seven bridges of Konigsberg’ (1736),

these objects in space are represented as nodes and their relations as links between them.

Euler’s approach would then lay foundation to ‘topology’ where the object’s rigid geometry is not of concern, but rather the abstraction of the object and its relation within the space.

In topological study the objects (rooms in the case of architectural floor plans) are represented as vertices and their links (direct connectivities between the said rooms) as edges linking these vertices and the system as a whole can be referred to as topological graphs or maps.

The earliest works in decoding architecture to graphs and configurational models can be dated back through two lines of works as seen in 'Architectural Morphology' (Steadman, 1983) concerning dimensionless graphical representation of architectural drawings and in 'The Social logic of space' (Hanson and Hillier, 1984) focusing in on building genotypes and their arrangements as syntactics relations.

Steadman's work focuses on the geometrical theories behind architectural plans, wherein the focus goes beyond just the generation of the plans from configurational graphs or the aforementioned topological maps, into the attempt of creating a building science that helps architects articulate thoughts in a strategic level pre-design. On the contrary the works of Hanson and Hillier gives us the analytical possibilities of these said graphs into the realms of syntactic (or logical) arrangement of spaces and how the local interacts with the global scale.

[A]

[**A**]
Ik compound and its respective buildings and boundary representation as seen in *'The social logic of space' (pg 133, Bill Hillier & Julienne Hanson, 1984)*

Before we can formally look into how designing with an awareness of spatial configuration is advantageous, we need to define what configuration in architecture and space representation means before furthering into examples of some ways of representing the same.

Configuration can be seen as a concept conceiving the idea of a whole system over its individual element where each of the elements are interrelated to one another directly or indirectly to keep it functioning as a whole. In representing architectural configuration, we represent the spaces (or rooms) as vertices or points and the immediate connectivity between them as edges or lines. Thus the architectural configuration is a representation of spatial connectivity among two or more rooms in two-dimensional space. The connectivity is defined through the direct access of the spaces through doors, various entrances from the exterior to the interior (if needed) and any other form of gateways that would allow physical unrestrained access between the said spaces, in other terms providing permeability and adjacency respectively.

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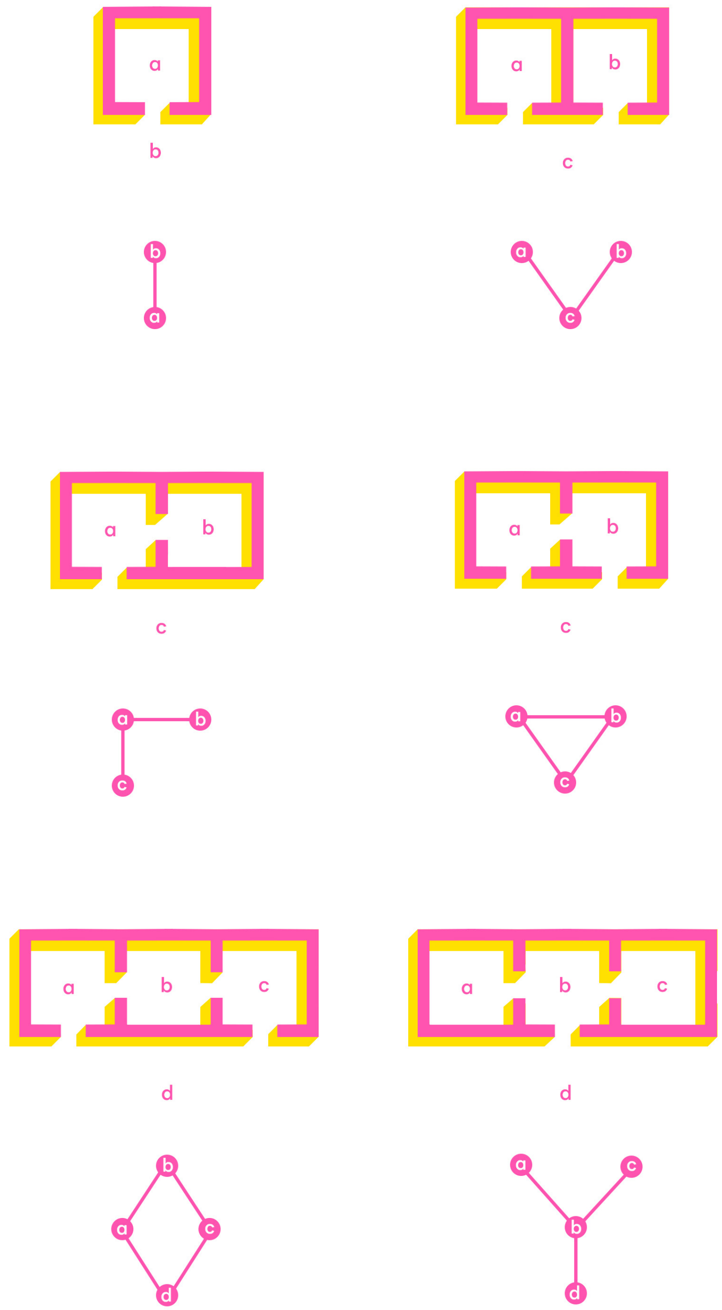
This peculiar interpretation of configuration can be easily understood from the visual on the right. When there are spatial relations between two or more spaces, a spatial configuration is said to exist when these relations can be altered in some way or another changing the way that these spaces thus interact or are approached. In architecture, these spatial relationships are shown as architectural configurational diagrams which can also be termed as bubble diagrams, very often used by architects as a first step to map out an architectural programme in regards to spatial hierarchies and other social and functional factors.

[B]



Bubble diagrams, Architect’s configurational graphs ?

There’s a certain mystery to bubble diagrams, since architects are aware of them and very much use them for their programming approach in developing a floor plan, they remain quite unseen by the majority of people involved within the project and even outsiders as they are never a part of the final deliverable. Of course one can still compare bubble diagrams to flowcharts in other scientific fields, since their primary function is to be able to understand flow of spaces.

The flow is represented using edges connecting bubbles (vertices or points) of various programmatic functions.

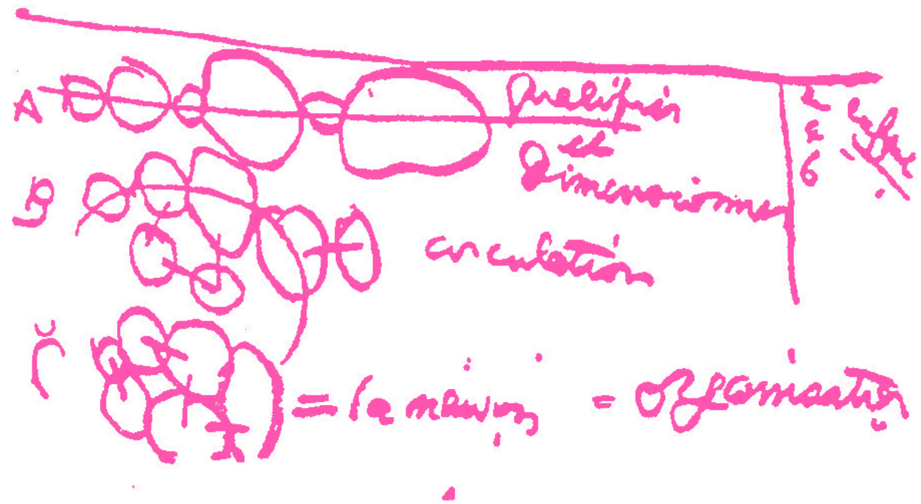
Even though the use of bubble diagrams extend far and wide, there is no particular rule as to how they are supposed to be represented. They serve the purpose of thought abstraction and have been used ever since design has been under study. They have been within the process of architectural design reference books such as the Architect’s Data by Ernst and Peter Neufert and also in ‘The Time-Saver standards, which are two widely referred books by students and architects alike.

An early example of a use case of bubble diagram can be seen from none other than Le Corbusier in his 1930 book titled,

‘Precisions on the present state of architecture and city planning’.

His diagram is shown in steps representing the spaces and their proportional sizes represented by the diameter of the bubbles arranged in a linear

[C]



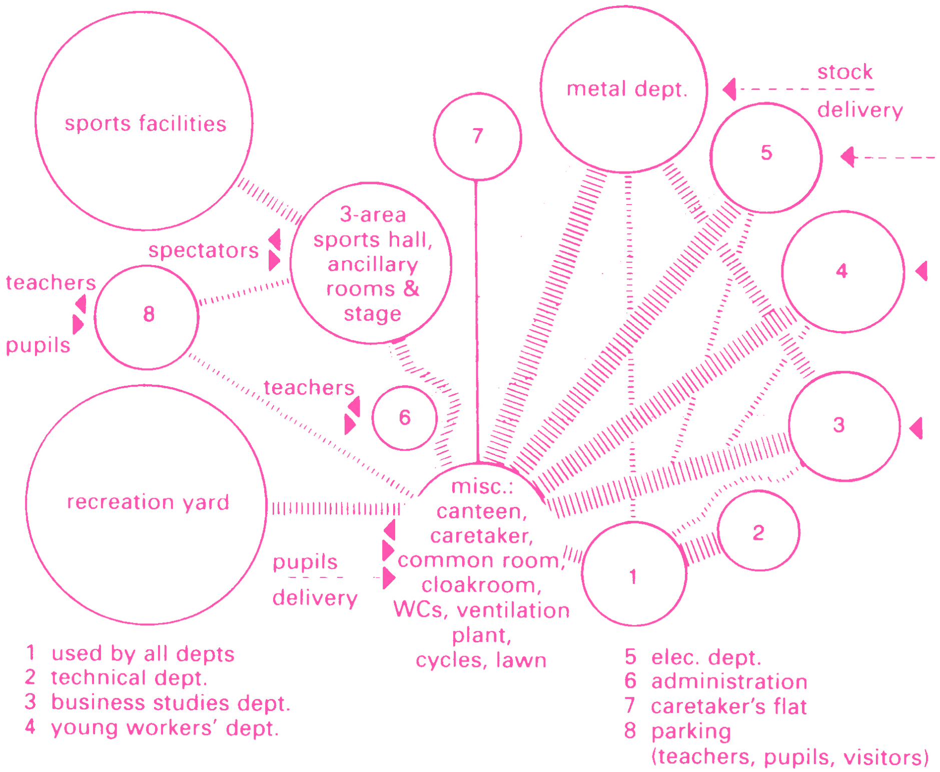
order of sequence (A) which is then organised around the necessity of circulation

(B) while placing spaces that require a direct connection through the lines between them.

And finally in (C) we notice ‘la maison’ with each space adjoining each other,

yet retaining those lines between them showing the necessary connections. (Corbusier, 1930, p.223)

[D]



Hence bubble diagrams can be termed as close to what an architectural configuration diagram can be imagined as, it cannot fall short from being termed as an annotated graph drawing with the various bubbles representing the nodes, except they vary often in size showcasing the close-to-reality area proportionately represented as the bubbles and the lines connecting them as the necessity for physical connections when concretised into the design of a floor plan.

One of the limitations to this can be seen by the absence of corridors as functional spaces, hence not being provided as a bubble. There are plausibly two explanations to this, one, where the brain is tricked into believing that the corridors are linear in nature and cannot be represented as a bubble graphically and two, the existence of the connection lines, graphically linear tends to mimic the functionality of what a corridor does, in providing the access between multiple spaces that need to share proximity to one another. But on the contrary corridors are rarely programmatically mentioned as 'spaces' unless otherwise mentioned in building typologies such as hospitals, one might consider them to be part of the untouched plane in the bubble diagram, the crevices, the negative spaces between these bubble shaped rooms.

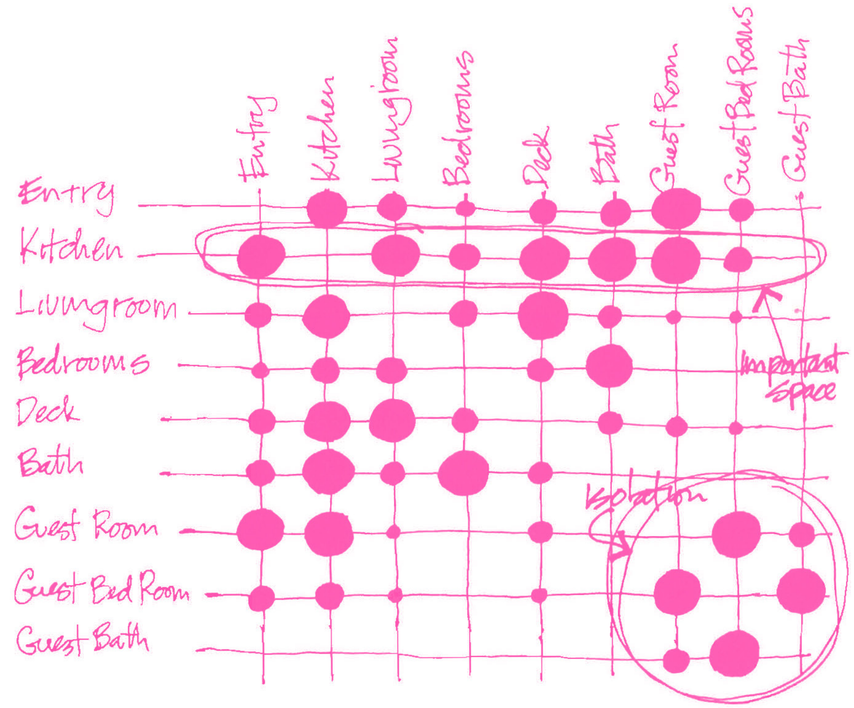
Adjacency matrix and activity relationship charts

Architects and designers tend to create a very logical mapping of rooms through somewhat of a tabular representation known as an adjacency diagram.

This is often used as
a first step of mapping
out the relationships
of spaces
and their dependencies
on a varying scale of
proximity requirement,
usually from
mandatory,
desirable,
neutral to undesirable.

But this can also be ranked by numbers or any other forms of labelling as desired. The image on the right shows an example of an adjacency matrix diagram; in a rather graphical method, one can find more rigid forms of denotation for the adjacency matrix as well.

[E]

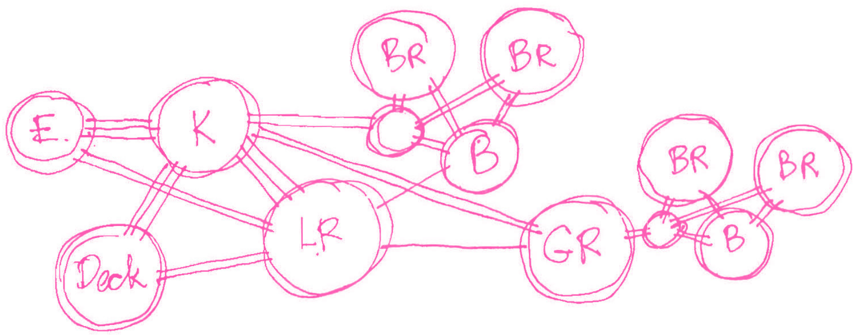


These adjacency matrices or also often mentioned as ‘activity relationship charts’ are what precedes

the bubble diagrams,
which falls into the pattern of
graphic thinking that architects
tend to adhere to
before concretizing their design.

The above adjacency matrix is translated to the following bubble diagram which is then refined to form the various steps of architectural drawings where the floorplans are refined to end up as a construction document of the building on the site.

[F]



Thus the adjacency chart can be defined as the classifying and categorizing stage of design before actually putting the program onto a graphical representation as a bubble diagram.

And while this seems like a very linear design process, this research is primarily focused on looking at the architectural DNA from the abundance of data that surrounds us as floor plan drawings.

And although adjacency matrices help us in the primary stages of design, they don't serve too much purpose when it comes to the graphical thinking of the human brain, we believe that the configurational graphs hold the power in informing us just enough from designs when a large set of similar kinds of projects are to be studied in pattern recognition or other forms of design understanding.

And before looking at
how and why we believe that
this task in hand,
of graph based representation
of floor plan drawings as
configurational graphs or
topological maps are suited
in the realm of computer vision,
it is beneficial to look at
what advantages
these graphical representations
have in the design process.

This also inevitably helps in understanding what representational technique should be used as the output.

[A]
Ik compound and its respective buildings and boundary representation as seen in 'The social logic of space' (pg 133, Bill Hillier & Julienne Hanson, 1984)

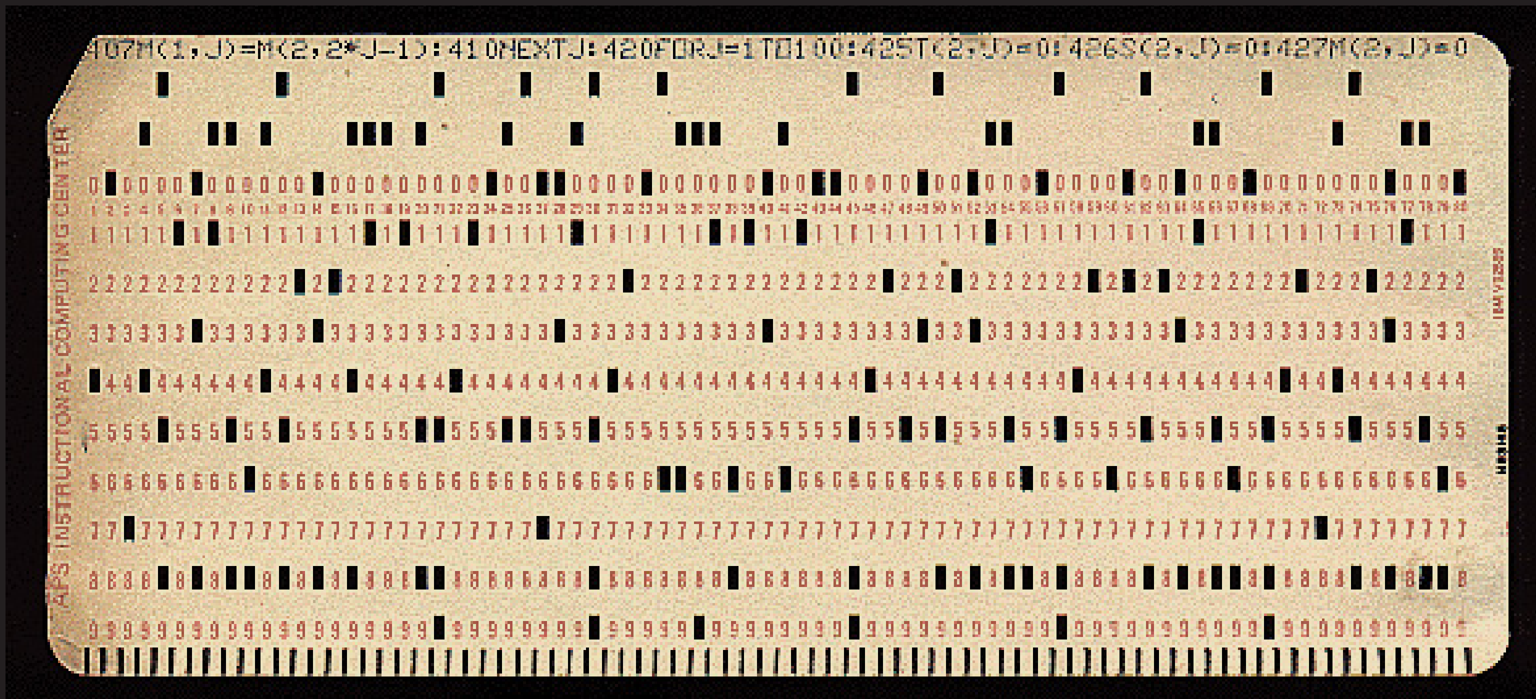
[B]
Various room layouts and their respective configurational graphs visualised

[C]
Bubble diagram from the Third edition of Ernst and Peter Neufert's Architects Data, © Ernst Neufert (Author), Peter Neufert (Author) © Wiley-Blackwell

[D]
Le Corbusier's bubble diagram from 1929 during a lecture in Buenos Aries

[E]
Adjacency matrix diagram of a house design as seen in © Paul Laseau - Graphic Thinking for architects and designers book. © Wiley

[F]
Bubble diagram of the functional relationshs as seen in © Paul Laseau - Graphic Thinking for architects and designers book. © Wiley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APS INSTRUCTIONAL COMPUTING CENTER

[3]

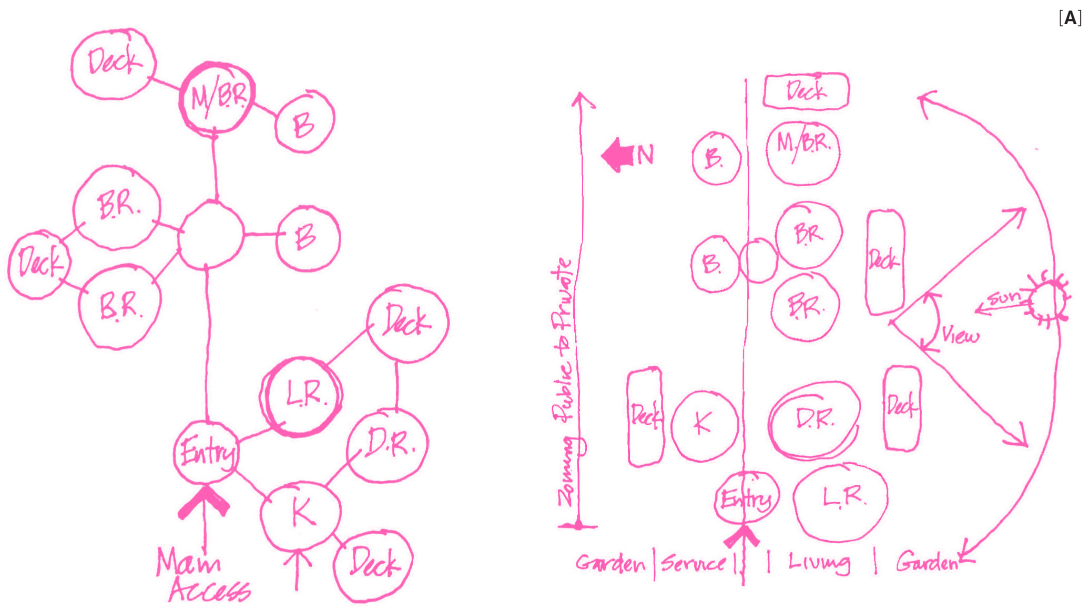
Graphical Thinking for Designing

The human brain is fascinating when it comes to idea generation. But the large majority of ideas are proven to be an iterative form of visuals and experiences from the past. The more the number of times they are run by the mill, the more refined they get. And in each individual step of the process, we subconsciously take decisions in letting go or adding in new features to the thoughts that make up the final decision.

In the above process of where the adjacency matrix and bubble diagrams were expanded upon,

we selectively decide
to leave out contextual conditions
in which these designs
are being made.
And even though these are crucial
to the way we design,
it is known that these are factors
that compliment the very
same process of design mentioned.

[A]



Site conditions and context are the added attributes while moulding the design in its bubble diagram phase.

We tend to utilise various
indicators to showcase
these factors and l
et our mind take note of
these dependencies,
as seen in the example below from Paul
Laseau's book, 'Graphic thinking for
Architects and Designers, 1980'.

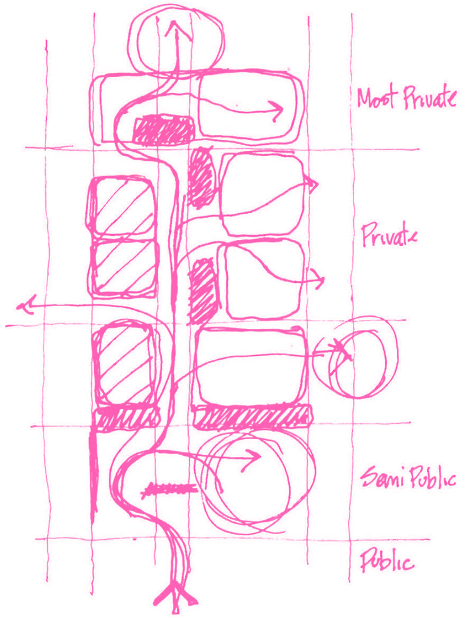
Laseau in his book notes the importance of graphic thinking and even though this does not specifically concern topological graphs, it is fair to point out

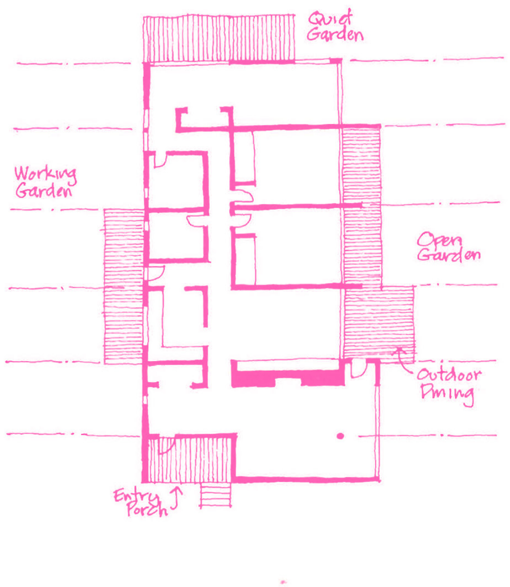
that his approach of design finalisation was an iterative process of working with rooms as bubbles on paper.

He talks about the 'perceptual image', which would segregate spaces based on their knowledgeable relationship with each other. The mental imagery inspired from the bubble diagram would lead to eventual shaping of his design as seen with the image below.

Graphic thinking
creates connections
and patterns
that we might not see just from an end
image of a floorplan,
but when given the opportunity to
make visual connections
between rooms
through a bubble diagram
or even a topological map,
we start to recognize patterns.

[B]





And when this process is iterated across the abundance of floor plan imagery available now, it can give

various hypotheses,
ideas and
decisions to utilise
for designing.

This shall be covered in the following section where we look specifically into the advantages of going from an 'image to graph' based approach towards design.

Benefits of an Image to Graph approach to Designing

In this data rich era where hypotheses and conclusions can be made on being able to sample large datasets, architecture with its main medium of representation as finished floor plans can barely be used in multiplicity to gain an overview from these drawings.

Architecture schools tend to mostly orient towards the final design presentation and architectural offices are focused on producing final working drawings towards construction. In both the scenarios we end up with a finished design with floor plans into which lots of thoughts and ideas were put in, but these thought based design decisions cannot be retrieved from just looking at the final images of the plans and are instead shown as a couple of design renders that try and make up for the lost reasoning of spatial decision making grammar with visual representation. Note that the word 'image' is used here in replacement to 'drawings' since even though architects use softwares that deal with the vector space, the final viewer always tends to receive the image based rasterized output which leads to deletion of valuable insights.

The major advantages of a vectorised floor plan over a rasterized counterpart can be in that

- they can be easily scalable in terms of information retrieval or in the ease of viewing across devices
- they tend to be editable, giving freedom to make changes and thus being further usable in other situations

– they provide options of layer management which makes working with them favourable and with a higher resolution, the details can be read with ease and precision.

[C]

An abundance of rasterized data of floor plan imagery can be found online and through architectural archives. Archdaily, for example, the most visited website for architecture having over 160 million views a year has over 49,000 architectural projects as of the time of this writing (January 2023).

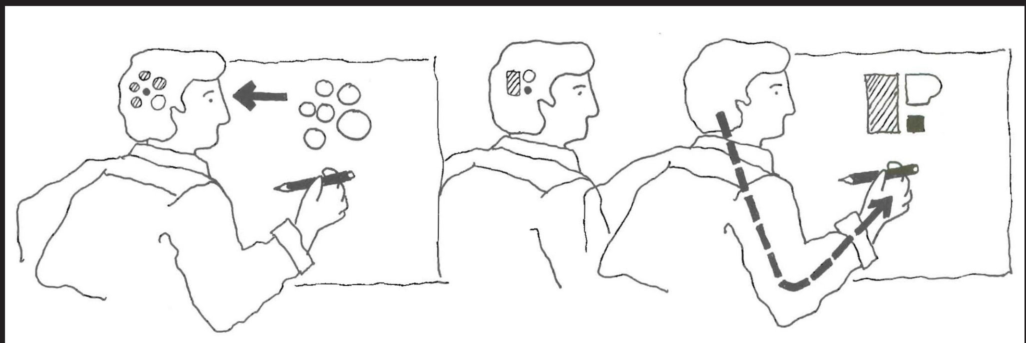
These projects are typologically separated into 12 categories and have over 129,000 images under the category of drawings.

And while they do include other graphical representations of the projects such as

site diagrams,
sections
axonometrics
renders and
details, to name a few,

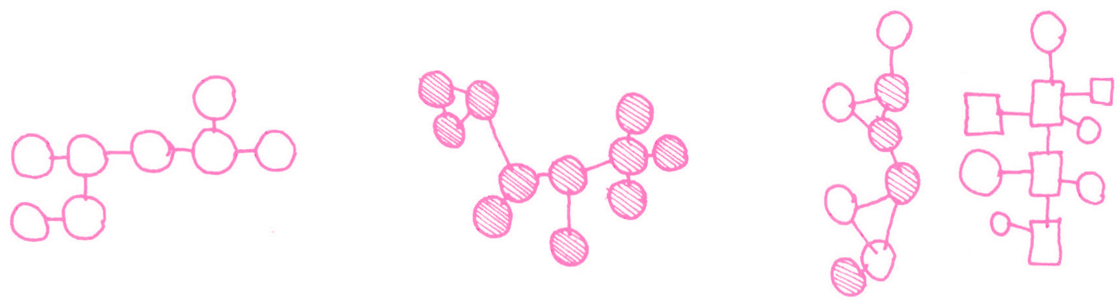
it would be safe to assume at the least 15% of them are floor plan images (~19,000+) that can provide immense information to start design tinkering and have a data back approach towards early stage design decision making.

But going into this step with a set of successfully recreated vectorised floor plans, does not imply the ease of generating visual thinking from them. It might be possible to take inspiration from a handful of them, but the quantity would still be far too low to claim design conclusions. If you were to be self informed towards a data-backed design decision, before taking a final call for your own design or to even become aware of a design hypothesis a vectorised floor plan might not suffice.



[D]

This is where we look into an alternative form of representation which was stated early in the chapter - bubble diagrams, for representing spatial configuration. These spatial diagrams in its raster form can be represented by carrying various qualities of their verbal form. These verbal forms for example as seen in Laseau (1980, p.56) can be represented graphically as diagrams showing their structural sequence based on position, the proximity of spaces and the similarity between the spaces based on common characteristics.



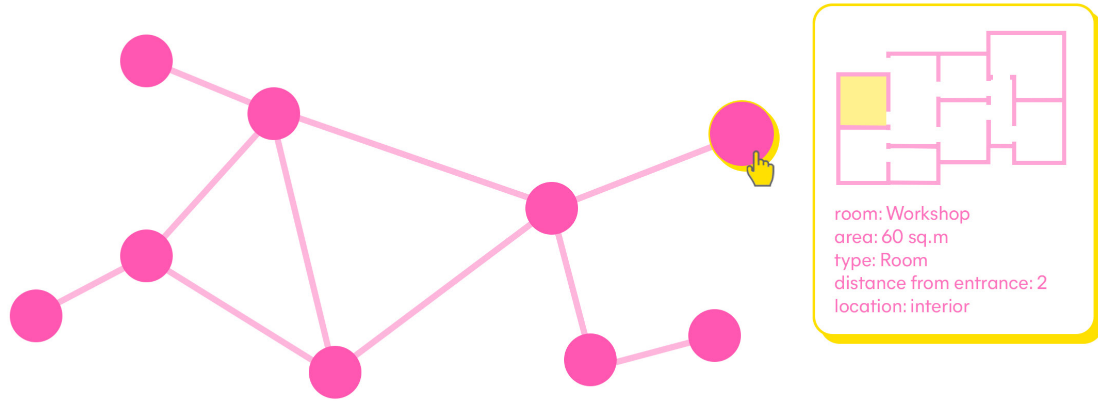
[E]

But making
the vectorized floorplan
into a rasterized
bubble diagram
will lead to deletion
of information and
require large quantities
of storage.

Meanwhile the topological map as a vector form of the configurational graph can hold all of these grammar and mathematics based information in their nodes as shown below. These nodes can also hold pixel based room data in its matrix form, meaning the room or a key plan can be stored and visualised in the node. A diagram of how it might be approached is represented below, with the node showing all the stored details that were extracted from the rasterized drawing.

