Carbon Uptake Estimation of U.S. Building Sector: Insights from Single Building Elements to the National Building Stock

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ACI Concrete Convention Spring 2024

March 24, 2024

Motivation

Annual carbon uptake roughly 20% + 3% of national calcination emissions from existing building stock in use + end-of-life phases, respectively

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17% of production emissions
Carbon uptake of existing building stock, using previous 100 years' cement consumption
Sweden

10% of production emissions
Carbon uptake of one year's production during coming 50 years
Switzerland

18% of production emissions, incl. recovery
Carbon uptake of one year's production during coming 100 years
Norway

43% of calcination emissions
Carbon uptake of existing building stock, using previous 70 years' cement consumption
Global

23% of production emissions, incl. end-of-life
Carbon uptake of one year's production during coming 60 years
Netherlands

17% of calcination emissions
Carbon uptake of one year's production during coming 100 years
Switzerland

16% of calcination emissions
Carbon uptake of one year's production during coming 100 years
Ireland

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OBJECTIVE

Create clear guidelines for carbon uptake estimation

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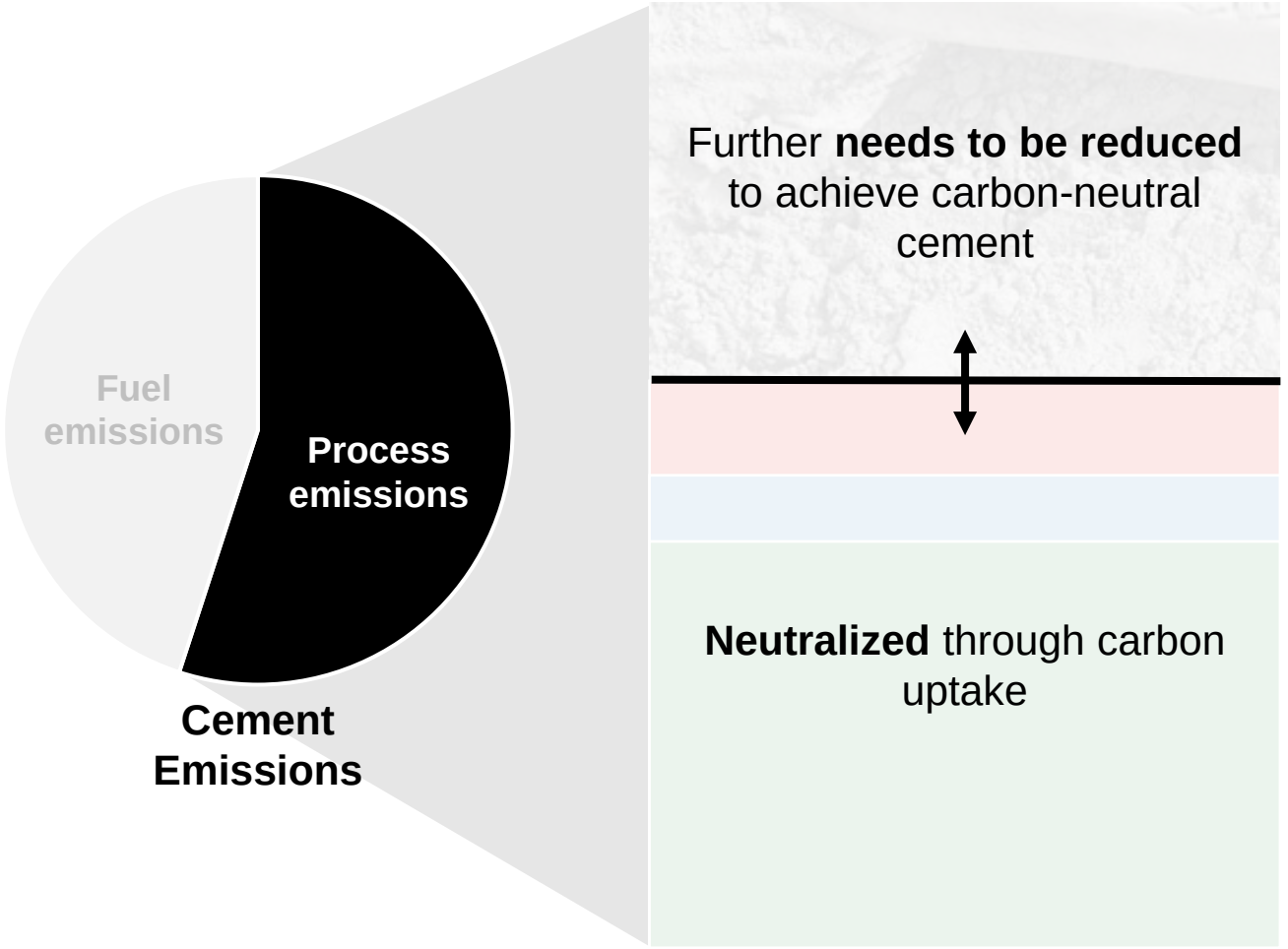
- Evaluate potential for carbon uptake to neutralize cement emissions (This presentation focuses on process or calcination emissions)
- Inform methods for environmental product declarations and greenhouse gas accounting
- Engage stakeholders to leverage properties of cement-based products to reach carbon neutrality targets

Methods

Crucial to produce *realistic estimate* of carbon uptake—*underestimate* understates benefits of cement-based products, while *overestimate* understates need for emissions abatement solutions

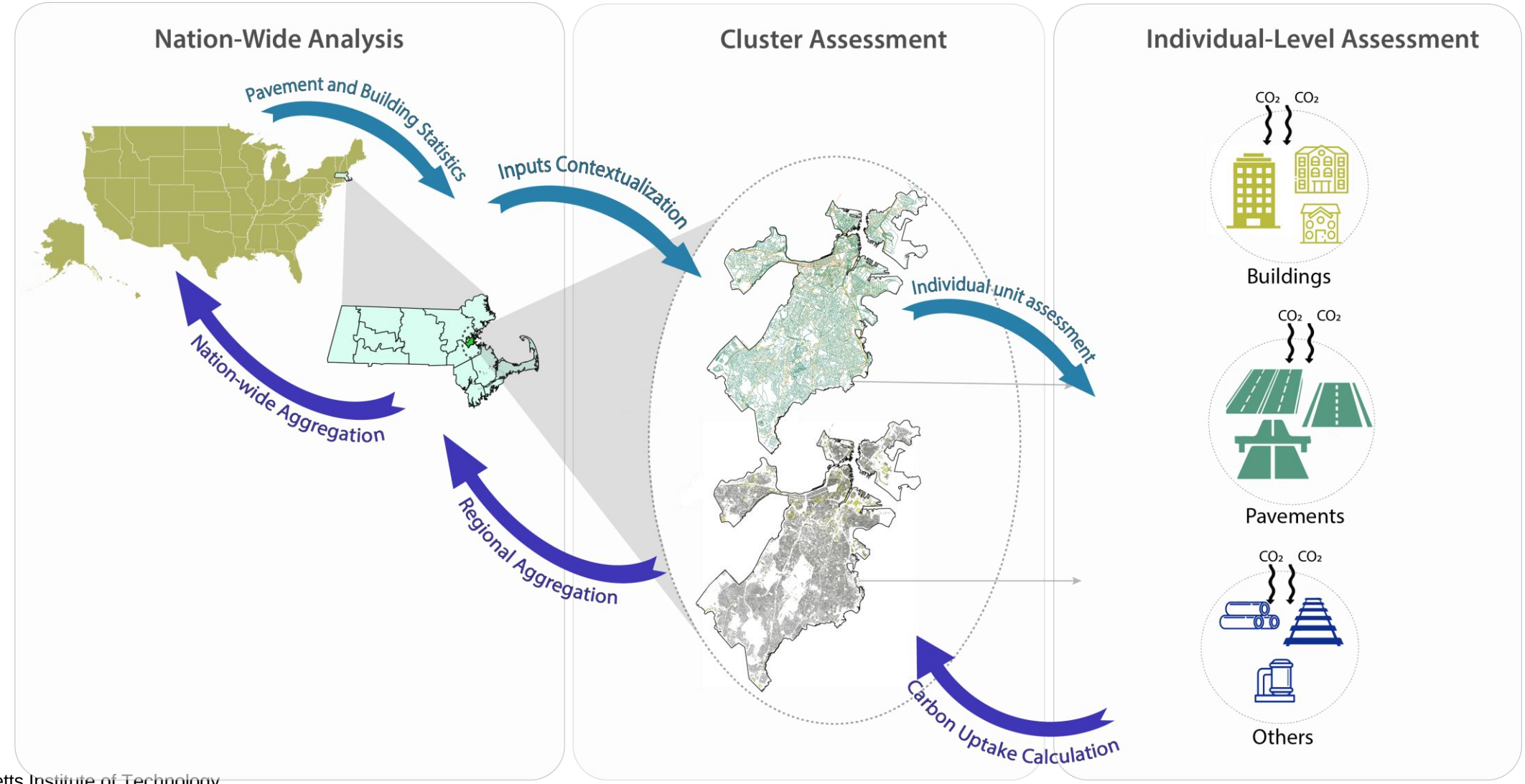


nature comms
"60%"
Cao et al. 2020

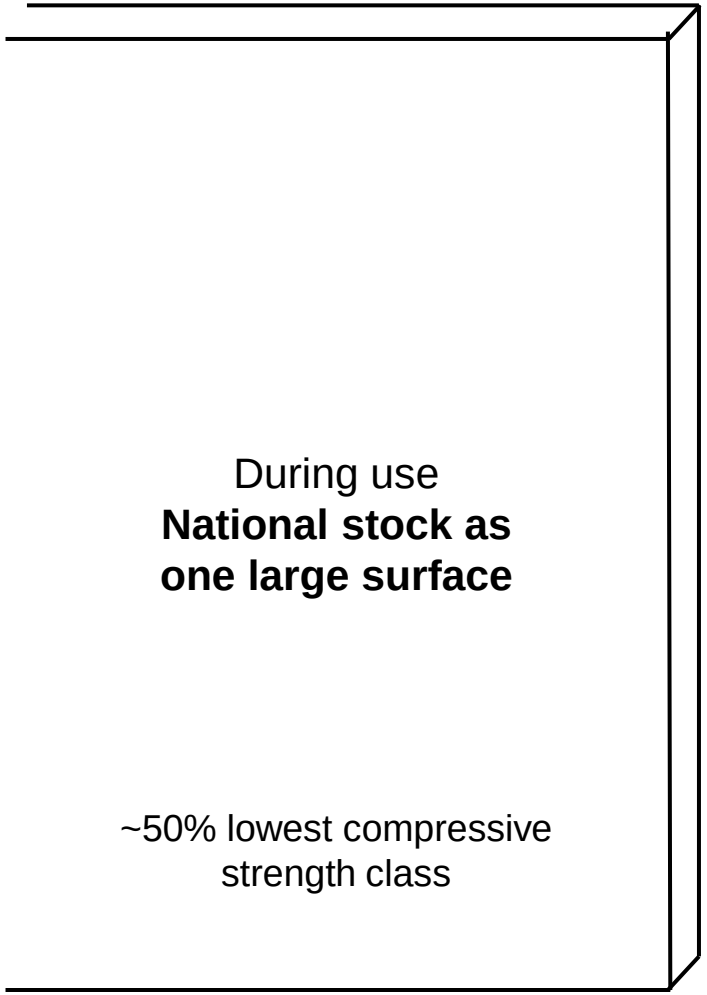
ipcc
"half"
Report 2021

nature geo
"43%"
Xi et al. 2016

To produce *realistic estimate* of carbon uptake, *bottom-up approach* makes use of data and modeling to characterize archetypes and context, assess individual units, and scale up to meet scope



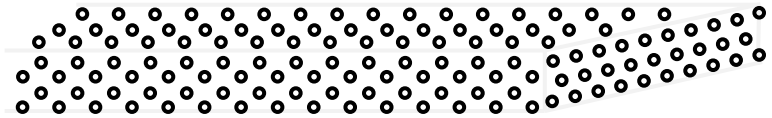
Previous Studies—Top-Down Approach *for* Carbon Uptake Estimation



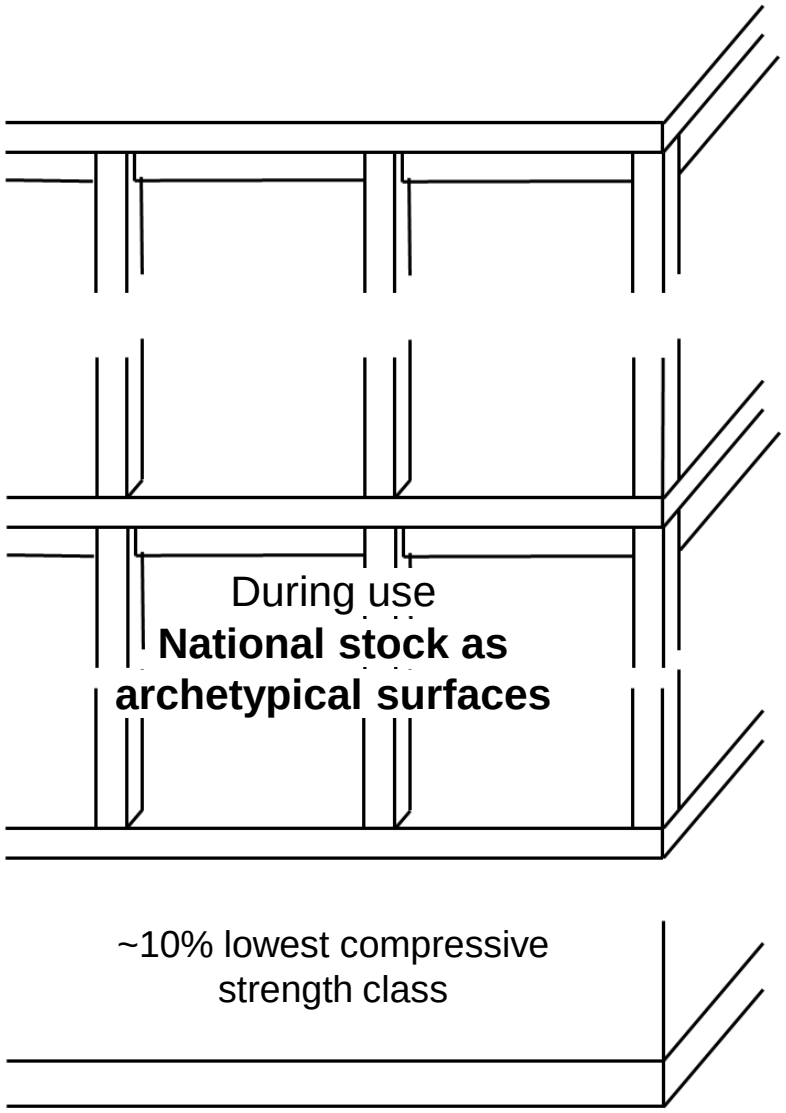
During use
National stock as one large surface

~50% lowest compressive strength class

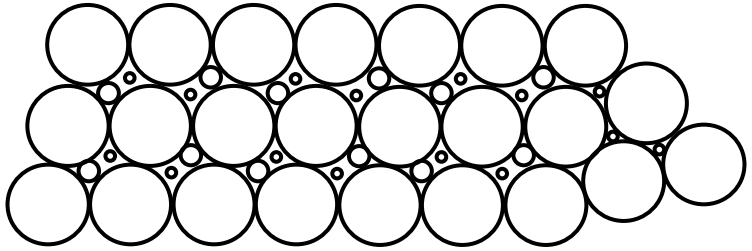
During end-of-life
Finely ground, spread out



Bottom-Up Approach *for* Carbon Uptake Estimation



During end-of-life
Mix of sizes, stockpiled



Bottom-Up Approach *for* Carbon Uptake Estimation

Carbon uptake occurs during various phases

- Cement kiln dust

Cement production

Concrete and mortar production

- Cement wastage

- Structures
- Concrete blocks, plaster, and render

Concrete and mortar use

End-of-life

- Reuse
- Recycle
- Landfill

Phases with insignificant amount of carbon uptake

Phases with significant amount of carbon uptake

EN 16757 Formula *for* Use-Phase Carbon Uptake

$$CU_{Use} = \left(\frac{k}{1000}\right) \times K_k \times U_{tcc} \times C \times D_c \times V \times \left(\frac{S}{V}\right) \times \sqrt{t}$$

- k: Rate of carbonation
- K_k: Correction factor
- U_{tcc}: Theoretical maximum
- C: Binder content
- D_c: Degree of carbonation
- V: Volume of cement
- $\frac{S}{V}$: Geometry factor
- $\sqrt{t}$: Service life

Bottom-Up Approach *for* Carbon Uptake Estimation

Material Definitions, **Exposure Conditions**, *and* **Geometries** *impact use-phase carbon uptake*

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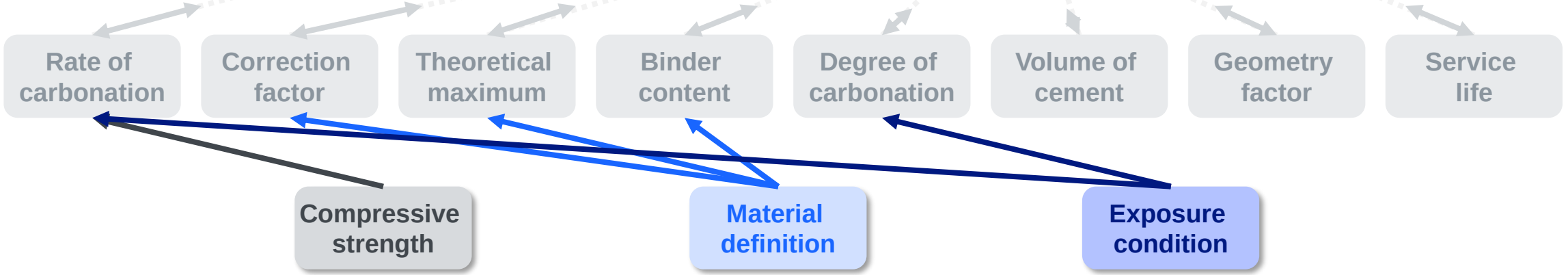

Bottom-Up Approach *for* Carbon Uptake Estimation

Local **Market Data** *informs* **Material Definitions** *and consumption*

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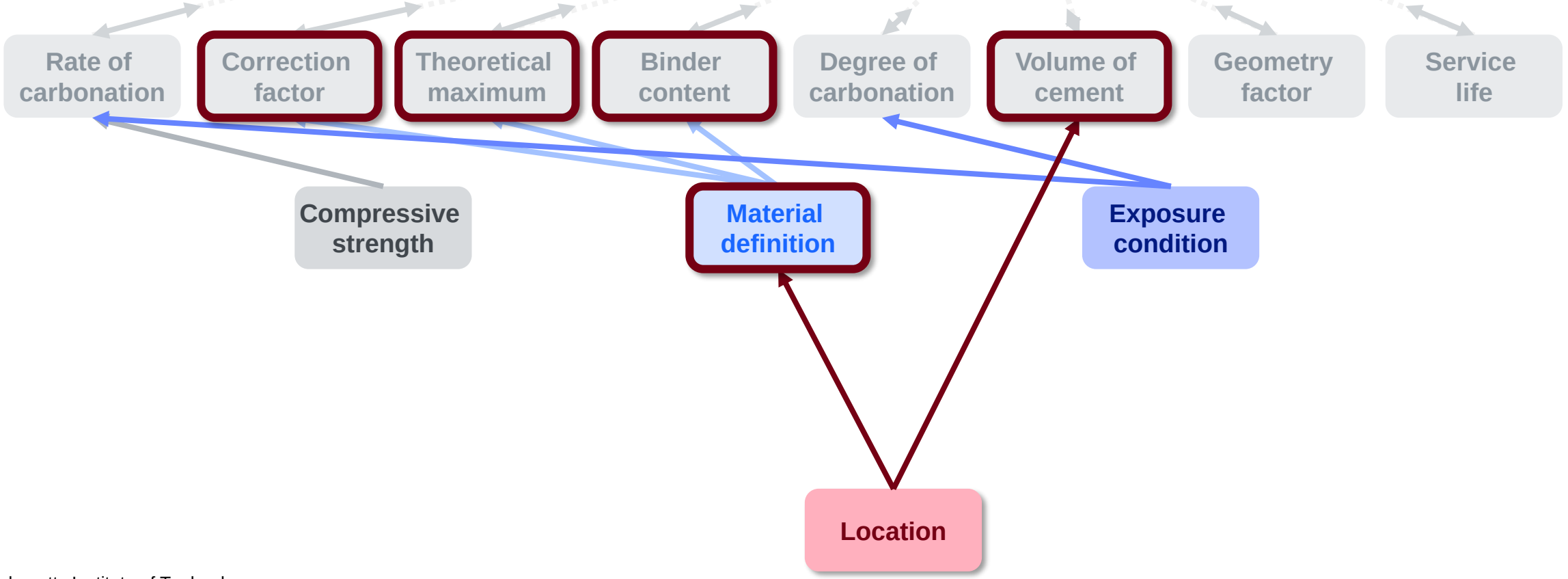
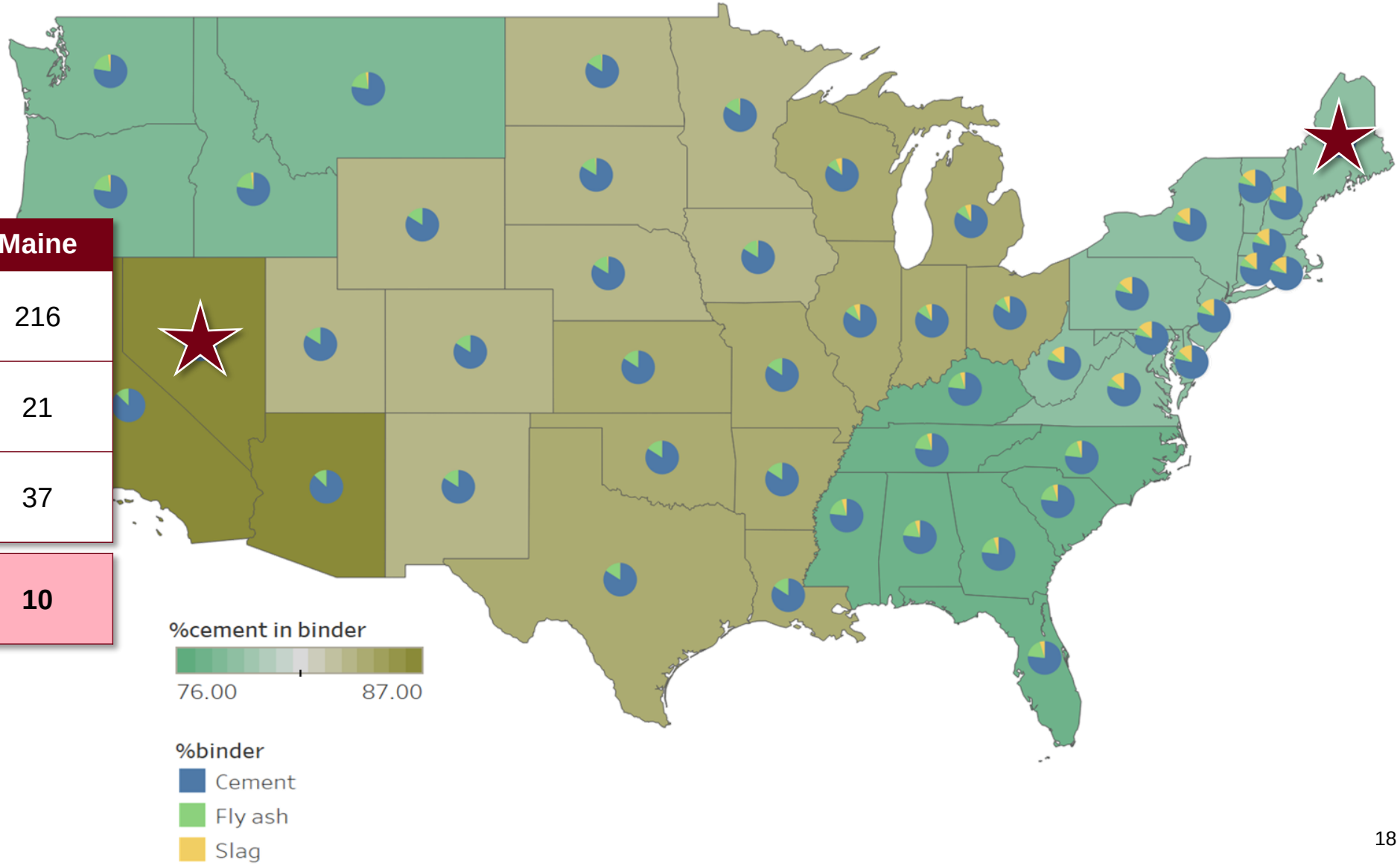