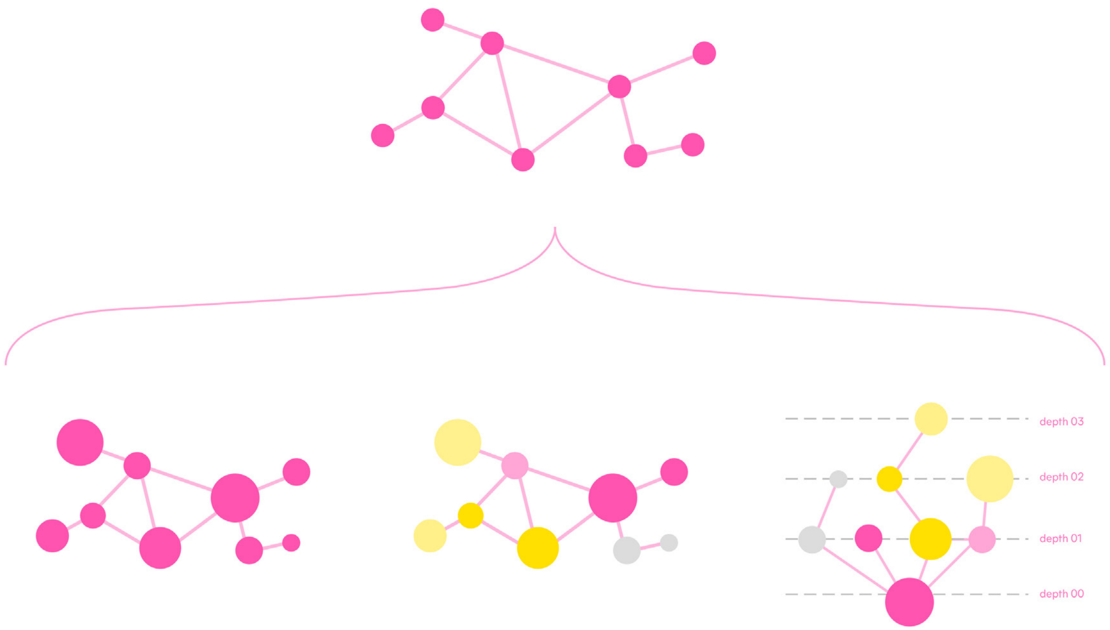
While this is beyond the scope of this particular research, it is good to note that the possibility is not limited with just the topological map as a single way of representing and can thus be visualised in some ways like the examples below.

The topological map
can possibly further
be adapted to
represent
one of those qualities embedded
within each of the nodes
when desired,
such that they make more
individual use cases,
such as room size hierarchies
or privacy estimation of certain spaces.



[F]

[G]



Our ‘ image to graph’ based approach through topological maps can thus

Help designers in simplifying large amounts of available floor plan images into their respective topological maps revealing underlying patterns common to them in the most efficient way

Quick access to a rather large set of data in a smaller scale representation that can hold all the rasterized information within the nodes making it lightweight as a format while still holding both vector and raster data.

Bringing graphical thinking of spaces within the early steps of design, where both success and failures of precedences can be looked at from the lens of the building’s topological map, thus improving design calls

Introduce more
informed design decision making
in unfamiliar
design territories or
even design typologies,
through the large availability of data.
Building types unfamiliar to one
can be studied
through a statistical lens

Help in being
able to visualise design features,
trends
and latent design patterns
that otherwise
cannot be noticed
just from floor plan images
that are widely available
(Lu et al., 2021)

Lead to a more holistic understanding of a typology within a context while not revealing a complete floor plan, which can otherwise lead to mimicry and unoriginal designs.

But beyond just the advantage of allowing designers a more configurational approach of designing, the process of image to graph brings forth a calculated creation of architectural datasets. There lacks a standardised format of architectural dataset creation which is why a graph based approach that relies on vectorisation as a first step not just helps to store data easily but also categorise them onto their building typologies.Thus commencing the creation of a more structured data storage which could be helpful in a range of various future researches.

Shortcomings in a Graph based design approach

While it can be beneficial to bring forth a more structured way of architectural data segregation as a consequence of the research and also advantageous in a way to support design decisions based on a large scale floor plan data, this configurational approach of decision making can come with its own limitations.

This approach cannot be used as a one size fits all, since architectural data are also very reliant on the context to which they lie in. A beach side house is unlikely to have the same design strategy as one that's within an apartment in a bustling city context, but still within the same country or a region. So it is important to note that it might be wise to filter out anomalies that can really sway an understanding. A few other limitations of this approach might be

In that one must
take care
to curate the outcomes
and not blatantly
replicate a graph,
otherwise this could lead to
uninspiring designs.

Where the programmatic understanding of a building is lost in understanding since the primary focus is drawn towards privacy and depth of the maps, in essence giving us the 'feel' for how complicated or how uncomplicated a design is.

Over-simplification
of the design approach.
If topological maps
become the only thing to rely upon,
it can lead to overlooking
complexities such as
vertical connectivities and
programmatic arrangement
that take into account these connections
towards the design.

Graph stage design can be somewhat limited in its ability to be shared and its intentions conveyed since it is not necessarily looked at in the same way by everyone. While this can be a drawback, this also makes this graphical approach towards design rather interesting.

While we shall look at the methodology and the workflow proposed to utilise this image to graph based model in the following chapter it is thus important to note that this graphical approach acts as a means to study design and can still become a strong partner in design as an abstraction tool as long as it is not considered to be a rigid set of rules.

It can become an efficient way to understand building types and/or their context along with their suggestive functional requirements. This in no manner is meant to dictate the design solution especially when it's quintessential to question the cultural, social and environmental aspects of the design challenges in a project. And thus is meant to be used as a point of departure rather than a perfect solution.

[**A**]
The left shows the bubble diagram and the right with the added in site attributes concerning solar paths, zoning/ privacy, entry and service conditions. (Paul Laseus, 1980, p.84

[**B**]
The left shows the varying scale and shapes of the spaces taking before the (right) final floor plan is concretised as the design. (Paul Laseus, 1980, p.85)

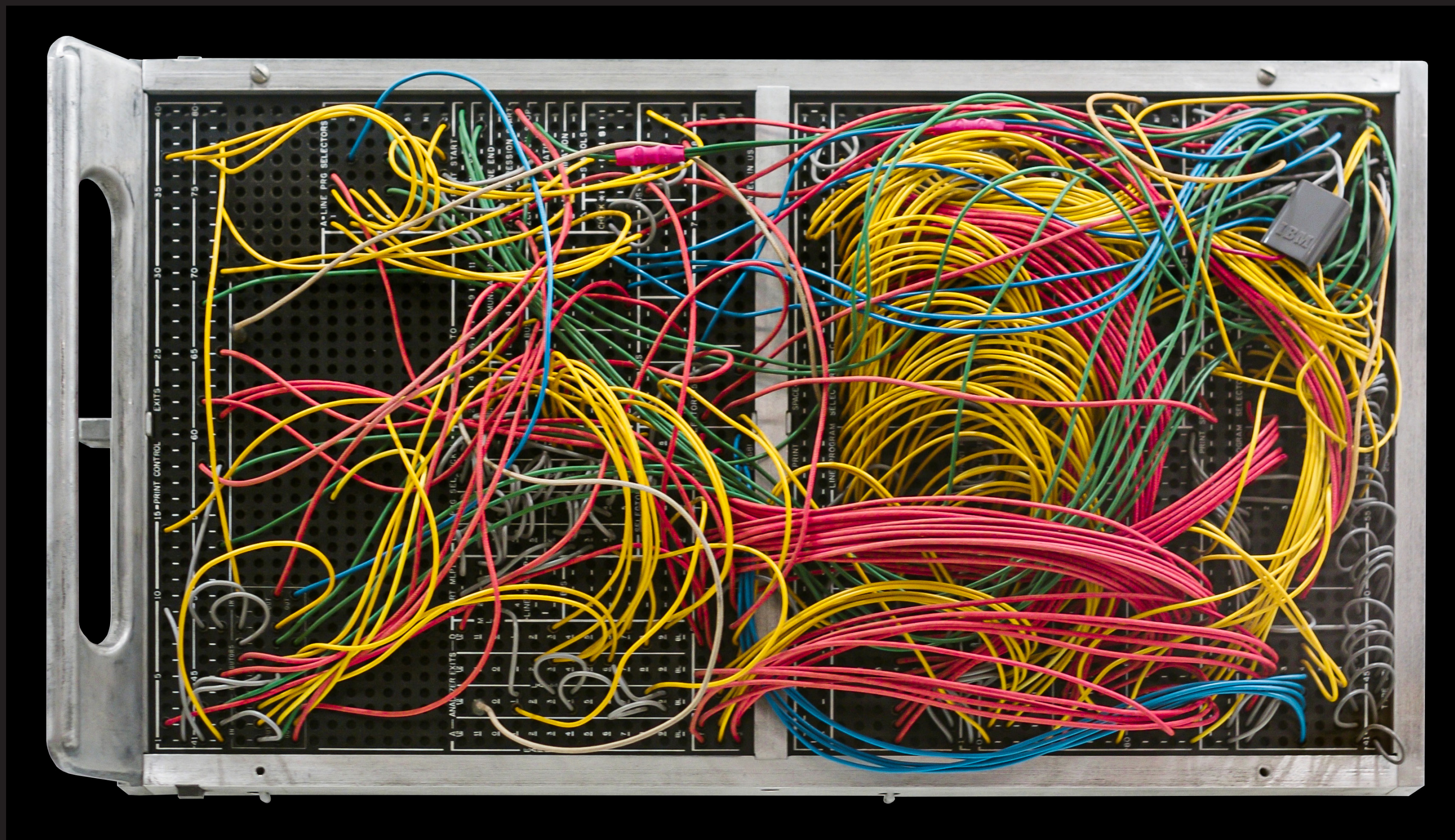
[**C**]
Results under the 'Drawing' category of images under projects on Archdaily

[**D**]
The left shows the varying scale and shapes of the spaces taking before the (right) final floor plan is concretised as the design. (Paul Laseus, 1980, p8)

[**E**]
From left to right: Remaking the bubble diagram based on position of spaces, by proximity and by the similarity of the spaces

[**F**]
A topological map of a university faculty with the nodes having embedded information

[**G**]
Topological map represented as their alternate graphical forms from the information stored in the nodes. From left to right: Map integrated with their relative areas, the same segmented with the program and the justified graph representing depth from a certain program



[4]

The core to the methodology suggested lies in the ability for a designer to use graphical thinking towards their own benefits as a starting point for their design.Since last chapter covered what bubble diagrams and topological maps were, it is crucial through this methodology to learn the process in which existing raster images of floor plans can be converted to their respective topological maps.

And while this still remains to be a domain explored by a wider few, which are going to be referenced in the chapters to come, it is yet not possible to have this functioning as a foolproof method for any kind of floor plan images. There seems to be quite a few bottlenecks while trying to come up with an efficient solution to the problem that will be documented at the end .

The methodology is a culmination of what was proposed through early works of Raster to vectorisation of floor plan images (Liu et al., 2017) alongside the designing through spatial analysis using graphical representation ((Hanson & Hillier, 1984). The comprehensive system encompasses a 3 step methodology

Image to Graph- design methodology

Firstly, rasterized floor plan images
are sourced from various online
and offline resources
as required as input,
where a certain building type from a specific context
is collected

Secondly, these floor plans
are segmented
in order to create their vector drawings,

which allows for all the necessary data points that need to be stored in the final step. And finally, third where the vectorised floor plan is utilised to generate the topological maps, with nodes and edges, where the nodes represent the rooms and hold their attributed data and the edges show the direct connectivity of adjacent rooms.

These topological maps can then be utilised in various ways

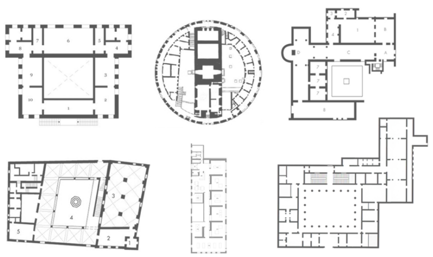
either as a tool,
where the designer
is allowed to borrow
spatial programs
from the input raster images
and attributes
that they deemed relevant
for their own design assignment.

Otherwise, the various topological maps as output can also be studied to look at context and trends within a building type and to analyse common patterns.

With the purpose of this method, the research proposes a strategic level application rather than a means to an end for designing.

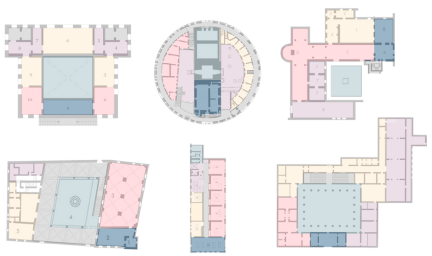
immutable form — malleable form

Raster floor plan images



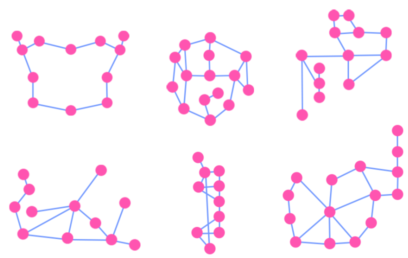
Creating/accessing a data-set of floor plan images of a similar building type

Vectorisation of floor plans



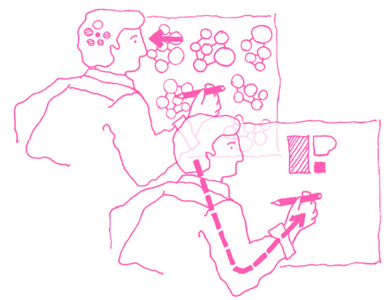
Vectorisation of the raster images of the plans with space recognition

Generation of topological maps



Respective topological maps of the images extract-ed from its vector format

Analysis and design decision making



Respective topological maps of the images extract-ed from its vector format

[A]

The above methodology can be further expanded expanded as the following workflow when a user wishes to approach this machine learning based image to graph model for their early stage design decision making.

1.
Data collection;
Collect and generate
a dataset
of raster images of floor plans
from a varying set
of available data.
This dataset might contain various sources, not limited to online archives, physical archives, scans, blueprints and imagery of plans.

2.
Image segmentation;
Similar to
Raster to vector approach
(Liu et al., 2017),
these images could
either utilise
Integer programming (IP)
alongside
a Convolutional Neural Network (CNN)
where low-level
geometric and
semantic information
are utilised
in creating the segmentation map
or through the framework suggested in Cubicasa5k (Kalervo et al., 2019) to generate the post processed diagram

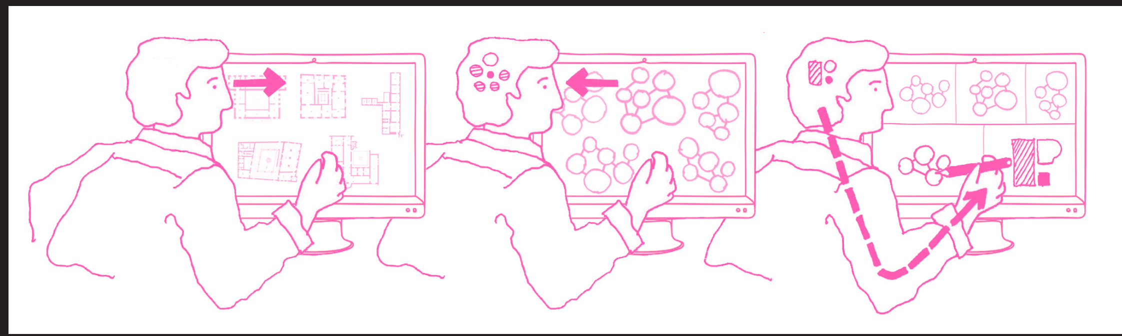
3.
Vectorisation;
This is rather the
intermediate output step
where the rasterized floor plan
is now available
in its vector format,
which could have its own applications in other researches utilising the attributes available due to vectorisation.

4.
Graph generation;
An algorithm similar to
CubiGraph5k ((Lu et al., 2021)
is then applied to
machine-parse
the floor plan data and
generate a graphical representation
or any other compatible
representation thereafter.

5.
Analysis;
The resultant graphs can then be viewed in a preferable format, for example, either with room areas proportionately representing the node sizes in the map, or as a justified graph showing floor plan depth, a colour coded graph for different programmable spaces on the plans, or their adjacency matrix or even the room's rasterized image stored in the node that represents it.

6.
Designing;
Utilising the insights from the analyses, informed decision making can either be made in the form of a design tool or can be used to generate early stage bubble diagrams or sketches for the designer's own assignment.

7.
Experimenting and further;
The design can then be iterated within an user interface, beyond the scope of this research, which can help designers make live changes to the topological map which could consecutively display the resultant floor plan with the likes of furnitures and services, making it truly a parametric model.



[B]

[A]
Image to graph methodology described in the broad steps of data collection, vectorisation, to graph extraction to analysis and designing

[B]
The Image to graph methodology in modification of Laseau's sketch, from left to right: gathering necessary floor plan images, individually or from a dataset, extraction of topological maps and finally using them towards designing

State of the art models of raster to vector(isation)

The research niche of vectorisation of raster images has had a fair share of academic focus for quite some time and while a lot of them do pertain to floor plan images, they are not very diverse when it comes to their recognition category, either of the image style or the architecture typology.

As you will note from the examples of works shown below, the two of the most effective state of the art open sourced research still have a lot to go, when it comes to reliability and efficiency. Nonetheless, they manage to initiate the process of vectorisation which is the primary step and a prerequisite to proceed further

Related works

01. Cubicasa5k (Kalervo et al., 2019)

The Cubicasa5k is one of the most complete datasets and research when it comes to floor plan parsing, it provides 5K floor plans along with 80 annotation categories to work with, the simple drawback is in its ability towards detection and limitation towards only residential plans. The detection seems to be rather ineffective when the floorplans have curved walls or even walls sitting on an angle in the plan. The other drawback of this is also in that it was trained with only images of residential floor plans, which makes its usage restricted.

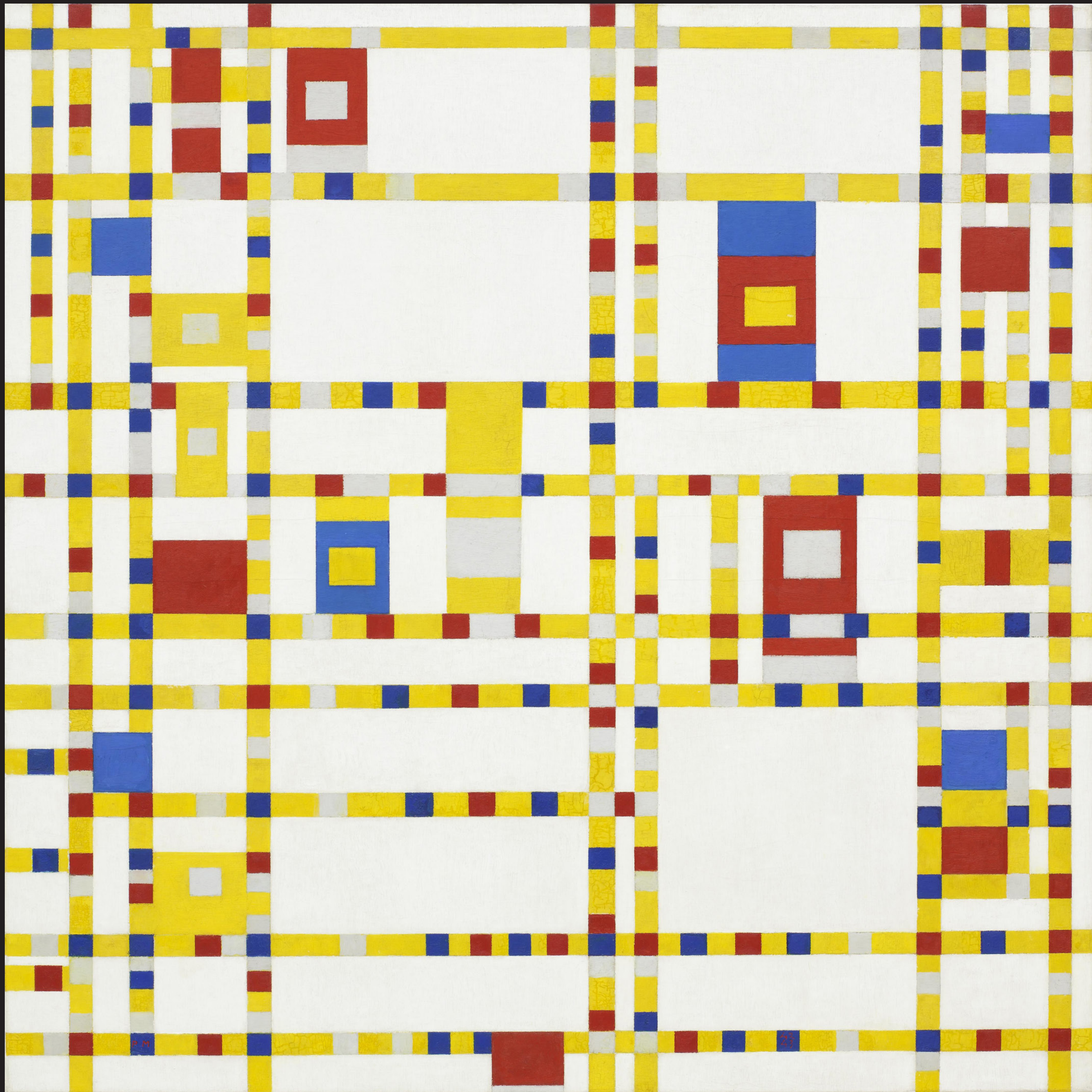
The research CubiGraph 5k (Lu et al., 2021) which focused on extraction of the graph of adjacency along with other representational forms relied on the CubiCasa5k dataset due to its availability of the SVG data, make the subsequent research limited in its approach even though it laid ground on a way to tackle the image to graph problem posed.

02. Robust Attributed Adjacency Graph Extraction with floorplan images (Chen & Stouffs, 2022)

This paper and open sourced research takes into account precisely the points mentioned above that every previous research had lacked. The research takes ensemble learning schemes into account of the state of the art segmentation models and manages to extract the attributed adjacency graph from the vectorised segmentation as a simple and multi-attributed adjacency graph.

They manage to juxtapose both semantic and instance segmentation utilising the walls, doors, windows and stairs separately and utilise the online architectural database, Archdaily to run it on, which at the time housed over 17,000 drawings of floor plans. This opens up the possibilities of variation in drawing styles but also the category of the buildings.

Both these models have been tested in the next chapter to see how the results would compare to a topological map extraction by an individual on the same floor plans.



To understand, verify and figure the shortcomings of the methodology proposed in Chapter Three, it was necessary to try and implement the workflow towards extracting the topological maps from the floorplans in a scenario other than residential floor plan images.

For this, we combined the research with the early stages of design conceptualisation for a task in hand to design the extension of the MAXXI museum in Rome, a building that would house a centre for experimentation linked to the relationship between AI with Art, architecture and urban regeneration alongside spaces for archival storage of contemporary arts and educational facilities.

MAXXI, the National Museum of 21st century Art, designed by Zaha Hadid was opened to the public in 2010. This sits as one of the very few contemporary architecture that can be seen within the urban fabric of Rome. While the style of building can be termed as abstract, it clearly resonates with its larger urban context when studied closely. Its fluid form is an extension of the flows of the streets it connects together. The height respects the older barracks from the war period it replaced and merges modern architecture with the neoclassicism of Rome.

Experiment

To have to design the extension of MAXXI we decided to approach the research methodology where early design decisions would be made learning from the distant features of not just the MAXXI museum it would sit next to, but also 39 other Italian museums set within such urban context from varying time periods across different cities.

This workflow will open opportunities to look at museum design through the lens of cultural contextuality; Through understanding these 40 museums on not just how they have been programmatically arranged but also how the design methodology changed over time or any other latent features from the varying time periods within the context of Italy.

The following sections will elaborate on the steps involved in the workflow, the challenges and their bottlenecks as well as the two state of the art models were referred to from the previous chapter.

1. The Design brief

To begin an architectural project, the first step is to determine the programmatic understanding of the building to be designed. The design brief is usually self sufficient in conveying the spatial requirements of the building since programs and their respective areas required (for the most) are mentioned.

And while the design brief encapsulates an understanding of what spaces are supposed to be related and in close proximity, it might not necessarily give the designer an idea of an expected step by step hierarchy of spaces.

Infrequently design briefs also miss out on mentioning exactly how much space different programs need and expect the designers to figure that out, in regards to the space required and their inter-relationship. While in our case, the design brief mention the following requirements for the spaces:

Storage - 1600 m2
Laboratories - 800 m2
Classrooms - 3360 m2
Circulations and services - 30% of the total area

And while the areas are made explicit, there is very little detail with regards to how exactly the labs need to be connected with the storage and classrooms and in turn their respective relationships.

In this step of absence of programmatic knowledge on how spaces need to interact with each other and in what ways, these are the main step architects take to further their understanding of the said spaces:

Research and analysis;
they conduct research
on the specific programs
from projects similar
to their building,
either by looking up archives
or online databases;
they also tend to look up design standards and codes or regulations surrounding building design and site context.

Programmatic sketches;
This step involves graphical thinking,
where bubble diagrams
of the programs are laid down
in a written

or digital format and connections between them are sought after and studied, again with case studies and examples, either of a whole building of the same typology or buildings that have shared concepts of the programmatic requirements and through

Conceptual diagrams;
where ideation of spaces
is experimented
with a design concept
with an outside-in approach
of form dictates functions,
while this is not necessarily always true,
design conceptualising is seen as a
trial and error process
to make the design requirements
work with each other.

Conceptualising is similar to design prototyping and should ideally be done as a step subsequent step of bubble-diagramming.

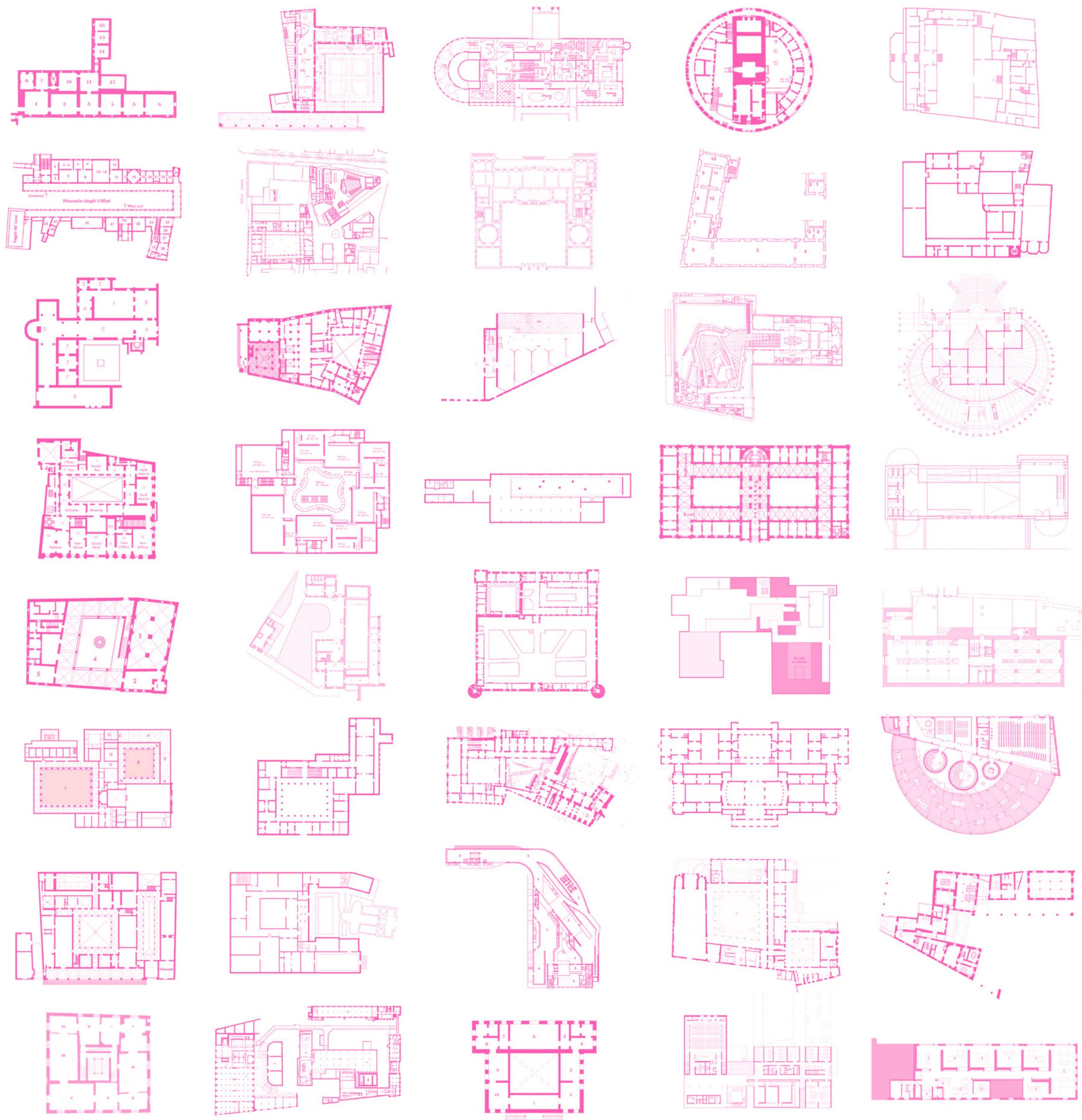
And while there is no one size fits all, we chose to conduct our research and analysis over a larger sample size not just to fit the context of this research methodology, but for the sheer inquisitiveness of museum design in a context we are unaware of designing for.

2. Data Collection

The floor plans images organised as an architectural dataset are scarce, especially when it comes to any other building typology other than residential buildings, since most researchers seem to use residential plan as their base to test out their research hypotheses involving architectural drawings, while a fair handful amount of datasets exists, it is hard to find relevant floor plan images of museums that can be used in this case. We thus rely on various online platforms to create our own dataset of museums.

These museum floor plan images
are curated
based on their location,
in that they are all based in Italy and have a program similar to the brief and lie within a context that is comparable to that of the design to be made.

In table1, you will find information pertaining to all these museums, from what they mainly host, to when they were built and the links to their respective floor plans online.



[A]

3. Image segmentation And vectorisation

For this step we referred to the two existing state of the art open source models as referred to earlier in the related works.

From the image below you will be able to notice the inconsistencies within the image segmentation process.