Bottom-Up Approach *for* Carbon Uptake Estimation

Local **Market Data** *informs* **Material Definitions** *and consumption*

	Nevada	Maine
Portland cement (kg/m^3)	225	216
Fly ash (kg/m^3)	33	21
Slag (kg/m^3)	0	37
50-year uptake (kg/m^2)	**13**	**10**



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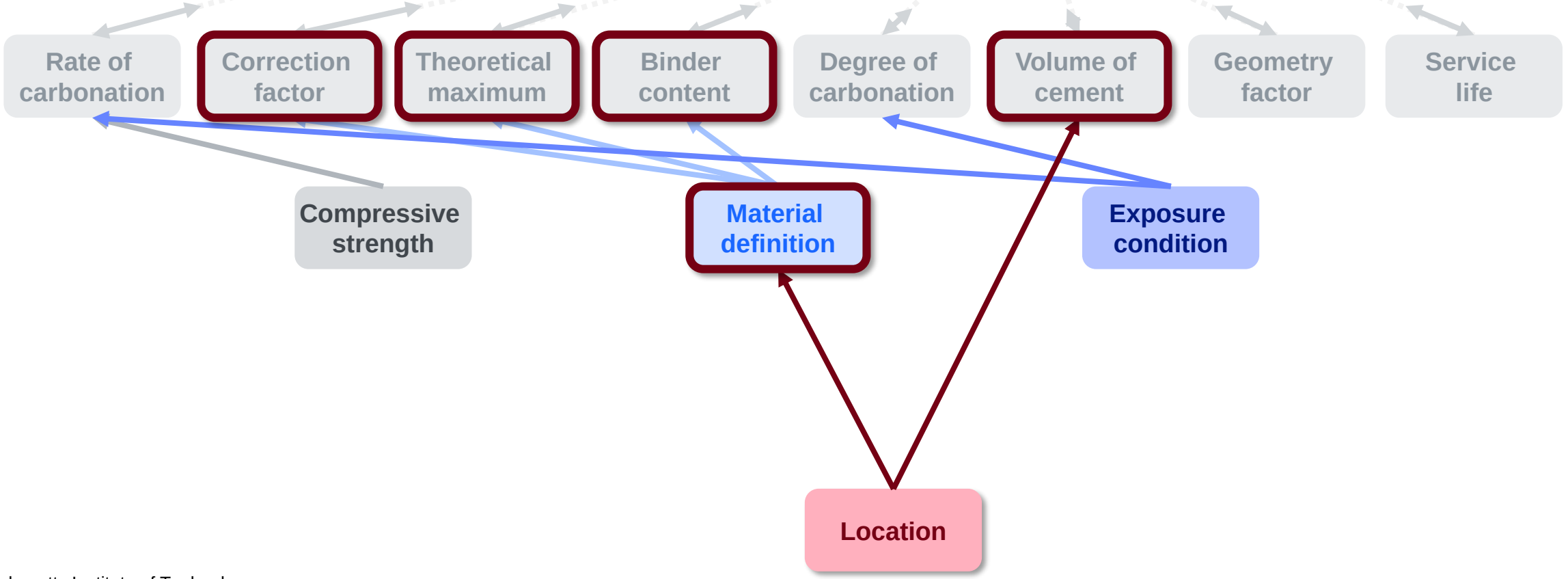

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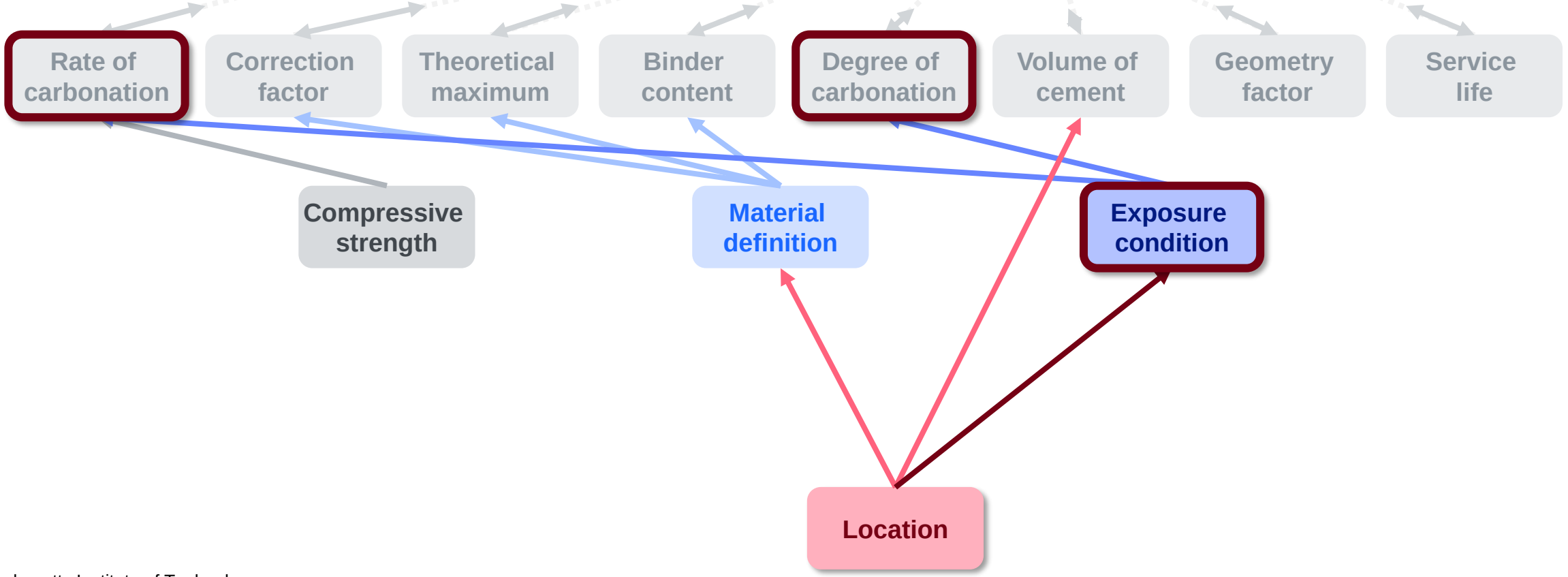
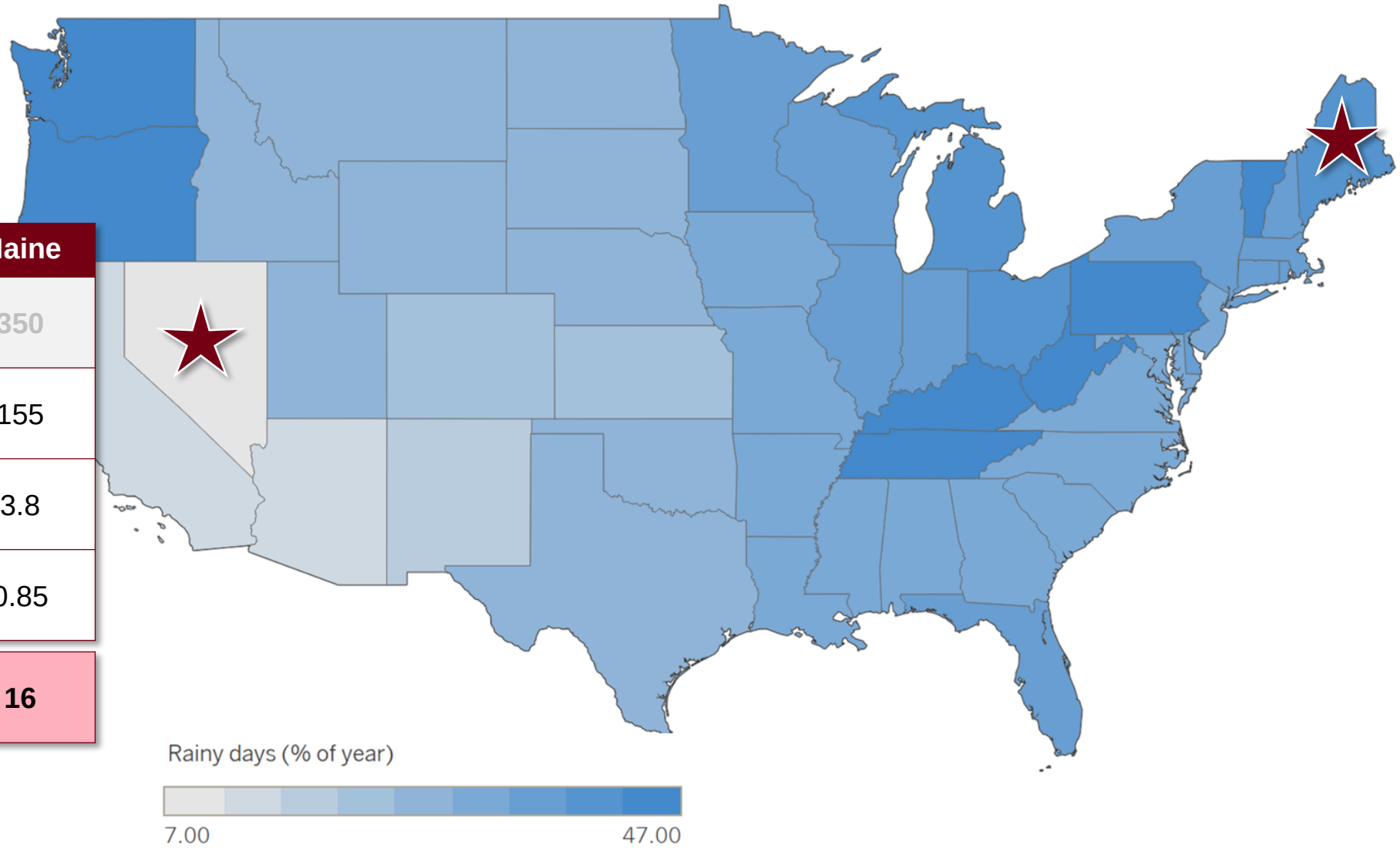


Bottom-Up Approach *for* Carbon Uptake Estimation

Local Climate Data *informs* Exposure Conditions

	Nevada	Maine
Portland cement (kg/m^3)	350	350
Rainy days	54	155
k	4.5	3.8
D_c	0.75	0.85
50-year uptake (kg/m^2)	**20**	**16**



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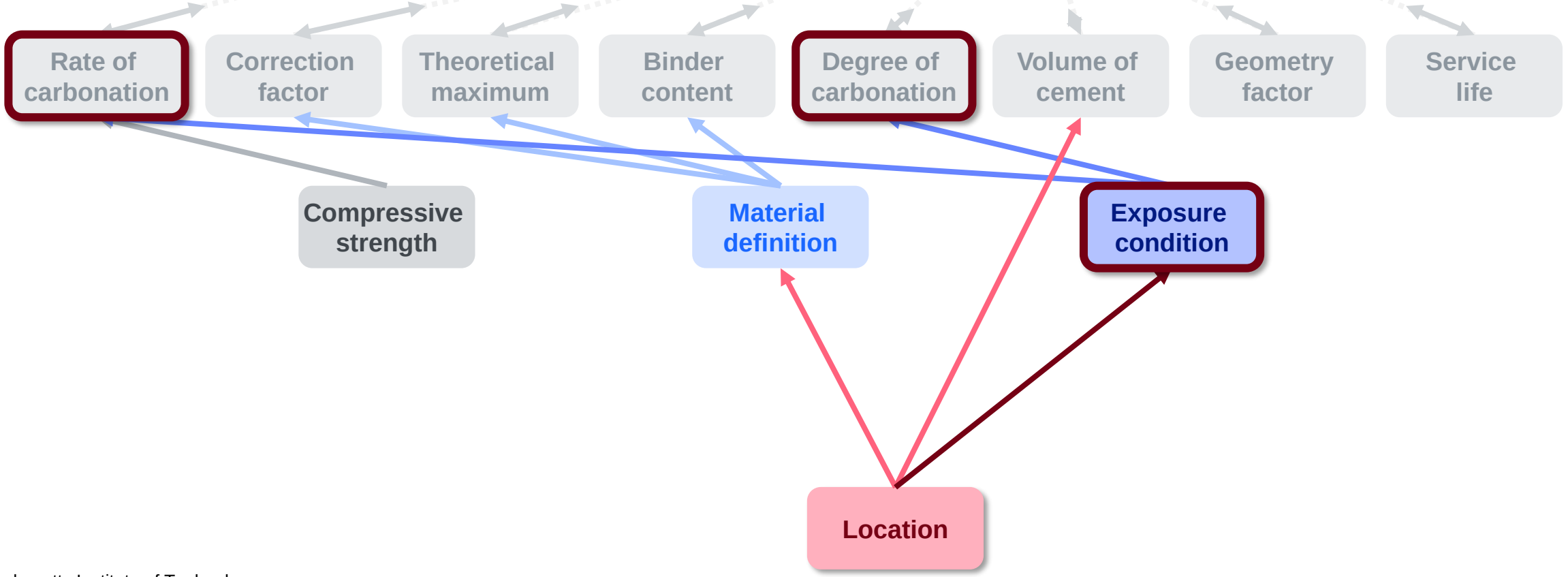

Bottom-Up Approach *for* Carbon Uptake Estimation

Local Housing Data *informs* Archetype Definition

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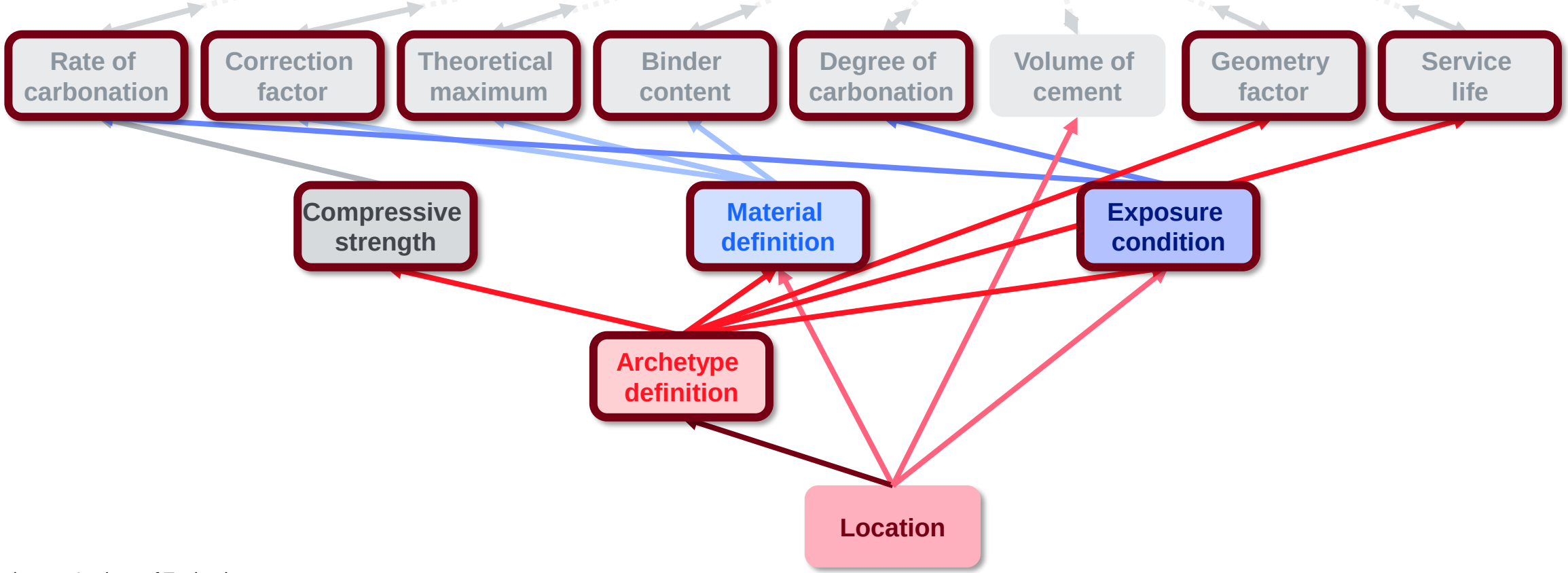

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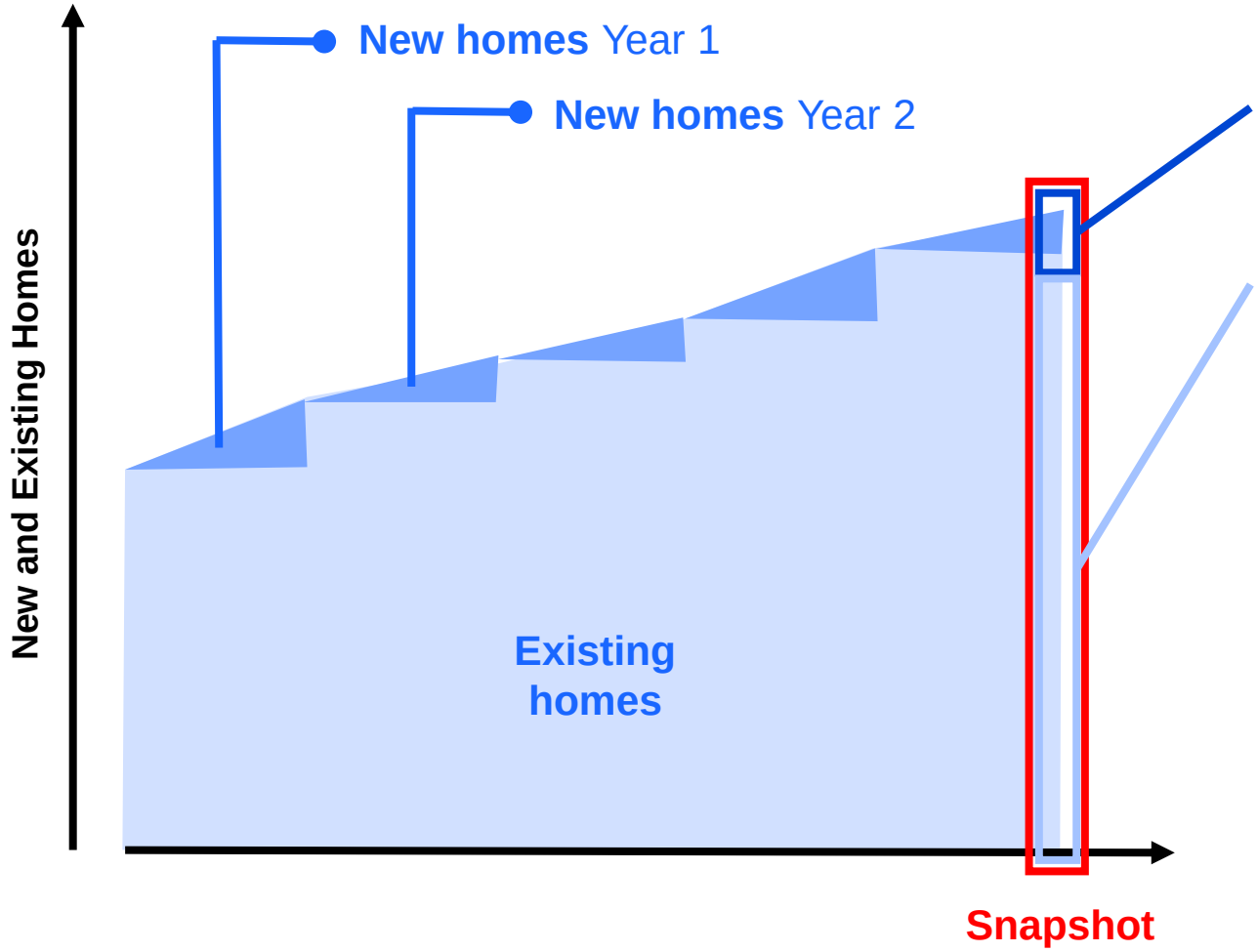


- **BPS** (Building Permits Survey)
- **SoC** (Survey of Construction)

- **AHS** (American Housing Survey)
- **MHS** (Manufactured Housing Survey)
- **RECS** (Residential Energy Consumption Survey)
- **HAZUS** (Multi-Hazard Loss Estimation Model)

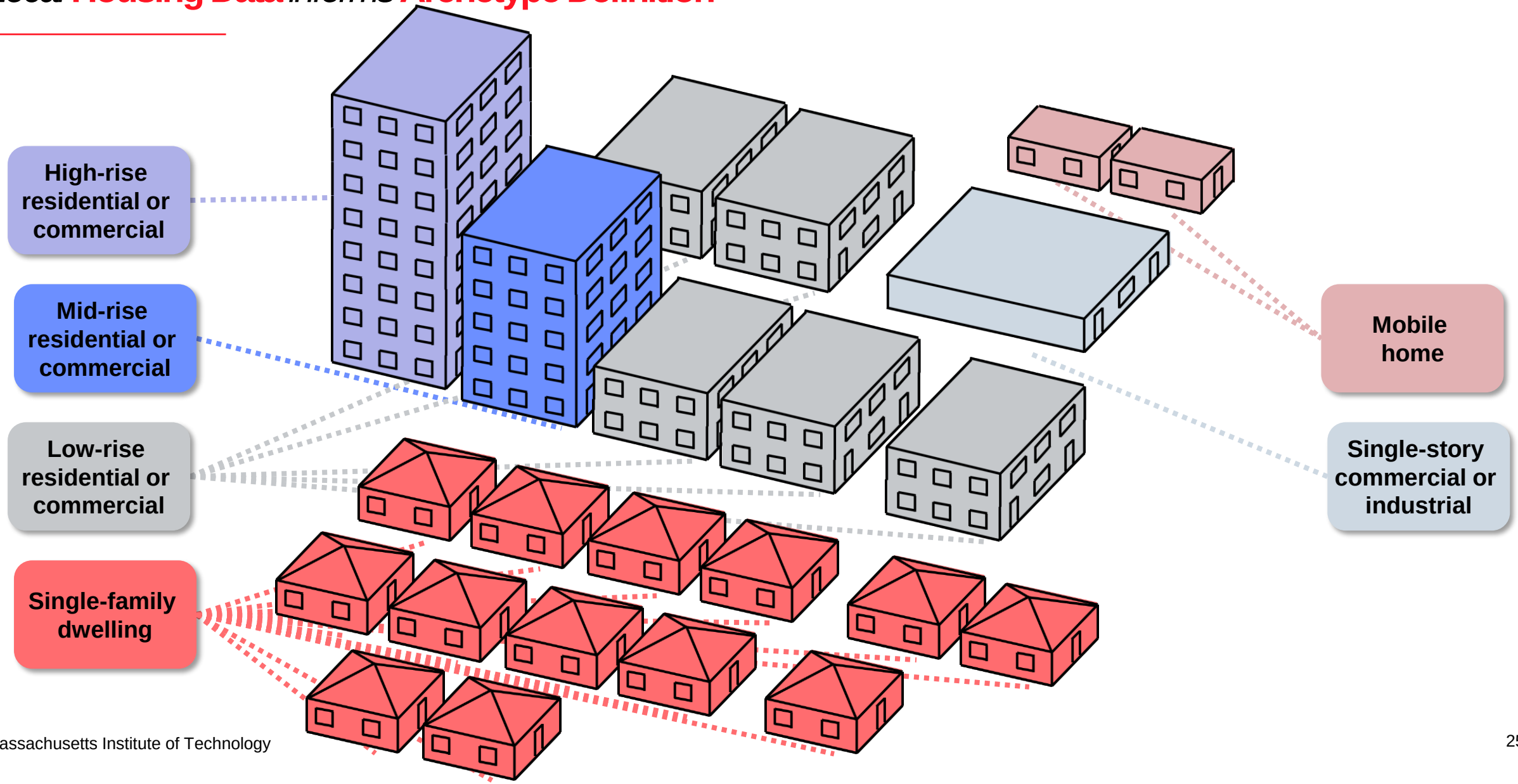
Other archetypes

- **CBECS** (Commercial Energy Consumption Survey)
- **HAZUS** (Multi-Hazard Loss Estimation Model)

Data sources

Bottom-Up Approach *for* Carbon Uptake Estimation

Local Housing Data *informs* Archetype Definition

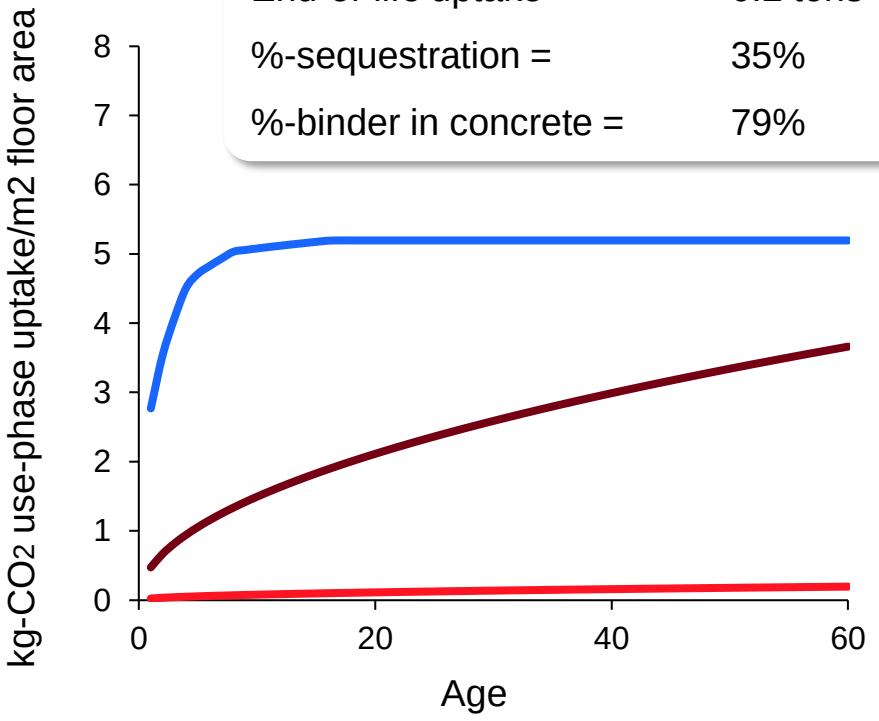


Case Study

Use-phase and end-of-life carbon uptake varies by application—defined by characteristics of archetype and its elements

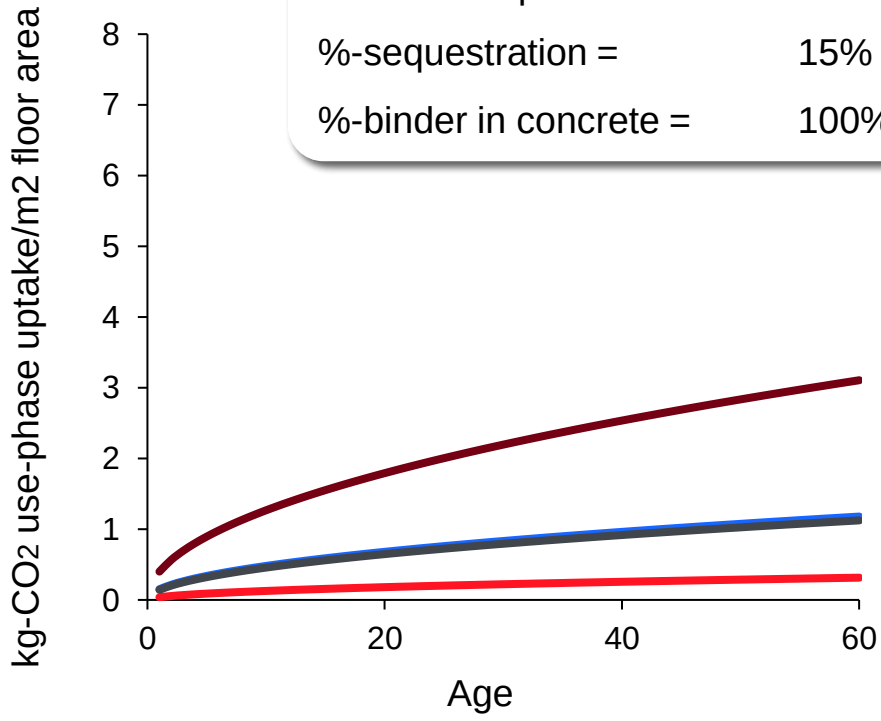
SINGLE-FAMILY DWELLING

Use-phase uptake =	2.1 tons
End-of-life uptake =	0.2 tons
%-sequestration =	35%
%-binder in concrete =	79%



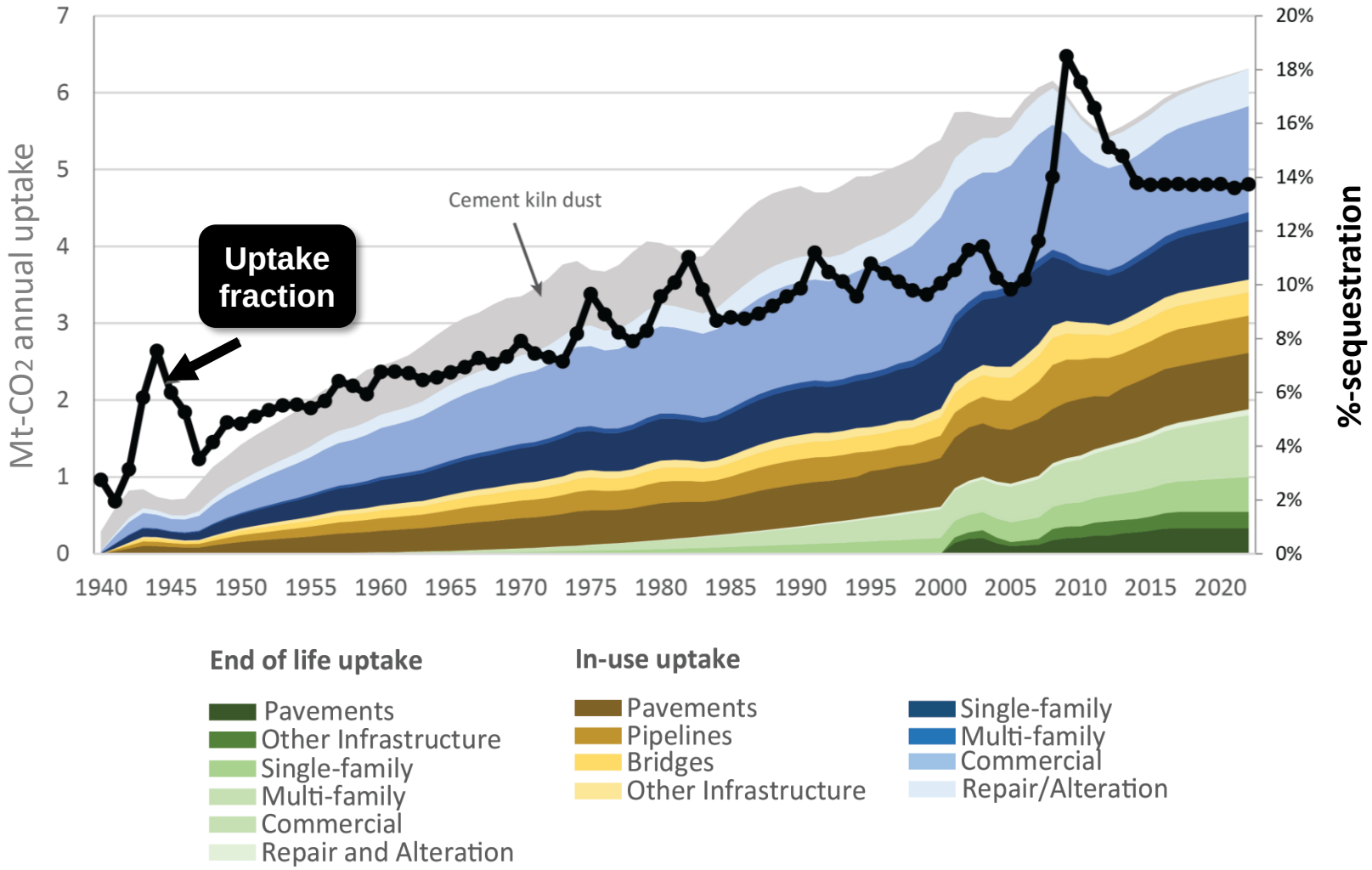
LOW-RISE COMMERCIAL

Use-phase uptake =	6.9 tons
End-of-life uptake =	3.0 tons
%-sequestration =	15%
%-binder in concrete =	100%



Slab Footing Basement wall Frame

Potential for carbon uptake to neutralize ~15% of annual, *nationwide* process emissions, similar portions of which from in-use buildings, in-use infrastructure, and end-of-life



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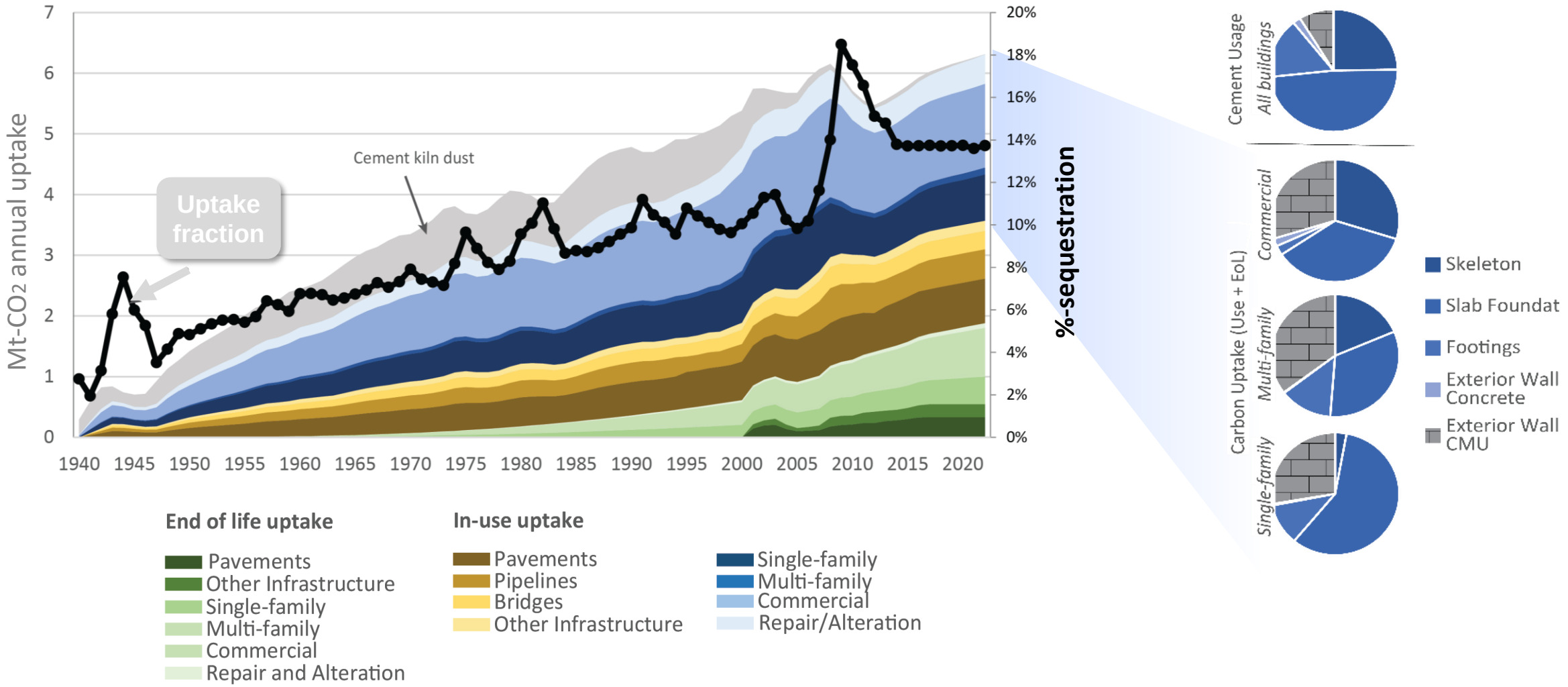
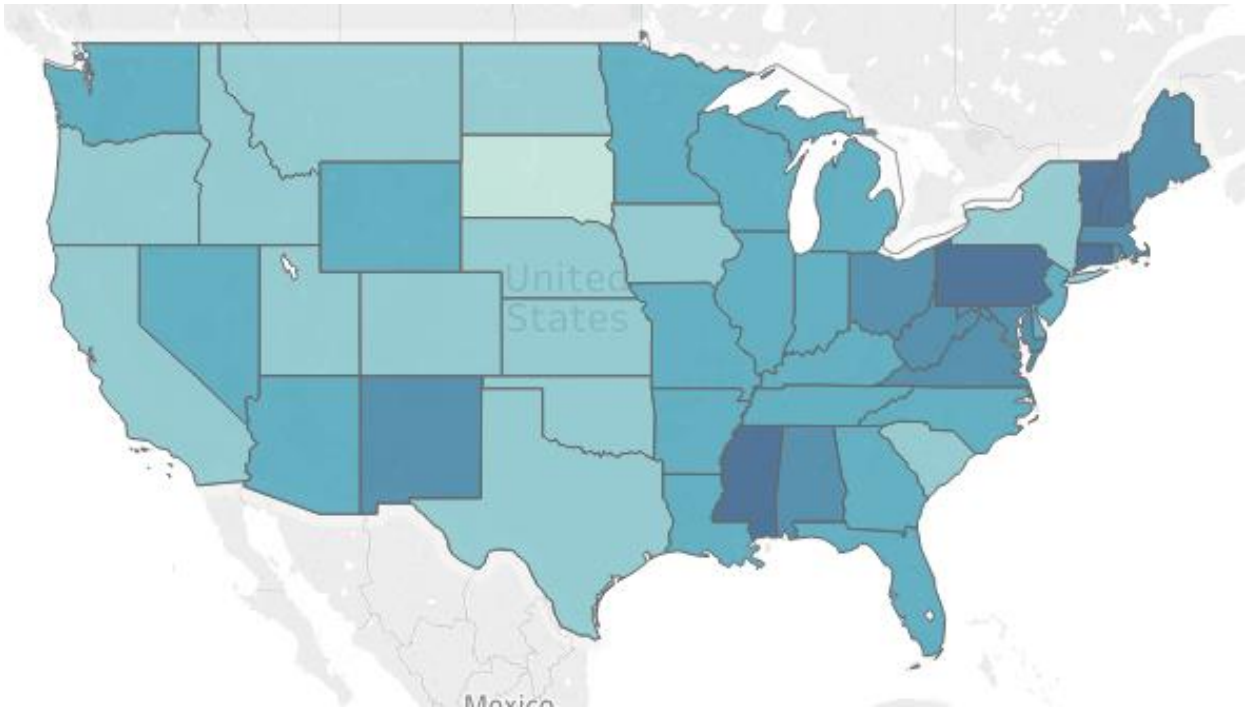
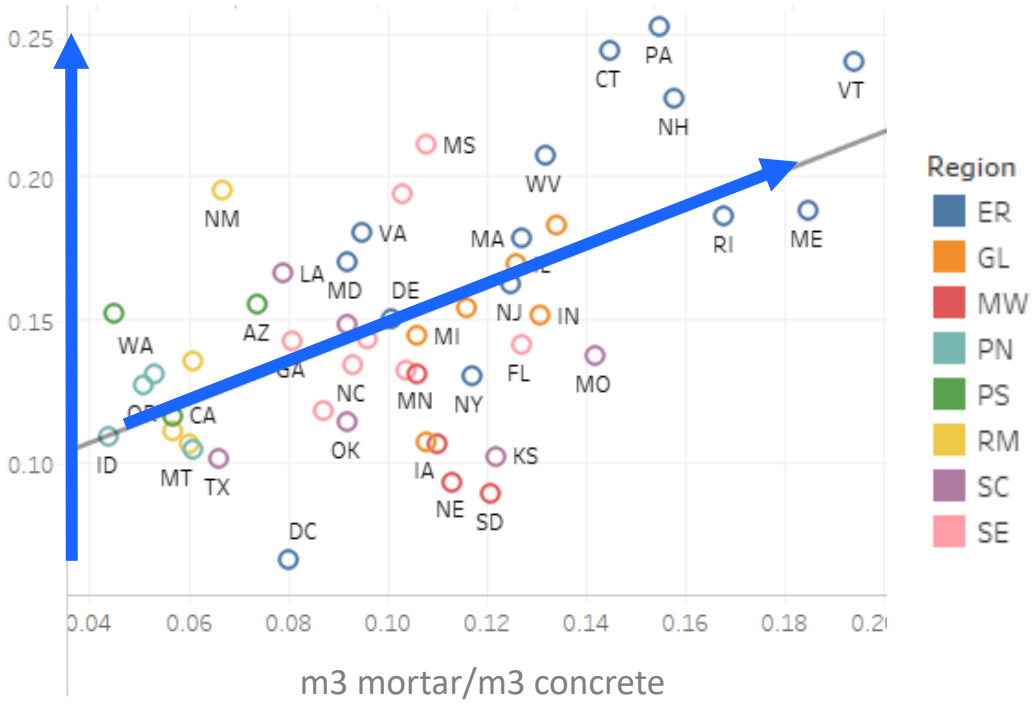


Potential for carbon uptake to neutralize 5-25% of annual, *statewide* process emissions, varying by mortar/concrete application breakdown



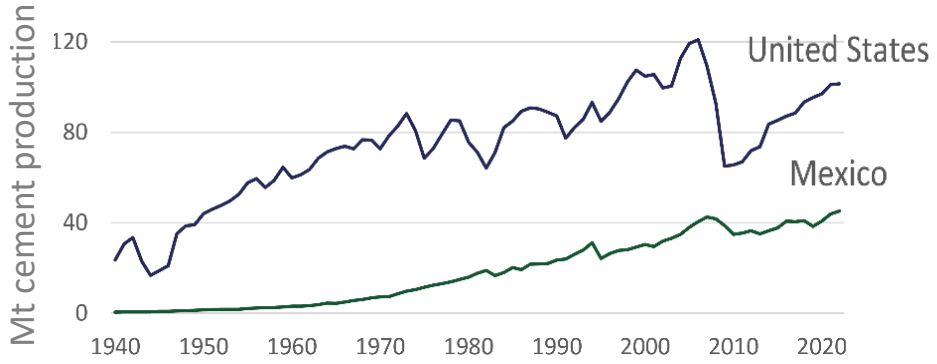
Sequestration

0.0500 0.2500

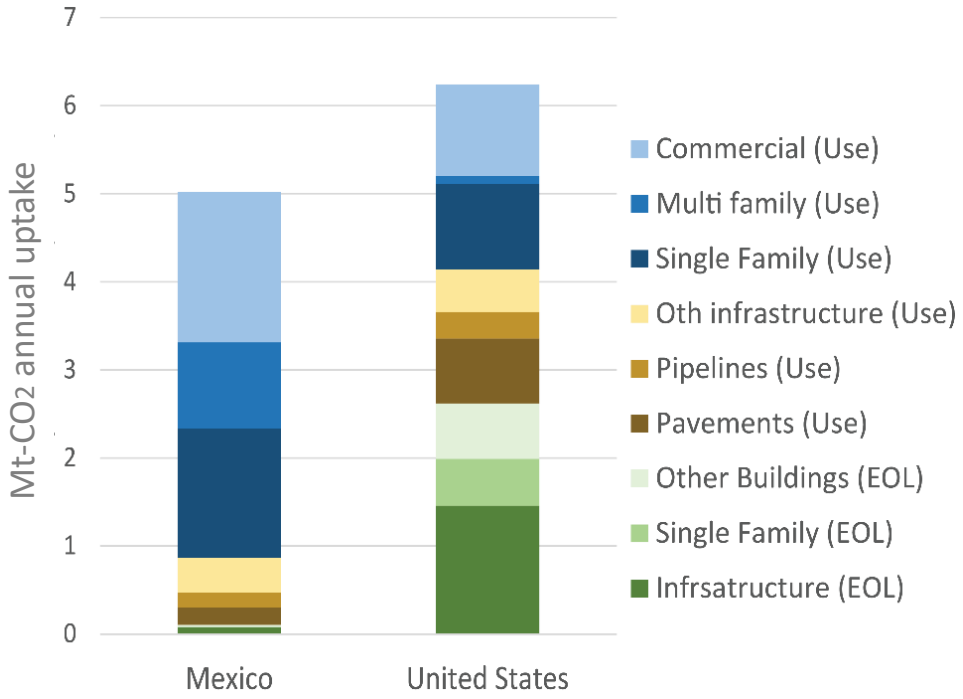


Higher potential for larger portion of mortar applications

Annual carbon uptake in Mexico similar magnitude to U.S., despite lower production, since higher portion of mortar, low compressive strength, and building applications



Half of production



Similar magnitude of carbon uptake

Takeaways

CARBON UPTAKE IS…

CRUCIAL

To accurately assess both benefits of cement-based products and need for emissions abatement solutions

SIGNIFICANT

Potential to neutralize annual process emissions by ~15% nationwide and 5-25% statewide, as shown in U.S. study

ACTIONABLE

Variation by archetype, element, and context, thus can be increased and not governed by consumption, as shown in Mexico study

POSSIBLE TO MODEL AT HIGH RESOLUTION

Bottom-up approach captures local variations in archetypes, materials, and exposure conditions, which impact various phases

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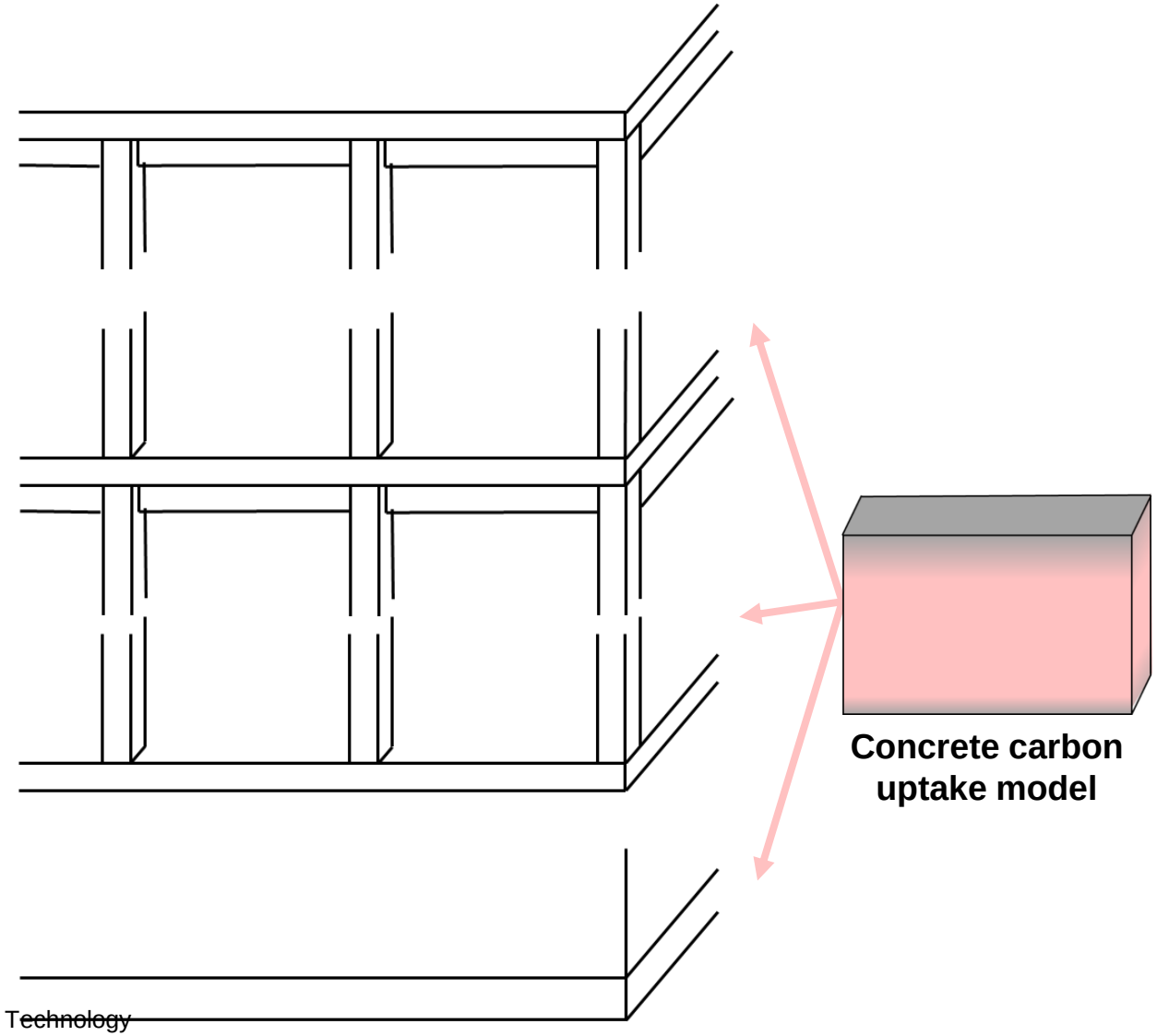
cshub.mit.edu | Concrete Sustainability Hub
msl.mit.edu | Materials Systems Lab