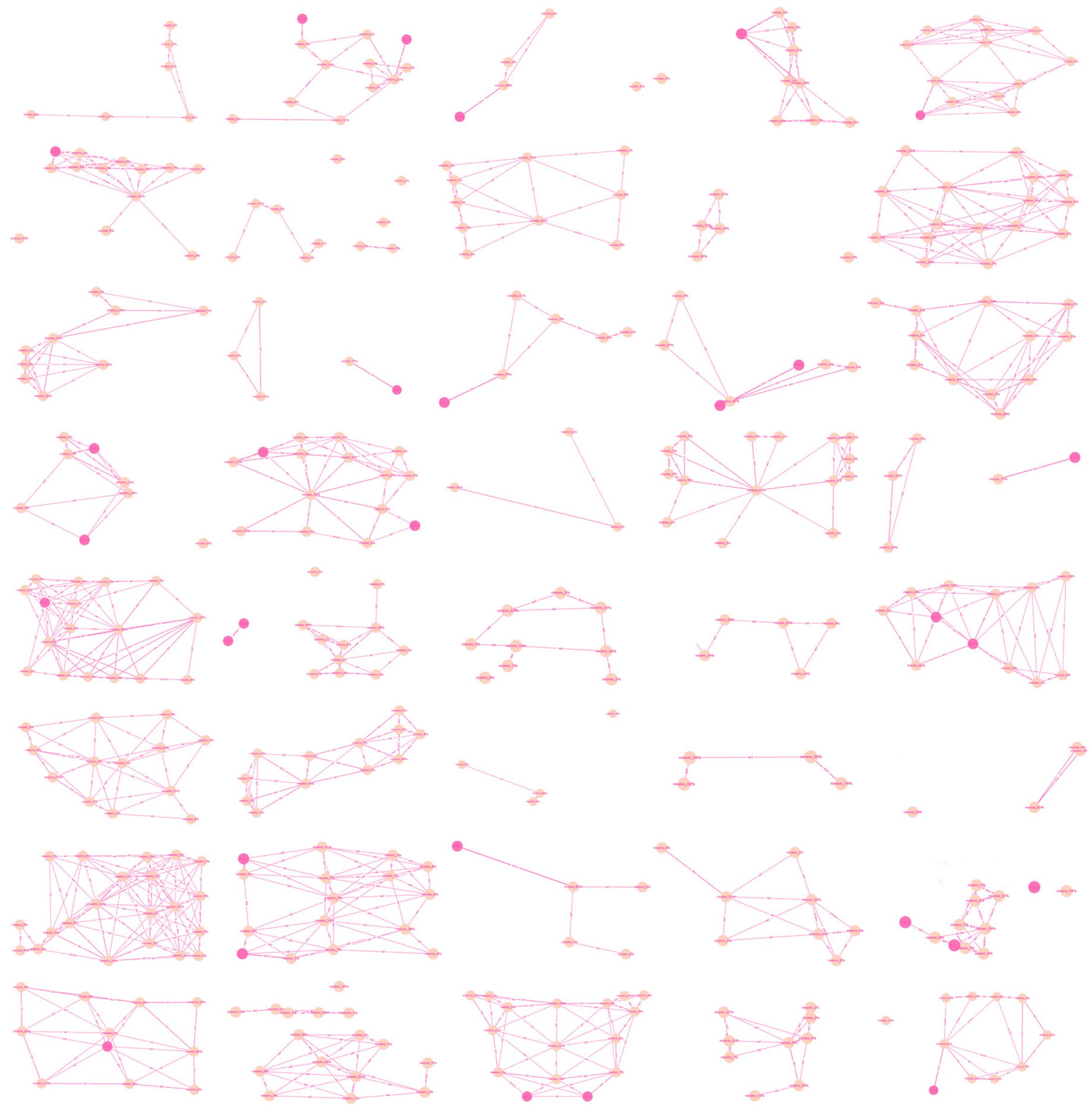
In this scenario with
museum floor plans
it was seen that
more of the older repurposed buildings
that did not separate
gallery spaces as detached rooms
with doors
and having thick walls
would lead to erratic unreliable room detection results. The outputs shown here from 'robust AAG' (Chen & Stouffs, 2022) still delivered impressive results over Cubicasa5k standalone.

[B]

4. Topological map extraction

From the vectorized segmentation maps of the rooms seen above the attributed adjacency graph, aka. the bubble diagrams are extracted using the robust AAG algorithm that can be seen here.

The graphs are the simplistic form of the topological map, removing the likes of the doors and stairs from the graph, which is seen to complicate them with the additon of excess edges between the nodes



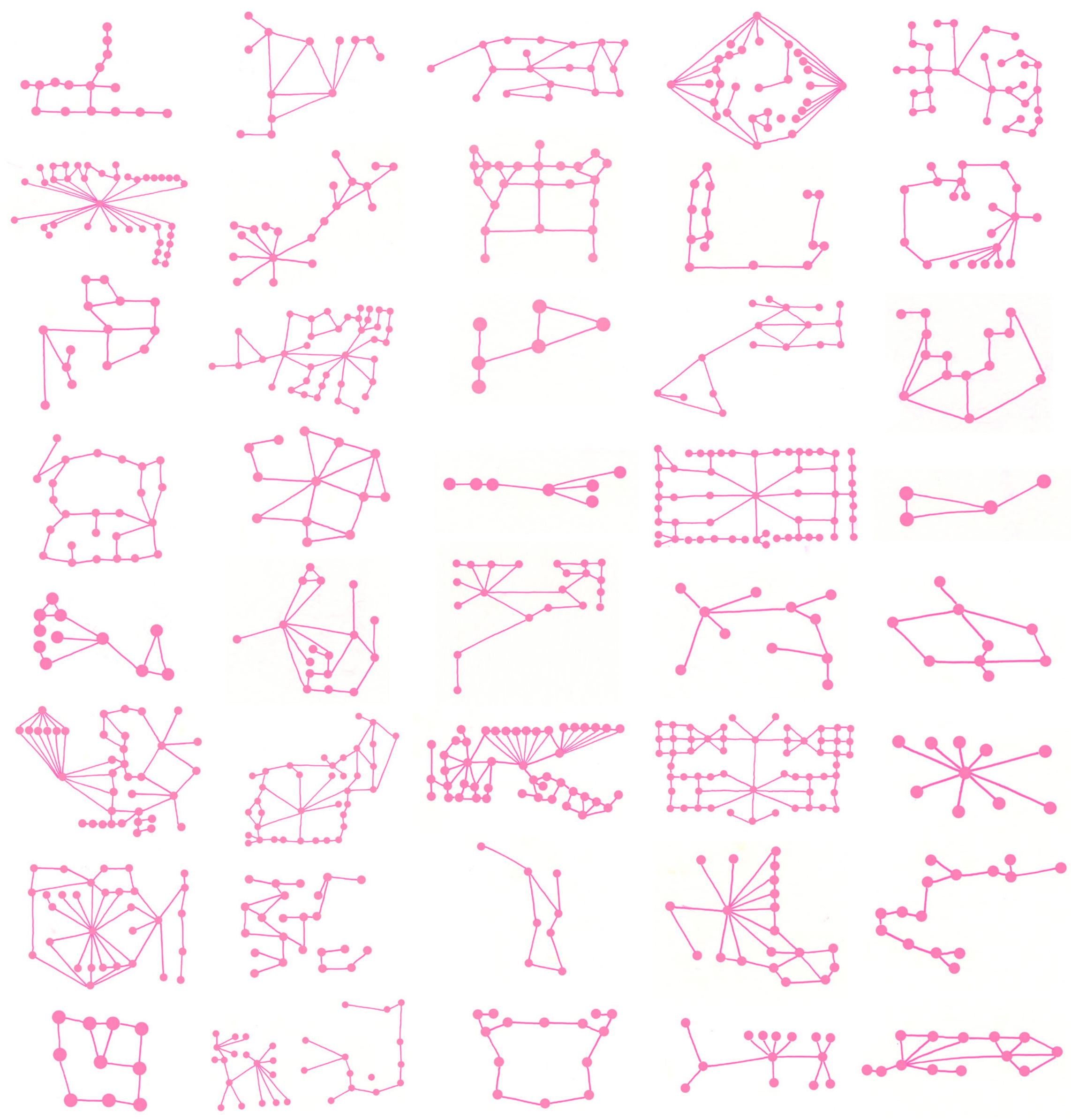
[C]

5. Comparison to Designer's perception

The same plans
were also drawn down
to their topological maps
by hand and
a human designer's experience
of the architectural space
within these
museum drawings.

The difference between the maps can be easily noticed, while being able to deduce that more recent plans and especially the ones acquired from archdaily seem to produce topological maps closer to the ones generated by the algorithm.

The plans that were not the most usual replica of the typical architectural blueprints did not have the right denotation towards semantics of a door, window or stair, making them more susceptible to incorrect readings.



[D]

6. Findings and shortcomings

Thus going from the current state of the art model to an architect's existing knowledge towards the same task, it's easier to establish a definitive list of where the shortcomings in the process have been for the machine learning task to make the tasks more efficient and robust for subsequent models and algorithms to come.

Below is a narrowed down observational findings of the bottlenecks in the process of automating the image to graph methodology:

Image resolution:

Since we tested out the algorithms with various images of projects from online databases, it was noticed that images were sometimes as small as 300x300, which would produce irrational detection results.

This was solved by either scaling it up on external applications like Adobe Photoshop, or let the algorithm scale it up pre-segmentation.

Boundary perception:

Since the models were trained in understanding room edges based on doors, windows and complete wall separations, any time two rooms were separated by just an opening or an archway, it failed to detect them as two separate rooms.

While in the case of a museum, it can be agreed that this is not the most simplistic task, even for a human, compared to a residential floor plan that tends to have simplified definite spaces.

Museums often have subsequent rooms without physical doors and can often tend to just continue as gallery spaces with a wall separation.
Human perception can make a judicial judgement in this case, since we know the two rooms in plan serve purposes of different display of works for example, hence describing them as two separate rooms, which the machine cannot correlate to just yet.

Line width recognition:

It was observed that
the algorithms
would fail
to identify the line widths and
their indicative purposes
on architectural drawings,

often architecture drawings will have single line indicators of the context around or details from floors below, providing a larger sense of plan readability. The algorithm in these cases seem to think of these grayed-out narrow lines as representative of rooms, that don't exist on the same floor.

Speed of detection:

The algorithm (Chen & Stouffs, 2022) manages to come closest to what the research's methodology sought.

But the biggest bottle neck to this approach was using the ensemble learning scheme utilising datasets of multiple state of the art models making it very GPU intensive.

The outputs utilising Google's Colaboratory platform (https://colab.research.google.com/) still required between 30 seconds and upwards up to about 5 minutes for each plan segmentation to adjacency graph plotting, depending on the complexity of the floorplan or in some cases, detecting things incorrectly.

[A]
Fig: the Image to graph methodology in modification of Laseau's sketch, from left to right: gathering necessary floor plan images, individually or from a dataset, extraction of topological maps and finally using them towards designing

[B]
The room segmentation denoted with varying colours within the floor plan. Quite a few of the rooms remain undetected or are wrongly detected with the outside surrounding being considered as a room

[C]
The attributed adjacency graphs extracted from the vectorised segmentation maps from Robust-AAG

[D]
The attributed adjacency graphs drawn by hand by the author

Design attributes and takeaways

And while the machine learning generated graphs cannot be fully reliable in this scenario, the room segmentation maps turned out to be rather helpful in this case, as mentioned earlier in chapter two,

a node in
a topological map
needs to
contain information
whenever it needs a keen eye,
away from high level design information
and analysis.

This is where the floorplans turning into their room segmentation maps with varying colours seem to play an important role for graphical thinking towards design decision making.

So there was a certain level of loss of visual information from the semantic maps to the topological maps that seem to be crucial while referring to spread of program on a floorplan.

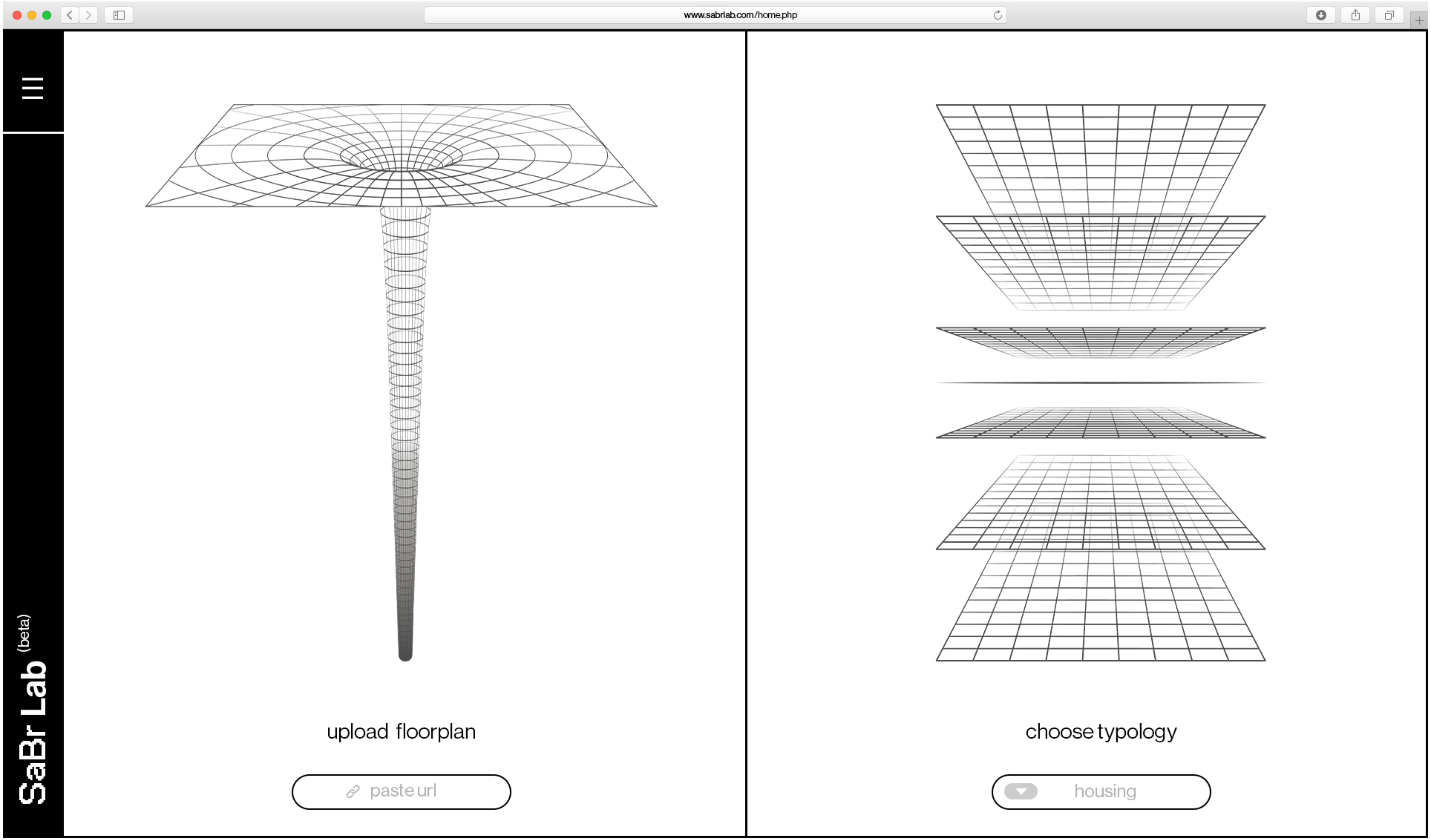
High level analysis towards the graphs denote the highly multimodal separation within the plans. A majority, 62.5% of the floor plans indicate the presence of a courtyard within the design, which surprisingly manoeuvres away from the idea of a singular node of approach of the structures. A closer look at the graphs indicate that while these courtyards act as central structures to the rooms around them, they still tend to have two other dictating nodes that guide the spaces around them, making them a very bimodal form.

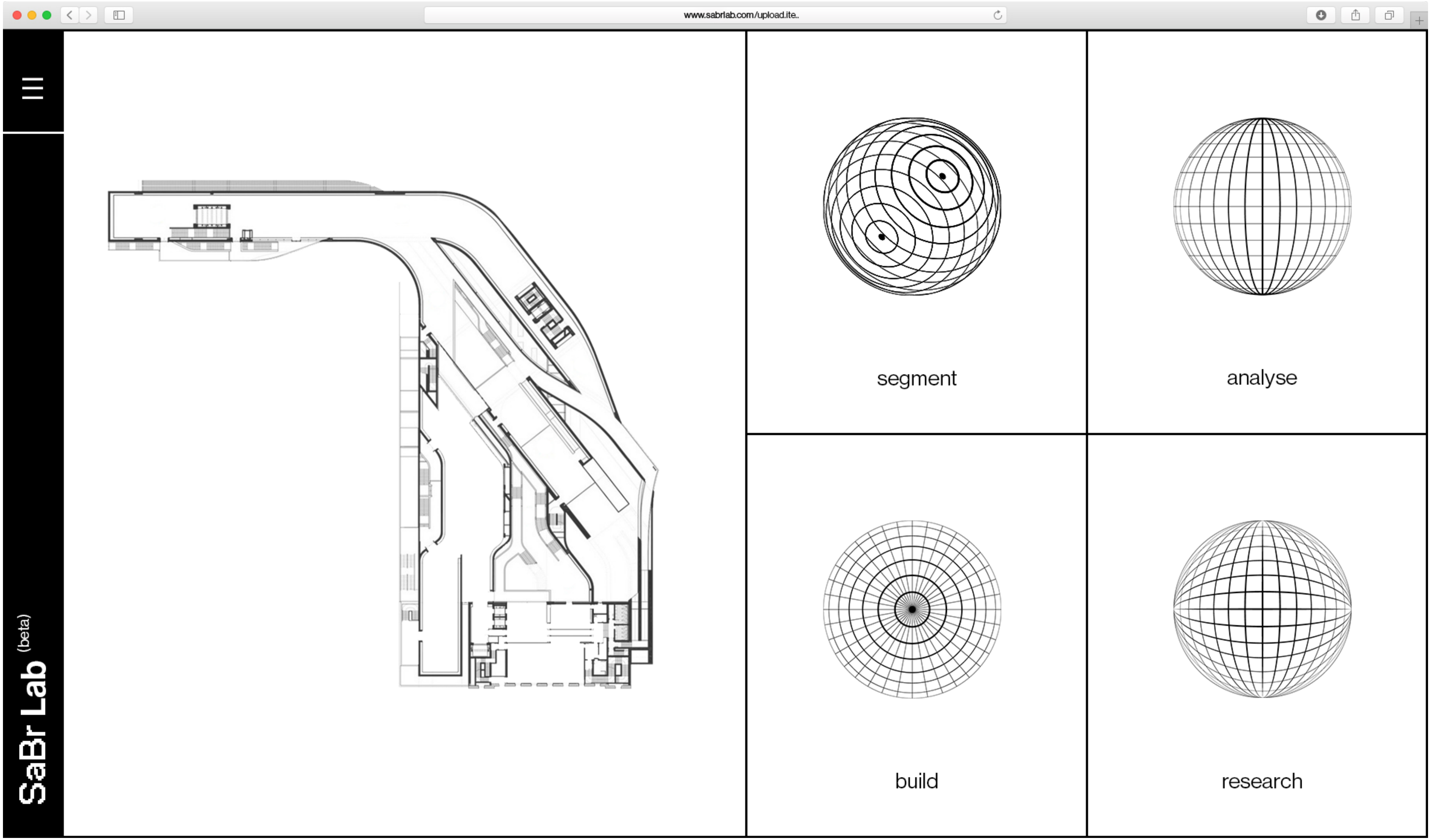
The depth of the museum from their respective entrances are always 4 or more with 52.5% having a depth of over 5. The primary of this group are structures preceding the contemporary style of the late 20th century. Modern architecture between the 1900 to 1980 seem to have the largest depths. It can be inferred that the typology of the museum has changed over time, at least topologically speaking, the museum of the 21st century possesses a rather simplified movement with their adjacencies showing not too much depth even with the structures being larger than the rest volumetrically.

One can take notice from the Appendix that with the passing of the years the topology of the museum has changed into a less complex structure, which otherwise might be harder to take a call on considering that the floor plans in the later periods have shown more curvilinear structures, making them seem more fluid and complex as compared to more rigid orthogonal plans of the past.

And while the methodology proposed a ‘raster to vector to graph’ approach for latent design patterns and architectural analysis, it can be concluded without a doubt that the coloured segmentation map really aids in the thinking process and in simplifying the plan. They help dumb down an otherwise complex technical floor plan and definitely help to add more information to a simple topological map. We reckon that the other forms of representation of topological maps, which was not visualised in the research, when automated might stand being even more helpful that the simplest topological maps, namely by using varying colours for the programs and nodes proportional to the area of the rooms along with their justified graphs can help provide invaluable information for design analysis of the said architectural images.

Artistic vision of the user interface

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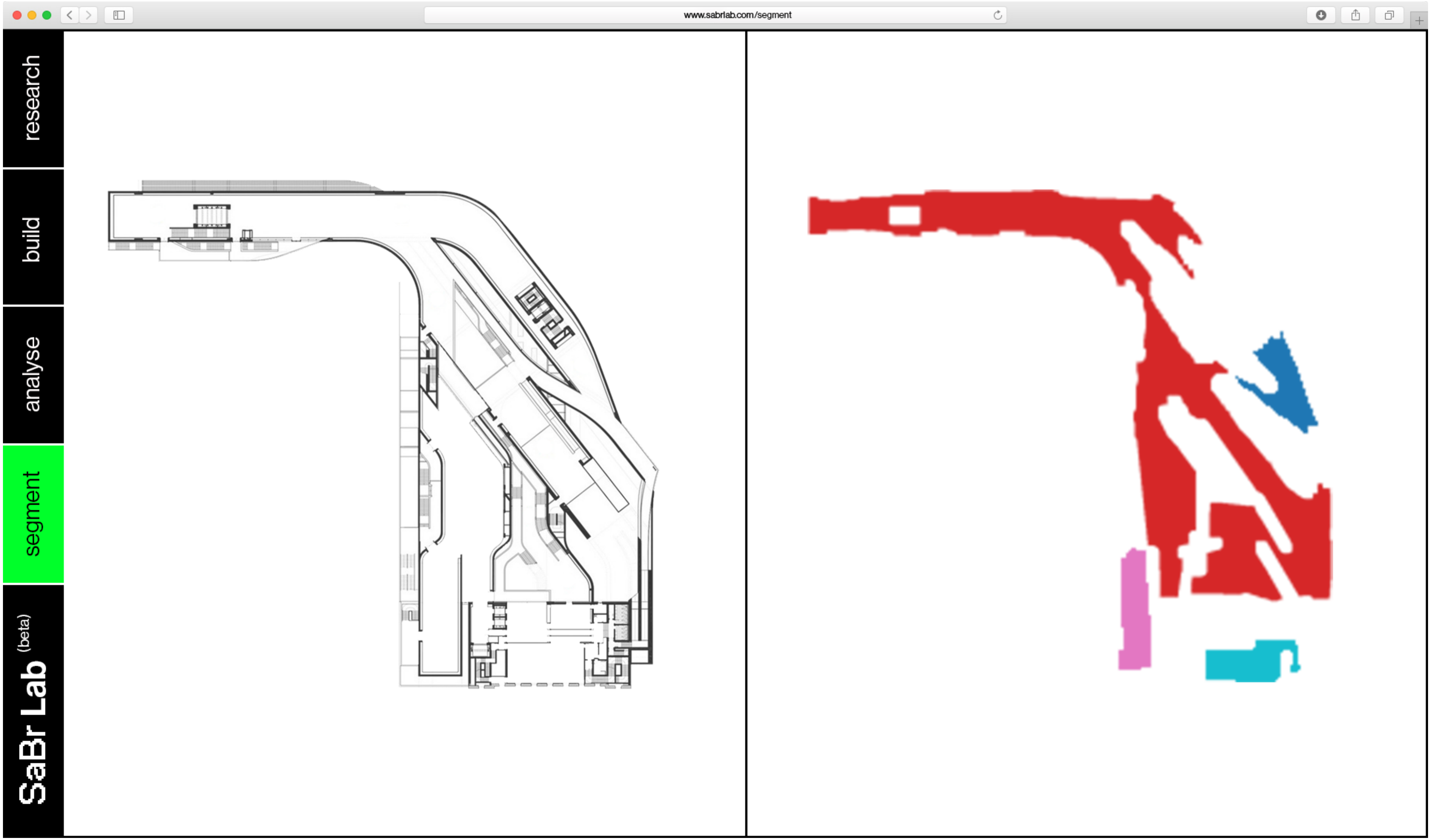
[B]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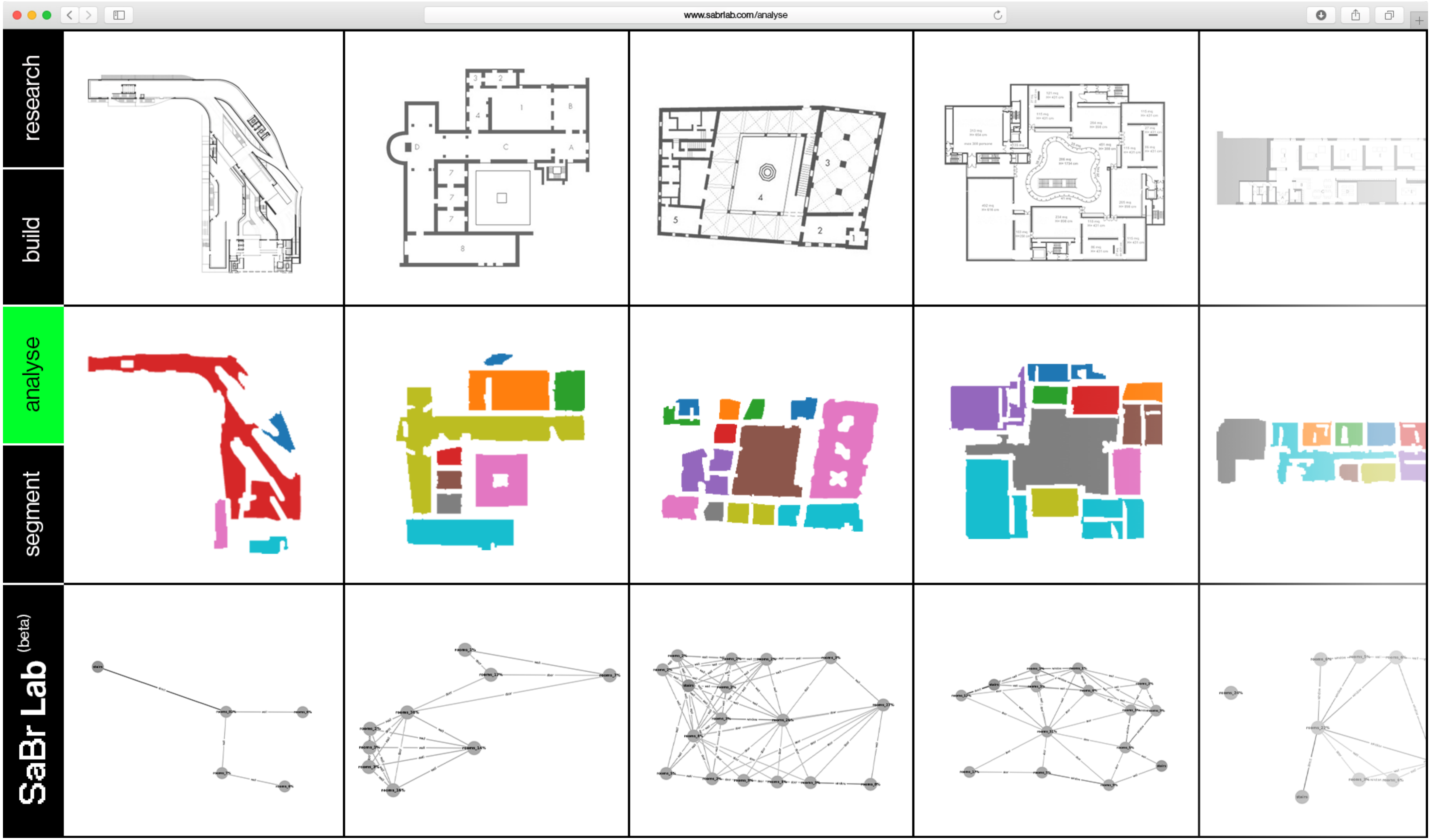
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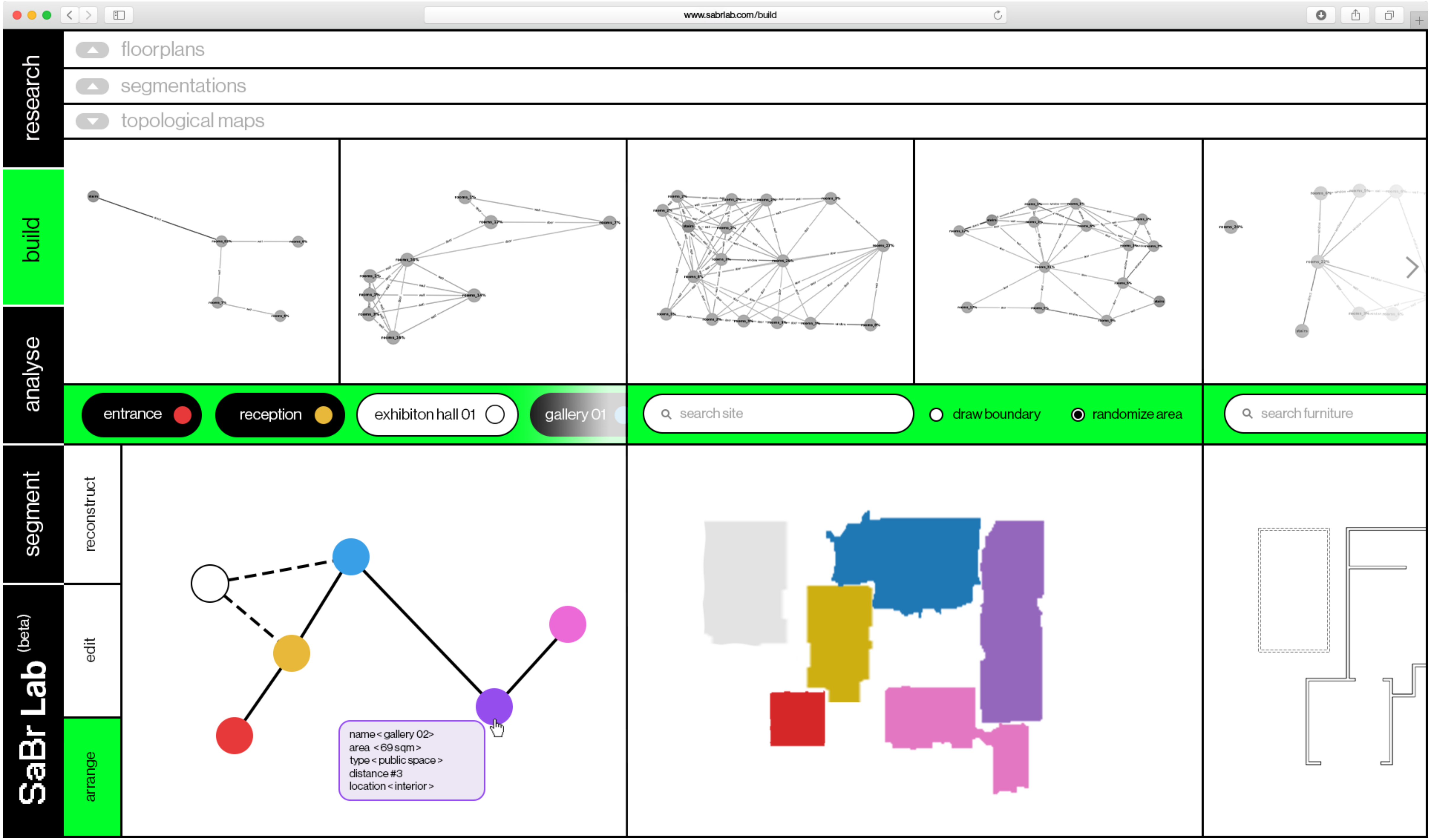
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reception
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gallery 01
search site
draw boundary
randomize area
search furniture
reconstruct
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distance #3
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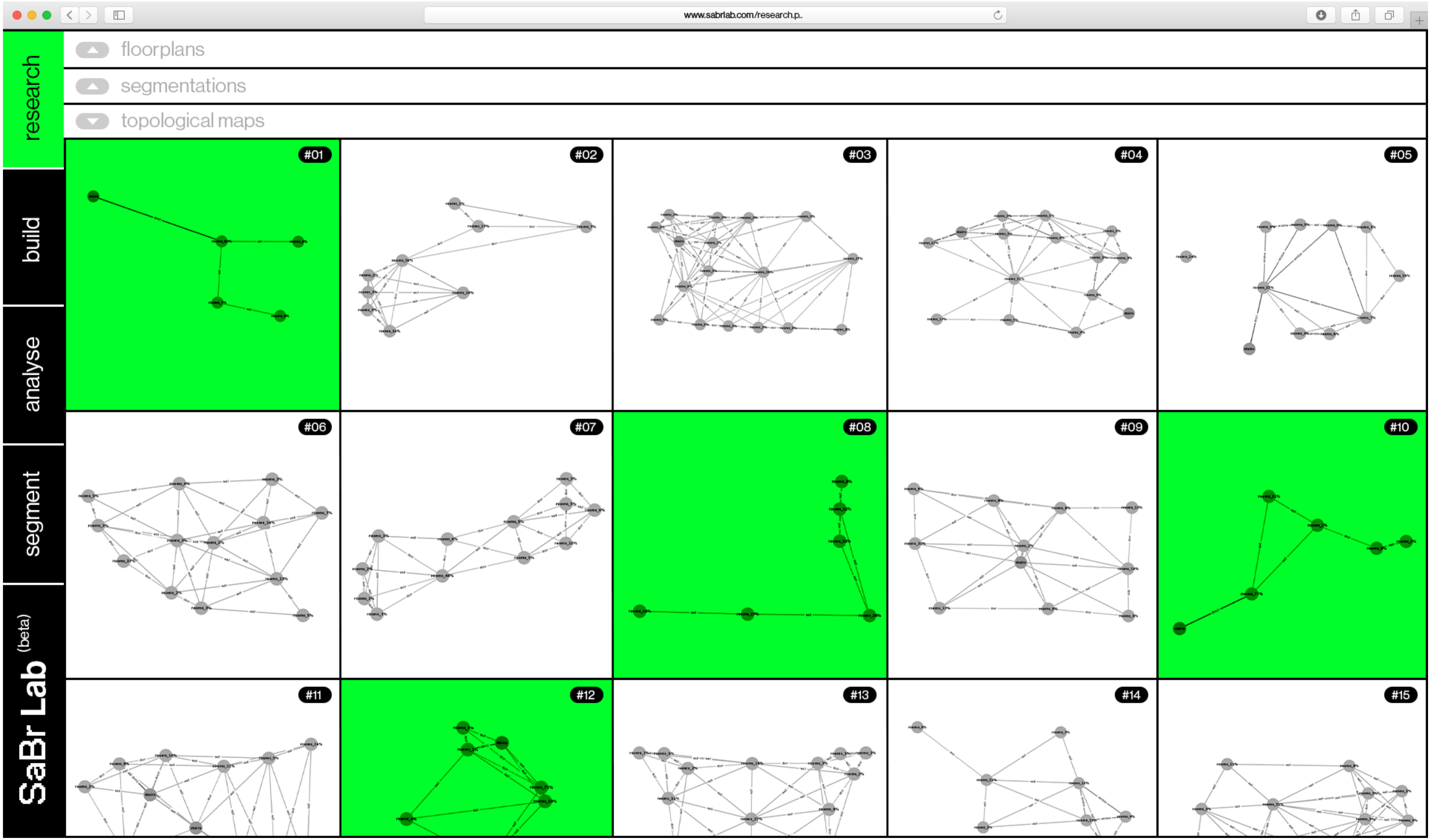
[E]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[F]

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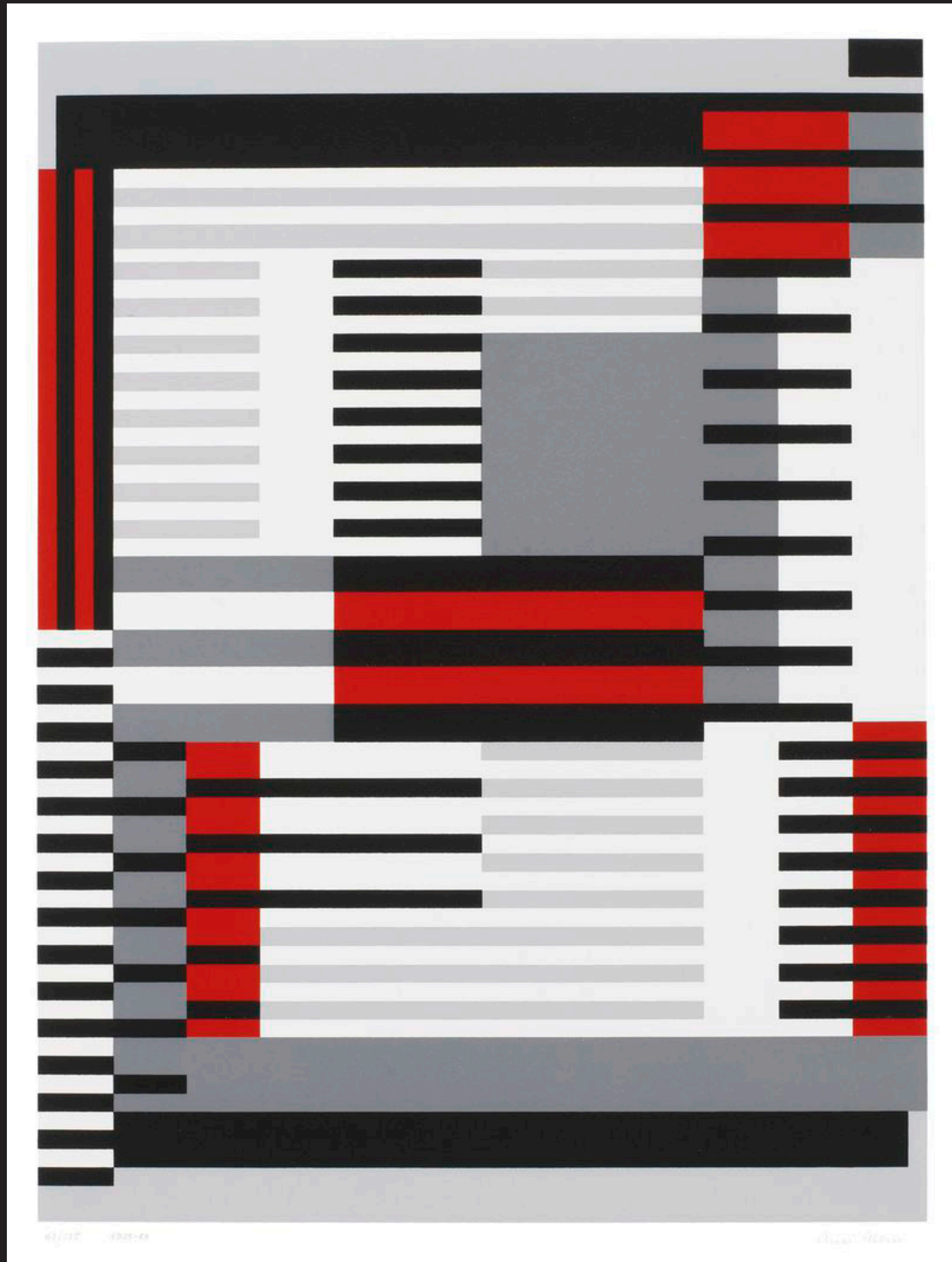


Visual Atlas images

1. Diagram of Logic Chip and Corresponding Microchip. (n.d.). MoMA. https://www.moma.org/collection/works/163875?artist_id=6612&page=1&sov_referrer=artist

2. Roberto Burle Marx, design for a mineral roof garden, Banco Safra headquarters, São Paulo, 1983. Gouache on paper, 31¾ x 39¼ in. (80.6 x 99.7 cm). Burle Marx & Cia. Ltda., Rio de Janeiro. © Burle Marx Landscape Studio, Rio de Janeiro. Reproduced with permission. All rights reserved. Photograph by Cesar Barreto

3. Punch cards to store binary information, unknown

4. Control Panel for IBM 305 RAMAC, Marcin Wichary, CC BY 2.0 <https://creativecommons.org/licenses/by/2.0>, via Wikimedia Commons

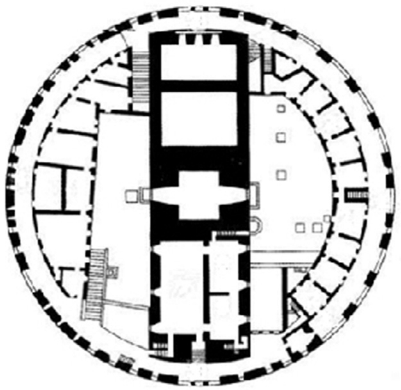
5. Piet Mondrian, Public domain, via Wikimedia Commons

6. Anni Albers, Smyrna-Knuepfteppich from Connections, 1983 The Josef and Anni Albers Foundation

Archive

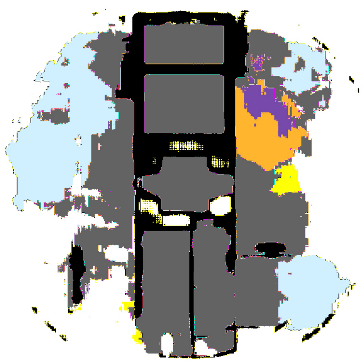
01	Nazionale d’Arte Moderna e Contemporanea

Rome	135 AD



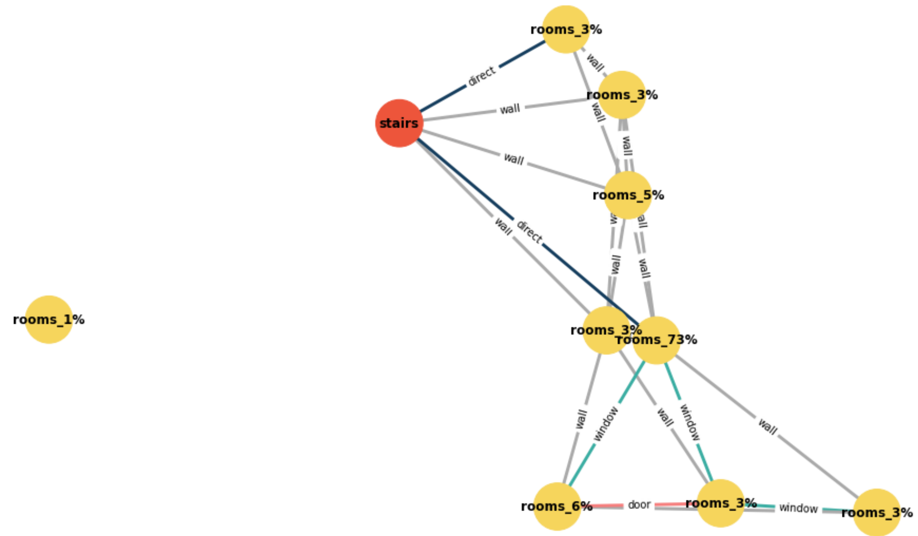
Housed within the impressive fortress of Castel Sant’Angelo, originally built as a mausoleum for the Roman Emperor Hadrian, the museum showcases a rich collection of archaeological artifacts, medieval weaponry, Renaissance paintings, and stunning frescoes. Explore the historic halls, courtyards, and secret passages, while admiring the panoramic views of Rome from the castle’s rooftop terrace. Discover the stories of emperors, popes, and artists as you delve into the fascinating heritage of this iconic landmark.

CubiCasa5k segmentation



Robust-AAG segmentation

Robust-Attributed Adjacency graph



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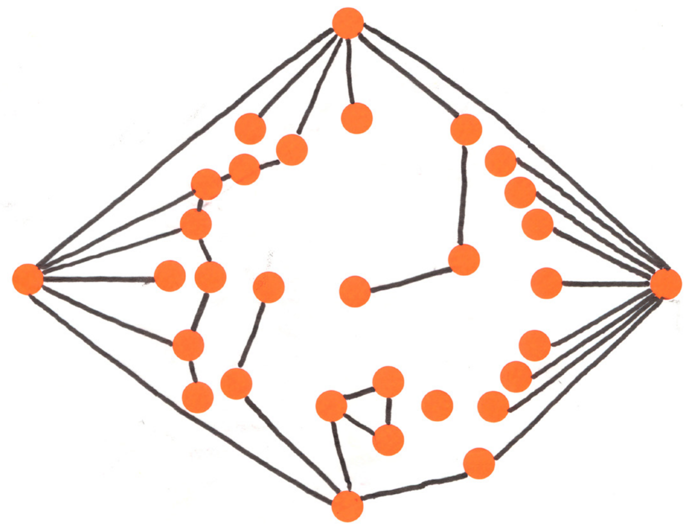
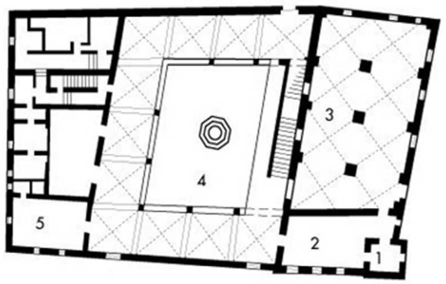


02

Museo Nazionale del Bargello



Florence

1255 AD

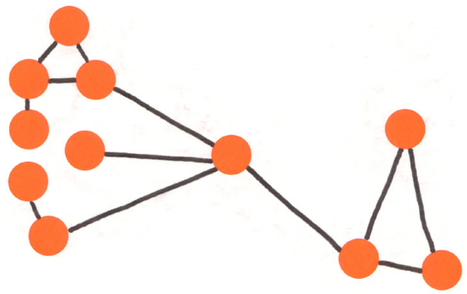
Offers visitors a captivating glimpse into the world of Renaissance art and sculpture. Housed in the historic Bargello Palace, the museum showcases an impressive collection of masterpieces, including works by renowned artists such as Michelangelo, Donatello, and Cellini. From exquisite sculptures to intricate metalwork and decorative arts, the museum's galleries provide a rich cultural experience. Explore the elegant courtyards and admire the architectural beauty of the palace, immersing yourself in the artistic legacy of Florence's past.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph

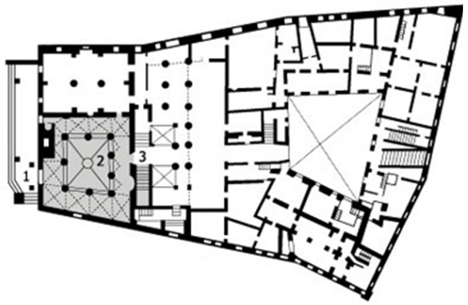
Ground truth



03

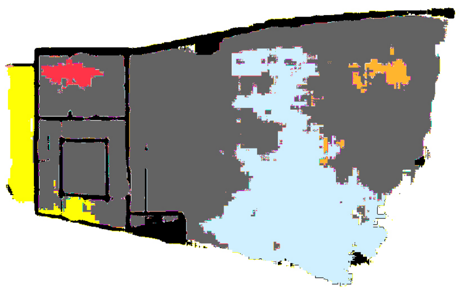
Palazzo Vecchio

Florence	1314 AD



This imposing fortress-turned-palace has witnessed centuries of political and cultural significance. Its majestic tower rises above the city's skyline, offering panoramic views of Florence. Inside, visitors can explore lavish chambers adorned with exquisite frescoes and ornate decorations, including the famed Salone dei Cinquecento. The palace also houses the impressive Hall of Maps and the opulent private apartments of the Medici family. A visit to Palazzo Vecchio is a journey through time, immersing oneself in the splendor of Renaissance Florence.

CubiCasa5k segmentation



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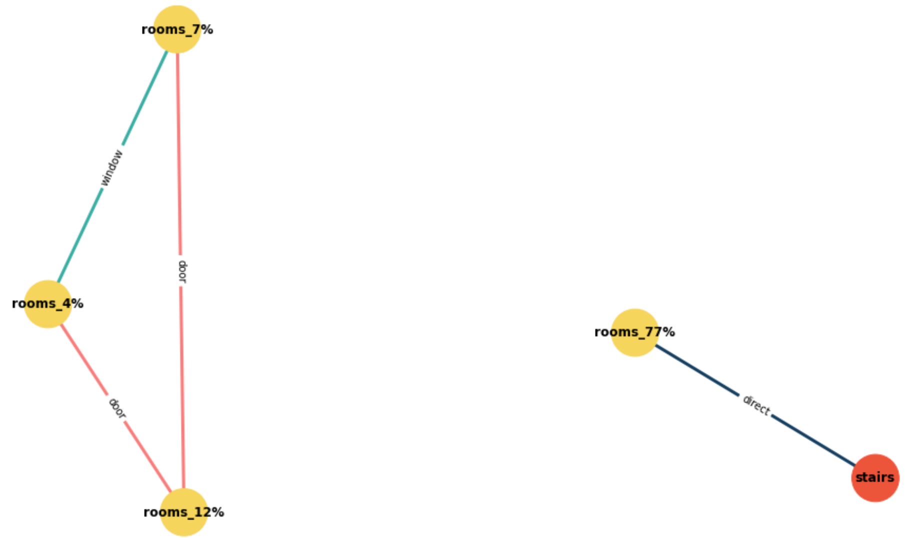

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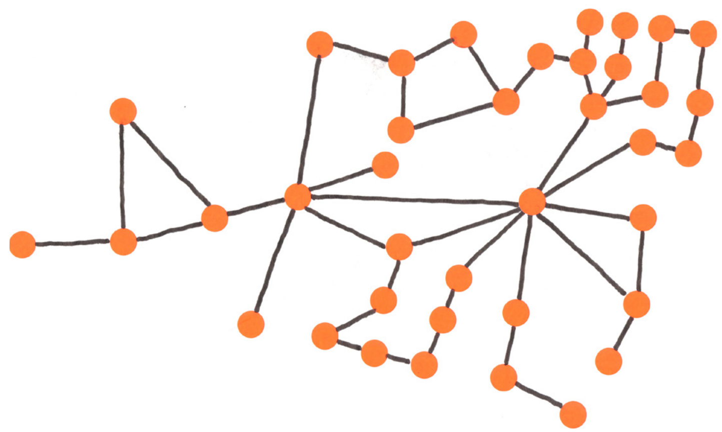
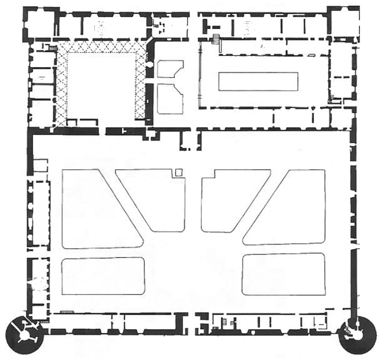


04

Castello Sforzesco



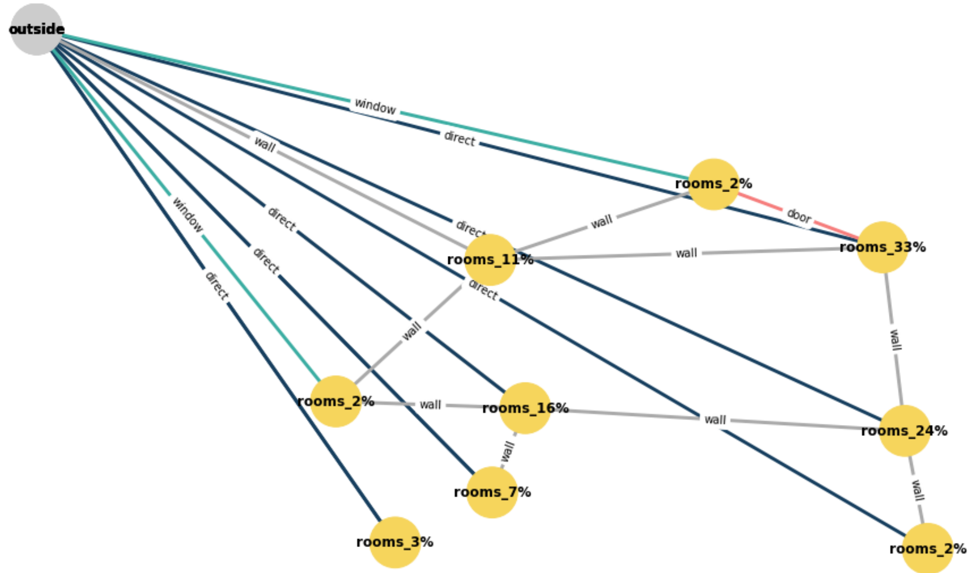
Milan	1380 AD

Castello Sforesco showcases impressive Renaissance architecture and serves as a testament to the power and influence of the Sforza family. Today, the castle houses various museums and art collections, including masterpieces by renowned artists such as Michelangelo and Leonardo da Vinci. Visitors can wander through its grand courtyards, explore its richly adorned rooms, and delve into the fascinating history of Milan. Castello Sforzesco is a cultural gem that offers a captivating glimpse into the city's past and artistic heritage.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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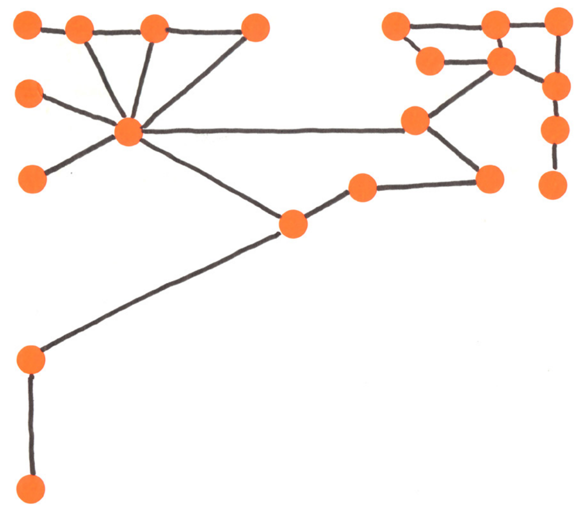
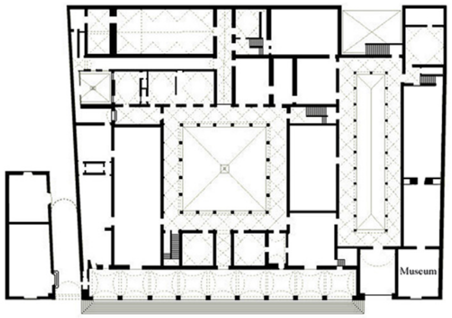


05

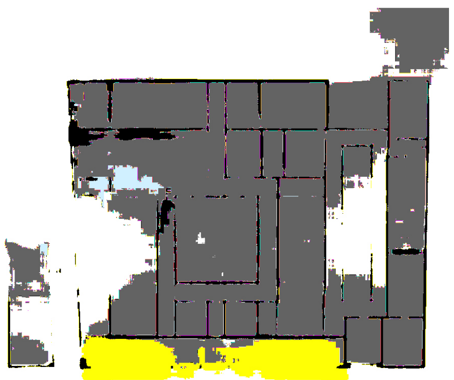
Galleria dello Spedale degli Innocenti

Florence	1419 AD



A magnificent Renaissance palace that houses a remarkable array of art collections. Originally built for the Pitti family, it later became the residence of the influential Medici family. The palace complex comprises several museums, including the Palatine Gallery, which features an extensive collection of Renaissance and Baroque paintings, the Gallery of Modern Art, showcasing works from the 19th and 20th centuries. With its opulent architecture, stunning gardens, and diverse art collections, Palazzo Pitti offers visitors a captivating journey through Italian history, art, and culture.

CubiCasa5k segmentation



Robust-AAG segmentation

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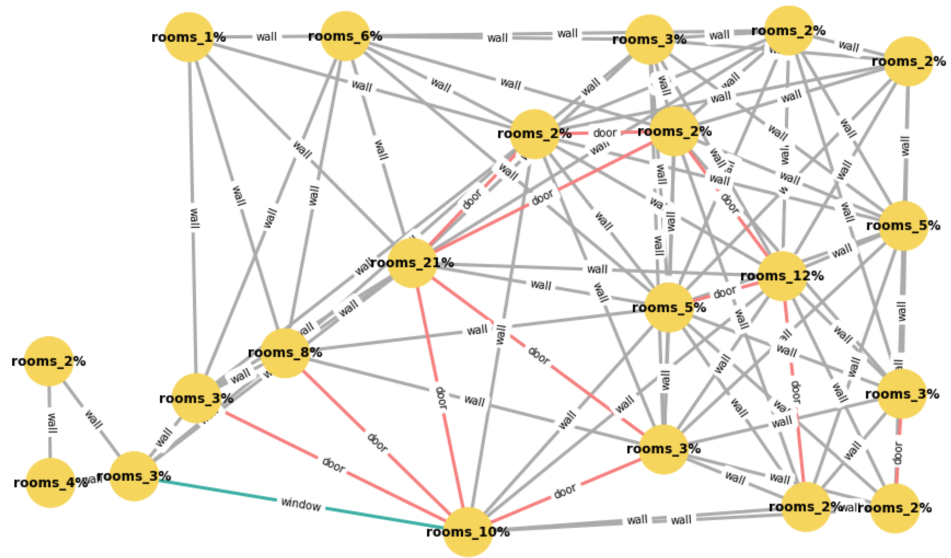

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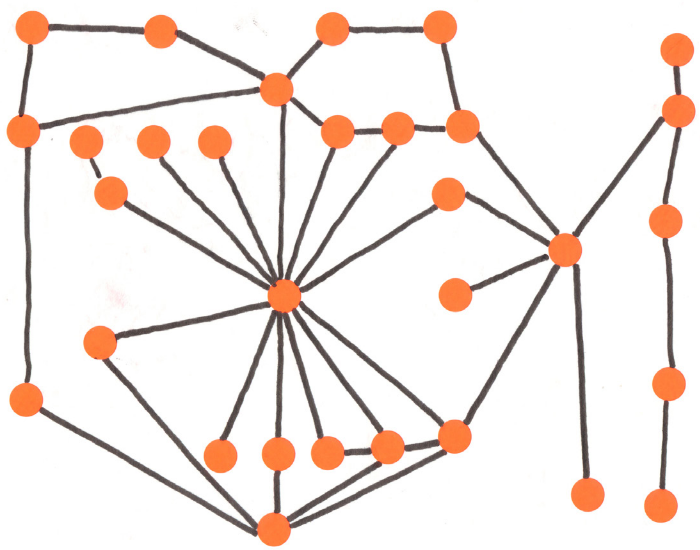
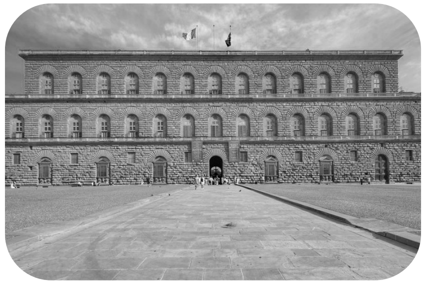
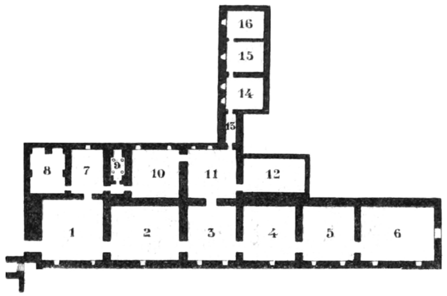


06

Palazzo Pitti

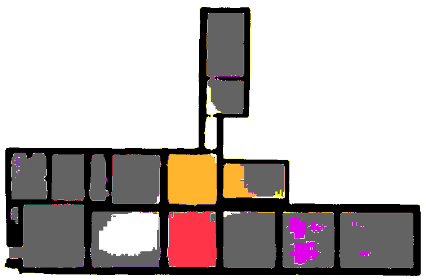




Florence | **1446 AD**

This imposing fortress-turned-palace has witnessed centuries of political and cultural significance. Its majestic tower rises above the city's skyline, offering panoramic views of Florence. Inside, visitors can explore lavish chambers adorned with exquisite frescoes and ornate decorations, including the famed Salone dei Cinquecento. The palace also houses the impressive Hall of Maps and the opulent private apartments of the Medici family. A visit to Palazzo Vecchio is a journey through time, immersing oneself in the splendor of Renaissance Florence.

CubiCasa5k segmentation



Robust-AAG segmentation

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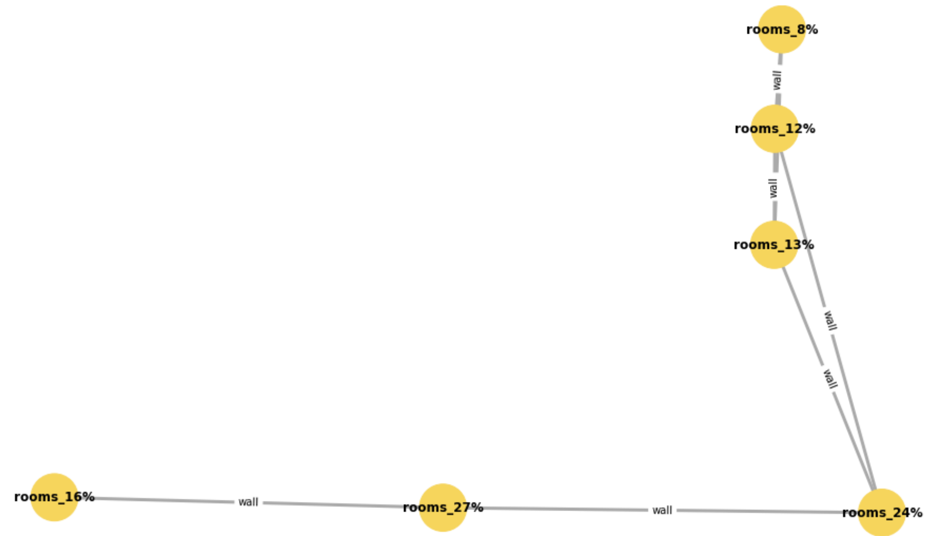

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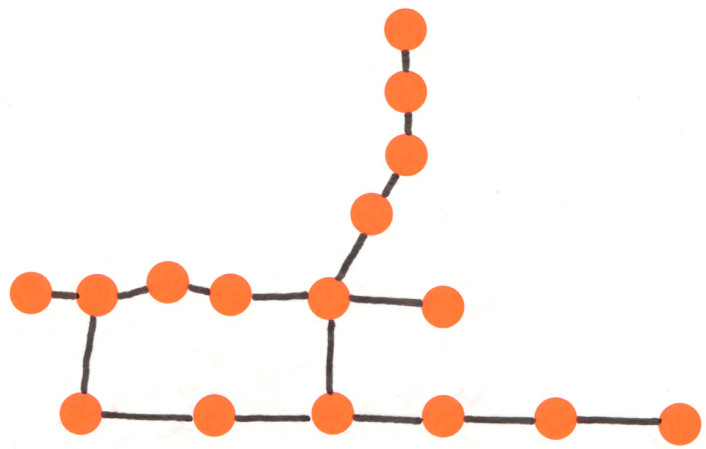
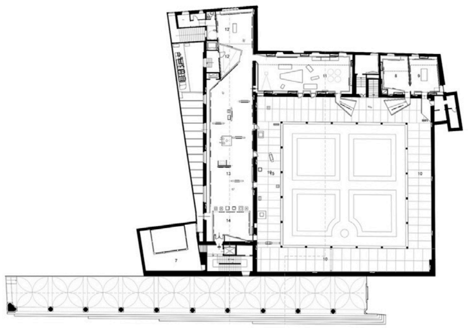


07

Museo Novecento



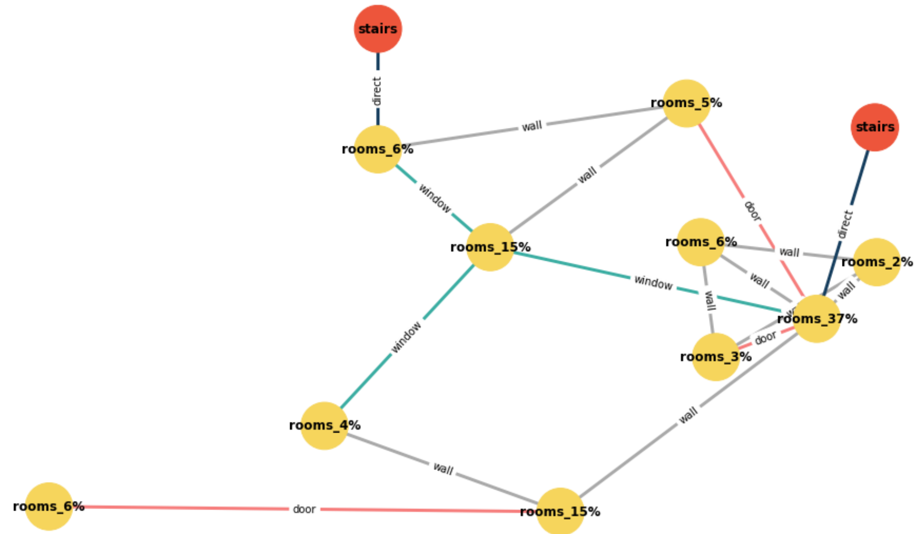
Florence	1459 AD

A modern art museum dedicated to the 20th-century artistic movements and trends. Housed in the striking Palazzo dell’Arengario in Piazza Santa Maria Novella, the museum showcases a comprehensive collection of paintings, sculptures, installations, and other artworks created by Italian artists from the early 1900s to the present day. With immersive displays, Museo Novecento offers visitors a vibrant and insightful exploration of the diverse expressions and innovations that shaped the art world throughout the 20th century.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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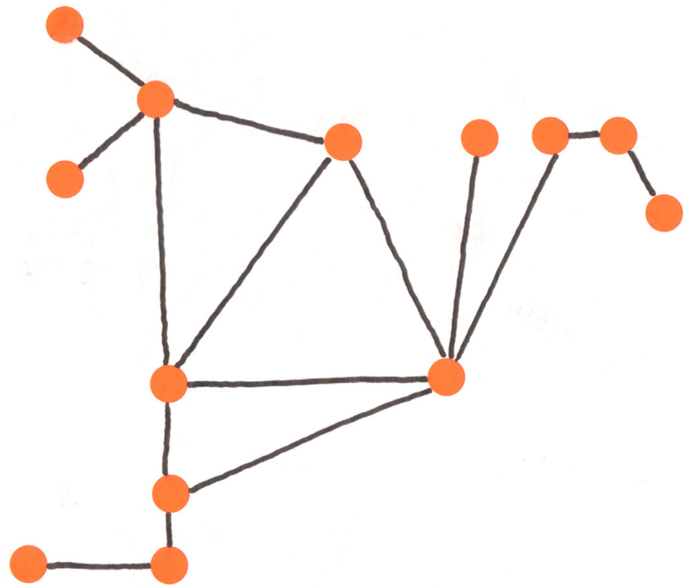
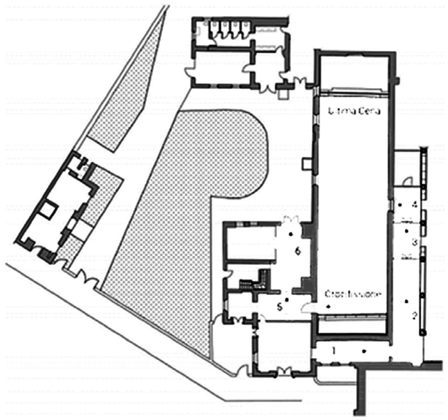


08

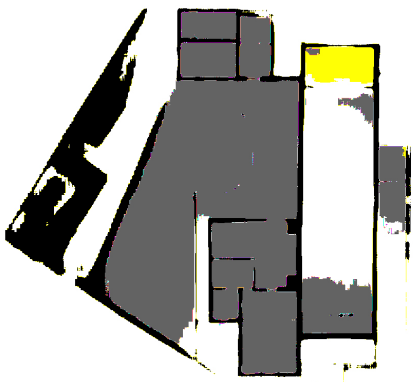
Cenacolo Vinciano Museum

Milan	1463 AD



Home to one of the world's most famous masterpieces - Leonardo da Vinci's "The Last Supper." Housed in the former Dominican convent of Santa Maria delle Grazie, the museum allows visitors to experience the awe-inspiring fresco painting firsthand. "The Last Supper" is renowned for its artistic brilliance and captivating portrayal of the biblical scene. The museum provides a unique opportunity to admire this iconic artwork and delve into its historical and cultural significance.