Ipek Bensu Manav


EPD and PCR Developers
• Include uptake as part of concrete PCR reporting
Architects
• Optimize geometrical design of cement-based products
Policymakers
• Consider natural carbon uptake in carbon market incentive programs
• Consider the impact of low-carbon policy on uptake
LCA Practitioners
• Account for uptake during use phase and end-of-life
• Include impact of M&R on uptake
Structural Designers
• Account for carbon uptake in concrete specs
• Design mixes for increased uptake (where not susceptible to corrosion)
Cement and Concrete Producers
• Avoid overdesign
• Avoid over-cementing

Stock > Archetypes > Elements > Material Definitions > Exposure Conditions



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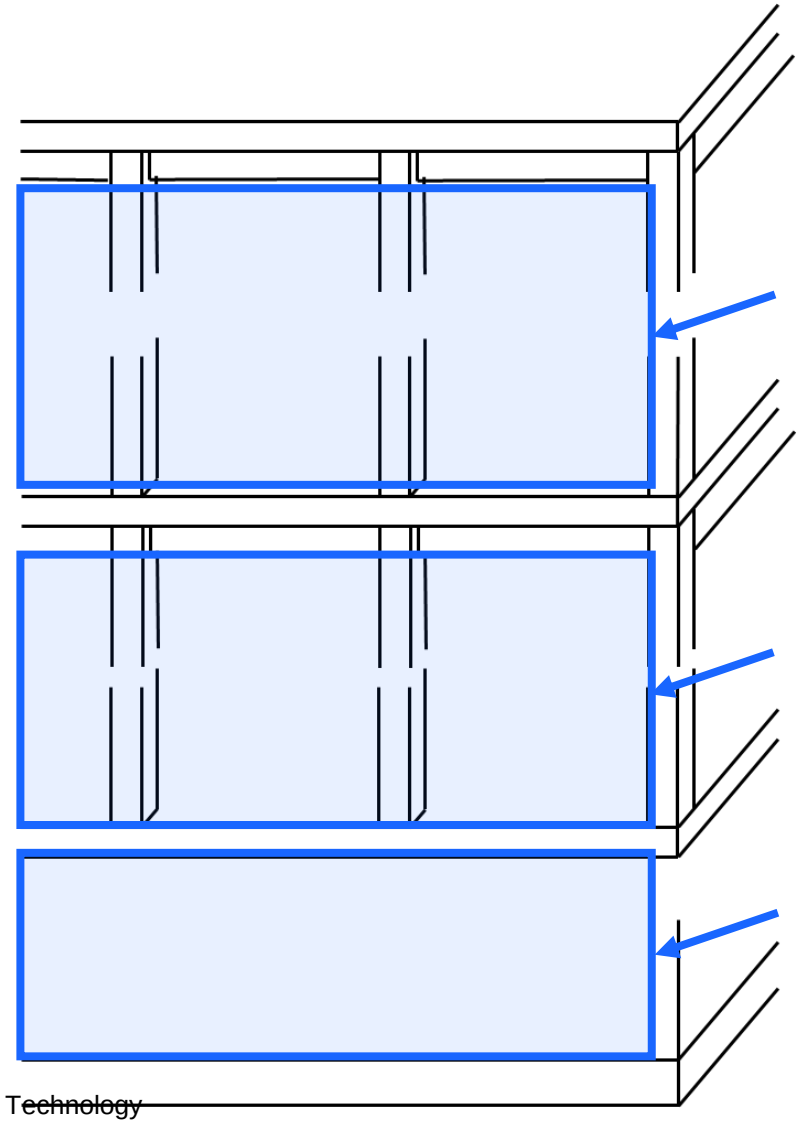

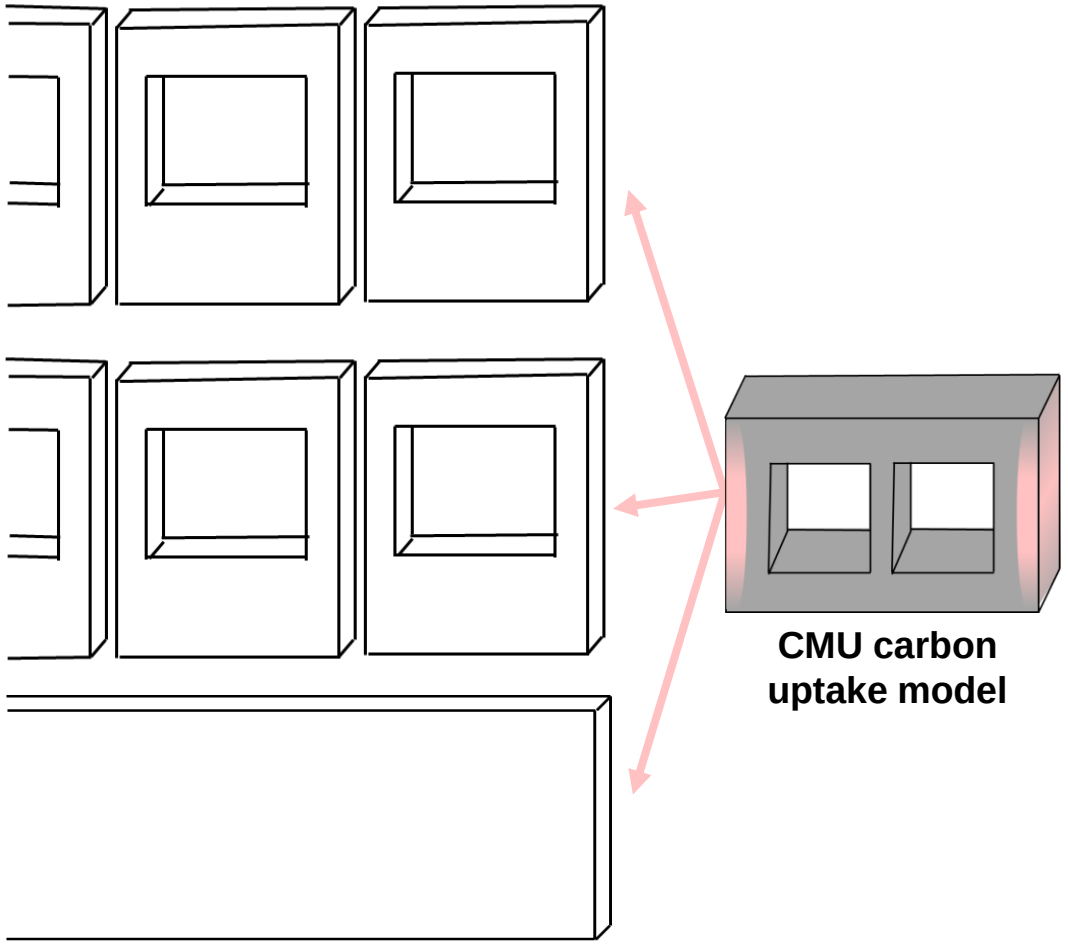

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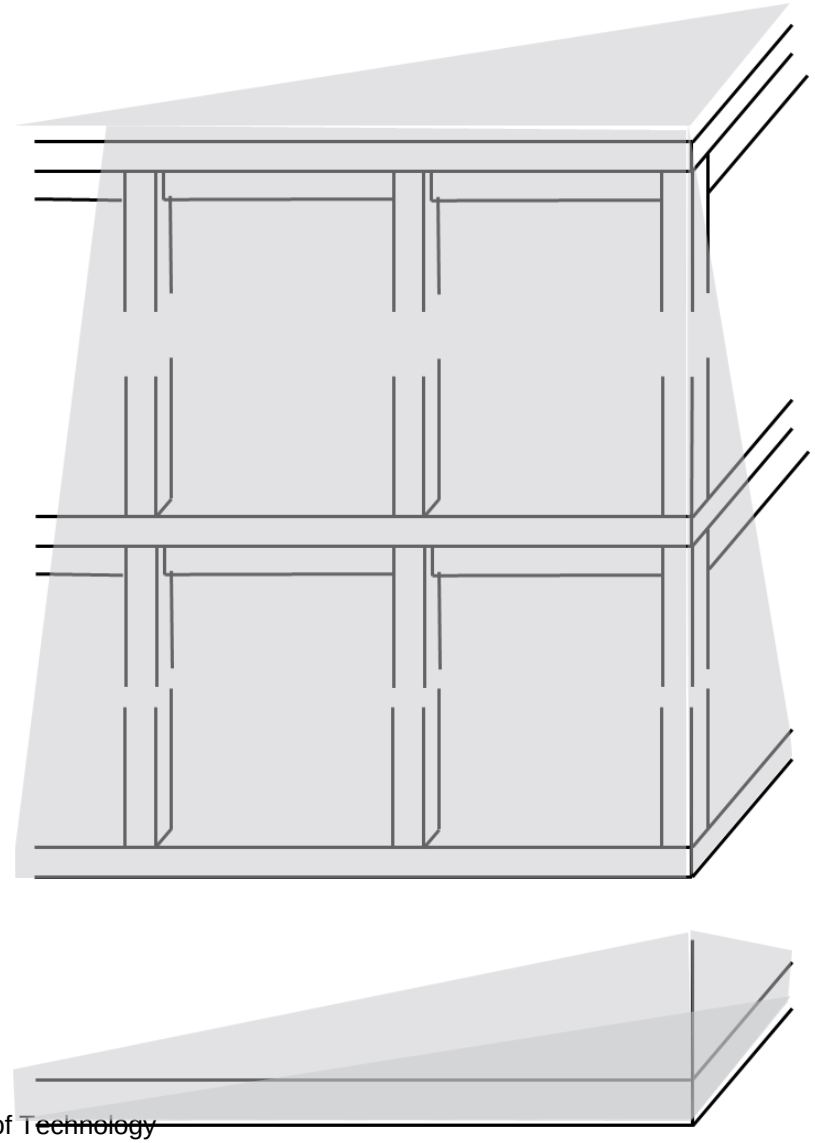


In ground
k = 1.1

Outdoor,
exposed to rain
k = 2.7

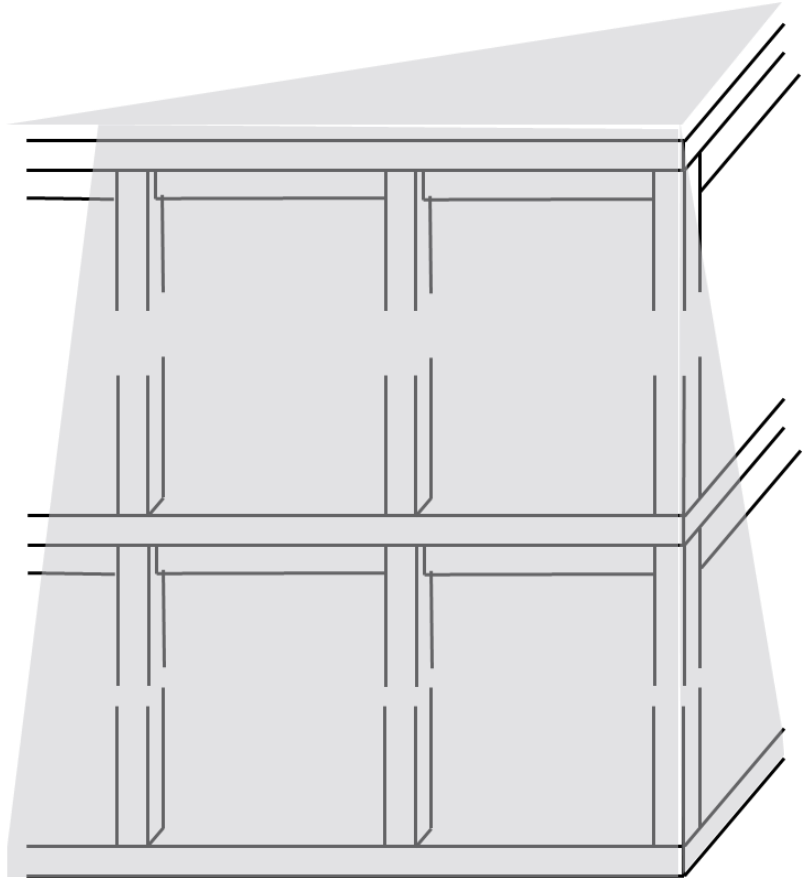
Outdoor,
sheltered from rain
k = 6.6

Indoor,
finished
k = 6.9

Indoor,
unfinished
k = 9.9

Exposure Conditions
k for concrete, 15-20 MPa

Stock > Archetypes > Elements > Material Definitions > Exposure Conditions



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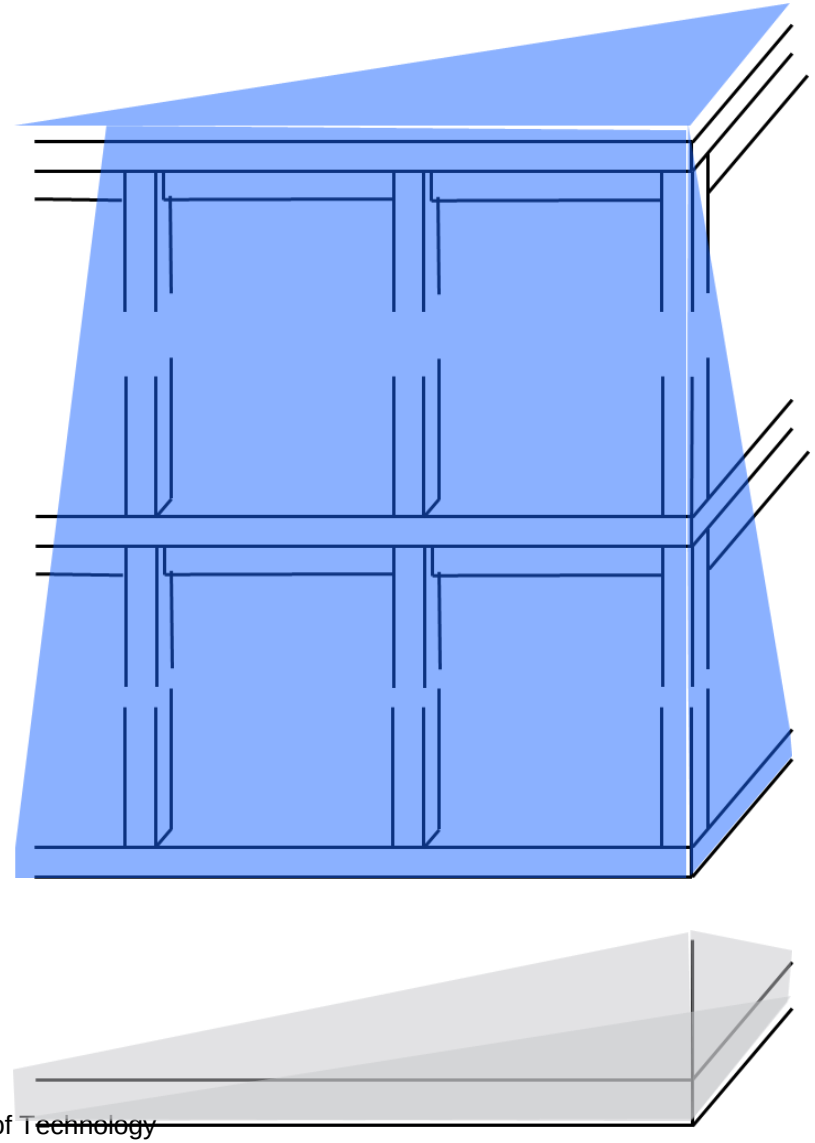

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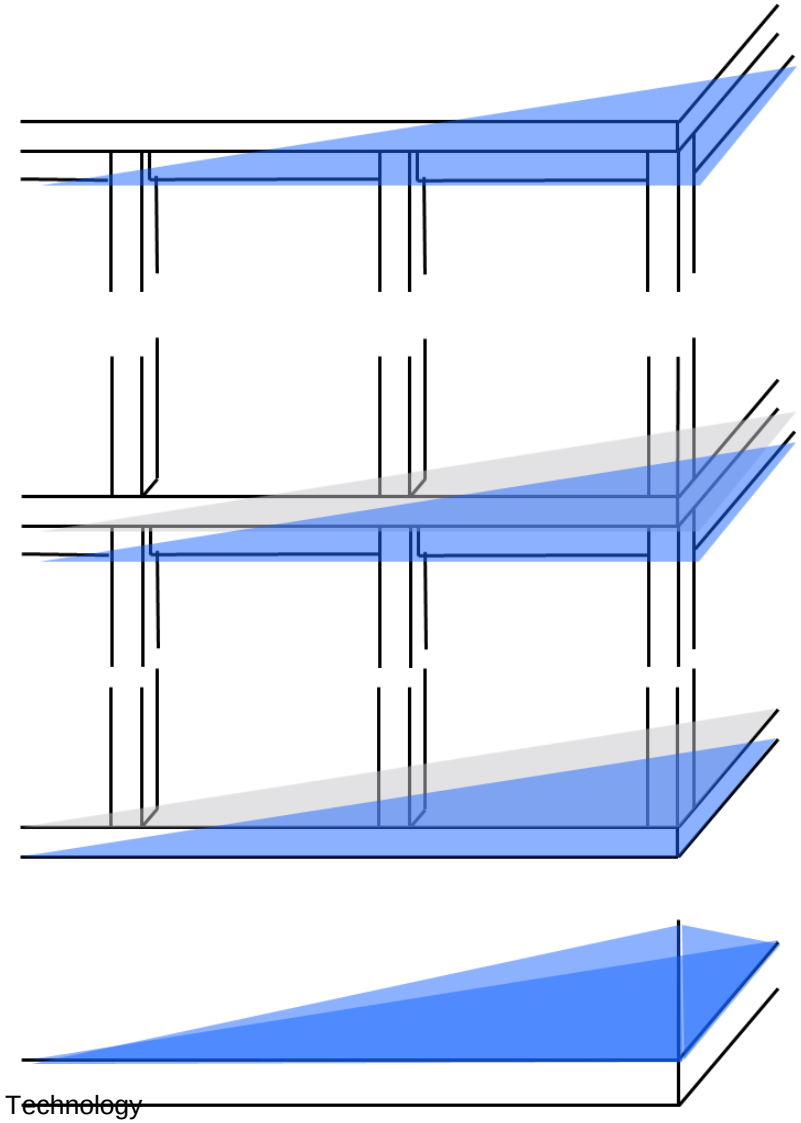

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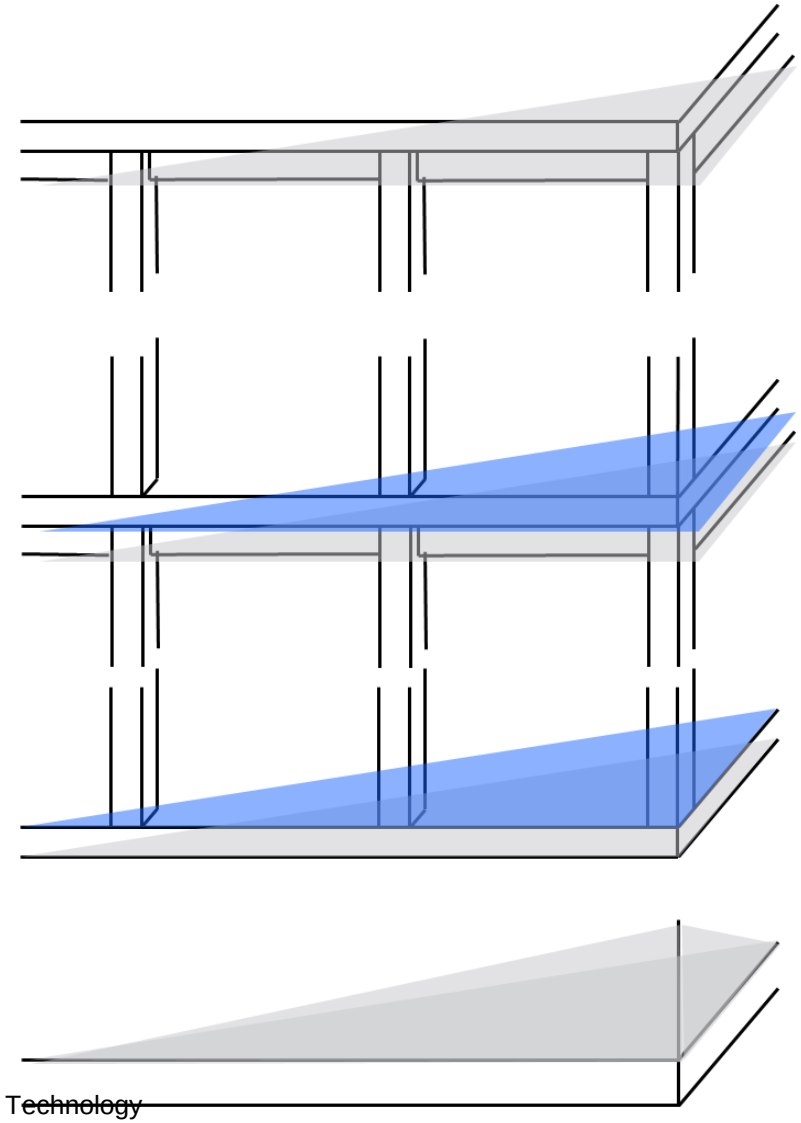

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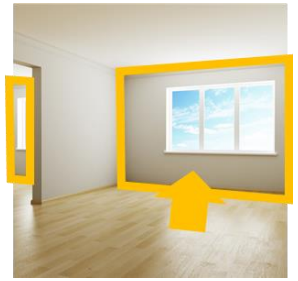

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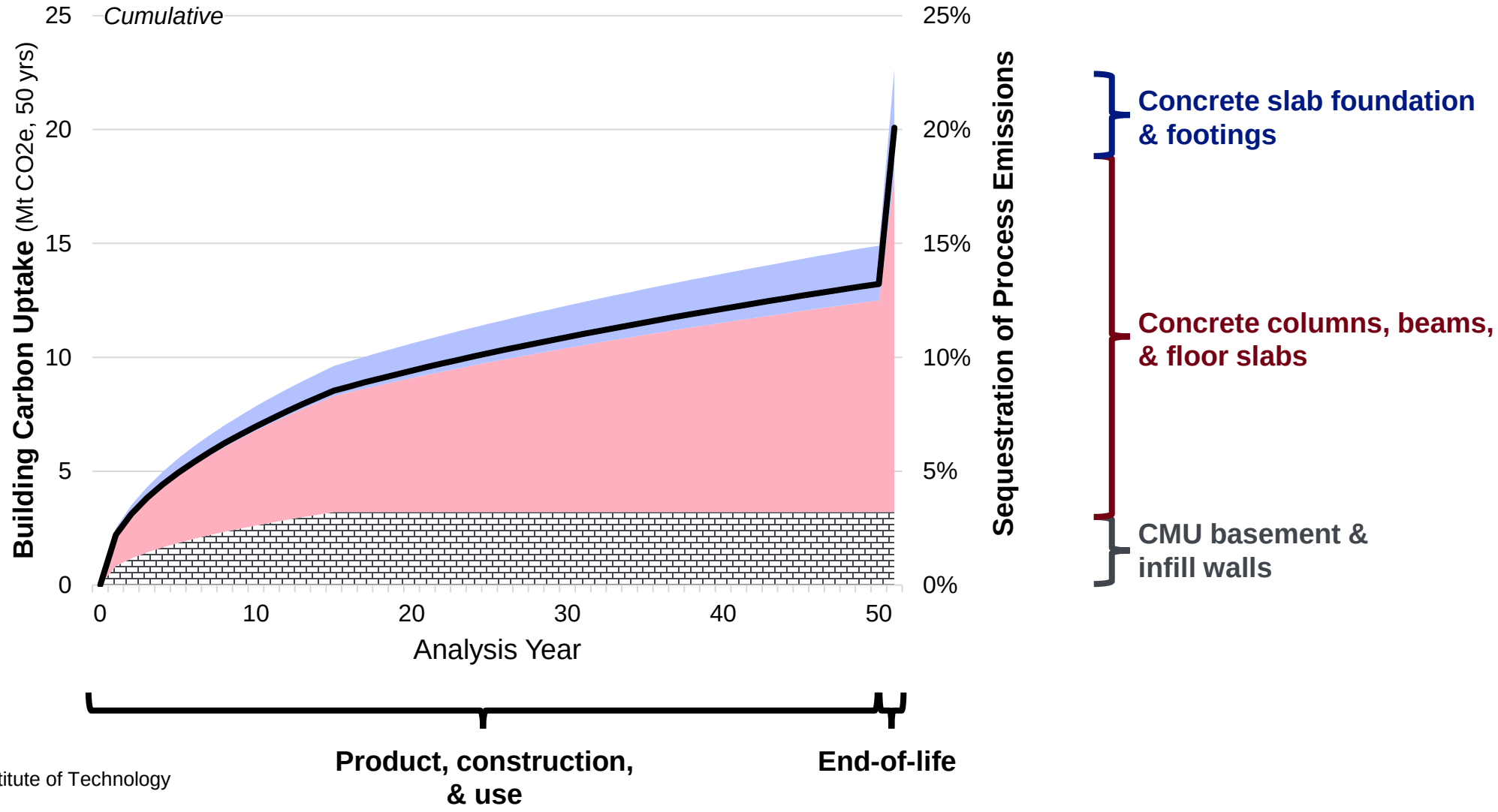
In 2-story residential building with concrete frame, masonry infill walls, and basement, around a fifth of process emissions neutralized through carbon uptake