CubiCasa5k segmentation



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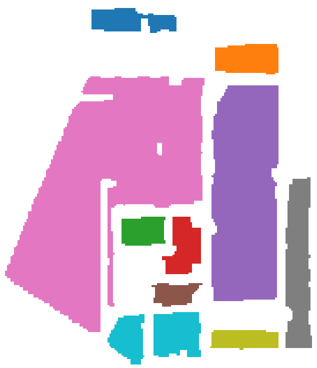

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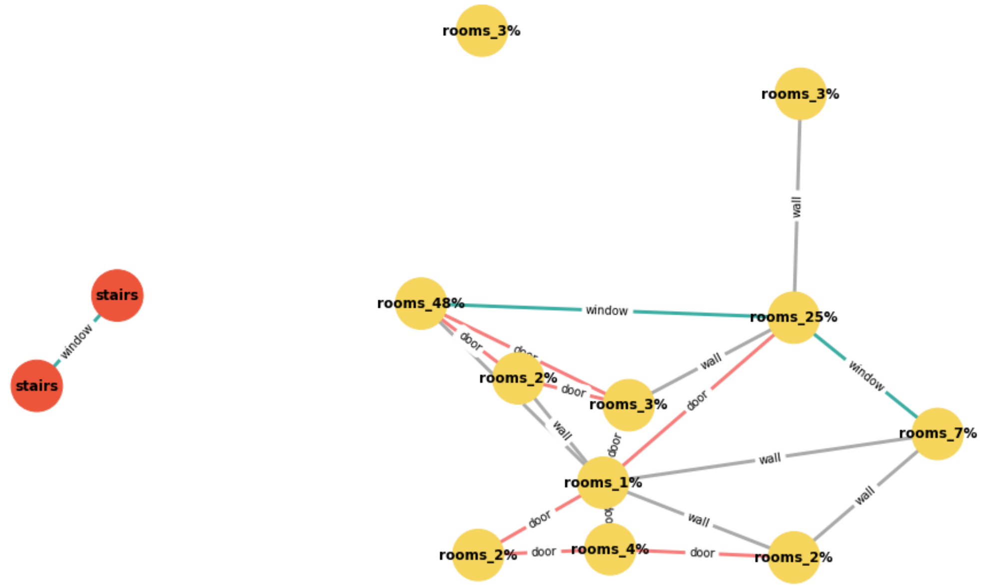

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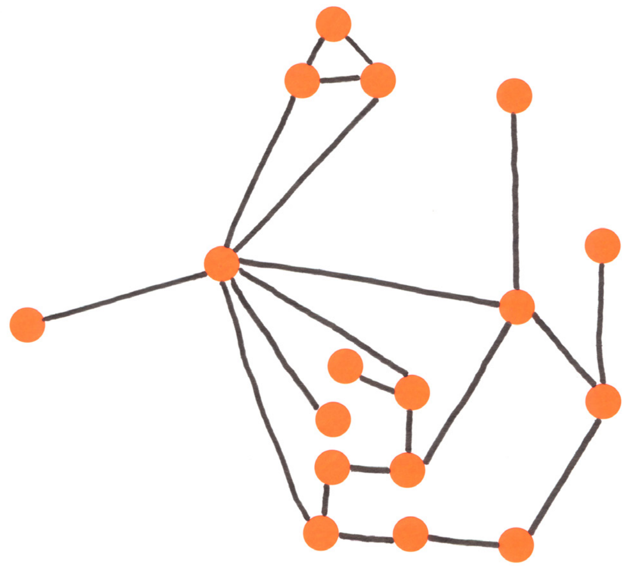
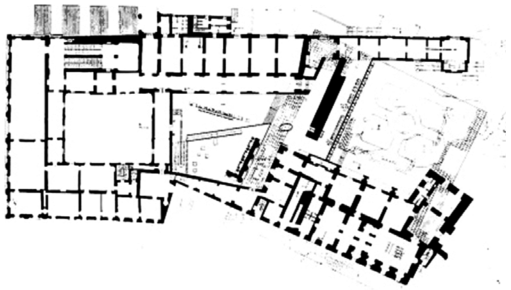


09

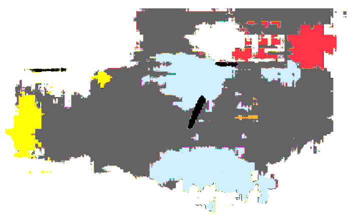
Capitoline Museums

Rome	1471 AD



The museums showcase a vast collection of sculptures, paintings, and archaeological finds from ancient Rome. Visitors can admire renowned masterpieces such as the Capitoline Wolf, the equestrian statue of Marcus Aurelius, and the iconic She-wolf suckling Romulus and Remus. The museums offer a fascinating journey through the rich history and culture of Rome, providing insights into the art, religion, and daily life of the ancient world. With its impressive collection and stunning architectural setting

CubiCasa5k segmentation



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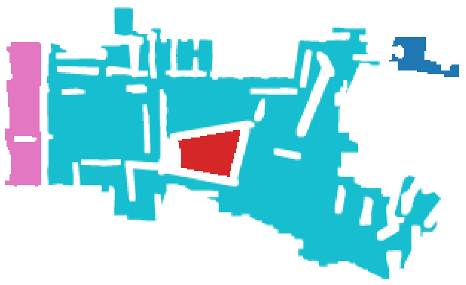

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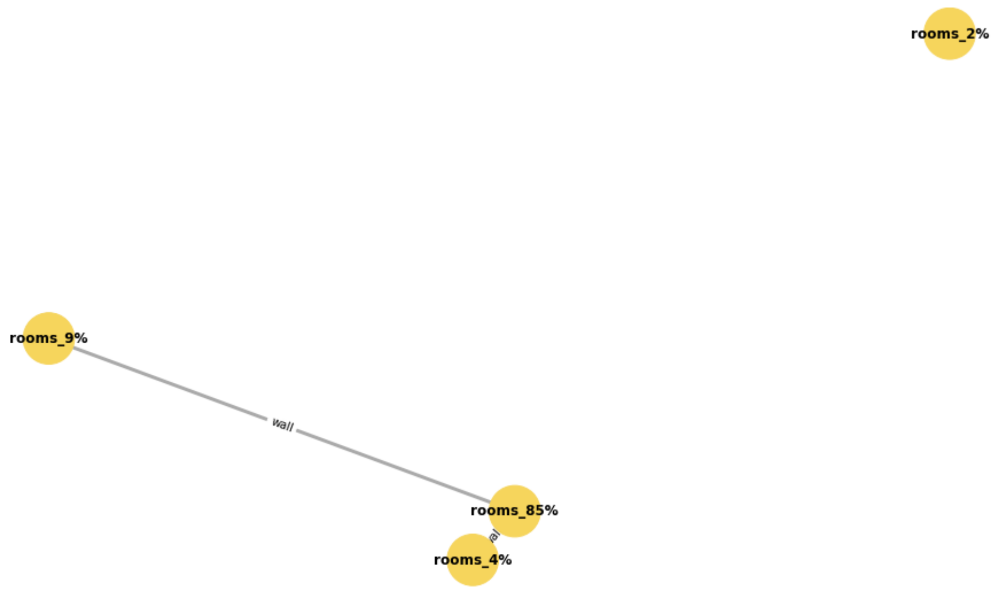

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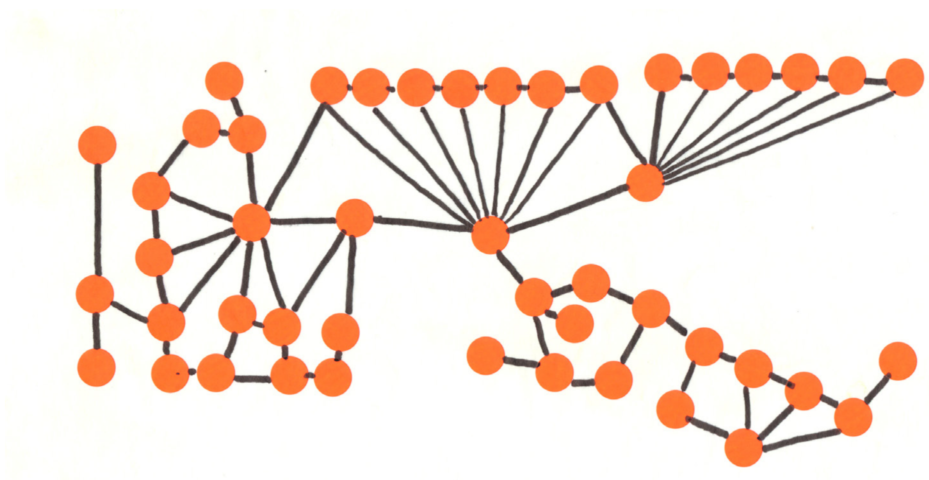
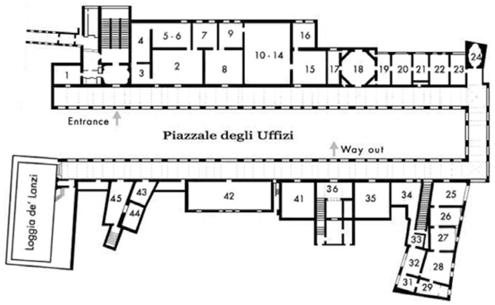


10

Uffizi Gallery



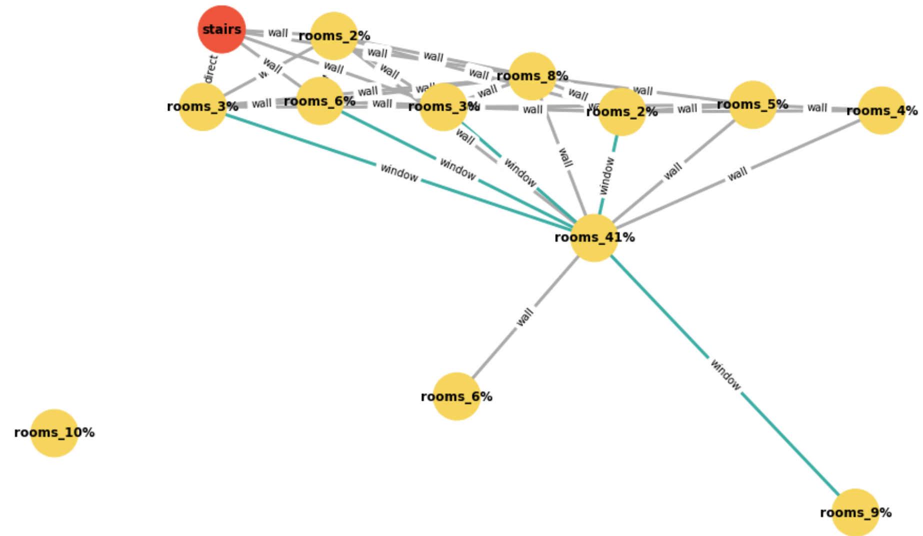
Florence | **1581 AD**

Founded in the 16th century, the gallery showcases an extensive array of paintings, sculptures, and decorative arts from prominent Italian artists such as Leonardo da Vinci, Michelangelo, Botticelli, and Raphael. Visitors can admire iconic works like Botticelli's "The Birth of Venus" and da Vinci's "Annunciation," among many others. The Uffizi Gallery's magnificent halls and corridors provide a captivating journey through the history and evolution of Italian art, making it a must-visit destination for art enthusiasts and cultural explorers alike.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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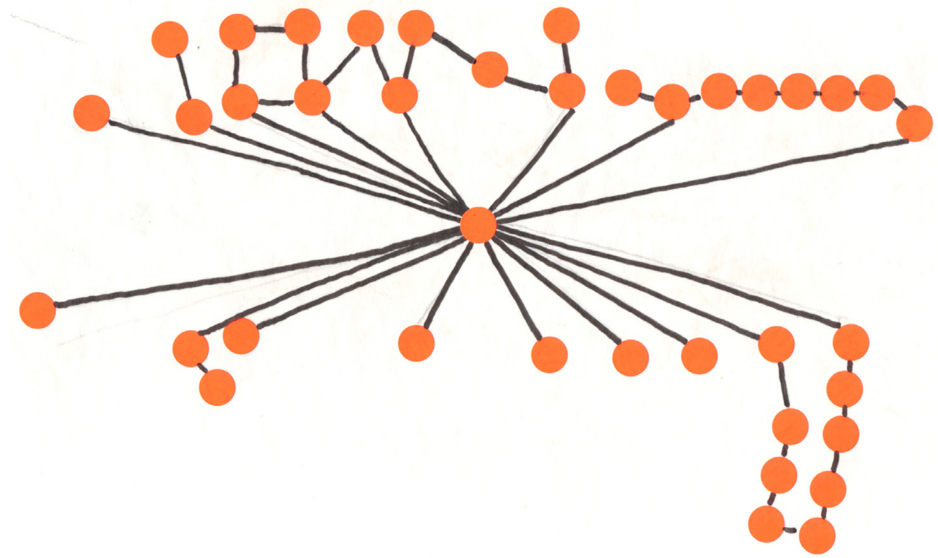
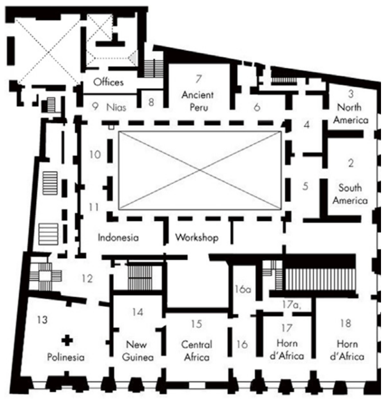


11	Museo di Antropologia

Florence	1593 AD

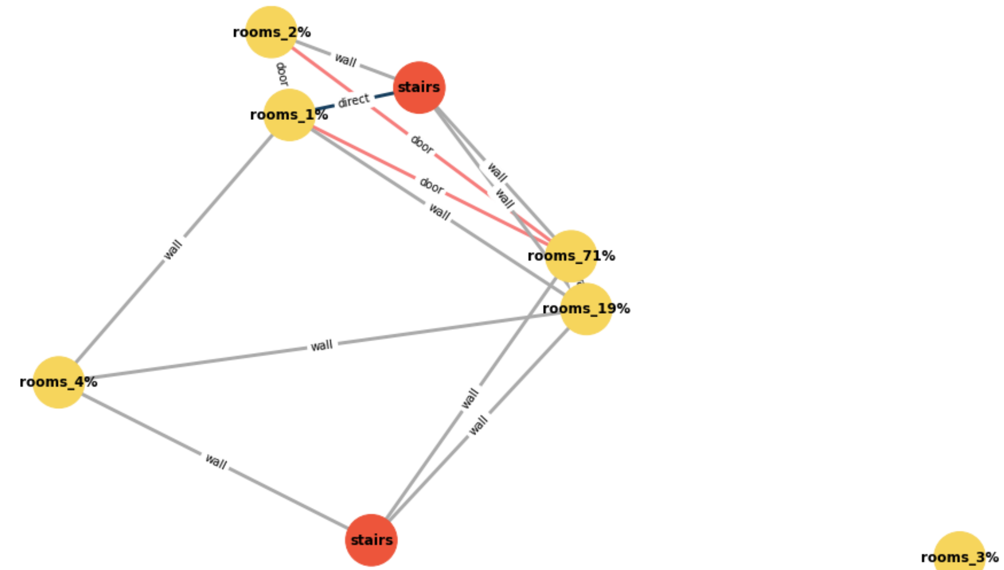


The museum houses a remarkable collection of artifacts, artworks, and exhibits that delve into the diverse traditions, customs, and beliefs of different societies from around the world. From ancient civilizations to contemporary indigenous cultures, the museum offers a unique opportunity to discover the rich tapestry of human existence. Through thought-provoking displays and immersive experiences, visitors can gain a deeper understanding of our shared humanity and the incredible diversity that defines us

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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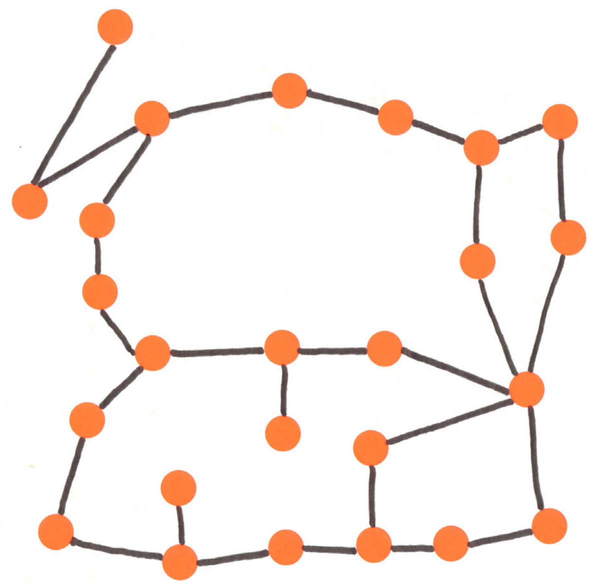
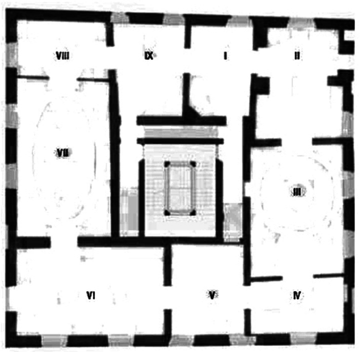


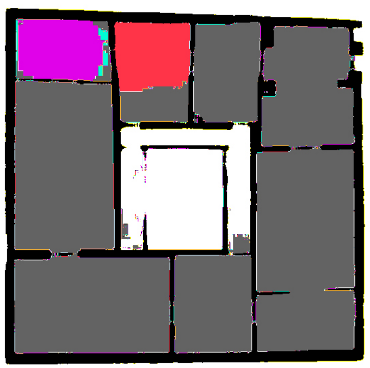
12 Galileo Museum

Florence	1593 AD



The museum showcases a remarkable collection of scientific instruments, astronomical artifacts, and manuscripts that highlight Galileo's groundbreaking contributions to physics, astronomy, and mathematics. From his revolutionary telescopes to his innovative experiments, visitors can delve into Galileo's world and explore the wonders of the cosmos through interactive exhibits and engaging displays. With its fascinating blend of history, science, and innovation, the Galileo Museum offers a unique opportunity to step into the mind of a visionary and discover the wonders of the universe.

CubiCasa5k segmentation



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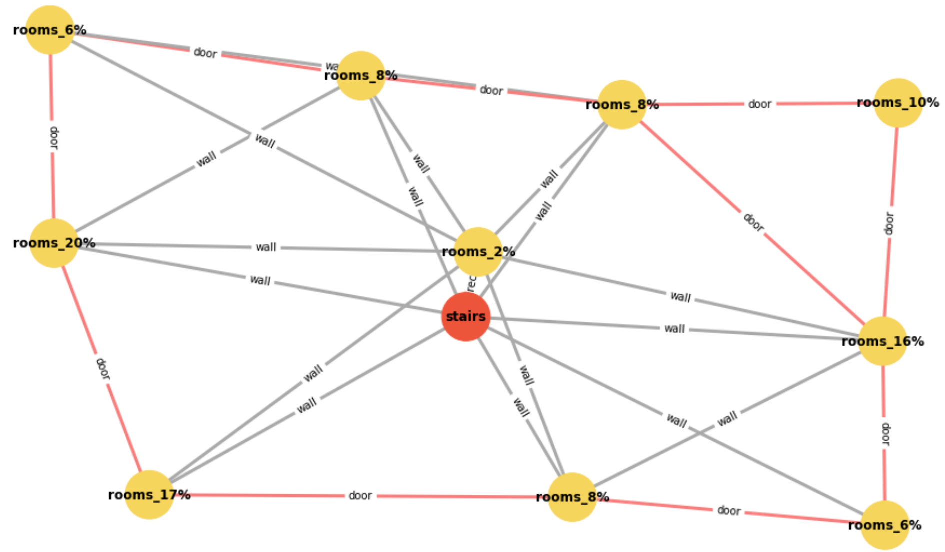

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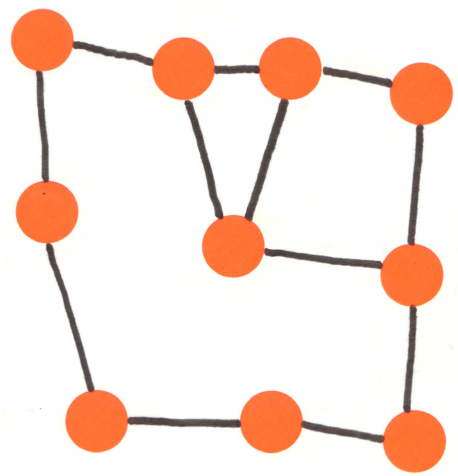
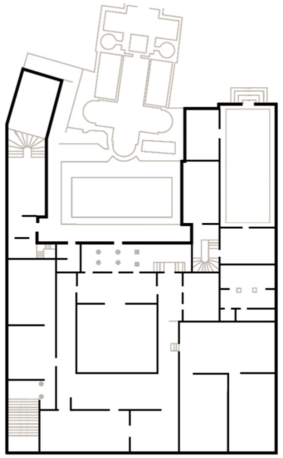


13	Ambrosiana Gallery

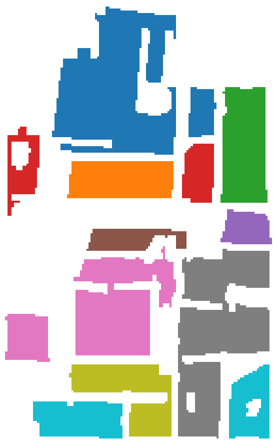
Milan	1607 AD



Located in the historic Ambrosiana Library, the gallery houses a remarkable collection of masterpieces from renowned artists such as Leonardo da Vinci, Caravaggio, Botticelli, and Raphael. Visitors can admire iconic works like Leonardo's "Portrait of a Musician" and Caravaggio's "Basket of Fruit," among many others. The gallery also features exquisite manuscripts, ancient books, and historical artifacts that provide insights into Italy's rich artistic heritage

CubiCasa5k segmentation

Robust-AAG segmentation



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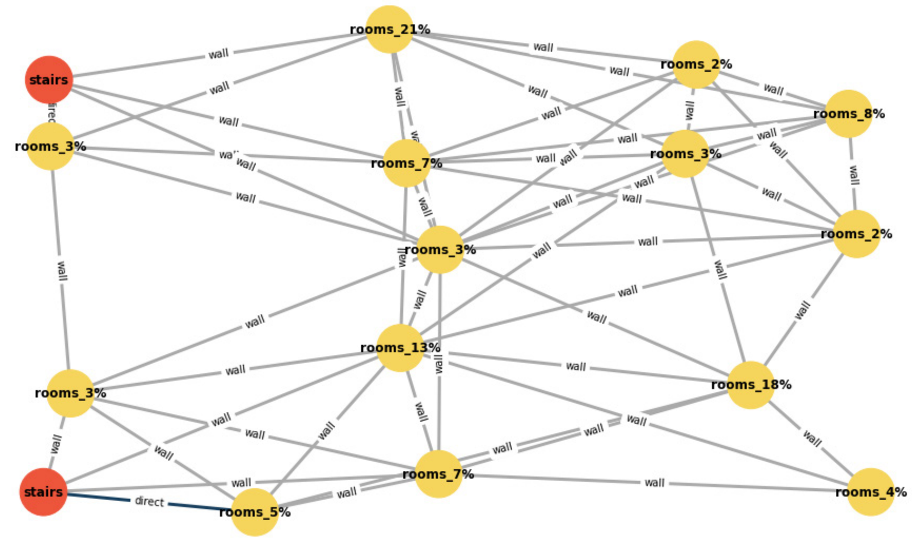

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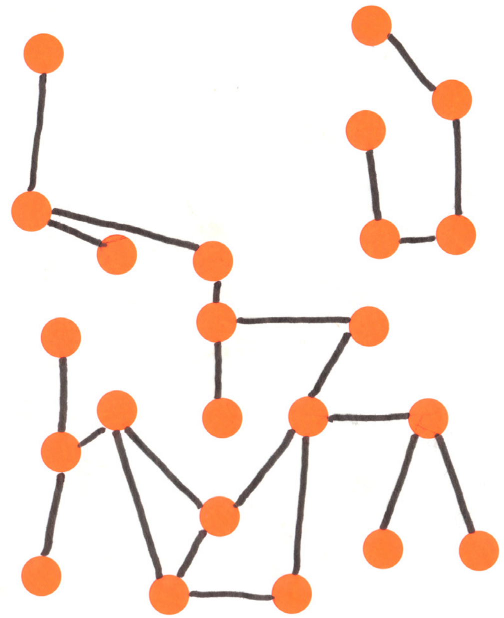
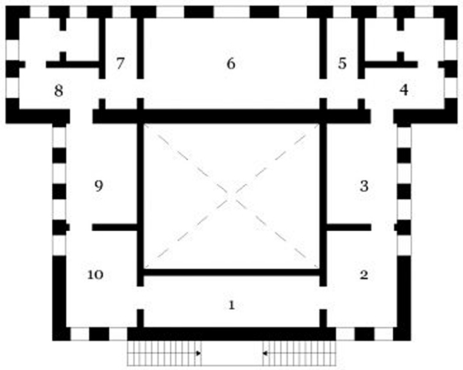


14

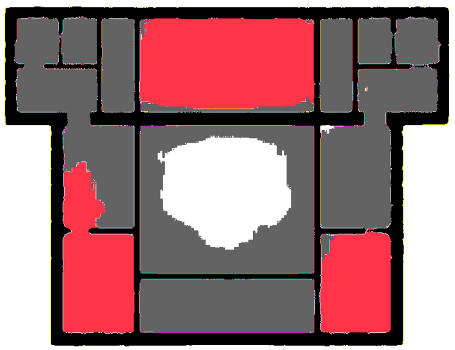
Galleria Borghese

Rome	1660 AD



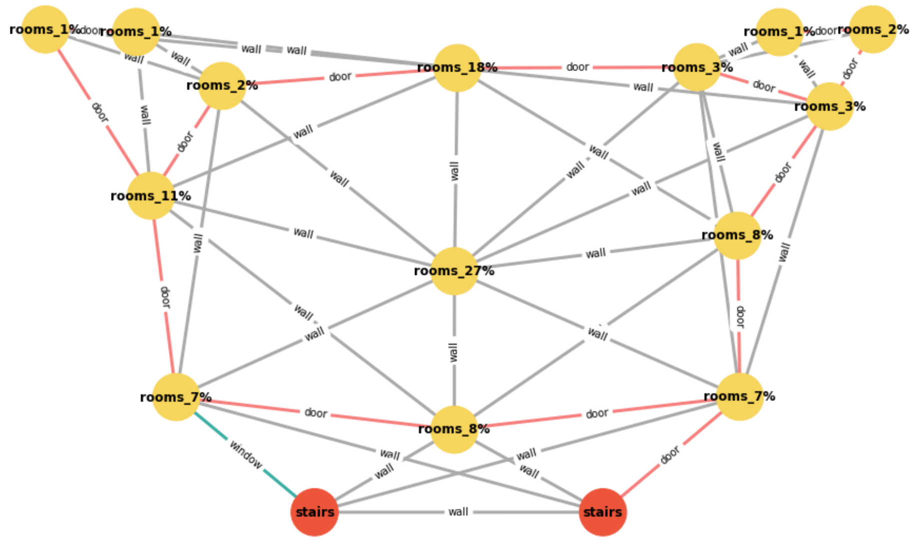
It boasts a stunning collection of masterpieces from renowned artists such as Caravaggio, Bernini, Titian, and Raphael. Visitors can marvel at iconic sculptures like Bernini's "Apollo and Daphne" and Canova's "Pauline Bonaparte," as well as admire exquisite paintings such as Caravaggio's "Boy with a Basket of Fruit" and Raphael's "The Deposition." The museum's elegant halls and beautifully landscaped gardens provide a serene setting for experiencing the timeless beauty of these artistic treasures

CubiCasa5k segmentation



Robust-AAG segmentation

Robust-Attributed Adjacency graph



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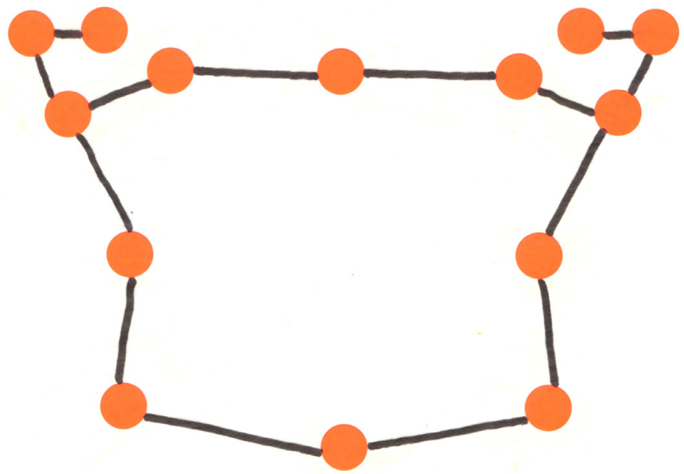
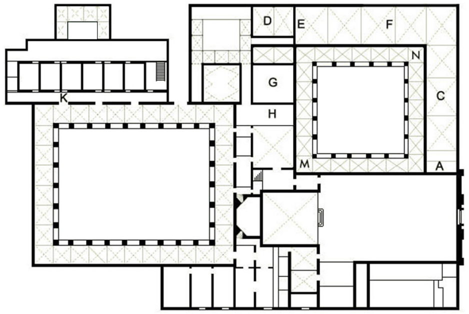


15

Museo del Convento di San Marco

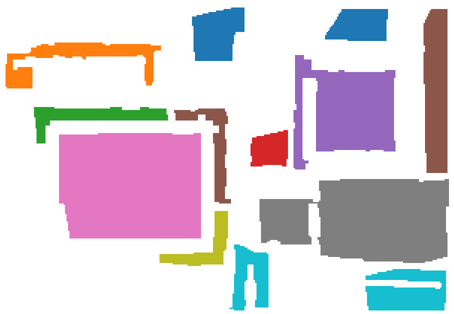
Florence | **1678 AD**



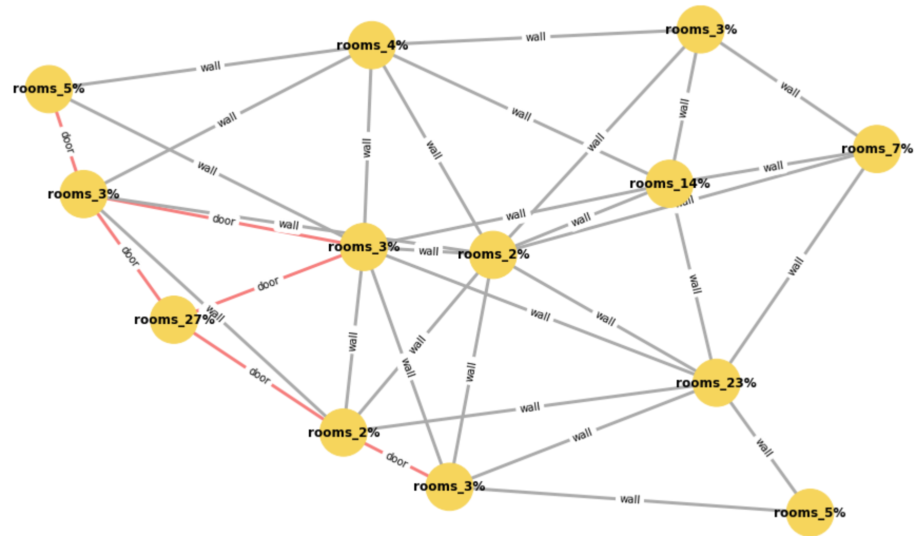
Housed in the beautifully preserved San Marco Convent, the museum showcases a remarkable collection of religious artifacts, frescoes, and sculptures. Visitors can explore the serene cloisters, admire the exquisite frescoes by Fra Angelico, and delve into the life and teachings of the influential Dominican friar, Girolamo Savonarola. The museum provides a peaceful and enlightening experience, allowing visitors to connect with the spiritual and artistic heritage of the Dominican tradition in the heart of Florence.

CubiCasa5k segmentation

Robust-AAG segmentation



Robust-Attributed Adjacency graph



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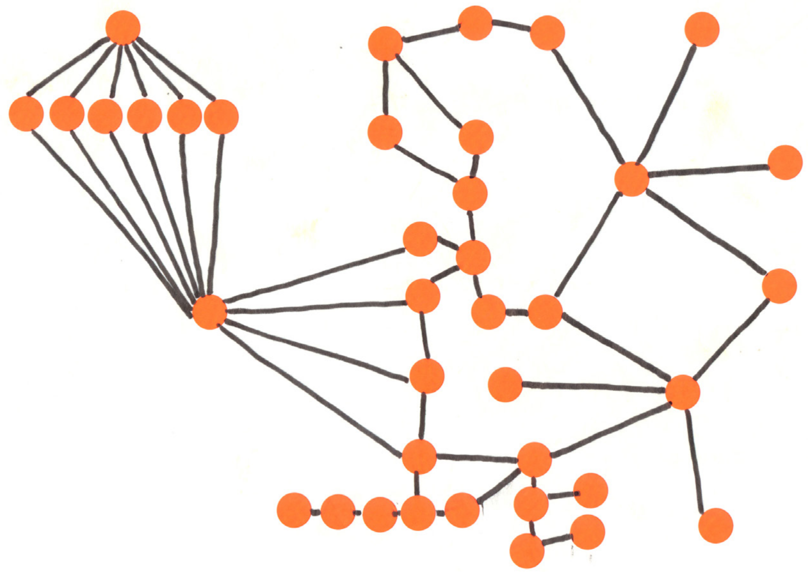
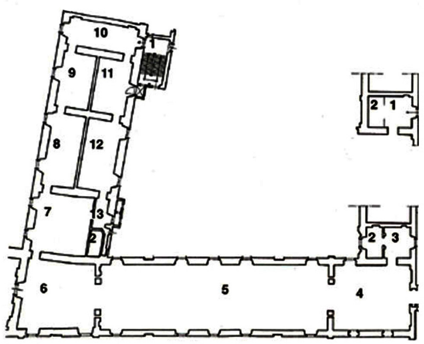


16

Palazzo Colonna

Rome	1700 AD

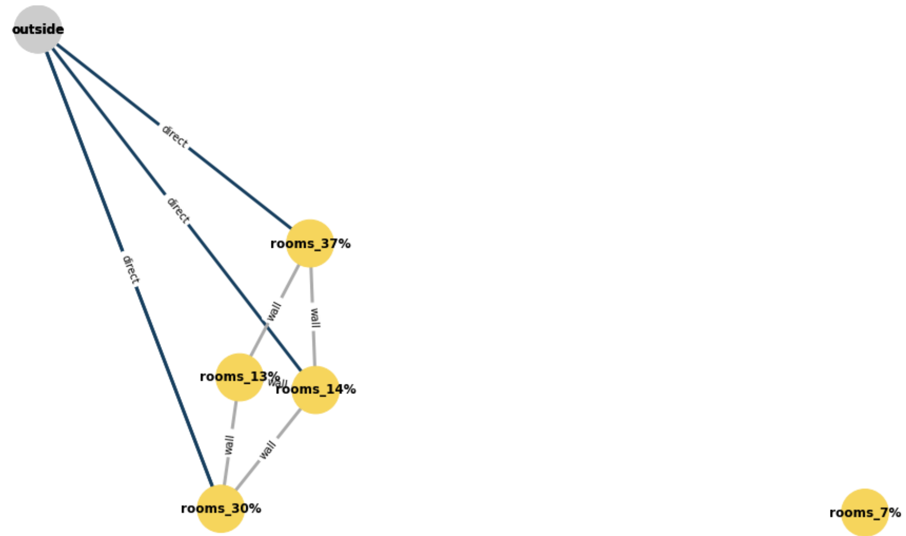


Palazzo Colonna in Rome is a magnificent Renaissance palace that stands as a testament to the city's rich history and architectural grandeur. This opulent residence, owned by the prestigious Colonna family, features stunning galleries adorned with intricate frescoes, sculptures, and luxurious furnishings. Visitors can wander through its lavish rooms, admire the remarkable art collection, and soak in the aristocratic ambiance of the palazzo. With its rich cultural heritage and captivating beauty, Palazzo Colonna offers a captivating journey into the past, showcasing the splendor and elegance of Renaissance Rome.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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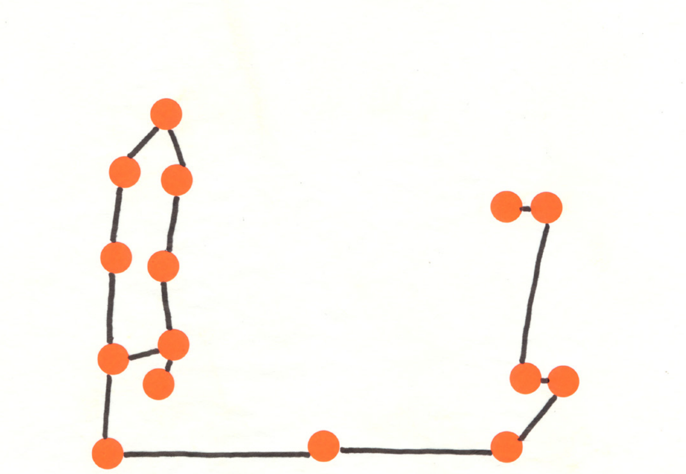
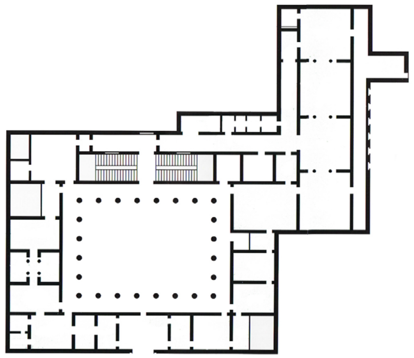


17

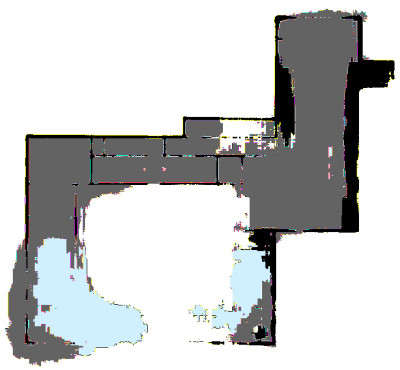
Brera Art Gallery

Milan	1776 AD



Brera Art Gallery, located in the heart of Milan, is a renowned cultural institution that houses a remarkable collection of Italian Renaissance and Baroque artworks. The gallery provides a captivating setting for visitors to explore masterpieces by renowned artists such as Caravaggio, Raphael, and Titian. From exquisite paintings to sculptures and decorative arts, Brera Art Gallery offers a diverse range of artistic treasures that reflect the rich cultural heritage of Italy. Immerse yourself in the beauty and history of Italian art as you wander through the halls of this prestigious gallery.

CubiCasa5k segmentation



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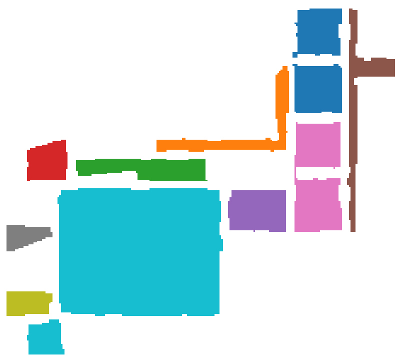

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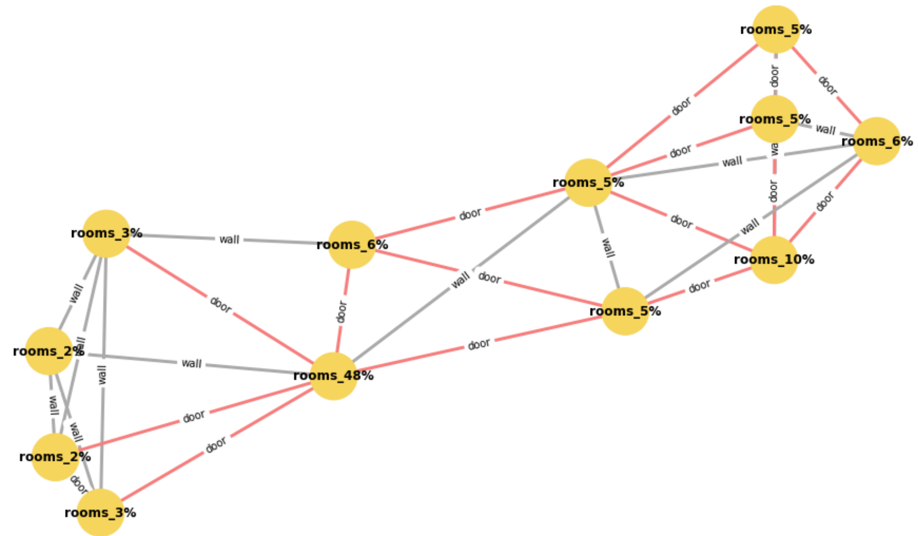

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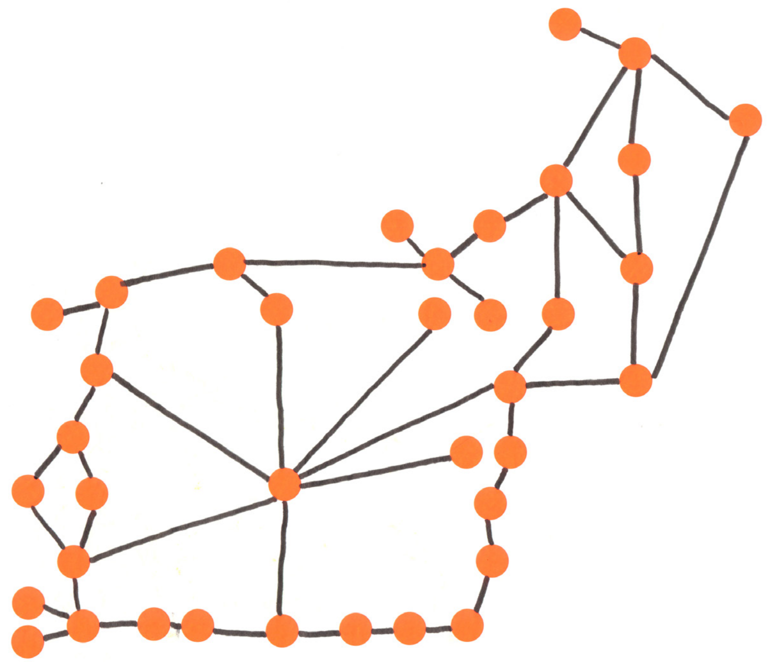
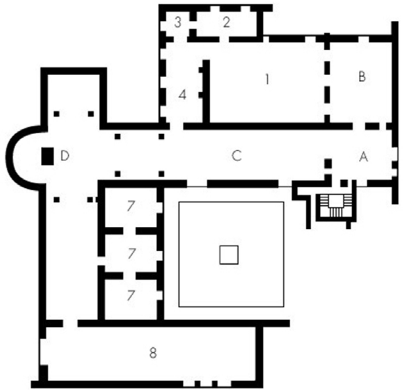


18

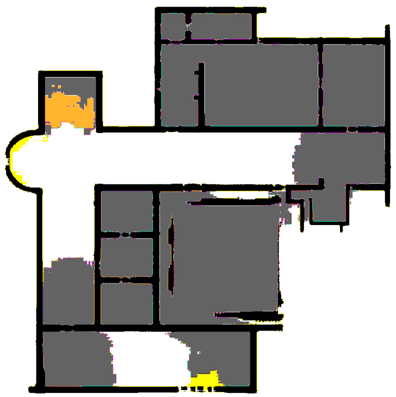
Galleria dell'Accademia

Florence	1784 AD



The gallery is renowned for housing one of the most iconic sculptures in the world - Michelangelo's David. As you step into the gallery, you'll be captivated by the impressive collection of Renaissance art, including stunning marble sculptures and magnificent paintings. In addition to Michelangelo's David, you'll have the opportunity to admire other notable works by renowned artists such as Botticelli, Ghirlandaio, and Pontormo. Immerse yourself in the artistic brilliance of the Renaissance period as you explore the halls of Galleria dell'Accademia.

CubiCasa5k segmentation



Robust-AAG segmentation

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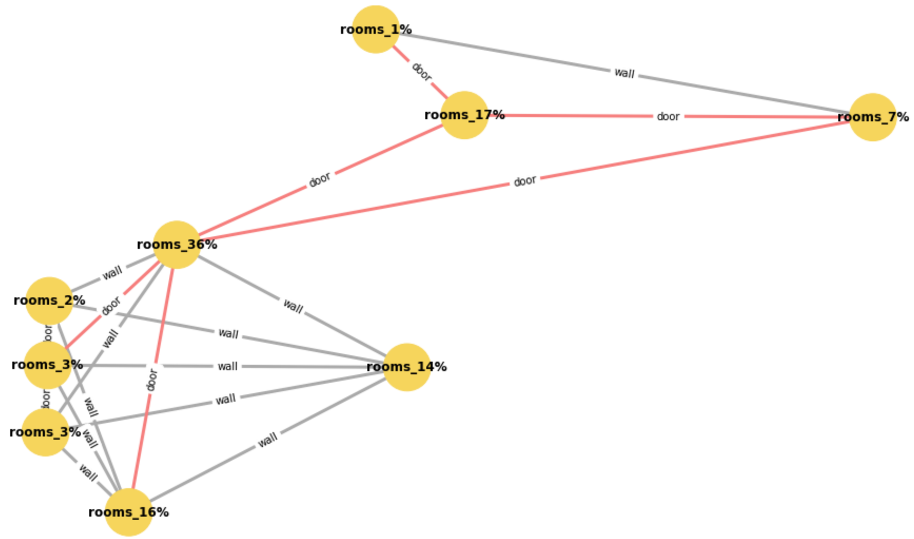

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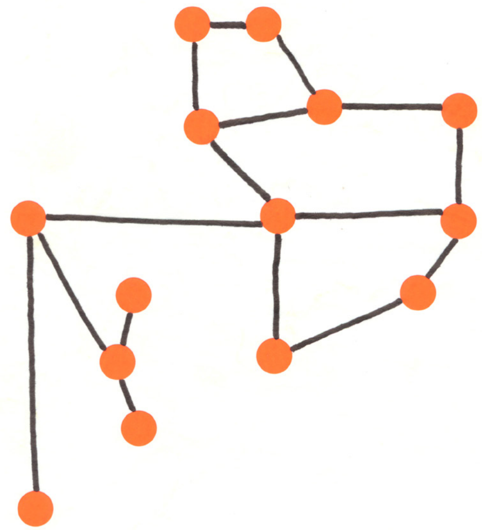
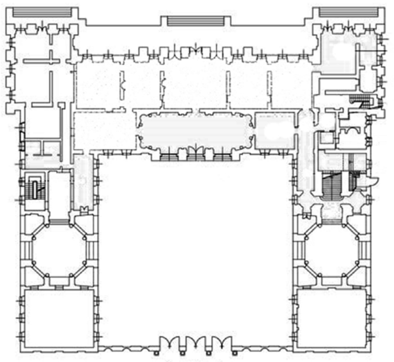


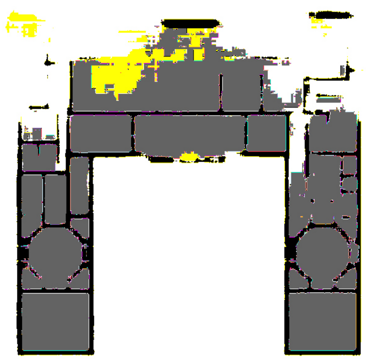
19	Galleria d’Arte Moderna

Milan | **1796 AD**



Housed in a beautiful historic building, the gallery presents a diverse collection of art-works from the 19th and 20th centuries. As you wander through the exhibition halls, you’ll encounter captivating paintings, sculptures, and installations by renowned Ital-ian and international artists. From the vibrant colors of the Fauvists to the bold exper-imentation of the Futurists, the gallery offers a glimpse into the ever-evolving world of modern art. Whether you’re an art aficionado or simply seek-ing creative inspiration, a visit to Galleria d’Arte Moderna is sure to be a rewarding experi-ence.

CubiCasa5k segmentation



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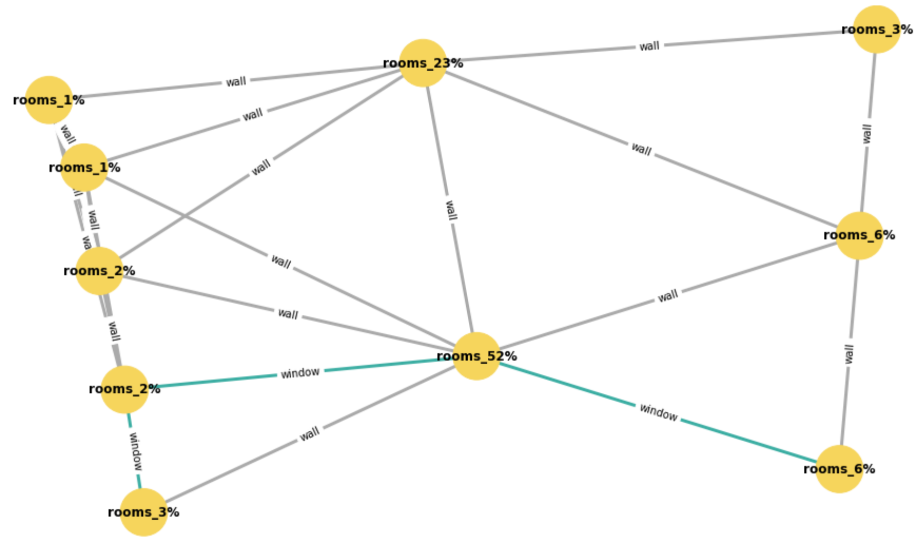

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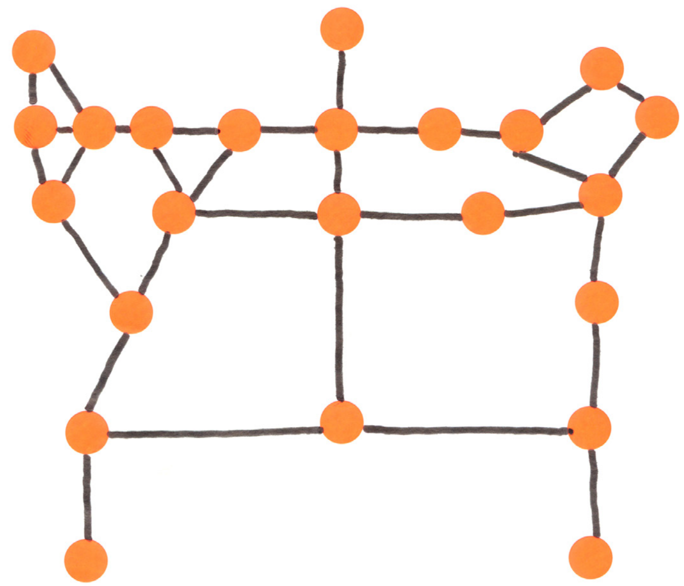
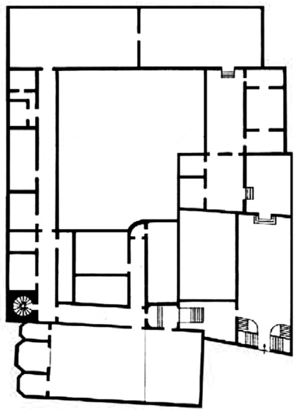


20

Gallerie dell’Accademia

Venice	1817 AD

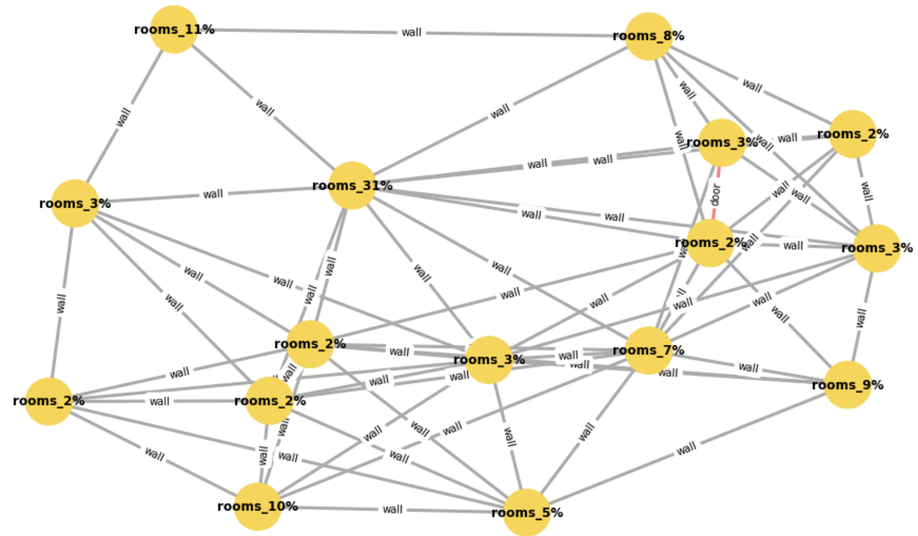


A prestigious art museum dedicated to the preservation and display of Venetian art. The museum’s impressive collection showcases the development of Venetian painting from the 14th to the 18th century. As you explore the gallery’s rooms, you’ll be captivated by masterpieces by renowned Venetian artists such as Bellini, Carpaccio, Giorgione, Titian, and Tintoretto. The collection includes iconic works like Bellini’s “Sacred Conversation” and Titian’s “Assumption of the Virgin,” among many others.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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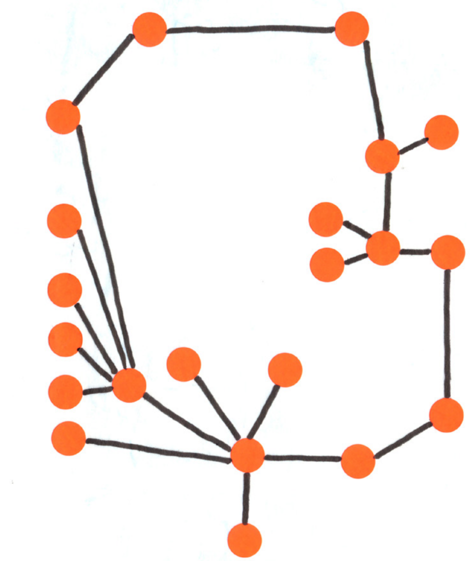
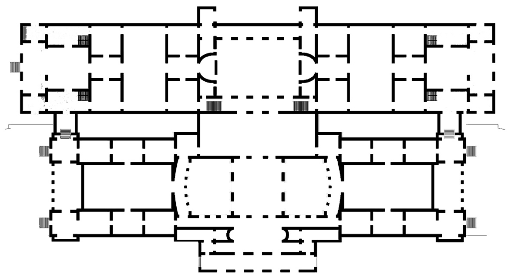


21

Nazionale d'Arte Moderna e Contemporanea

Rome	1883 AD

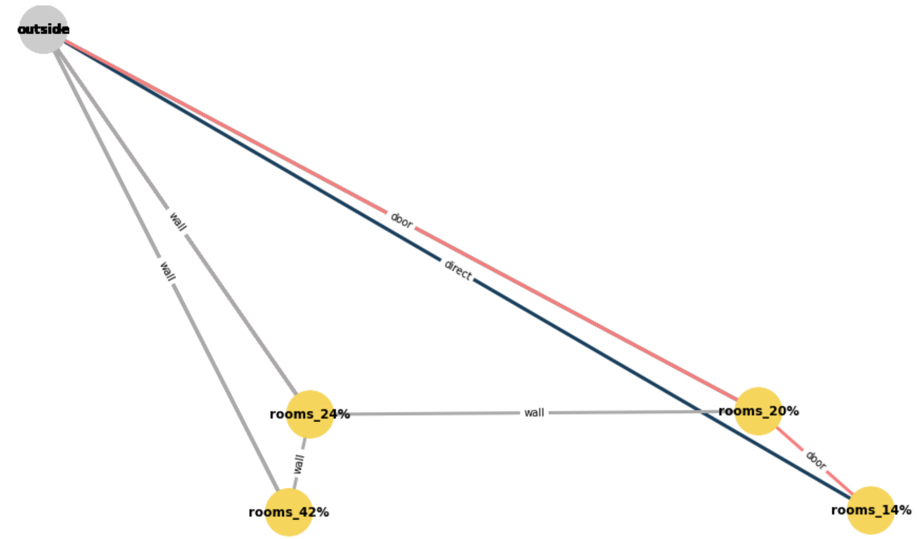


Nazionale d'Arte Moderna e Contemporanea, located in Rome, is a prominent museum dedicated to modern and contemporary art. Its extensive collection showcases artworks from the 19th century to the present day, representing various artistic movements and styles. As you explore the museum, you'll encounter works by renowned artists such as Balla, Morandi, Modigliani, De Chirico, and many others. From paintings and sculptures to photography and installations, the museum offers a diverse range of artistic expressions that reflect the ever-evolving nature of contemporary art

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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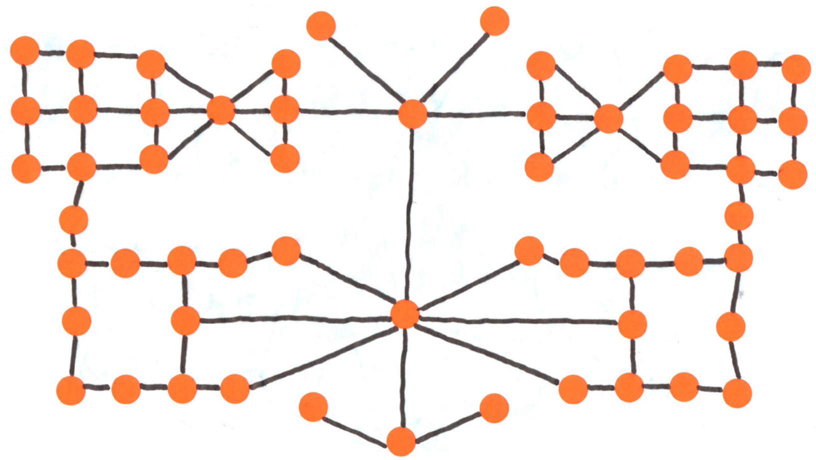
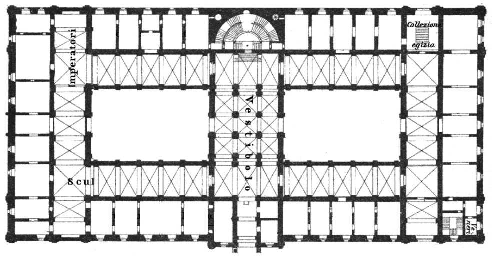


22

National Museum of Rome

Rome	1887 AD

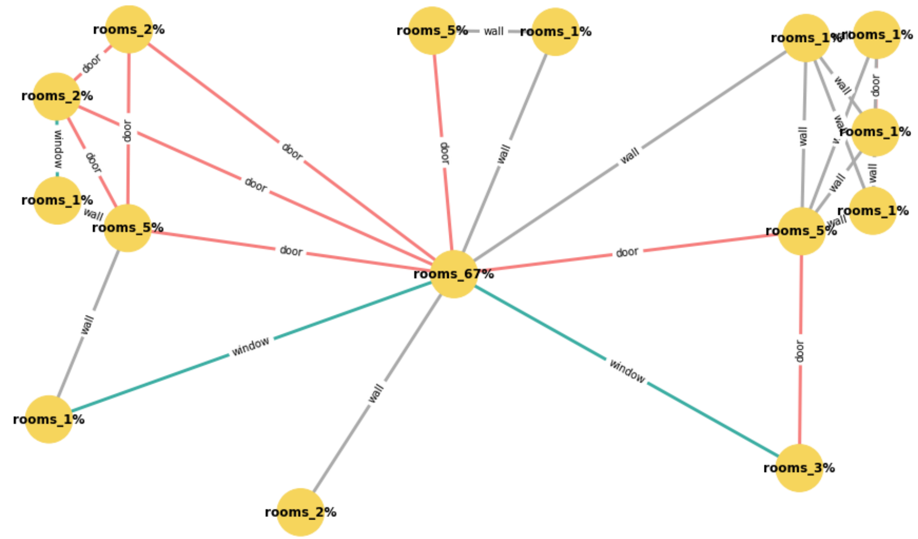


Spanning multiple buildings, including the Palazzo Massimo, Palazzo Altemps, Crypta Balbi, and Baths of Diocletian, the museum offers a comprehensive view of Roman history and culture. From intricate sculptures and intricate mosaics to exquisite frescoes and ancient coins, the museum's collections showcase the artistic and architectural achievements of the Roman Empire. Visitors can immerse themselves in the grandeur of ancient Rome as they explore the museum's halls and galleries, gaining insights into the daily life, mythology, and historical events of this legendary civilization