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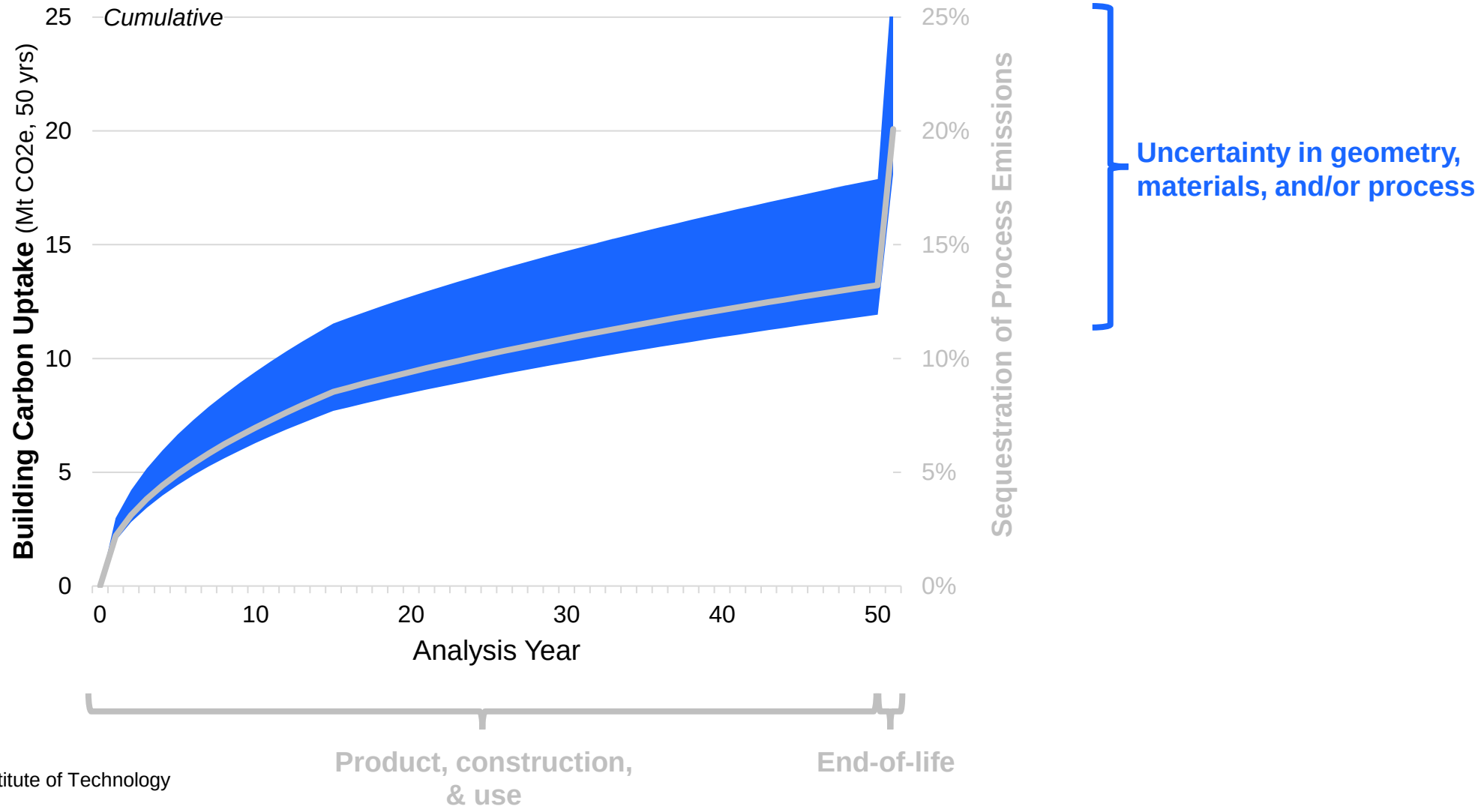
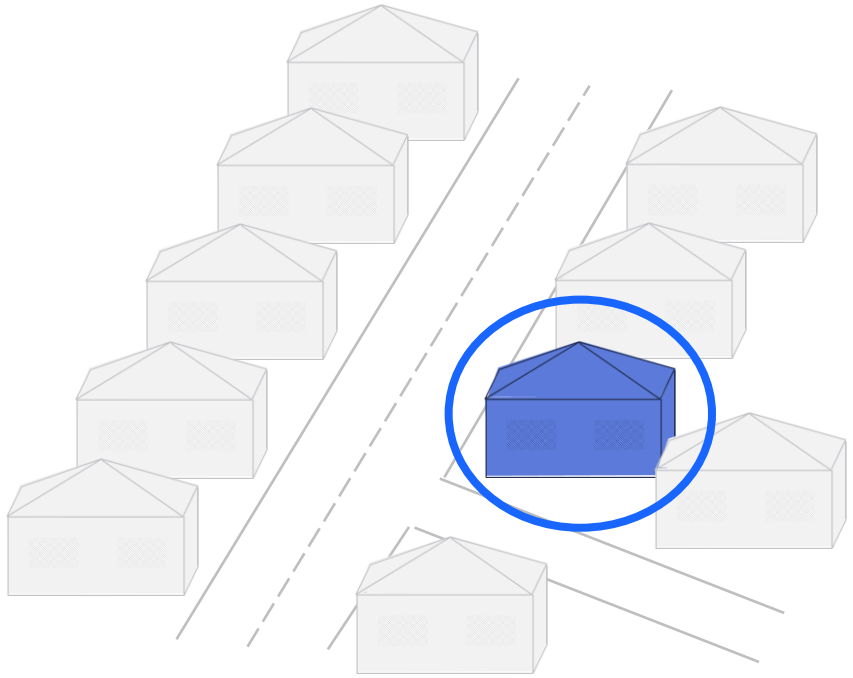


Time Series Elements

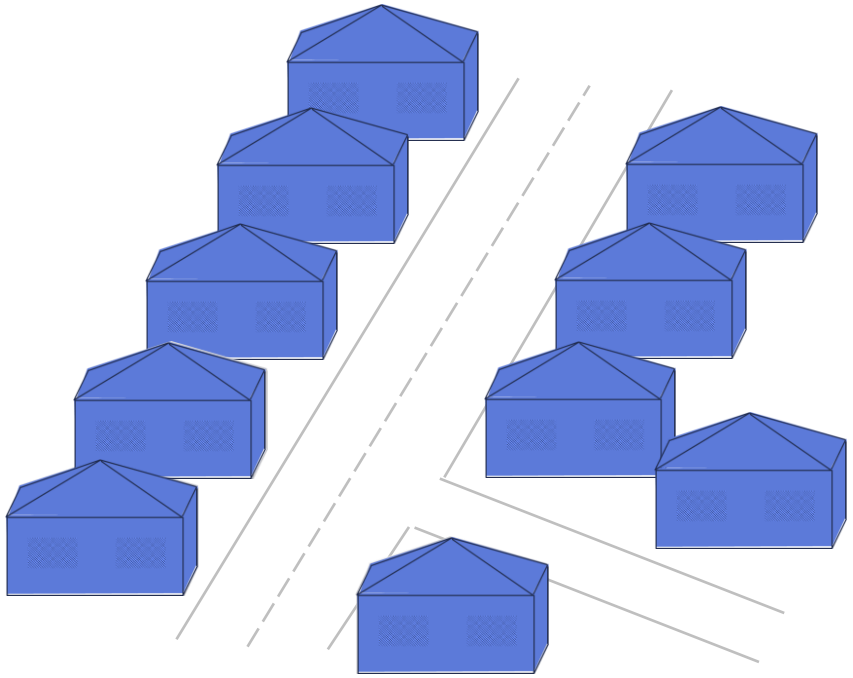


Building Life Cycle Assessment (LCA)

Given a specific building, what are the costs? Emissions?

- Building element and material configuration
- Cost, emission, and absorption models
- Damage and loss functions

Time Series Elements



Building Life Cycle Assessment (LCA)

Given a specific building, what are the costs? Emissions?

- Building element and material configuration
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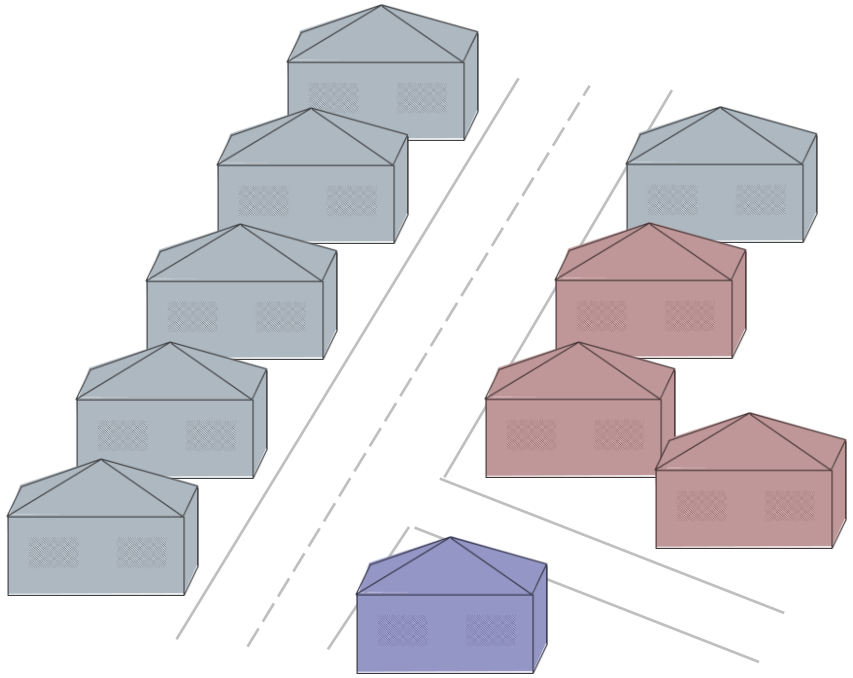
Housing Stock Analysis

What kind of buildings are there? Where?

- Building and household characteristics
- Geographic information
- Historic data and projections

Time Series Elements



Building Life Cycle Assessment (LCA)
Given a specific building, what are the costs? Emissions?

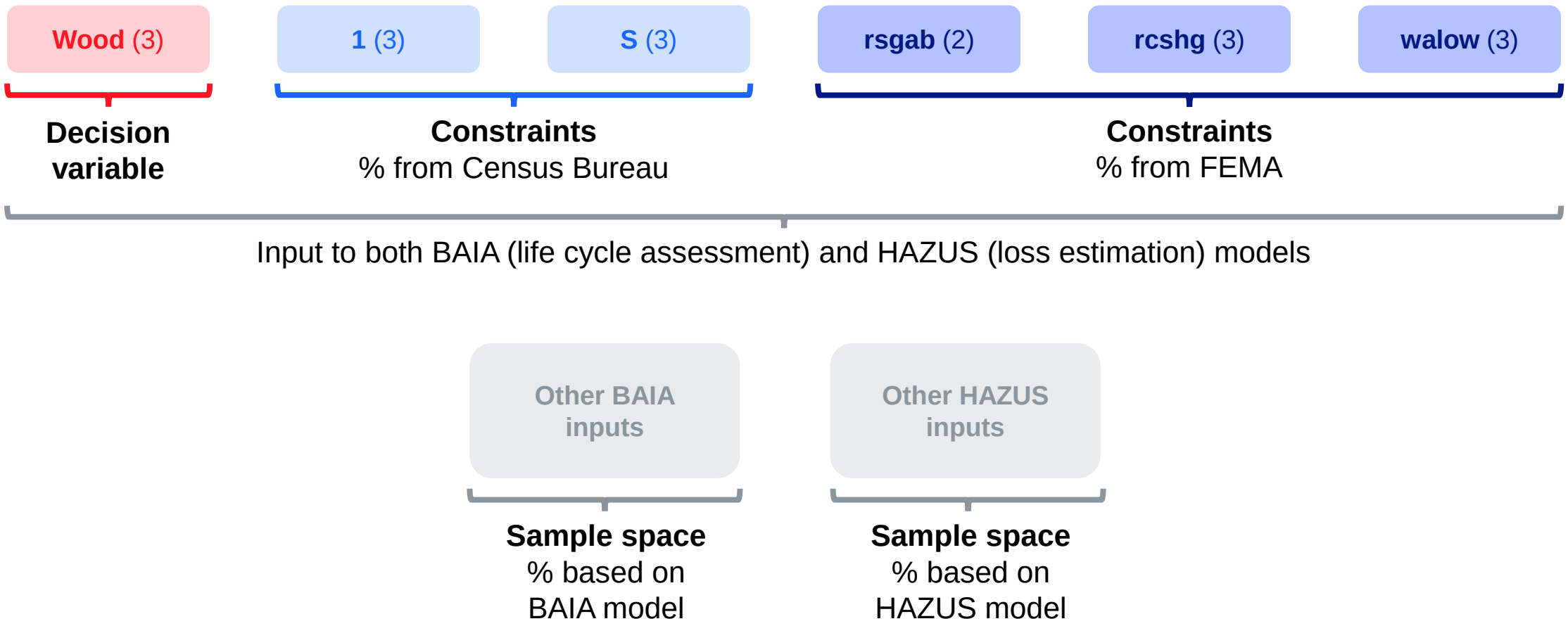
Do I have sufficient **detail**?

Building archetypes

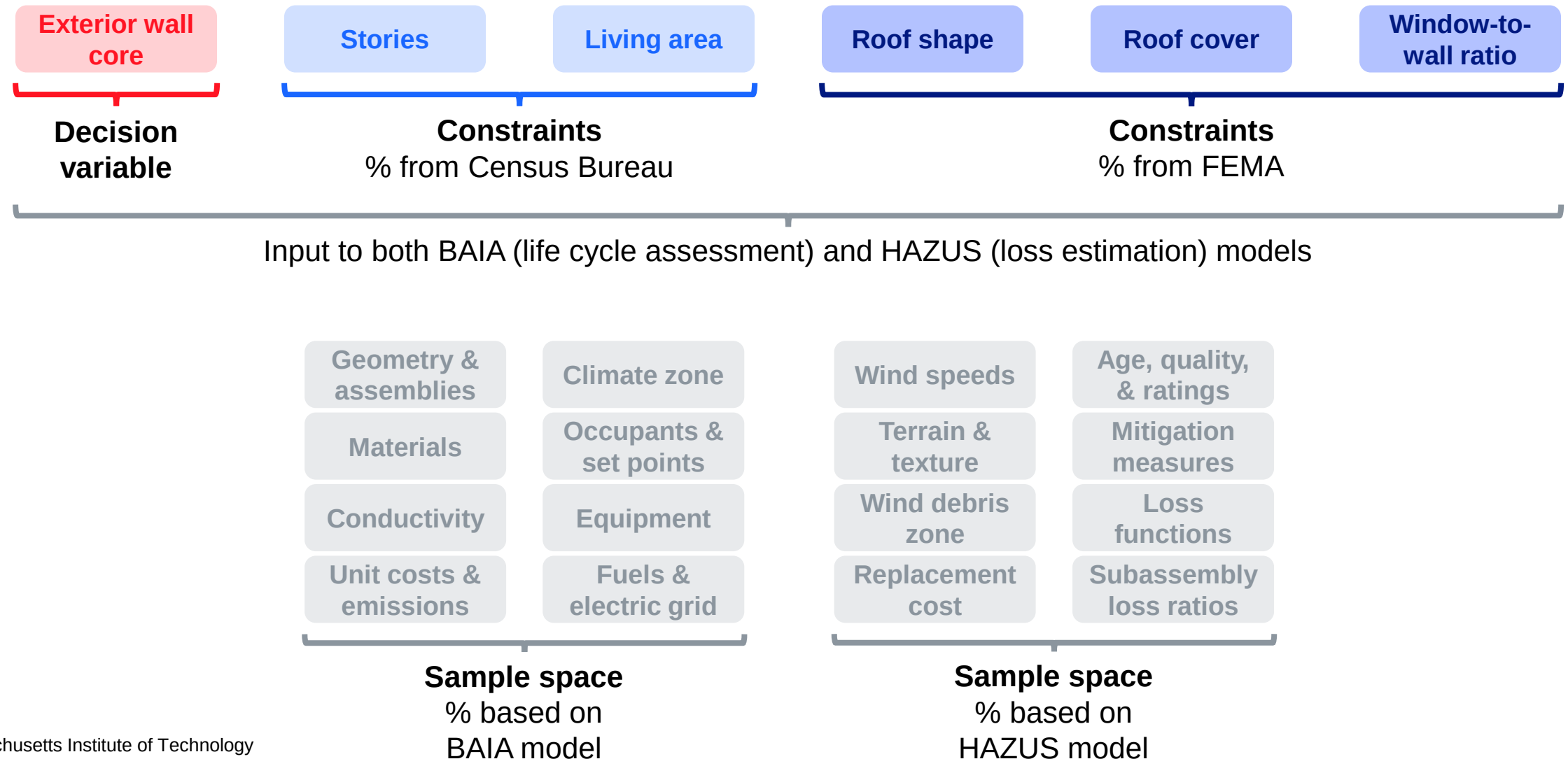
Housing Stock Analysis
What kind of buildings are there? Where?

Do I have sufficient **data**?