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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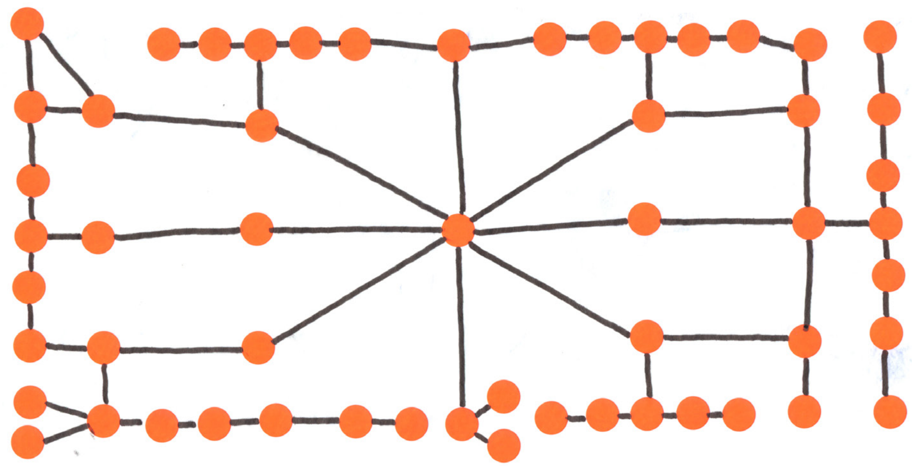
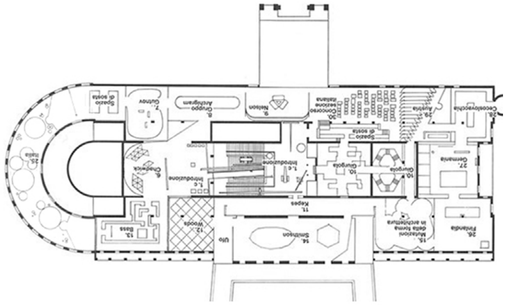


23 Triennale di Milano

Milan	1933 AD

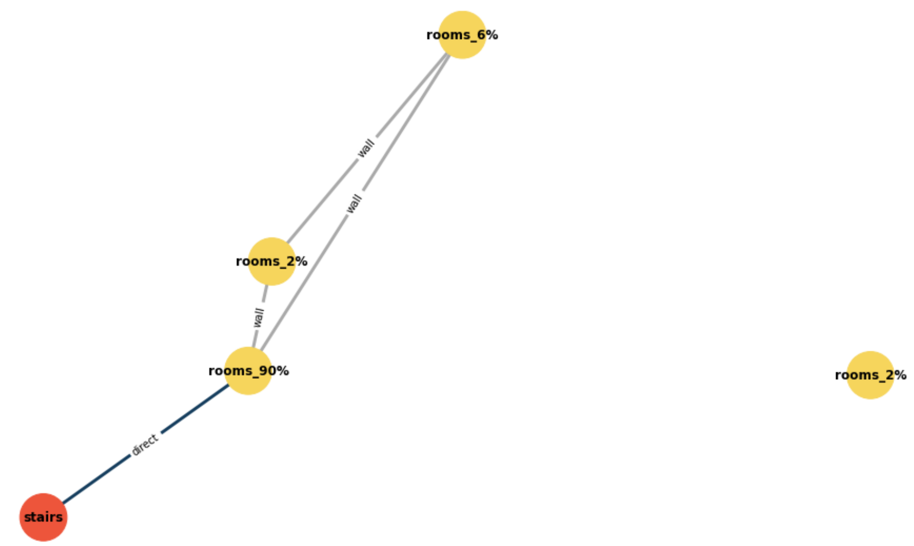


The museum hosts a diverse range of exhibitions, installations, and events that showcase the latest trends and developments in design and creativity. With a focus on interdisciplinary collaboration and experimentation, the Triennale di Milano fosters dialogue and exploration among artists, designers, and thinkers from around the world. Its iconic building, designed by Giovanni Muzio, provides a stunning backdrop for the exhibitions and creates an immersive environment for visitors to engage with contemporary art and design.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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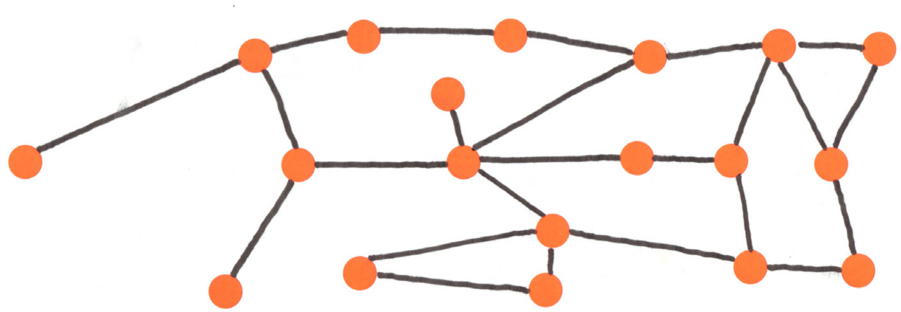
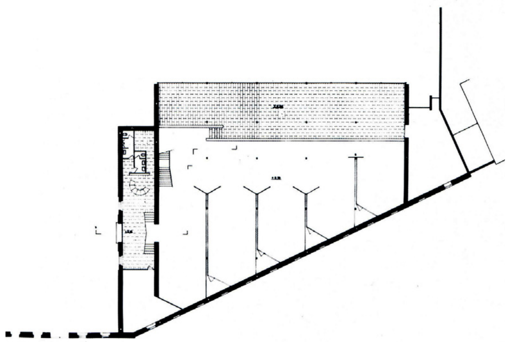


24 PAC - Contemporary Art Pavilion



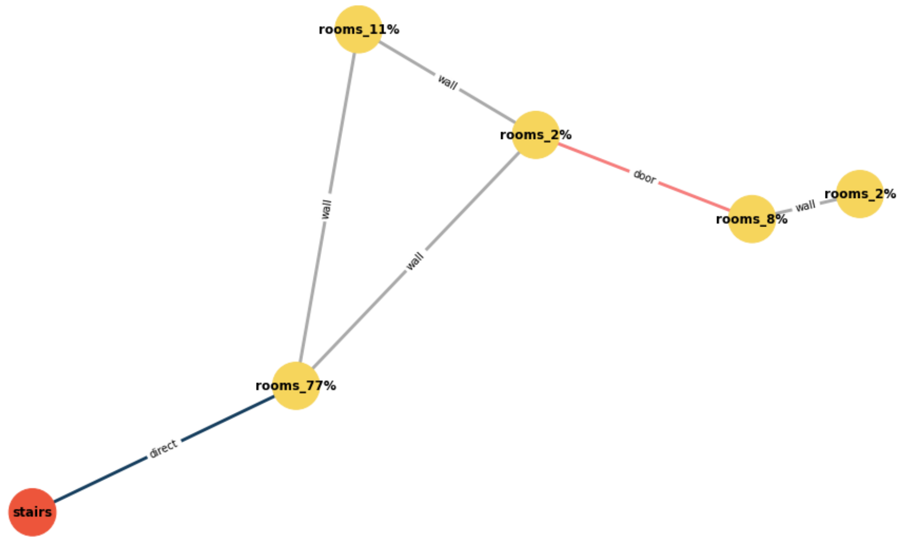
Milan	1947 AD

The gallery features a diverse range of artistic mediums, including painting, sculpture, photography, video, and installations, creating an immersive and engaging experience for visitors. With its ever-changing exhibitions and curated programs, the Contemporary Art Pavilion aims to stimulate dialogue and reflection on contemporary artistic practices and their relevance to society. The space is known for its bold and experimental approach, pushing the boundaries of traditional art forms and encouraging visitors to explore new perspectives.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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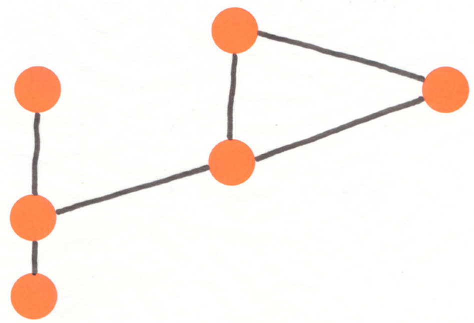
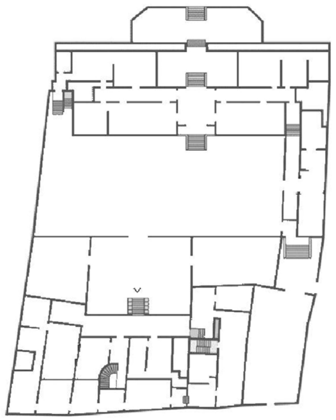


25

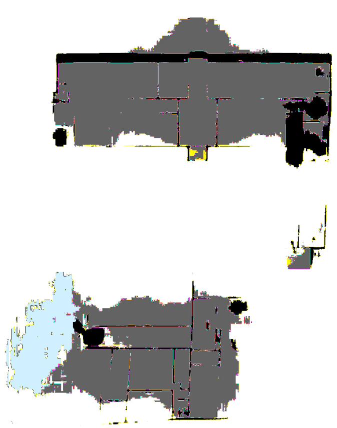
Peggy Guggenheim Collection

Venice	1951 AD



The Peggy Guggenheim Collection in Venice is a captivating art museum located on the Grand Canal. Housed in the Palazzo Venier dei Leoni, the museum showcases an exceptional collection of modern art, including works by prominent artists such as Picasso, Pollock, and Dalí. With its scenic waterfront location and remarkable exhibits, the Peggy Guggenheim Collection offers visitors a unique and enriching art experience in the heart of Venice.

CubiCasa5k segmentation



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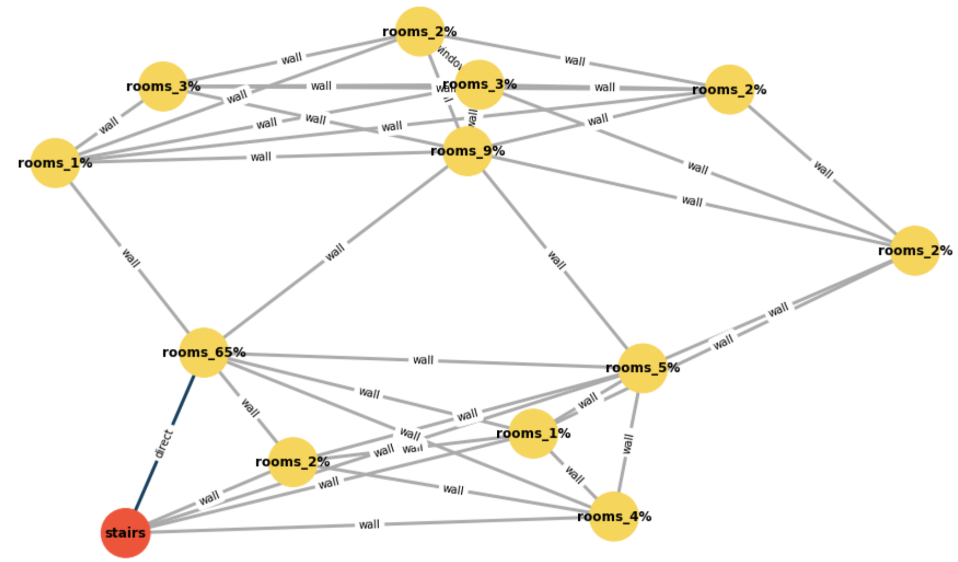

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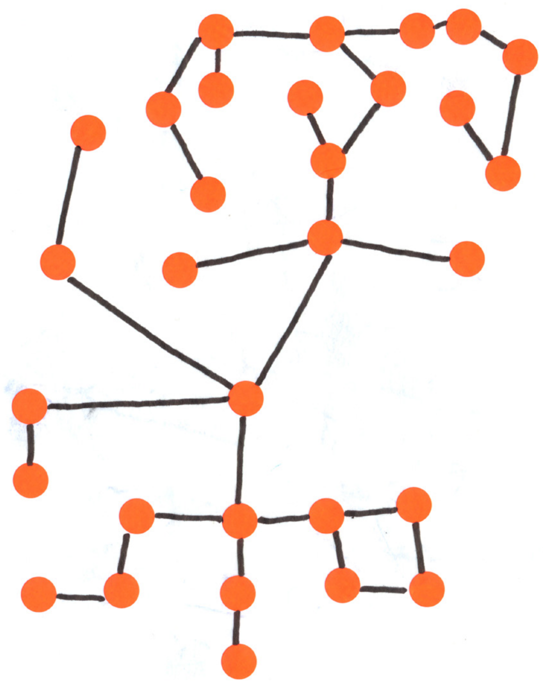
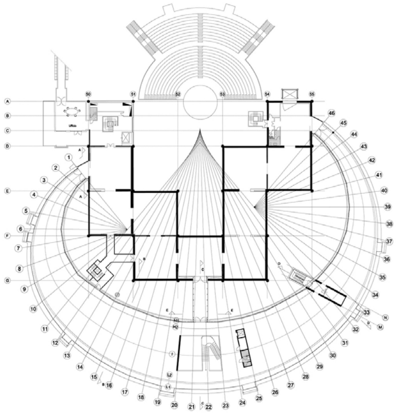


26

Luigi Pecci Contemporary Art Museum

Prato	1988 AD

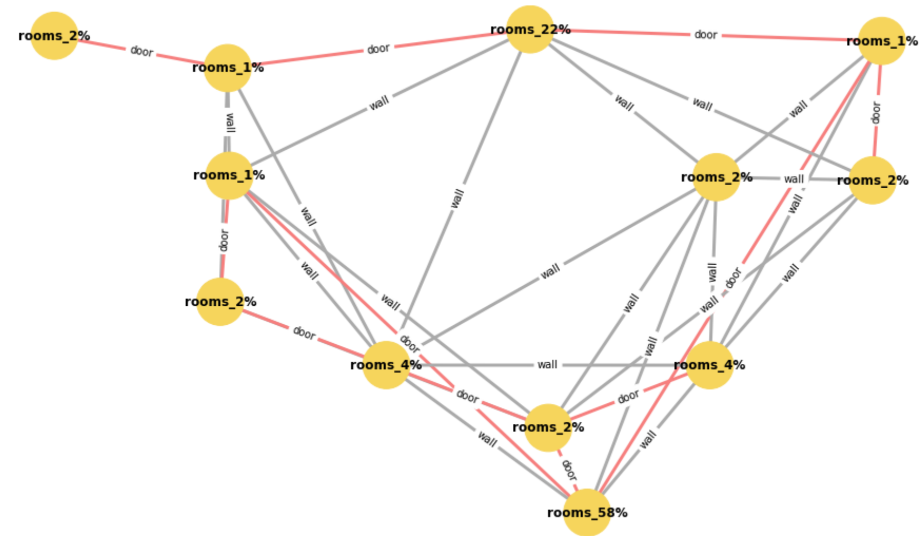


The Luigi Pecci Contemporary Art Museum in Prato is a dynamic cultural institution dedicated to contemporary art. Located in a striking architectural masterpiece, the museum showcases a diverse range of innovative and thought-provoking artworks from both Italian and international artists. With its engaging exhibitions, immersive installations, and vibrant programs, the Luigi Pecci Museum offers visitors a captivating journey through the world of contemporary art.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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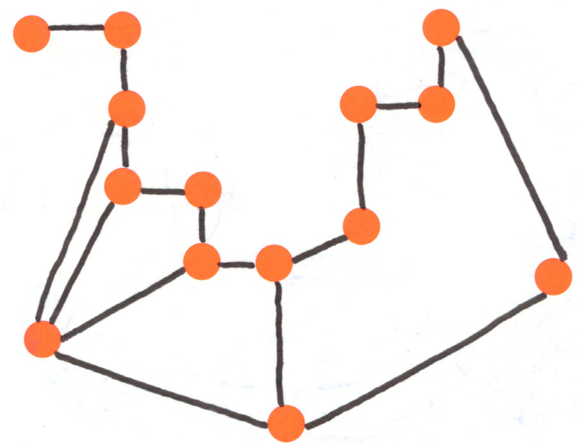


27 Centrale Montemartini

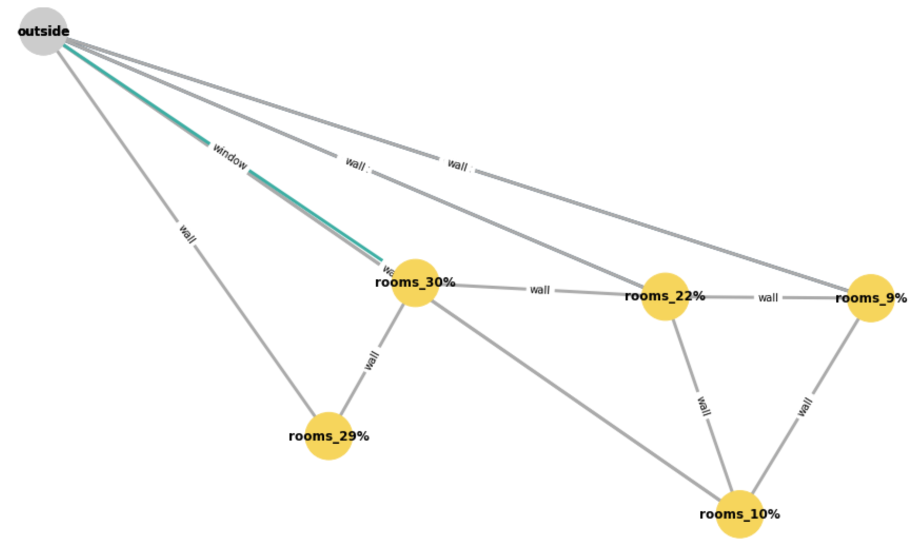
Rome	1997 AD

Centrale Montemartini in Rome is a unique museum that merges the worlds of art and industry. Housed in a former power plant, this captivating exhibition space showcases an extraordinary juxtaposition of ancient Roman sculptures and machinery from the early 20th century. The museum's industrial setting provides a striking backdrop for the classical artworks, creating a fascinating dialogue between ancient and modern. Centrale Montemartini offers visitors a one-of-a-kind experience, where the past and the present converge in a captivating and unexpected way.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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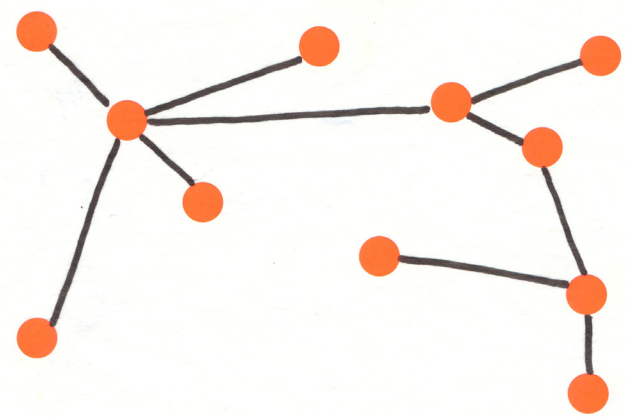
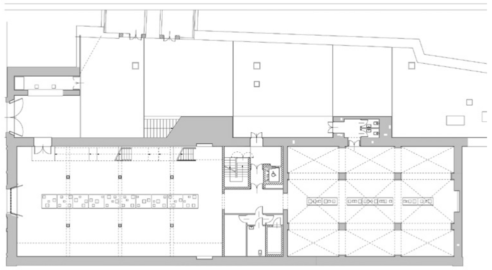


28

Tuscolano museum

Frascati | **2000 AD**

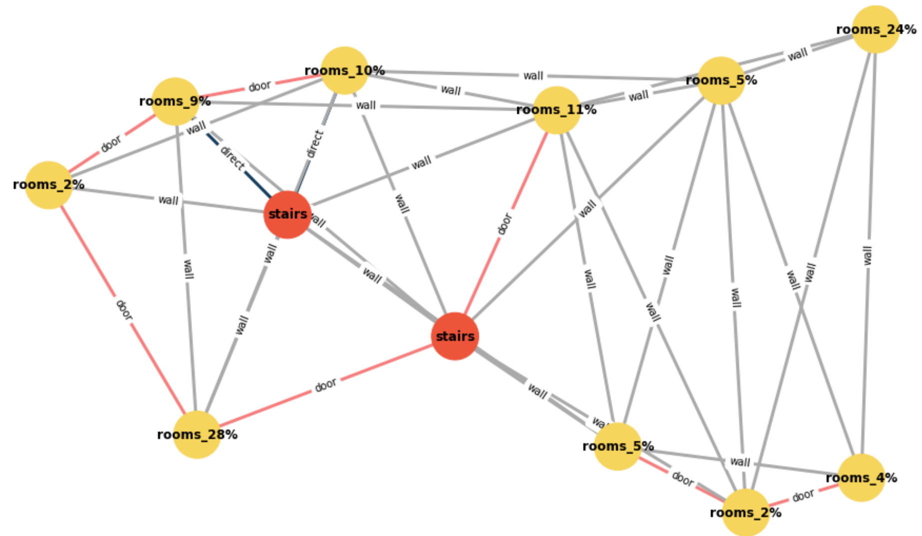


This museum is dedicated to preserving and showcasing the rich history and heritage of the Tusculum area. With its carefully curated exhibitions, visitors can immerse themselves in the fascinating stories of Tusculum's past, from its ancient Roman origins to its medieval and Renaissance periods. The museum's collection features archaeological artifacts, historical documents, and artistic masterpieces that offer a glimpse into the captivating history of this region

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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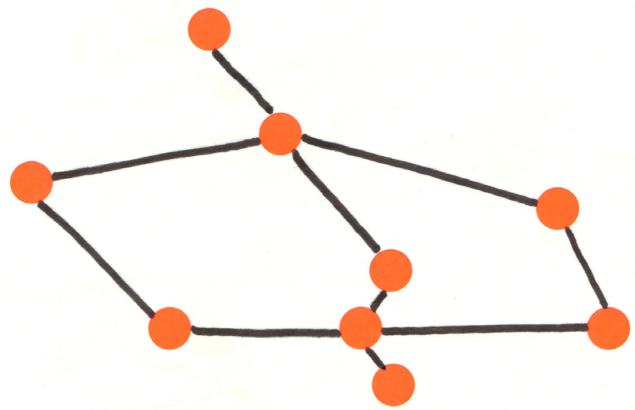
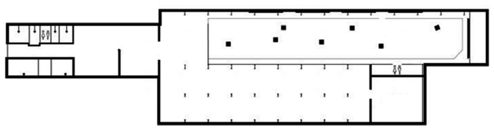


29

Pirelli HangarBicocca

Milan	2004 AD

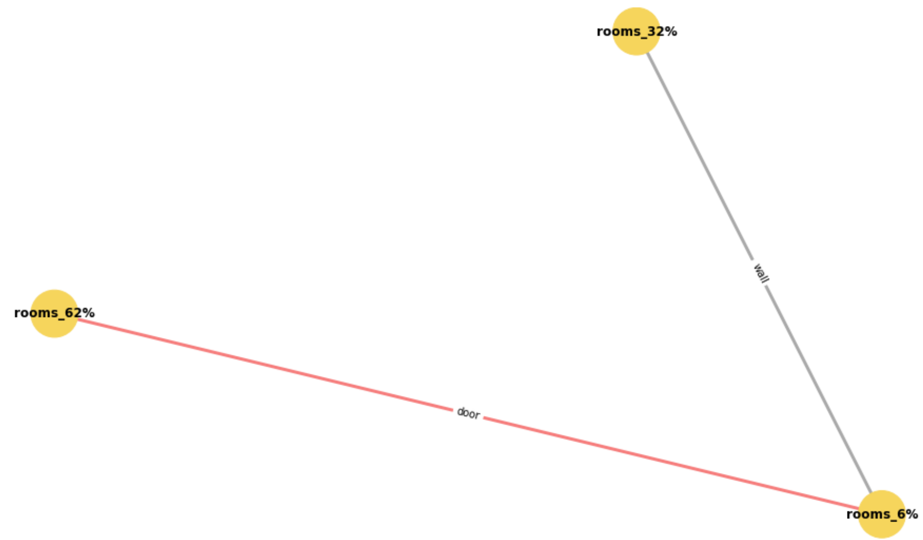


Pirelli HangarBicocca is a contemporary art space in Milan, Italy. It offers a vast industrial setting for immersive exhibitions and showcases innovative works by international artists. With its dynamic program, interactive exhibits, and engaging events, Pirelli HangarBicocca provides a vibrant platform for exploring and experiencing contemporary art. The museum also features an auditorium, bookshop, and café, creating a welcoming space for art enthusiasts to gather and engage with the artistic community.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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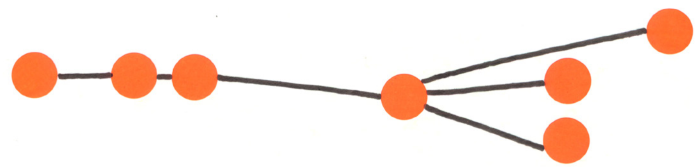
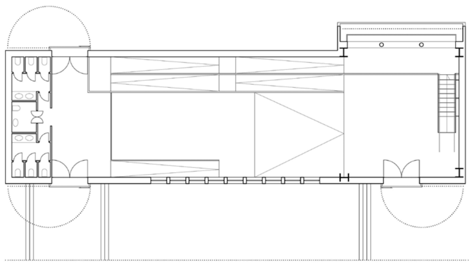


30

Mostra d’Oltremare

Napoli	2004 AD

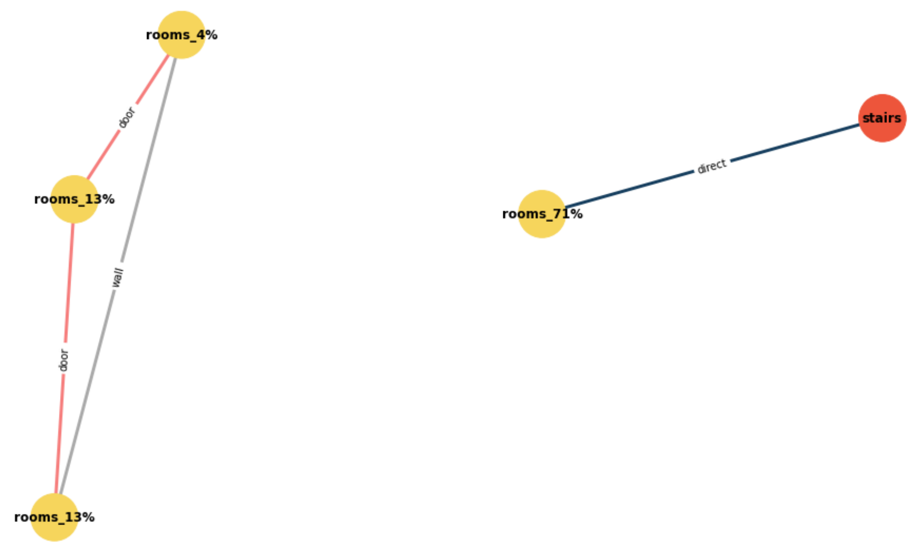


Mostra d’Oltremare is a multifunctional exhibition complex located in Naples, Italy. It serves as a versatile venue for hosting various events, including trade fairs, conferences, concerts, and cultural exhibitions. The expansive site encompasses indoor and outdoor exhibition spaces, conference halls, theaters, gardens, and recreational areas. Mostra d’Oltremare offers a dynamic and vibrant atmosphere, attracting visitors from different backgrounds to explore and participate in a wide range of cultural, artistic, and commercial activities.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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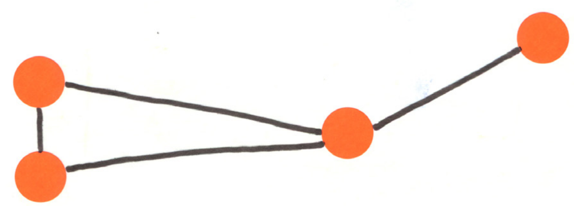
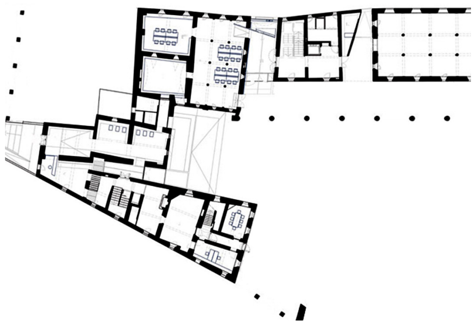


31

La corte cultural and civic centre

Padua	2006 AD

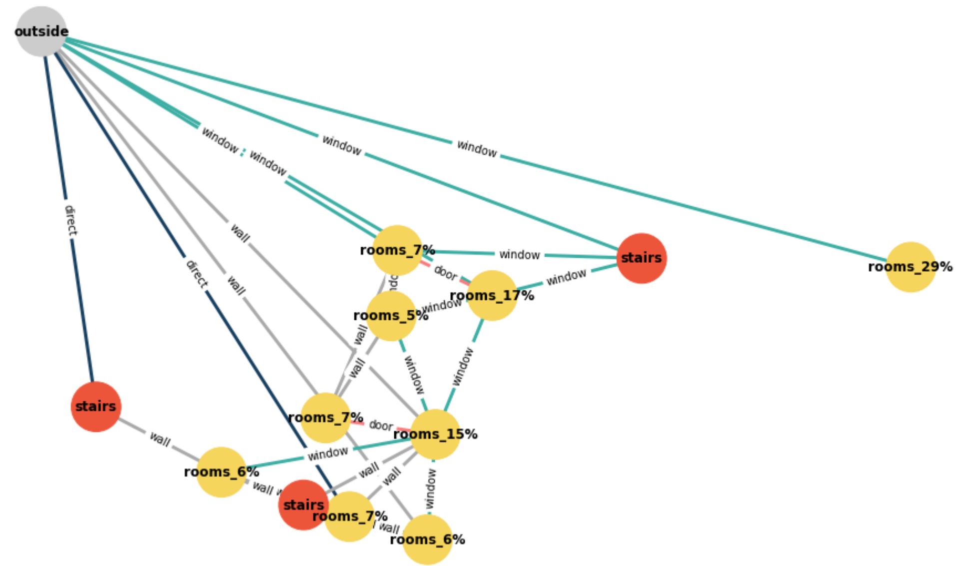


From art exhibitions and live performances to educational workshops and community gatherings, La Corte serves as a hub for creativity, learning, and social interaction. With its modern design and versatile spaces, it provides an inviting and dynamic environment for residents and visitors to engage with arts, culture, and community initiatives. Whether you're seeking inspiration, entertainment, or opportunities to connect with others, La Corte offers a vibrant cultural experience in the heart of Padua.