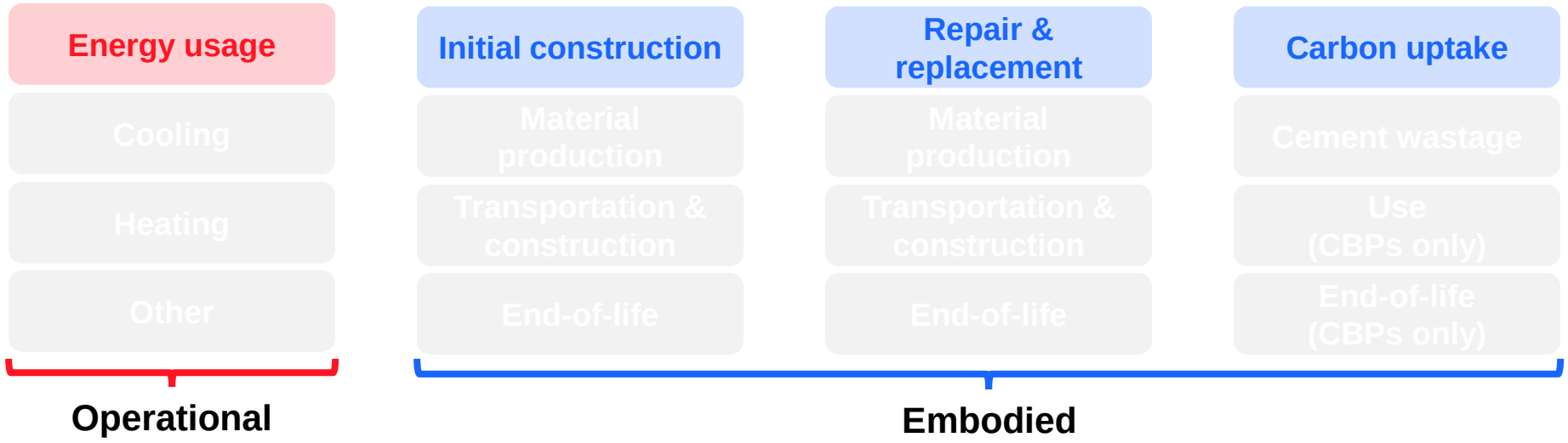
Building Archetypes comparative, paired

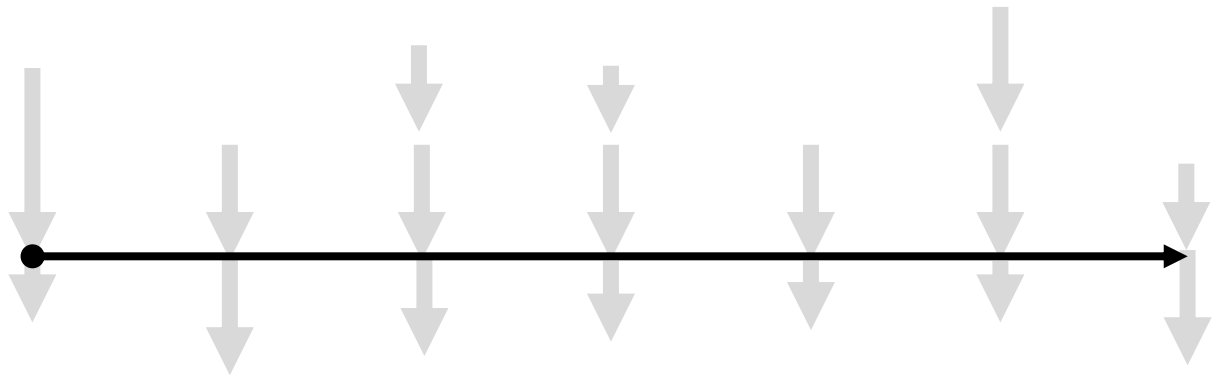


Building Archetypes comparative, paired



Time Series Elements | *Building Life Cycle Assessment (LCA)*





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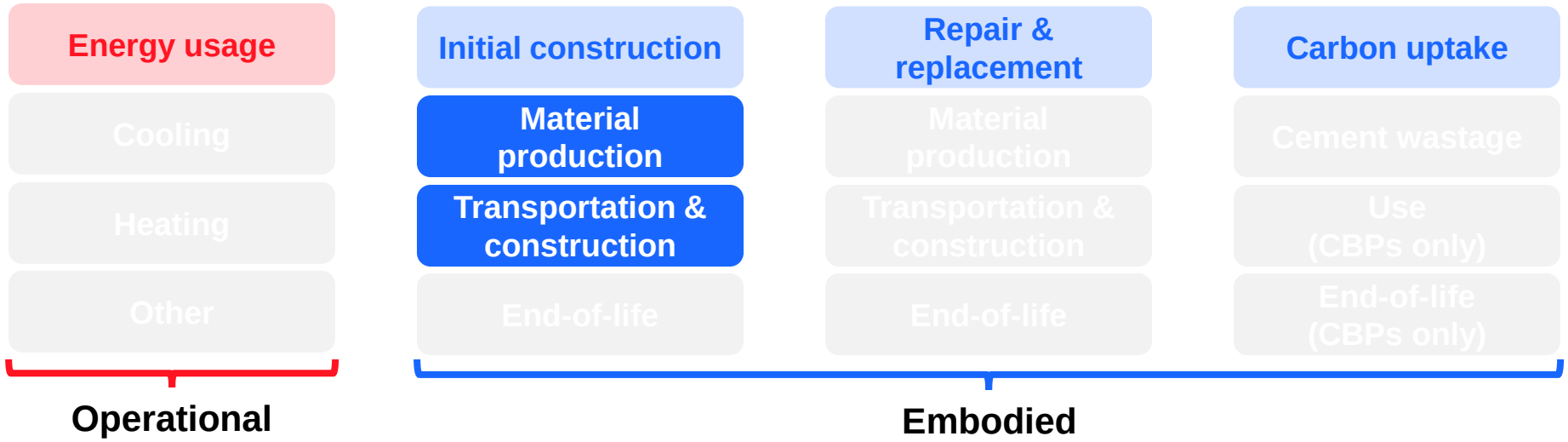
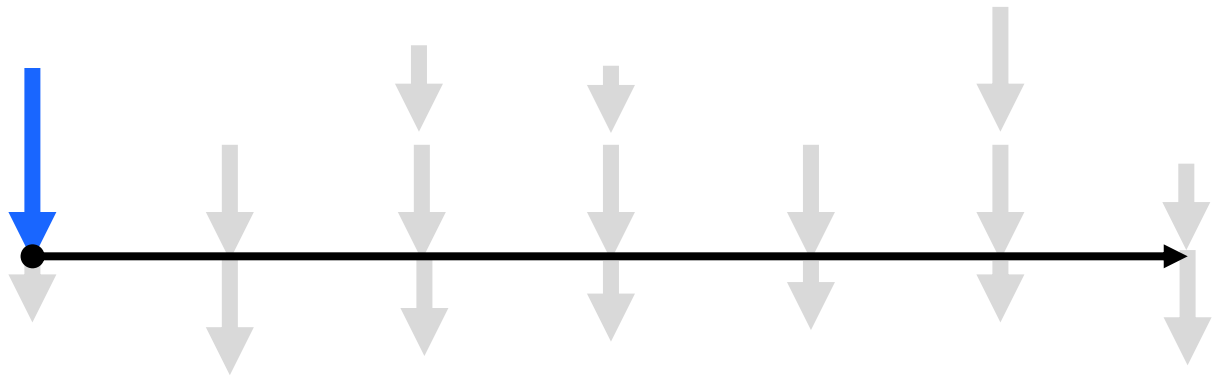
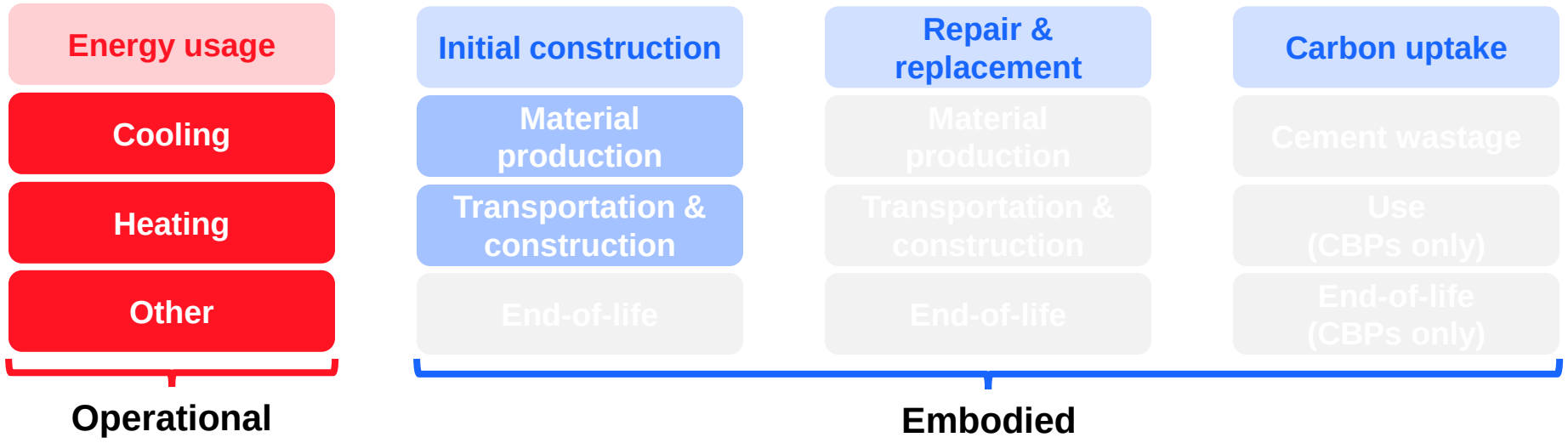
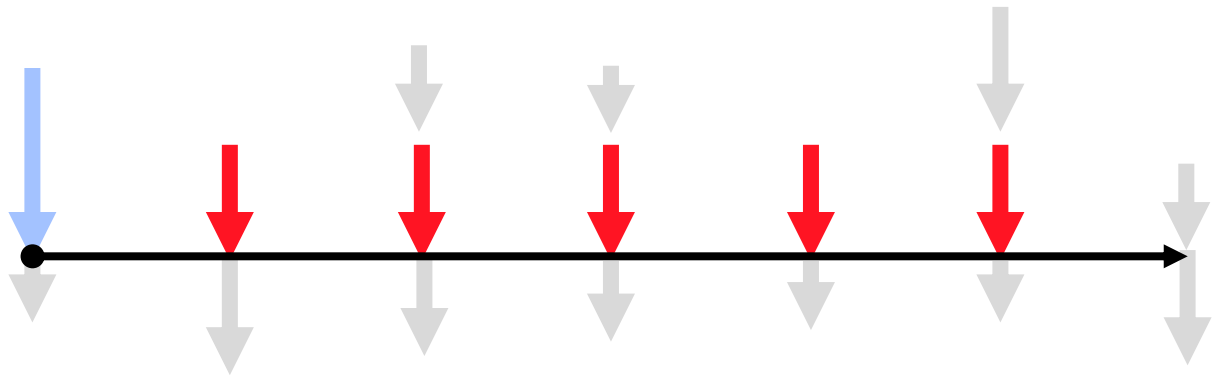




Time Series Elements | *Building Life Cycle Assessment (LCA)*





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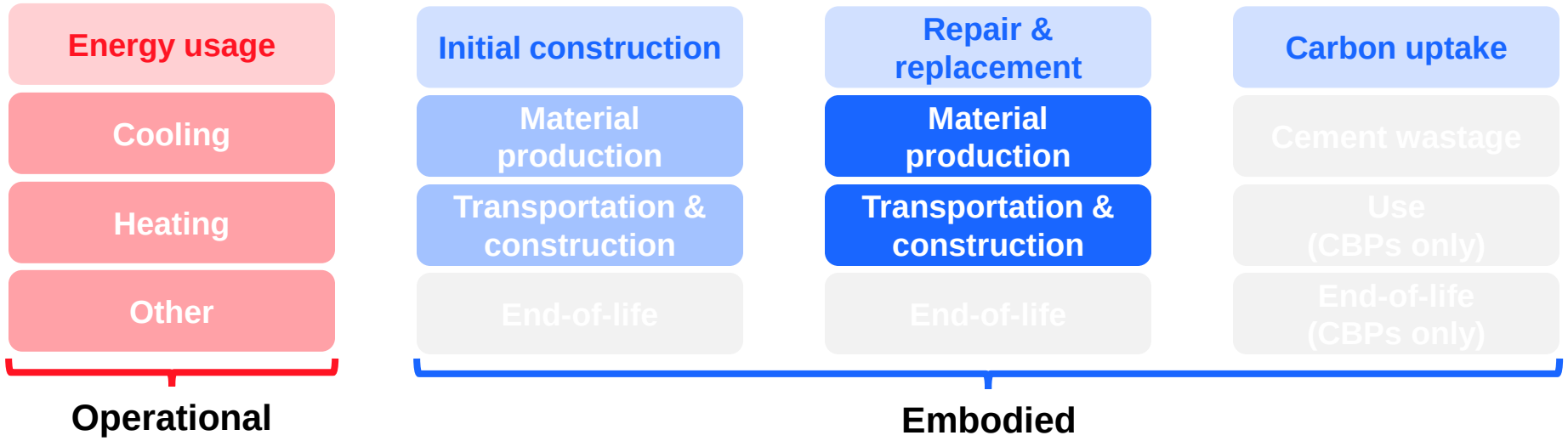

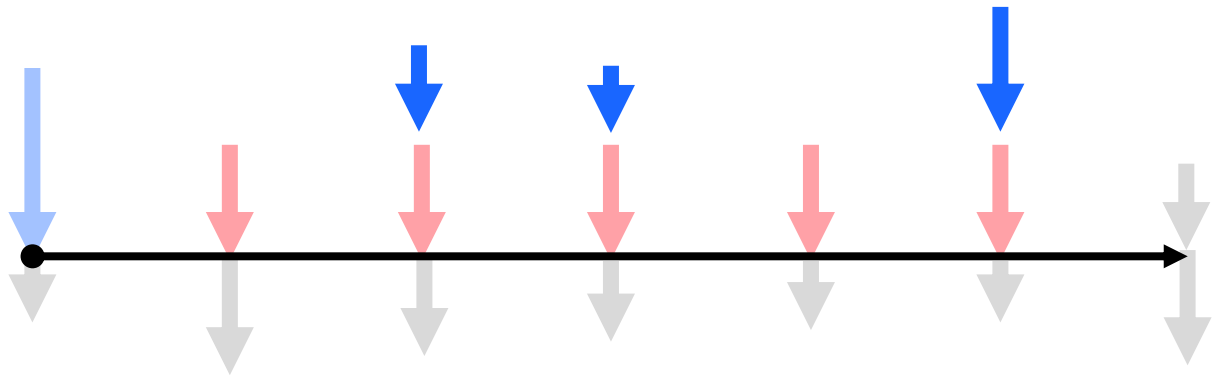

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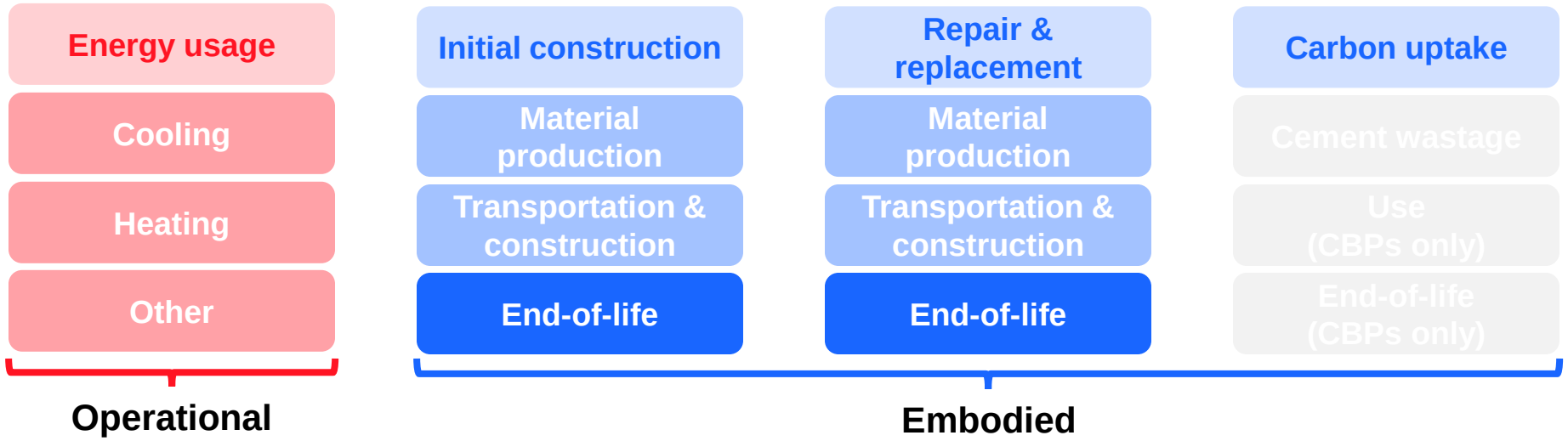

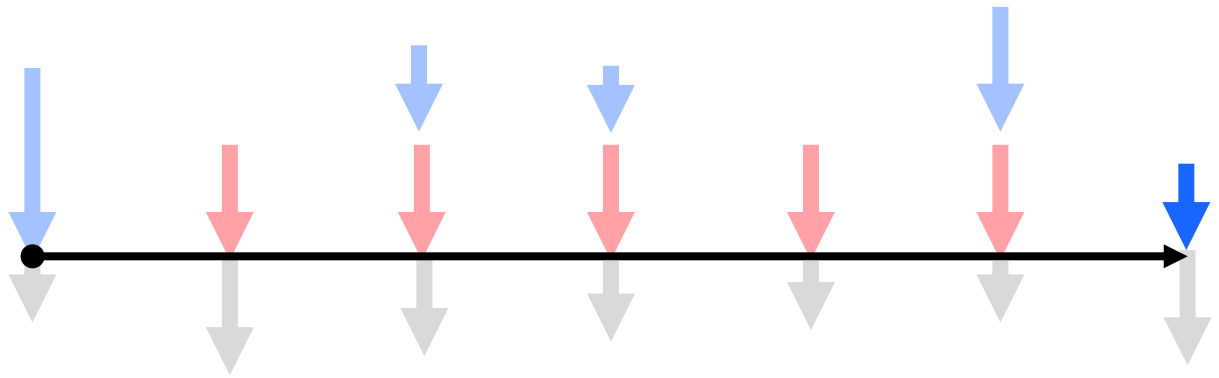

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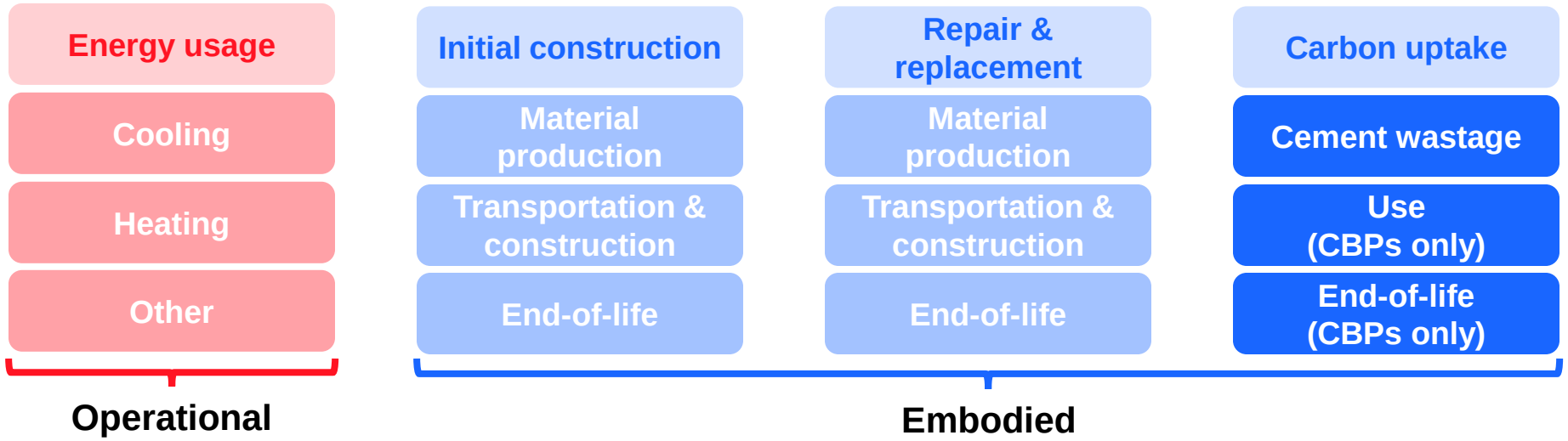
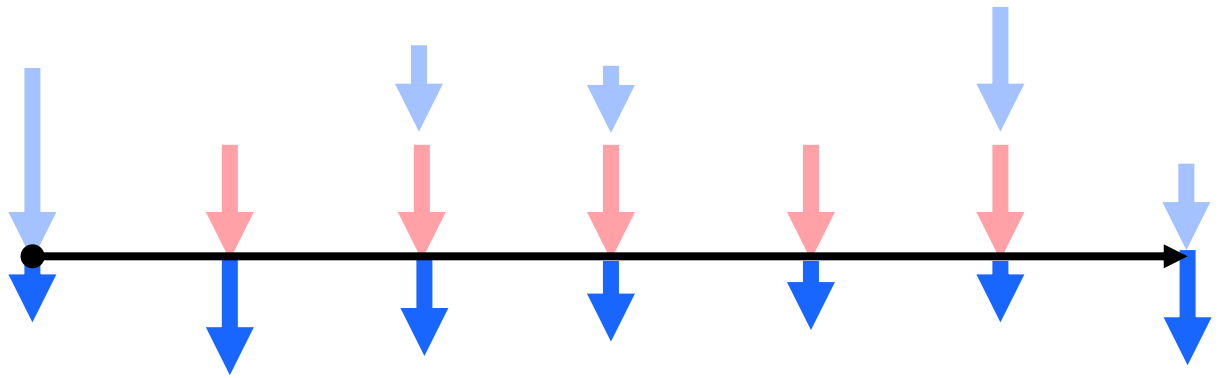




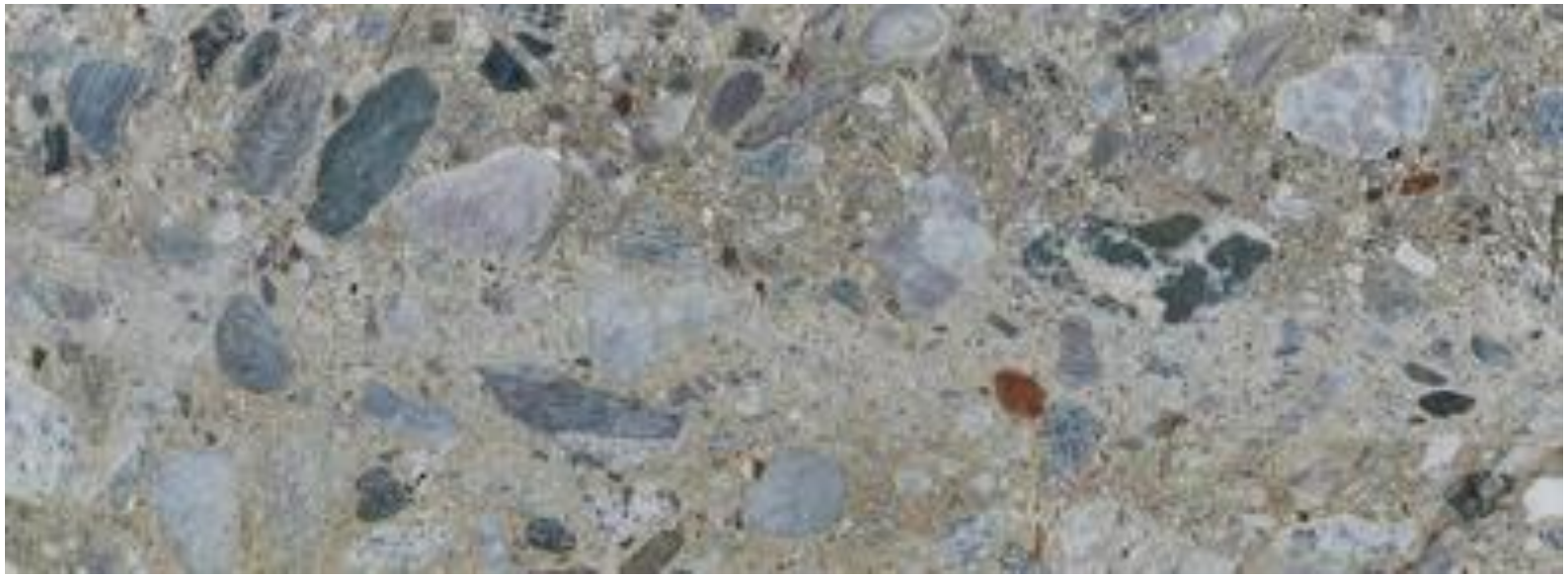
Contributions

Updated life cycle assessment model accounting for carbon uptake on concrete surfaces

Understanding carbon uptake critical to planning for carbon neutrality

overstating extent of carbonation hinders GHG reduction efforts

Concrete Surface



Understanding carbon uptake critical to planning for carbon neutrality

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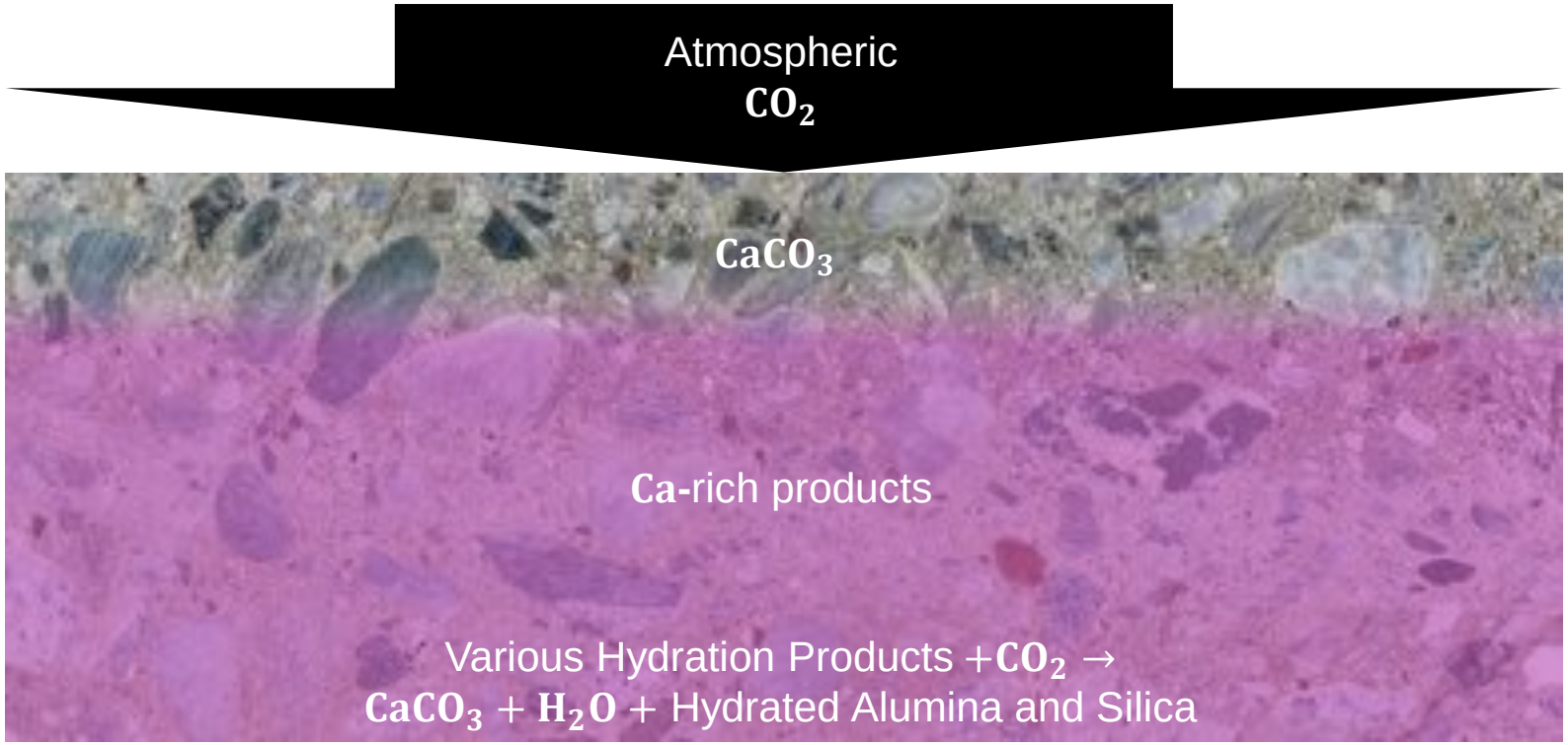

Understanding carbon uptake critical to planning for carbon neutrality

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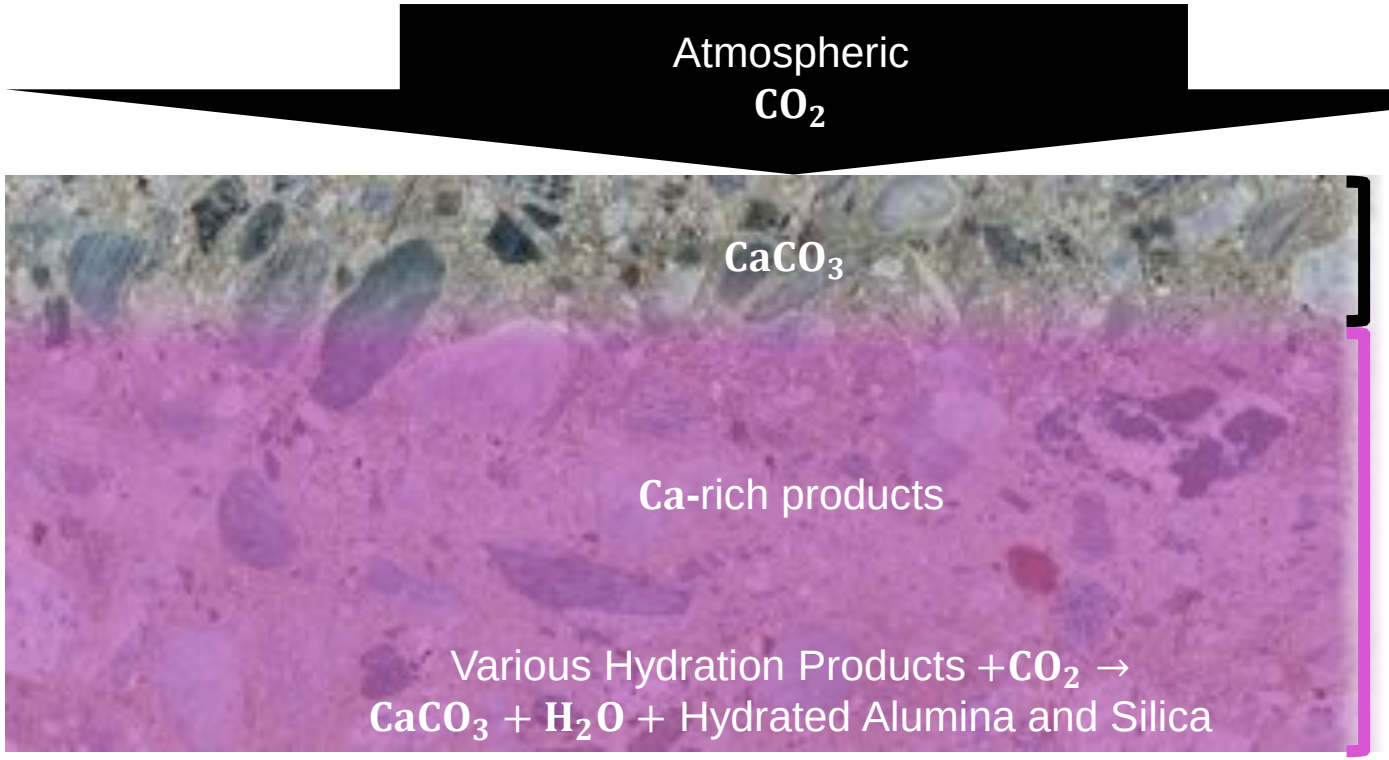


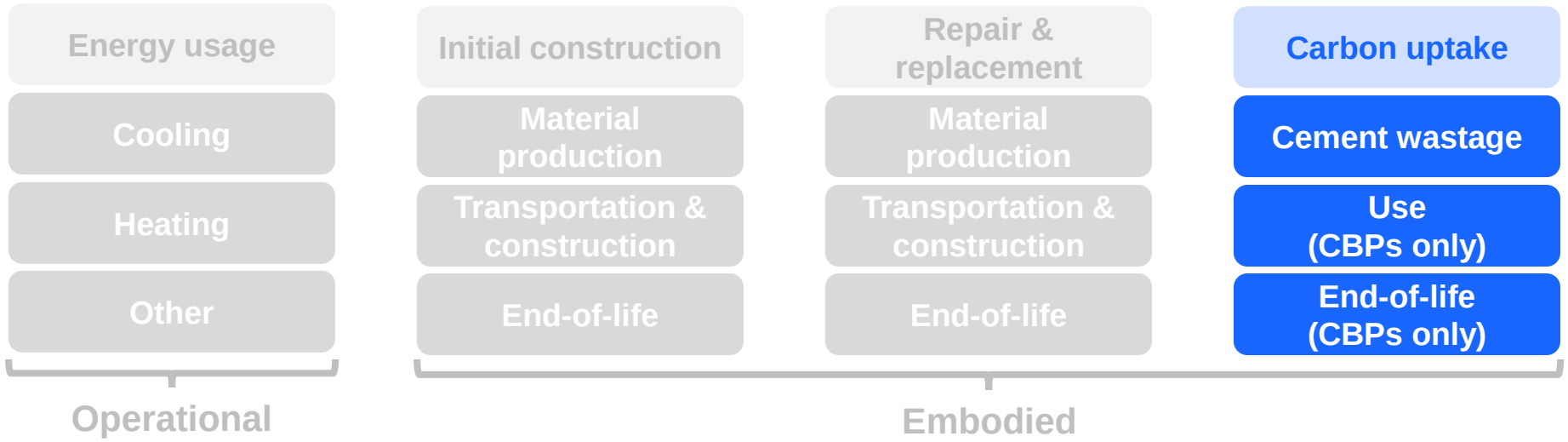
Carbonated Layer

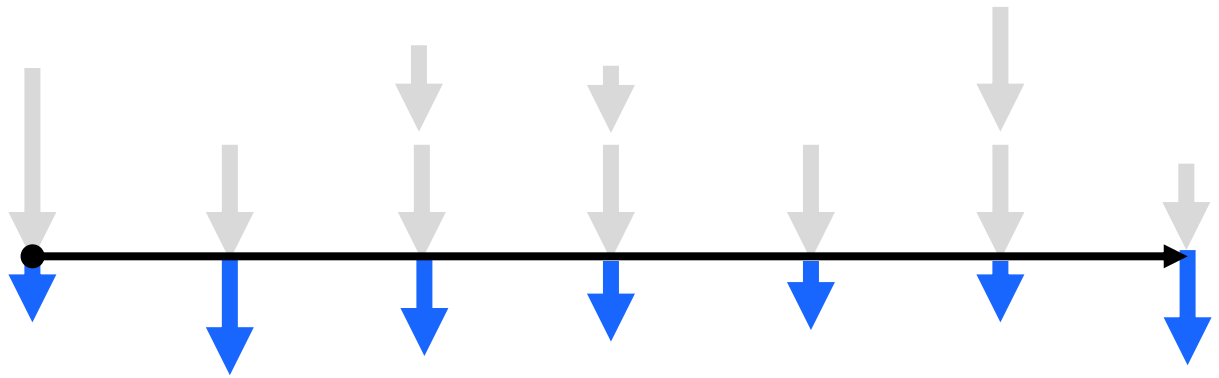
How much carbon is sequestered?

Uncarbonated Layer

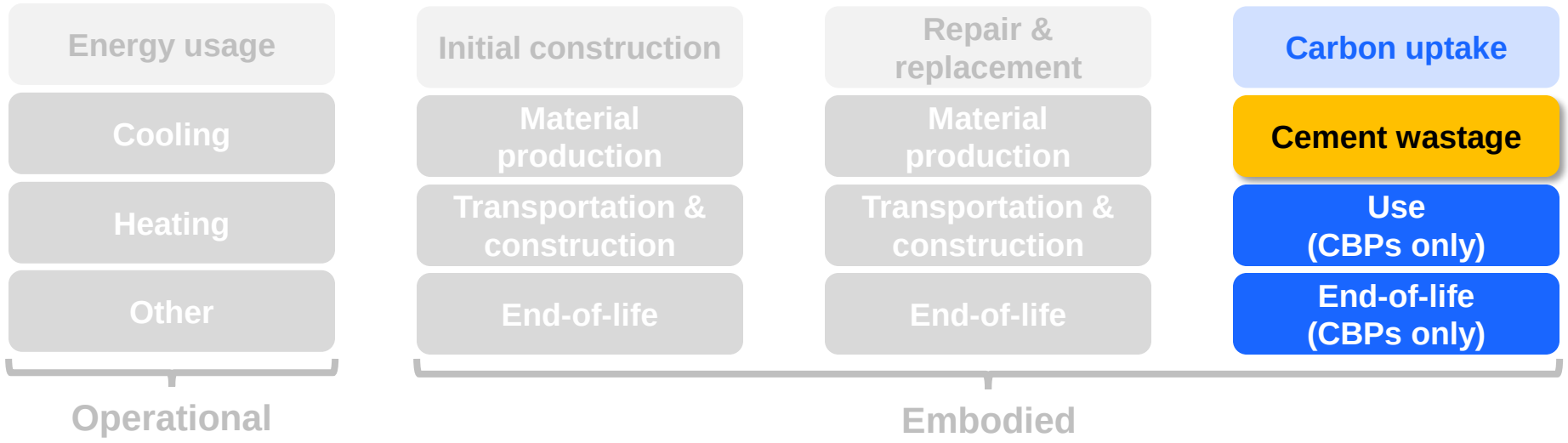
Is steel corrosion prevented?

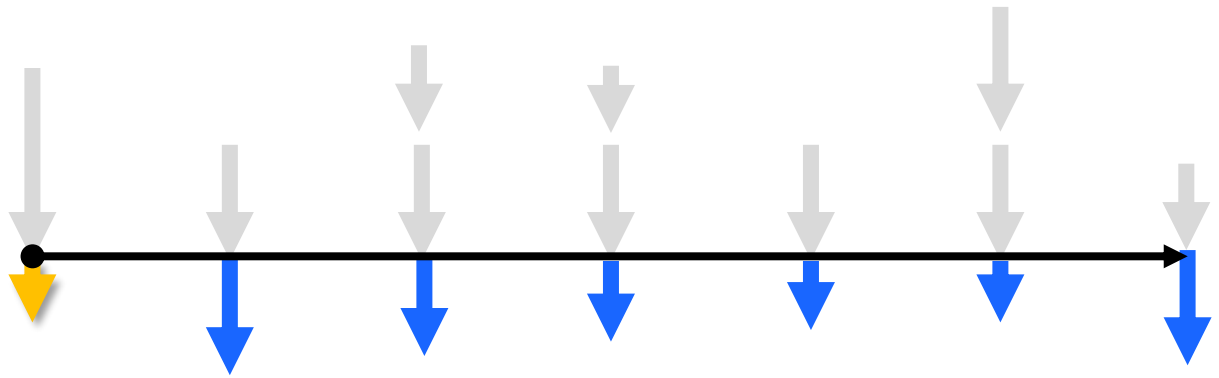
C-Up Model | *Building life cycle stages*





C-Up Model | *Building life cycle stages*





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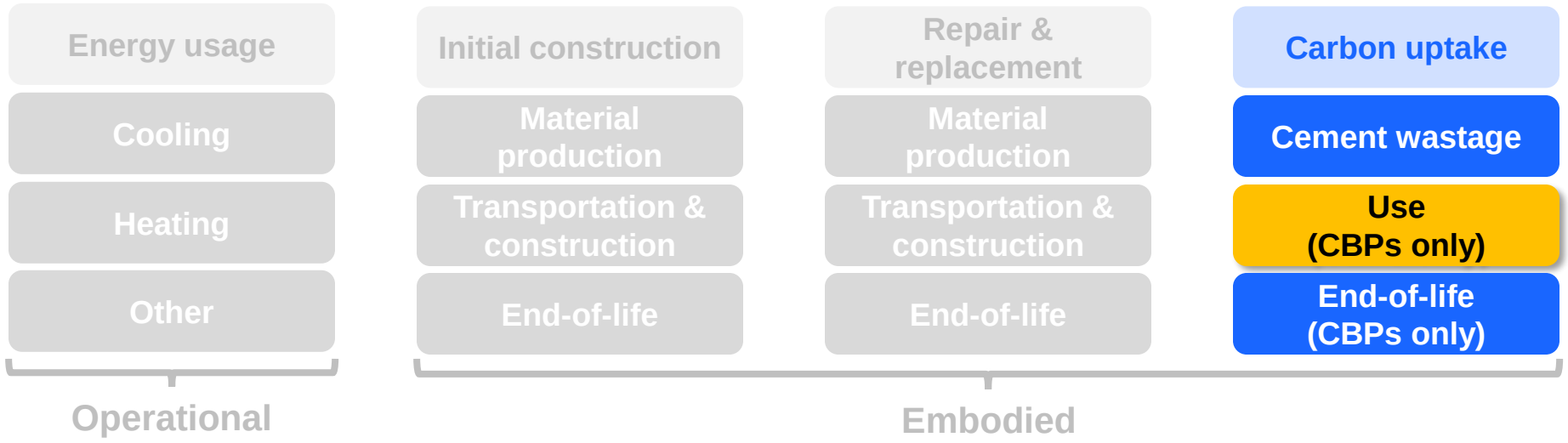
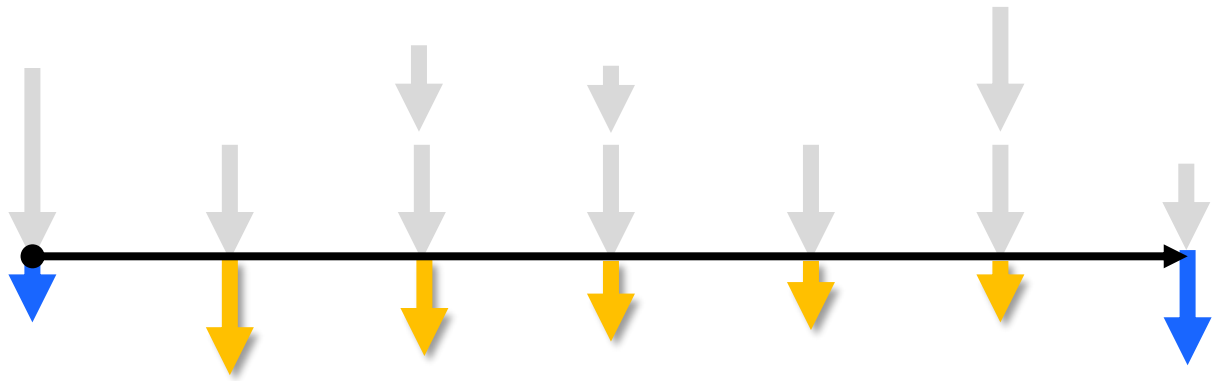
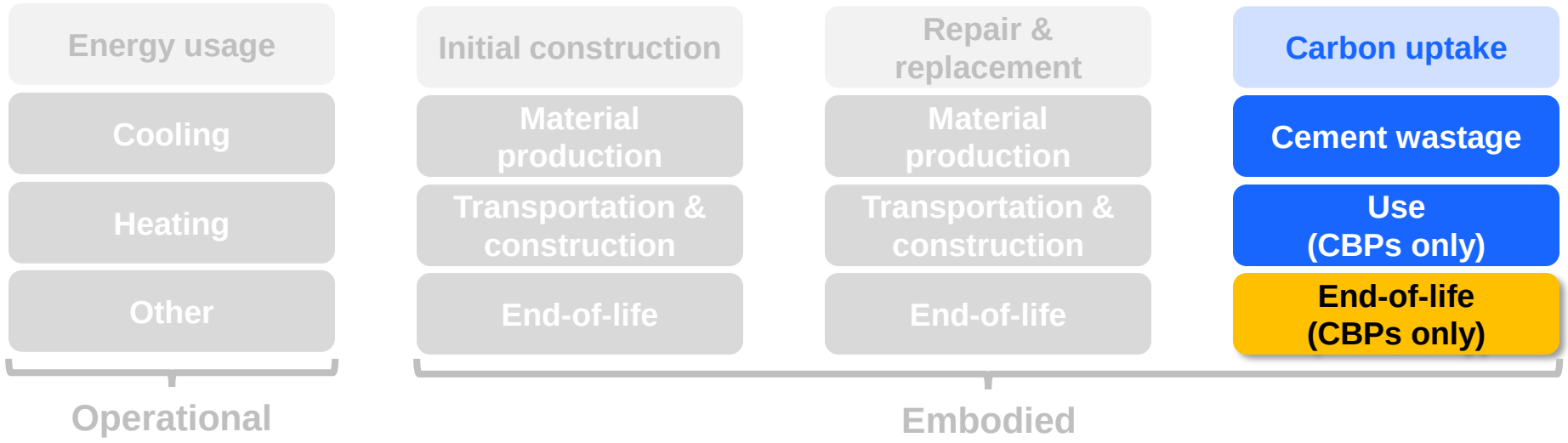
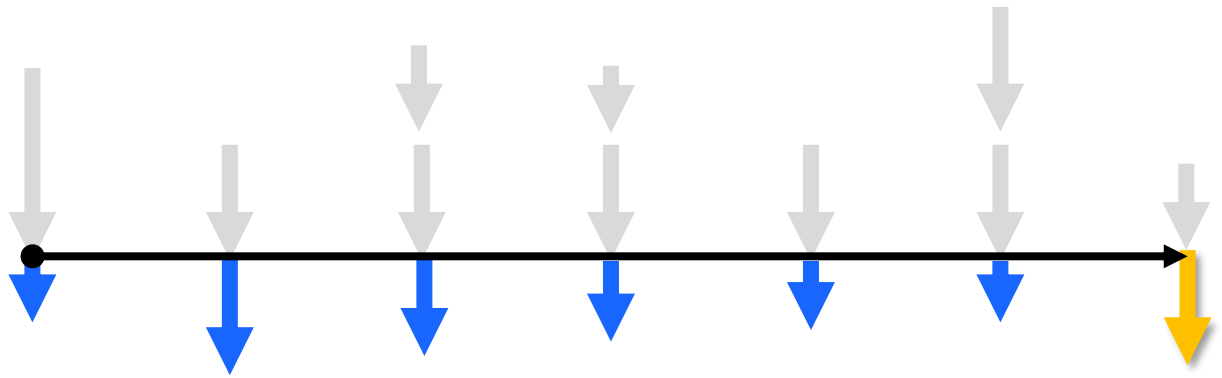




C-Up Model | *Building life cycle stages*



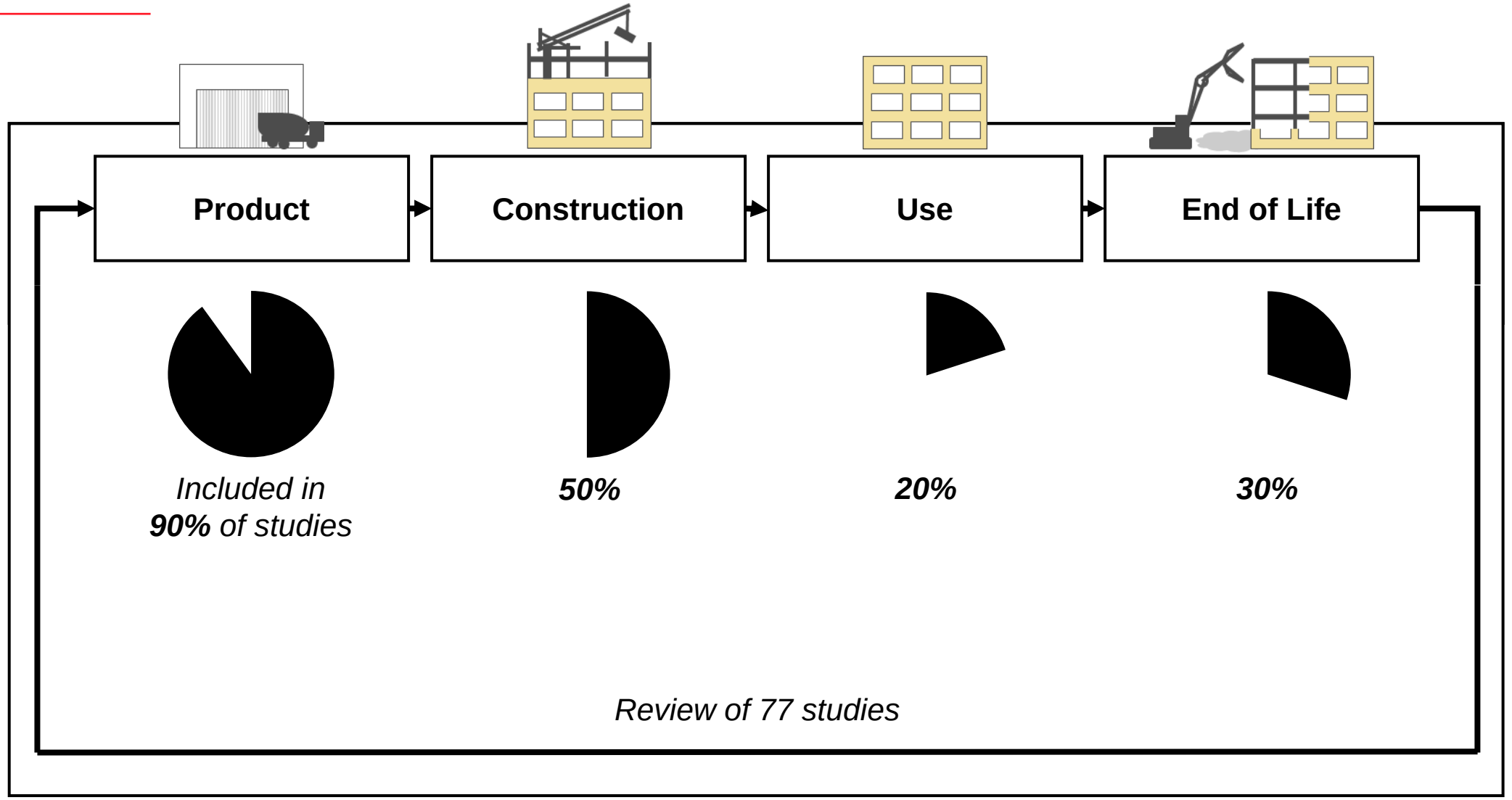


Contributions

Updated life cycle assessment model accounting for emissions caused by damages

In studies of building embodied emissions, use stage “most neglected”.