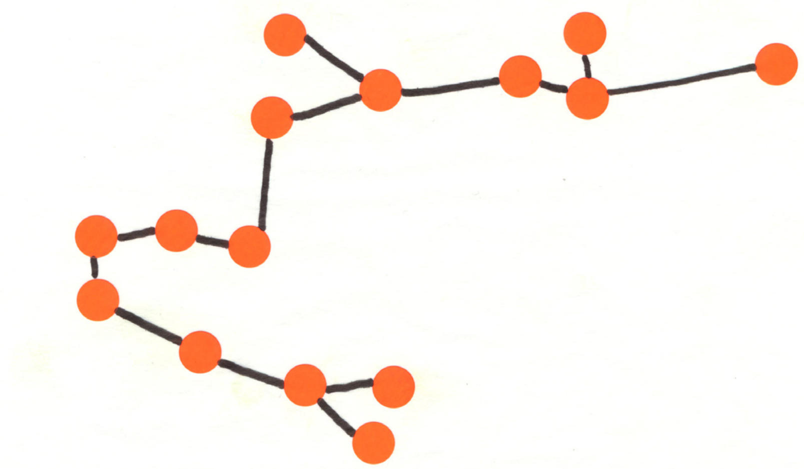
CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



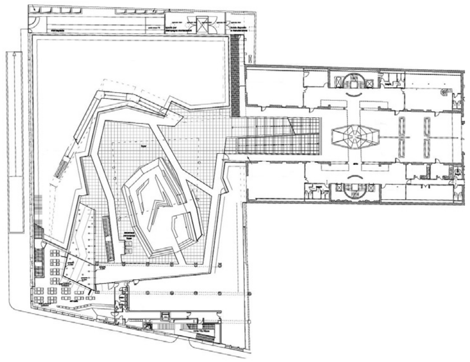
Ground truth



32

Museum of Contemporary Arts

Rome	2007 AD

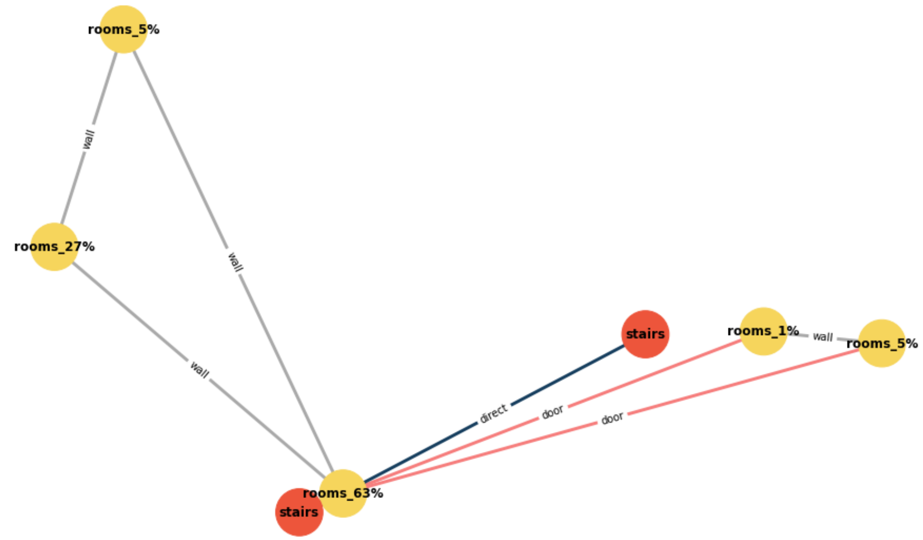


This museum provides a platform for emerging and established artists to exhibit their innovative works across various mediums. With its dynamic and ever-changing exhibitions, visitors can immerse themselves in thought-provoking installations, striking sculptures, experimental video art, and engaging multimedia presentations. The Museum of Contemporary Arts offers a unique and inspiring experience for art enthusiasts, fostering dialogue, pushing boundaries, and exploring the latest trends and expressions in contemporary art.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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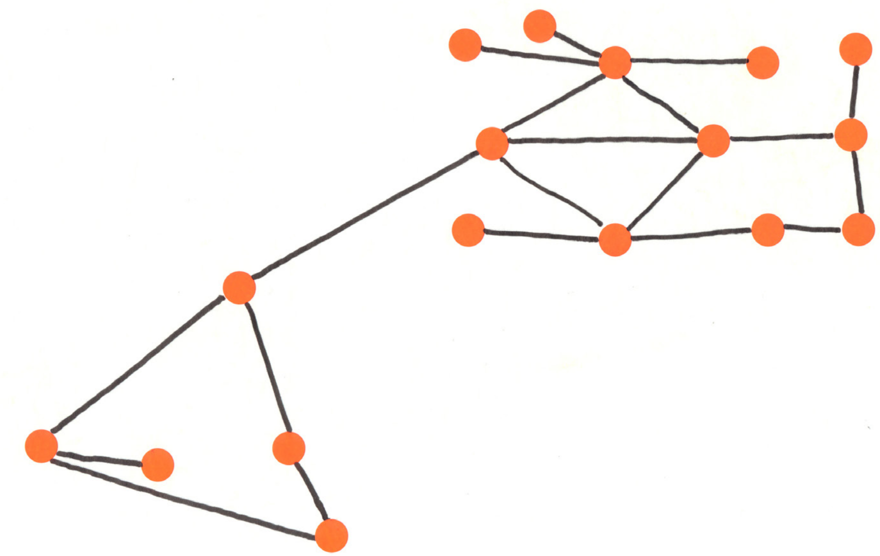
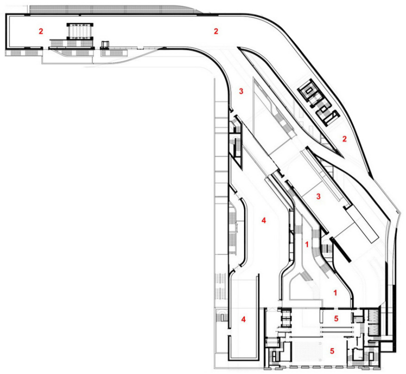


33

MAXXI - National Museum of 21st Century Art

Rome	2009 AD

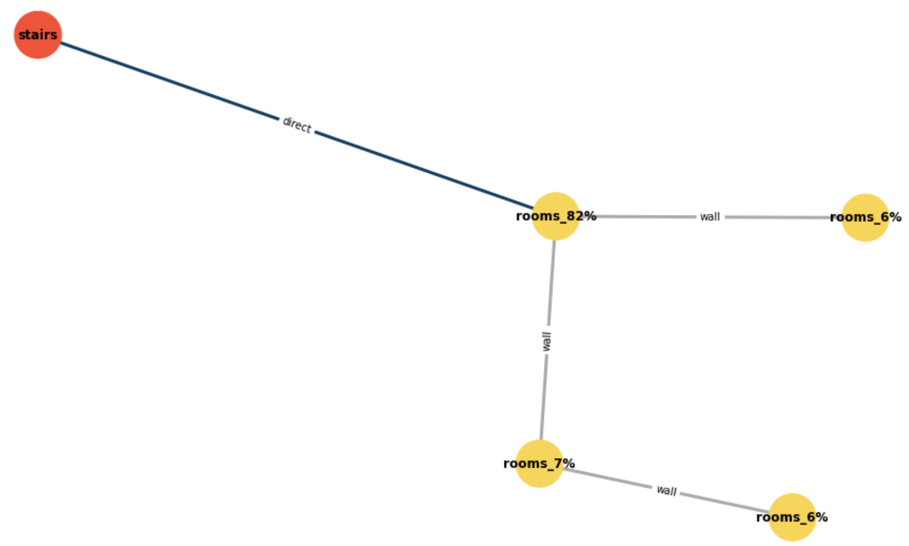


The museum's striking, avant-garde building itself is a work of art. MAXXI offers an immersive experience where visitors can explore a diverse range of exhibitions and installations by both Italian and international artists, spanning various disciplines including painting, sculpture, photography, design, and new media. With its innovative approach to showcasing contemporary creativity, MAXXI is a must-visit destination for art lovers seeking inspiration and an insight into the artistic expressions of the 21st century.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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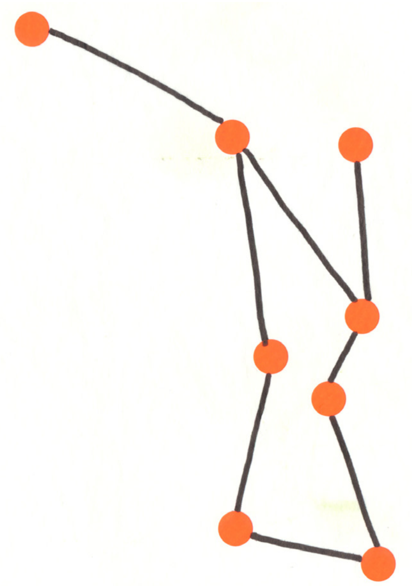
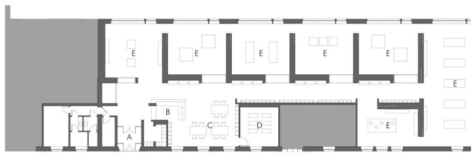


34 Le Stanze del Vetro



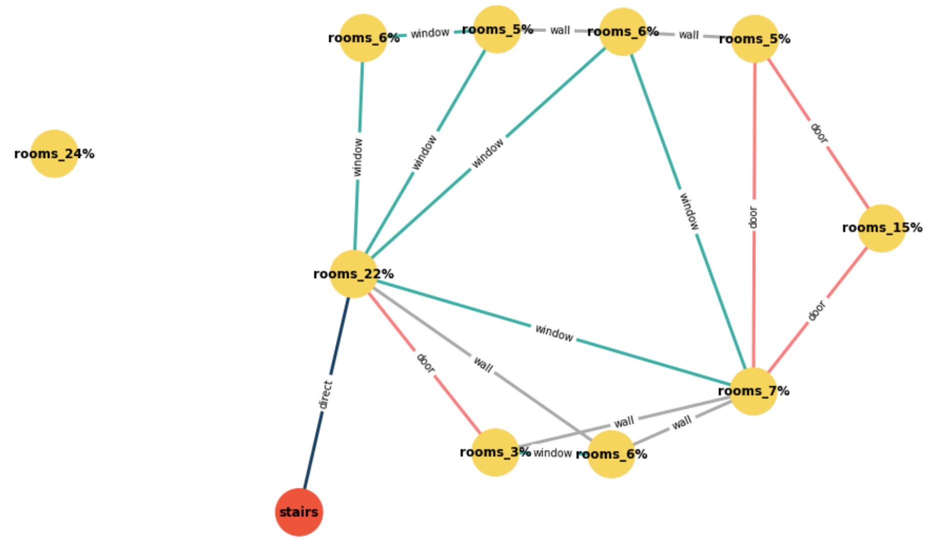
Venice | **2012 AD**

The museum showcases an exquisite collection of glass-works, ranging from ancient masterpieces to contemporary creations. Visitors can marvel at the intricate craftsmanship, delicate forms, and vibrant colors of the glass pieces on display. Through its carefully curated exhibitions, Le Stanze del Vetro offers a fascinating exploration of the rich history, artistic traditions, and technical innovations of glassmaking. It is a haven for anyone interested in the beauty and versatility of this unique medium, providing a glimpse into the world of glass artistry and its ongoing evolution.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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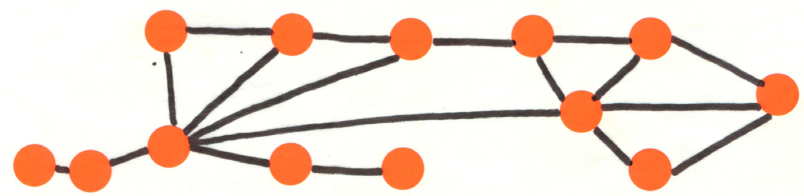
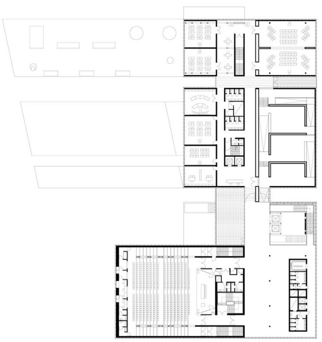


35

MAST Foundation

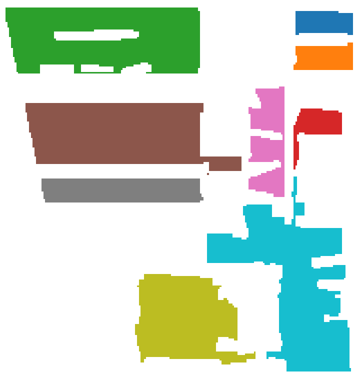
Bologna	2013 AD



MAST Foundation, situated in Bologna, is a dynamic cultural institution dedicated to the exploration of industry, art, and innovation. It offers a captivating space where visitors can engage with contemporary art exhibitions, thought-provoking installations, and multimedia displays that bridge the gap between art and technology. The foundation's mission is to foster dialogue, creativity, and critical thinking by showcasing the works of both established and emerging artists, while also delving into the social, economic, and environmental aspects of industrial production

CubiCasa5k segmentation

Robust-AAG segmentation



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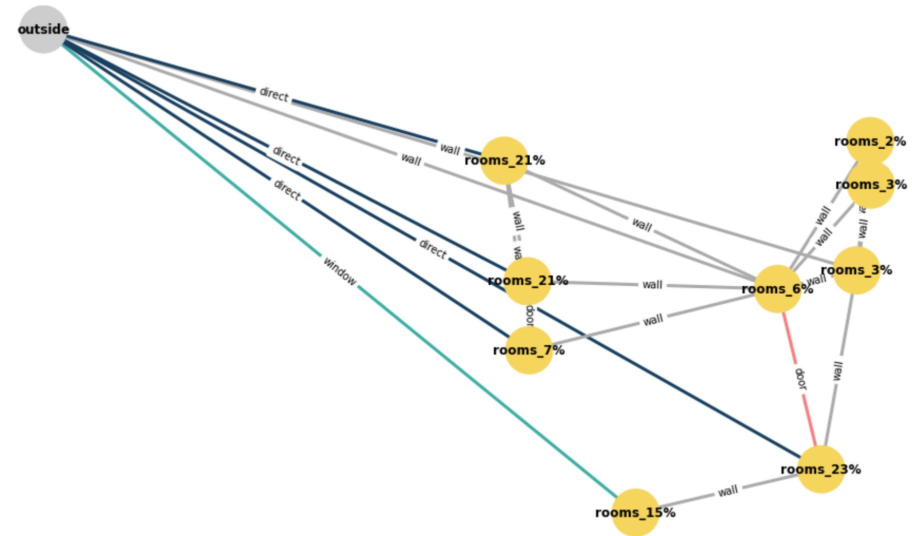

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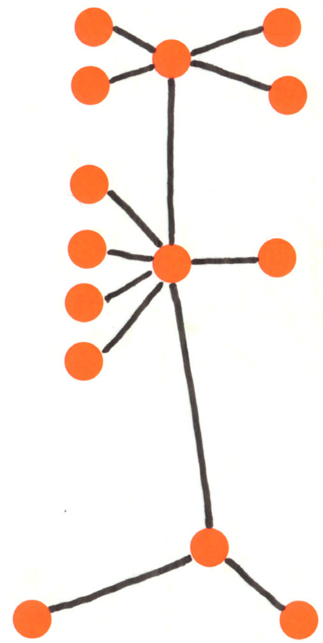
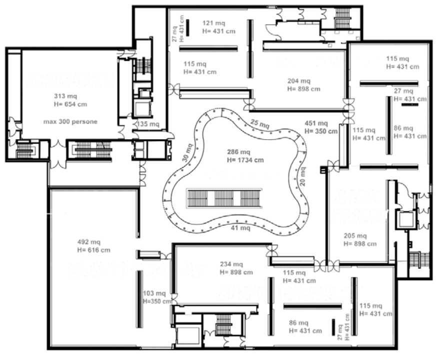


36

Museo delle Culture (MUDEC)

Milan	2015 AD

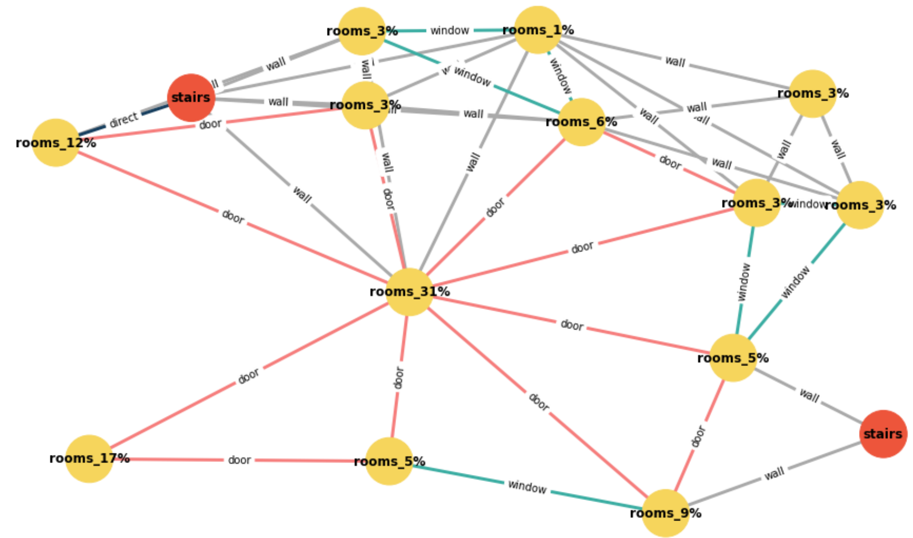


It is dedicated to exploring and celebrating the diverse cultures of the world through a rich collection of artifacts, artworks, and multimedia exhibits. MUDEC offers a captivating journey that takes visitors on a global exploration, showcasing the richness and diversity of human heritage and traditions. From ancient civilizations to contemporary cultures, the museum offers a dynamic and immersive experience that fosters intercultural understanding and dialogue. MUDEC serves as a platform for cultural exchange, promoting inclusivity, tolerance, and appreciation for the global tapestry of cultures that shape our world.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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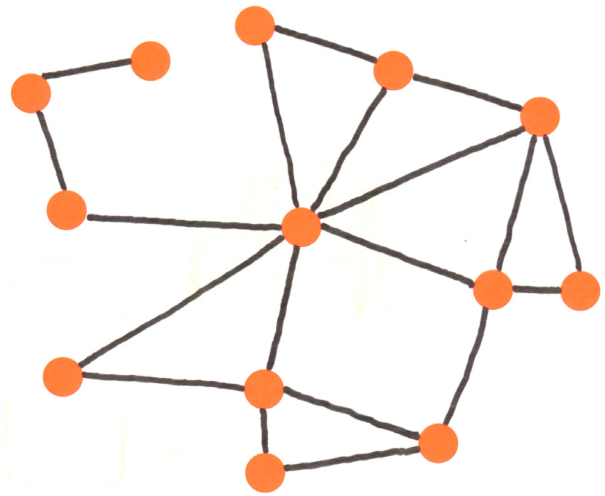
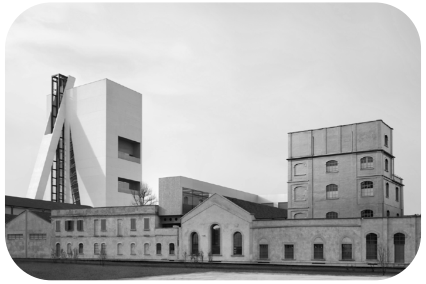
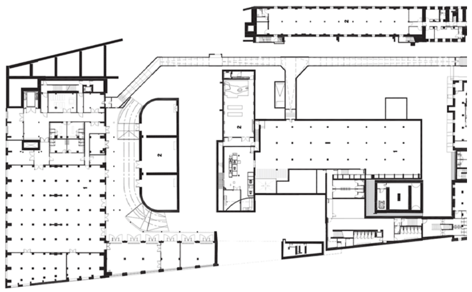


37

Fondazione Prada

Milan | **2015 AD**



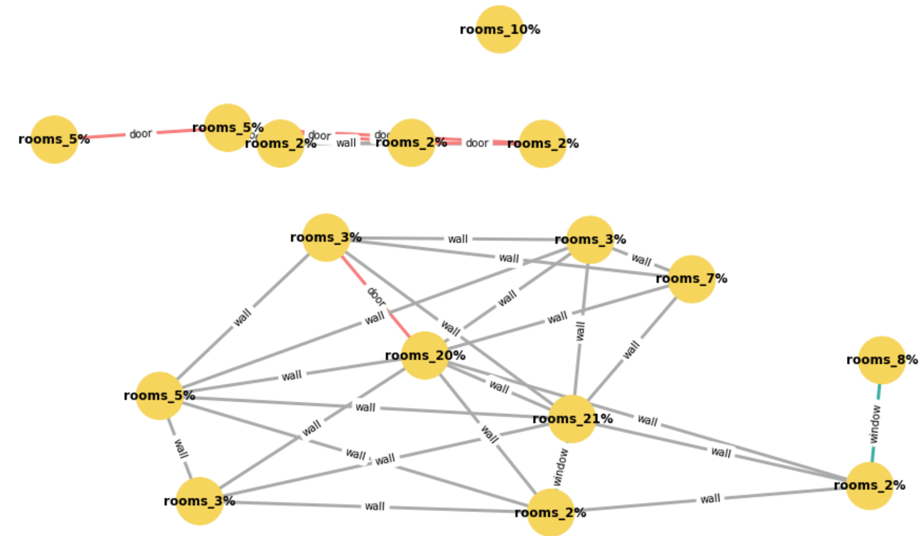


The foundation houses a diverse range of contemporary art exhibitions, installations, and projects that push boundaries and challenge traditional notions of art. With its unique blend of art, architecture, and culture, Fondazione Prada offers visitors an immersive and thought-provoking experience. The institution also hosts educational programs, film screenings, and performances, fostering dialogue and engagement with the arts. Through its dynamic and innovative approach, Fondazione Prada continues to contribute to the global art scene and enrich the cultural landscape of Milan.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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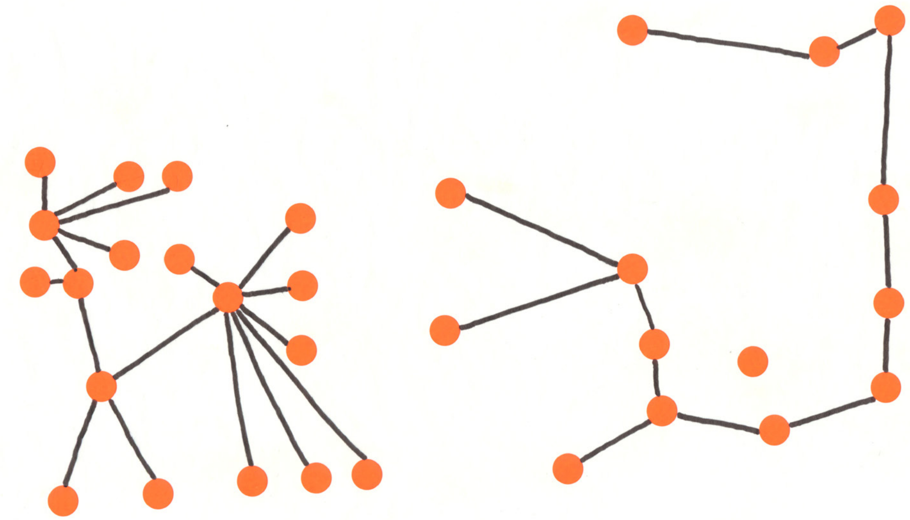


38

M9 Museum District

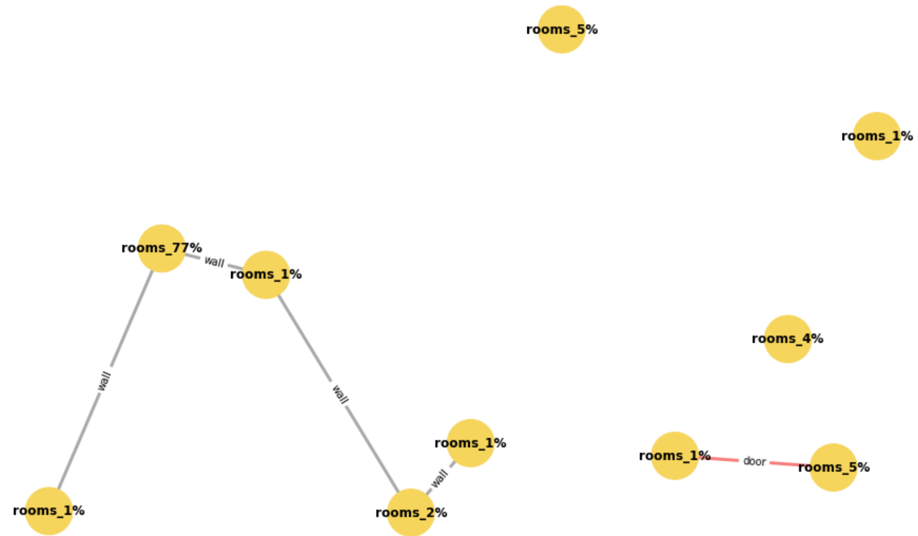
Venice	2018 AD

Offering visitors a dynamic and immersive experience that explores the history, culture, and contemporary aspects of the city. The district encompasses various museums, exhibitions, and interactive spaces, showcasing a diverse range of topics and artistic expressions. From art and design to history and technology, M9 Museum District presents a multifaceted exploration of Venetian heritage and global influences. With its innovative and interactive approach, it invites visitors to engage with the exhibits and participate in engaging activities.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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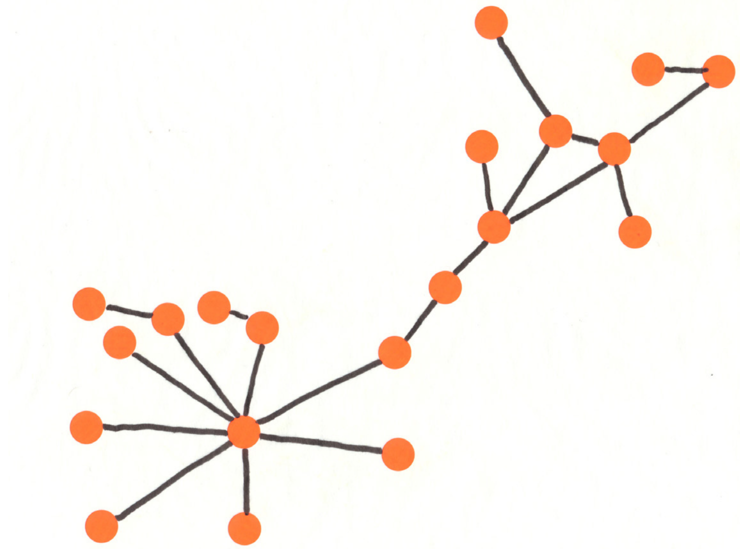
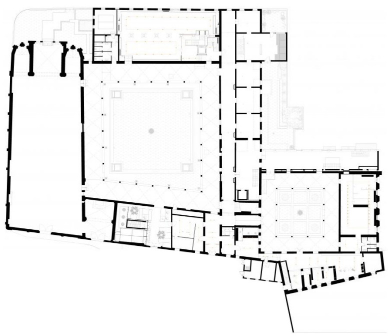


39

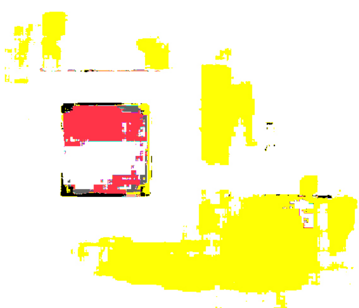
Santa Caterina Museum



Treviso	2018 AD

Housed in a historic building, the museum showcases a remarkable collection of art and artifacts, spanning various periods and artistic styles. Visitors can explore the museum's diverse exhibits, which include paintings, sculptures, archaeological finds, and religious artifacts. The museum offers a glimpse into the rich history and cultural heritage of Treviso, highlighting the artistic achievements and historical significance of the region

CubiCasa5k segmentation



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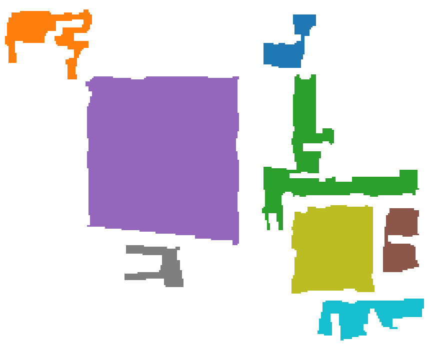

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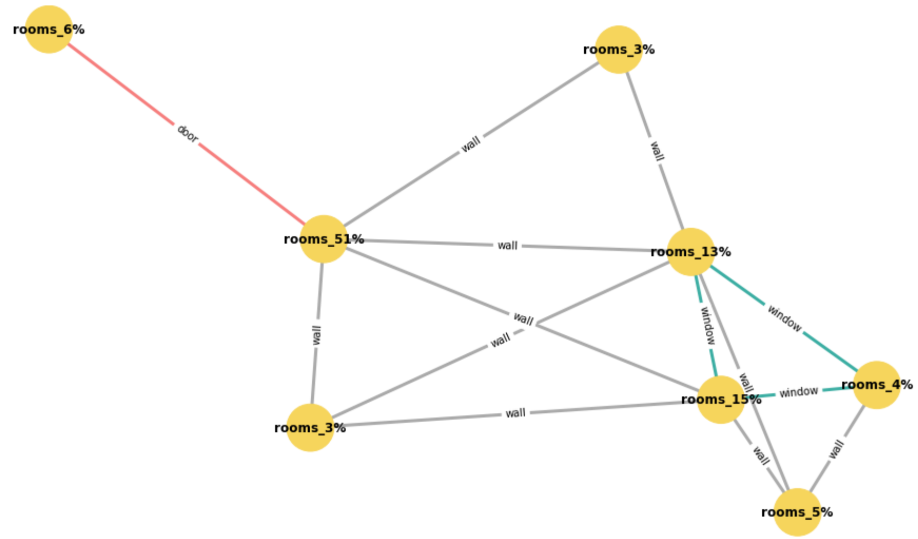

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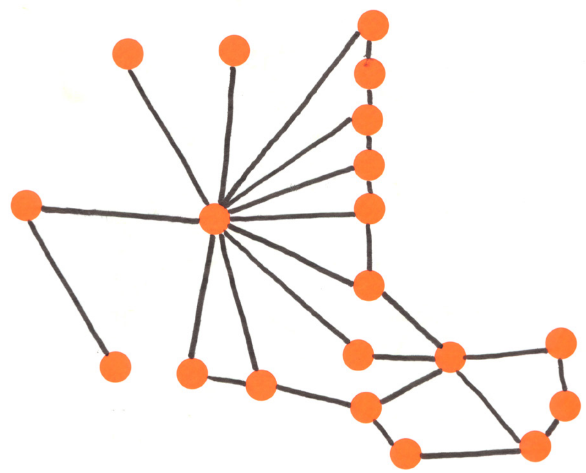
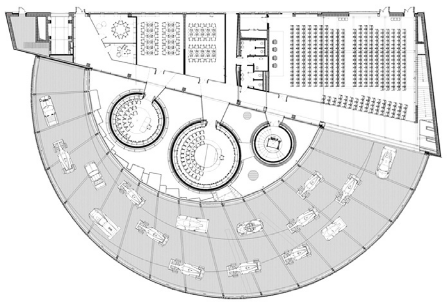


40	Dallara Academy

Parma	2018 AD

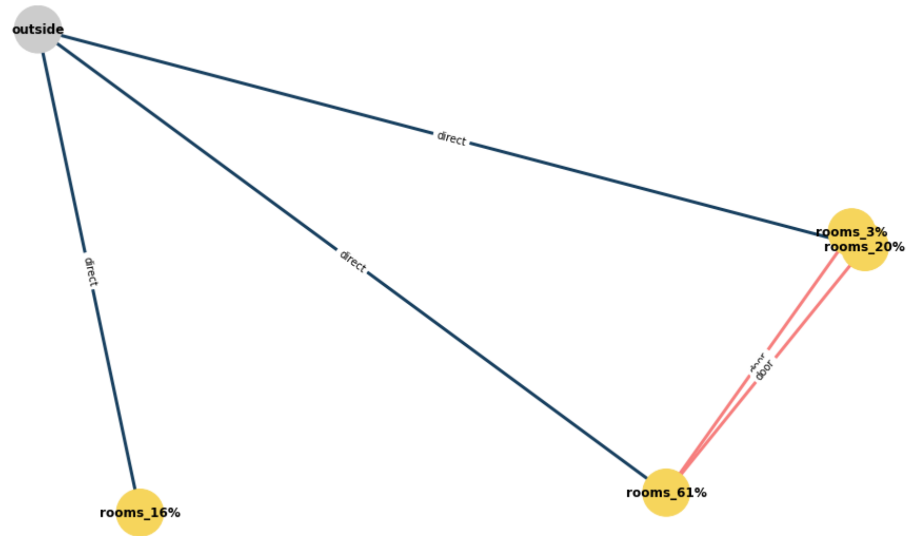


Designed as a center for automotive excellence, the academy offers a blend of education, research, and technology. It serves as a hub for motorsports enthusiasts, engineers, and students interested in automotive design and performance. The academy features state-of-the-art facilities, including classrooms, laboratories, and simulation rooms. It also houses a captivating exhibition area, showcasing iconic racing cars, technical displays, and interactive exhibits that highlight the rich history and cutting-edge advancements in motorsports.

CubiCasa5k segmentation

Robust-AAG segmentation

Robust-Attributed Adjacency graph



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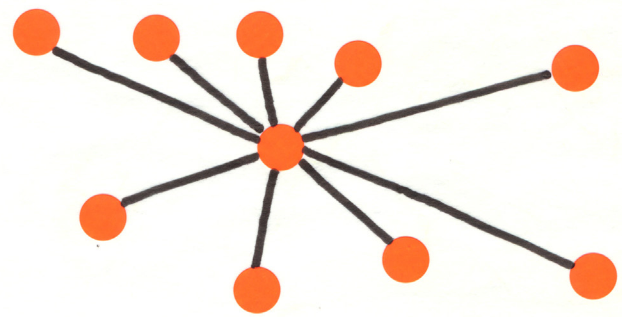

I would like to express my heartfelt appreciation to all those who contributed to the ideation and development of this thesis, and for their unwavering support throughout the entire process. I am particularly grateful to Casper for his invaluable contributions during our collaborative brainstorming sessions and in assistance towards implementing majority of the coding tasks. Without their involvement, this research would not have achieved its significant progress.

The realm of architectural design and conceptualization, despite witnessing advancements in design complexity facilitated by technological tools and fabrication techniques, appears to have experienced limited transformative change over time in the way we begin our design process. But is there an alternative way to look at architecture ? Perhaps a completely different way to begin a project ? Can the age of data abundance cause a shift in the way we look at architectural design ?

Delft University of Technology