Even in studies that consider use stage, repair limited to regular wear-and-tear



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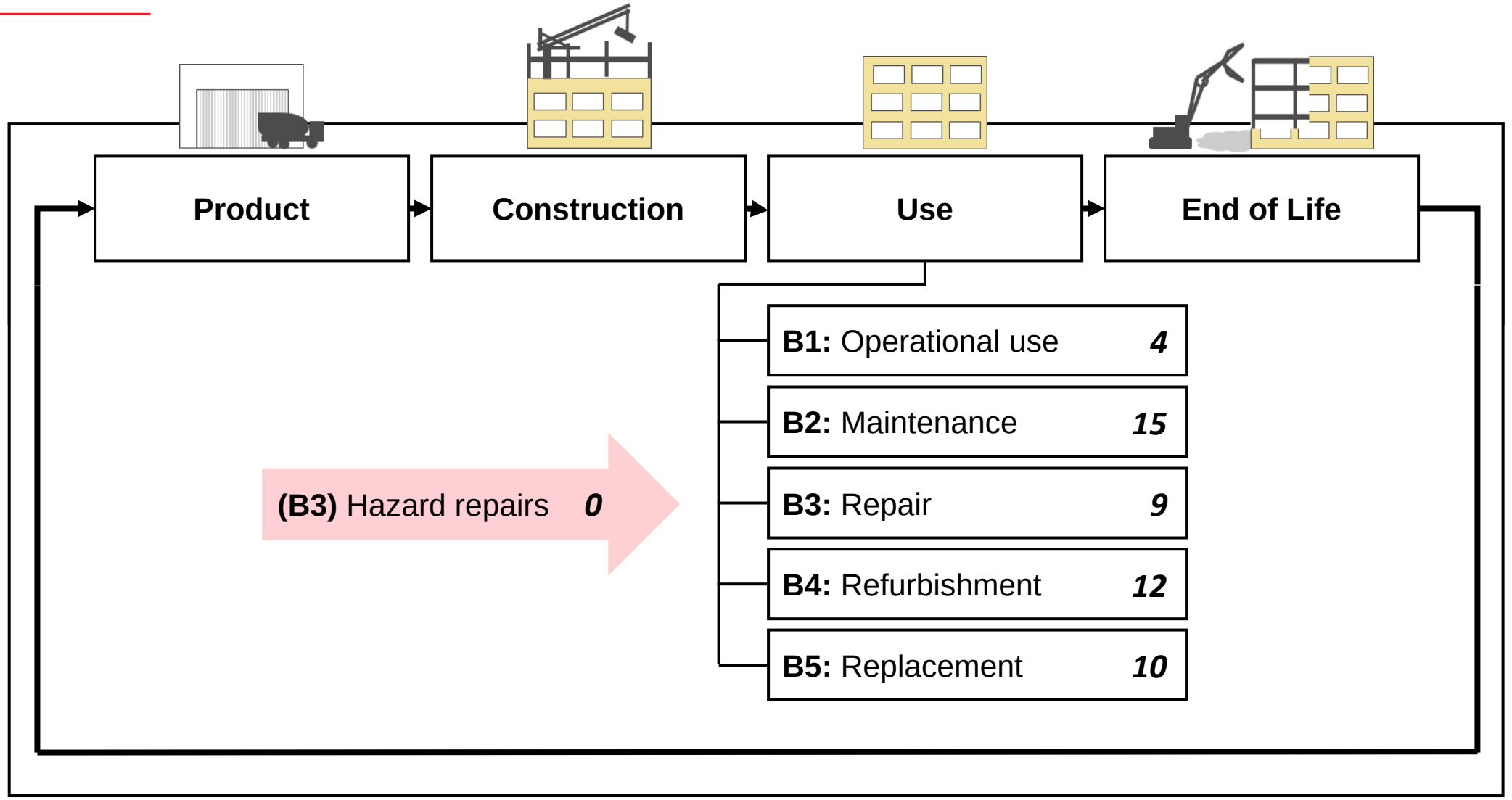
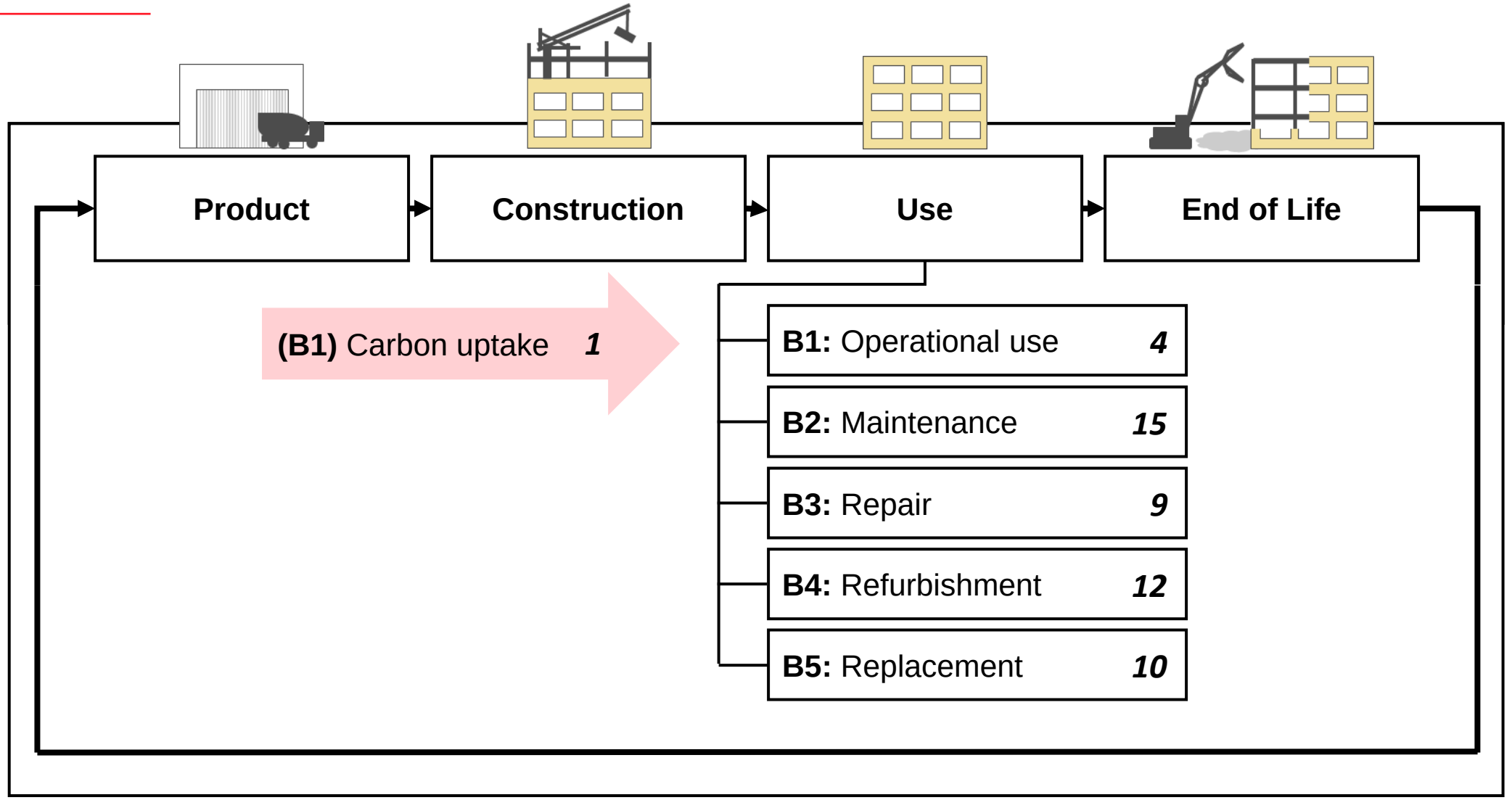
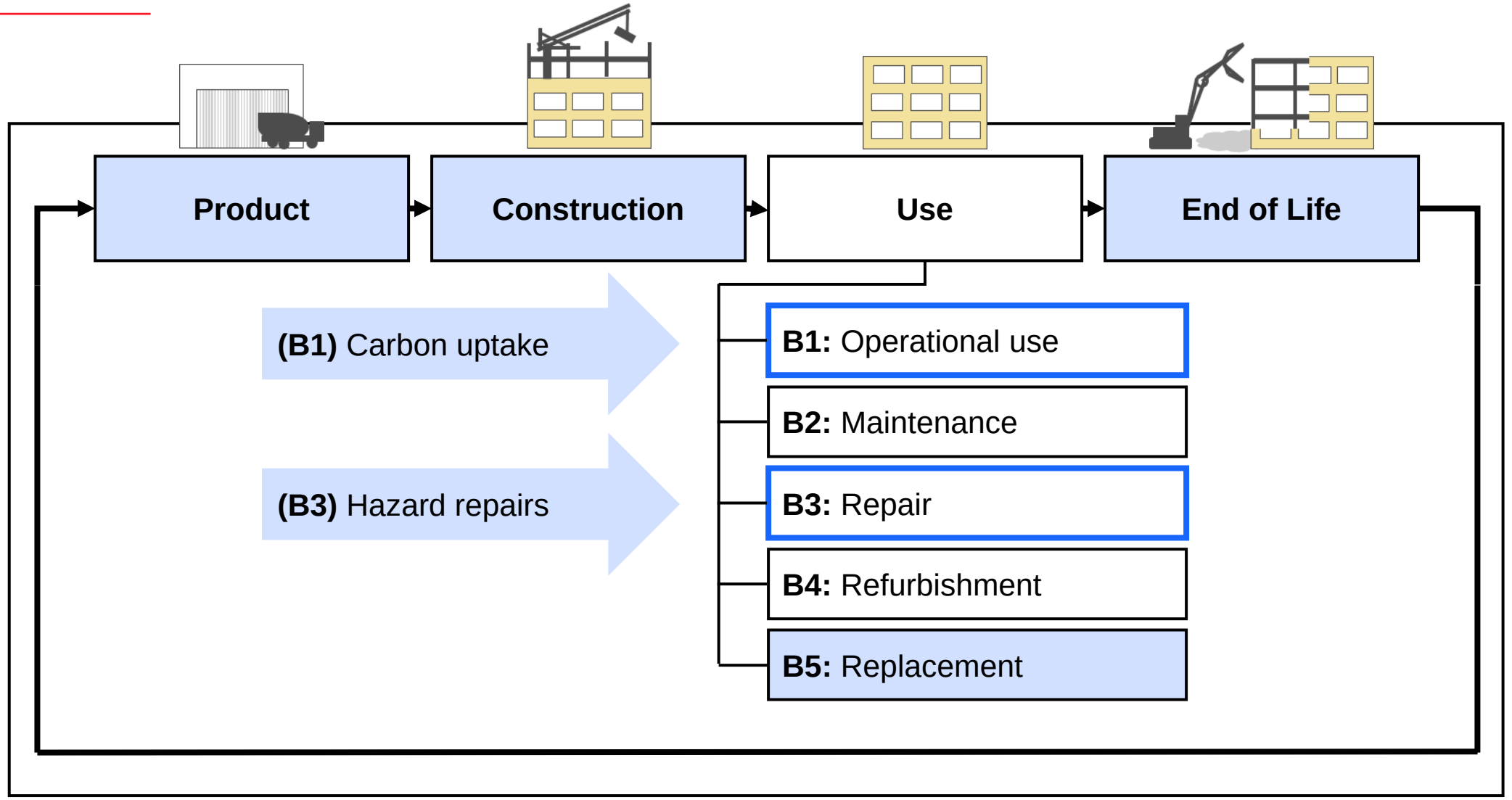


In studies of building embodied emissions, use stage “most neglected”. Even in studies that consider use stage, carbon uptake discarded or overestimated

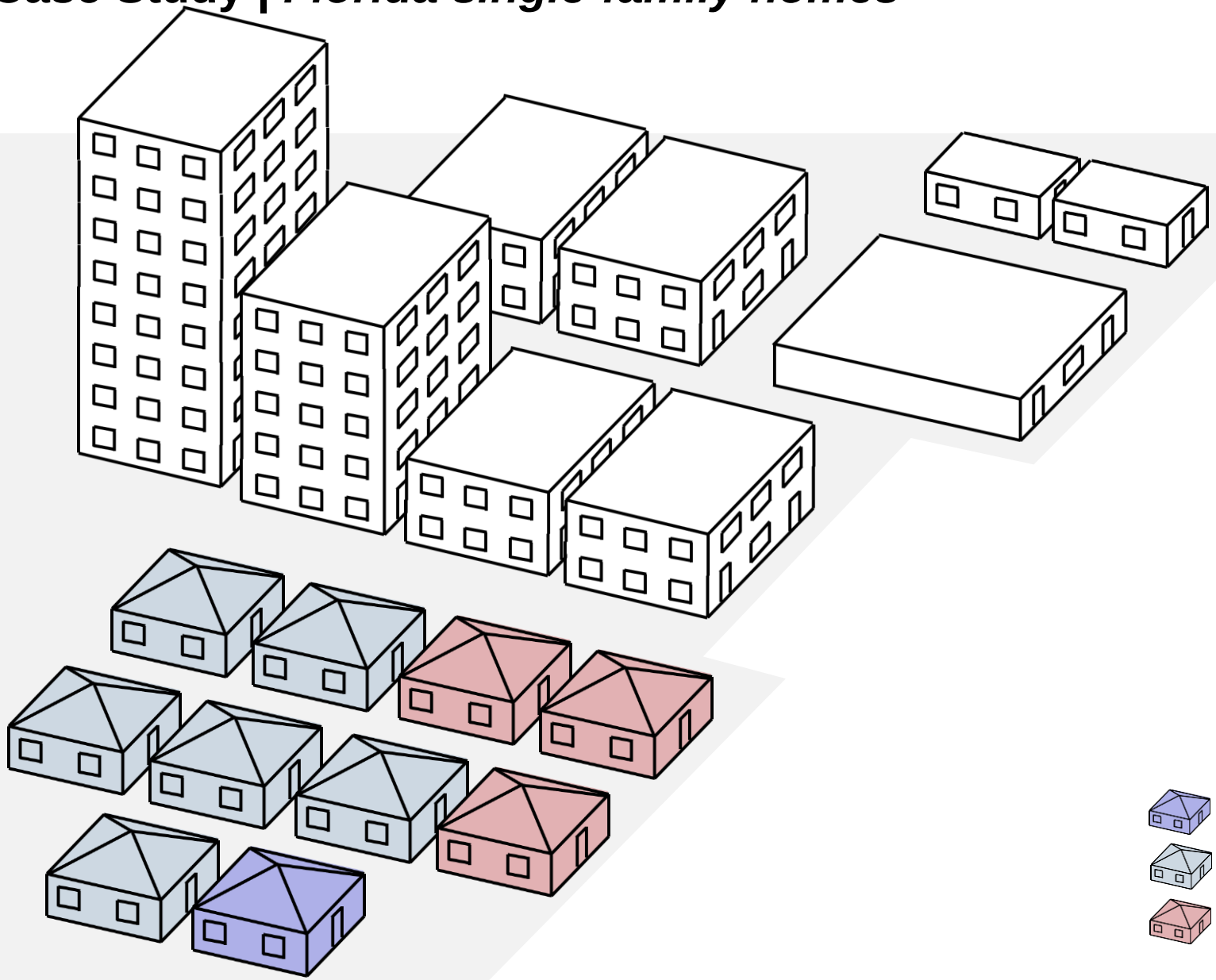


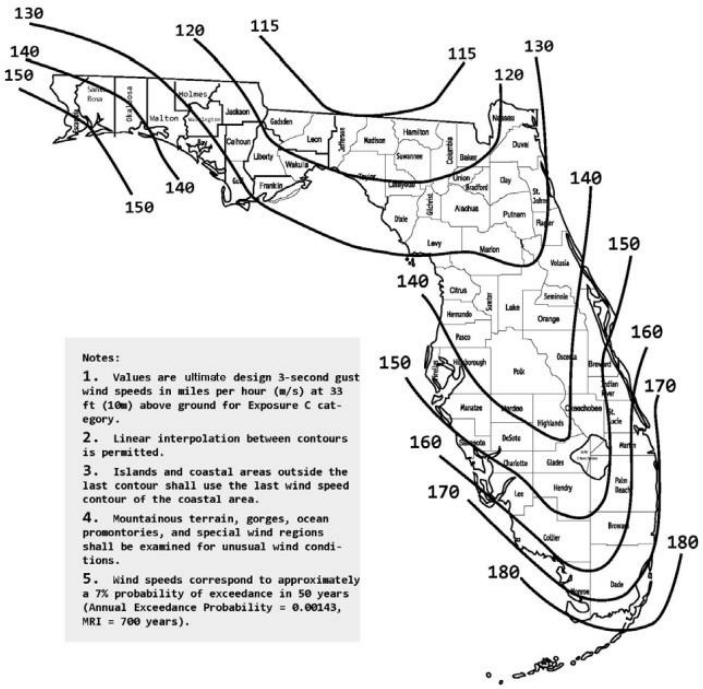
Pomponi and Moncaster | 2016

BAIA model considers use stage, ignores hazard repairs as well as carbon uptake, both of which my work addresses



Case Study | *Florida single-family homes*





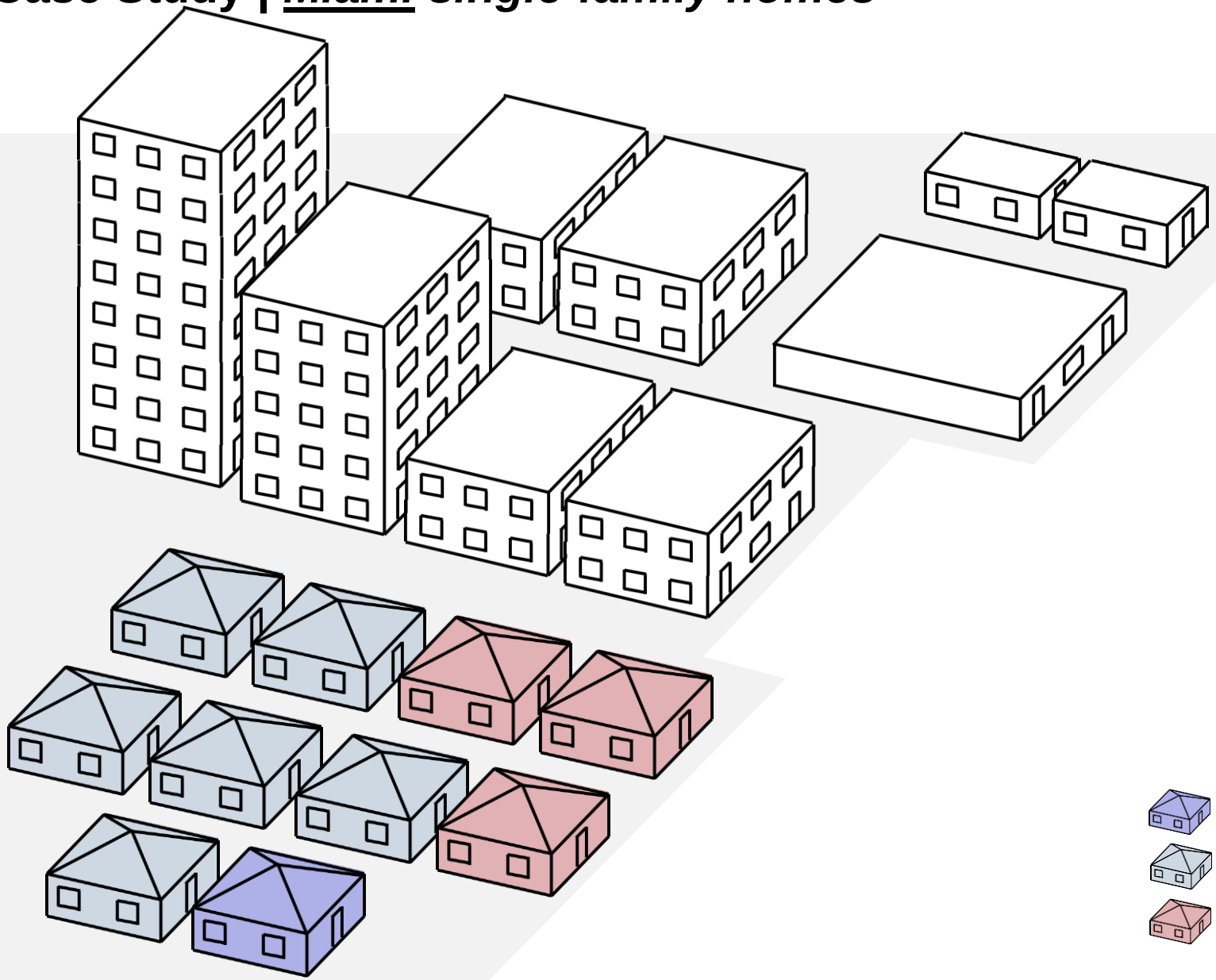
Ultimate Design Wind Speeds for Risk Category II

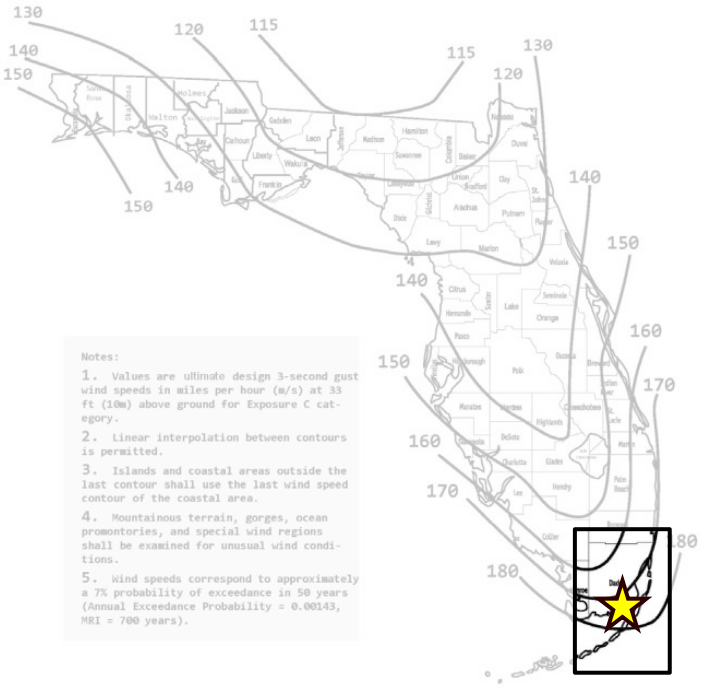
: ‘Concrete’

: ‘Masonry’

: ‘Wood’

Case Study | *Miami single-family homes*





Ultimate Design Wind Speeds for Risk Category II

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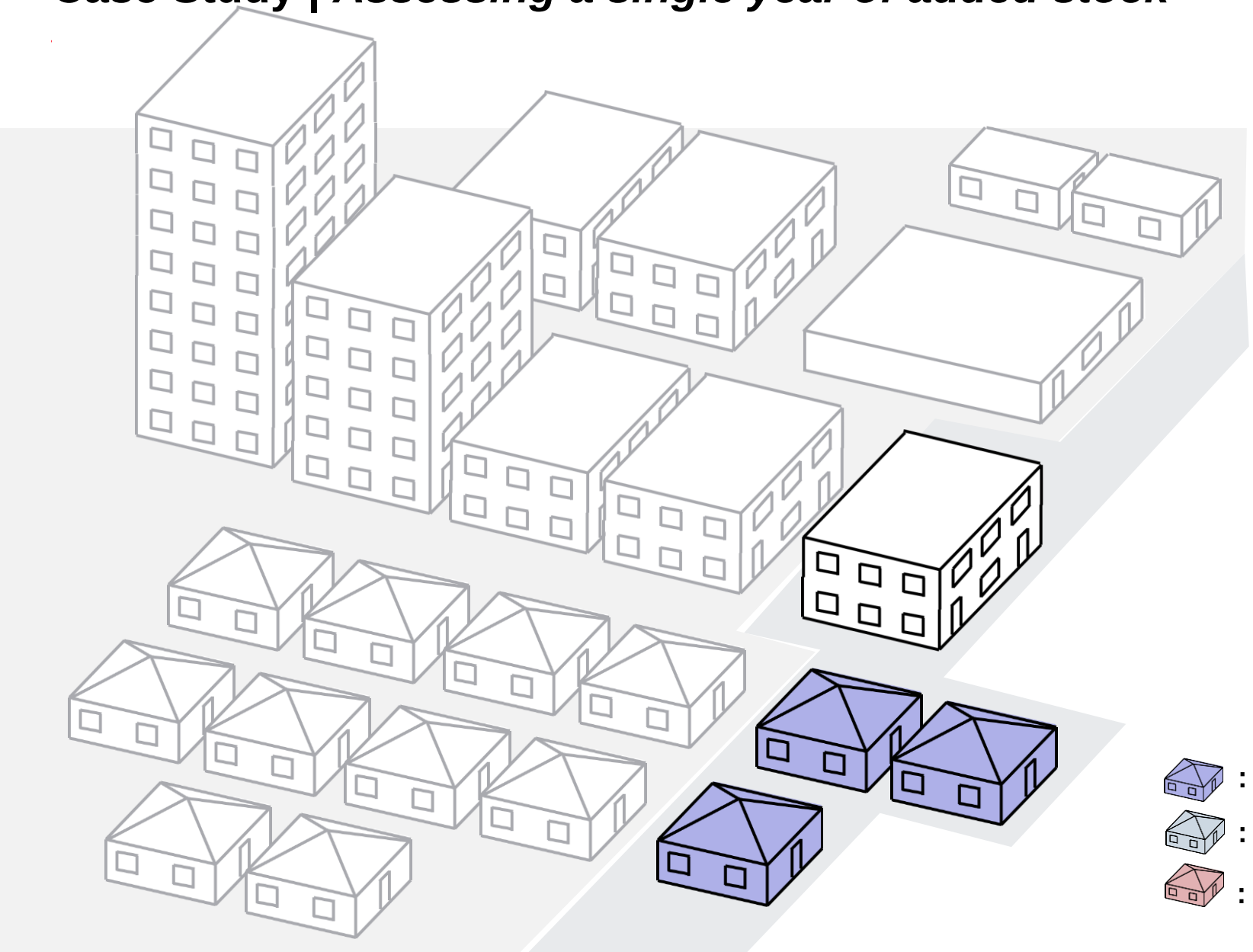
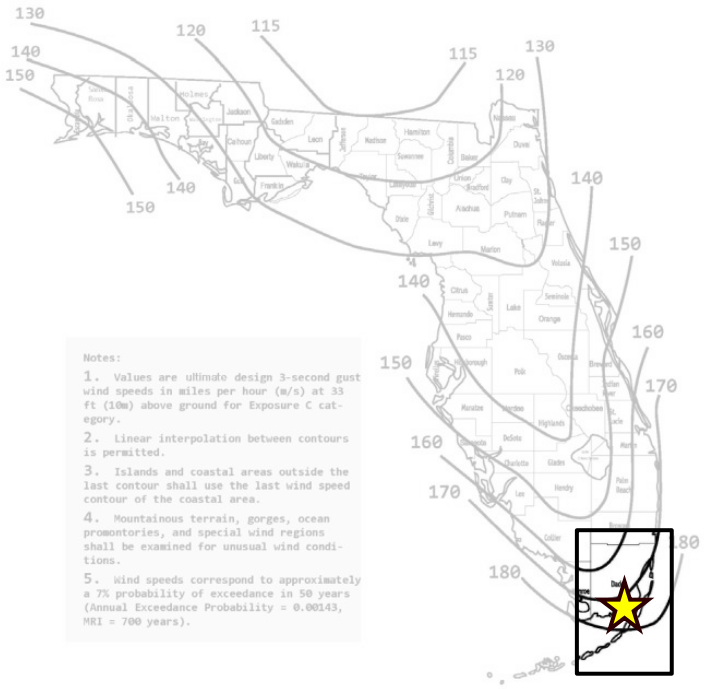
Case Study | *Assessing a single year of added stock*





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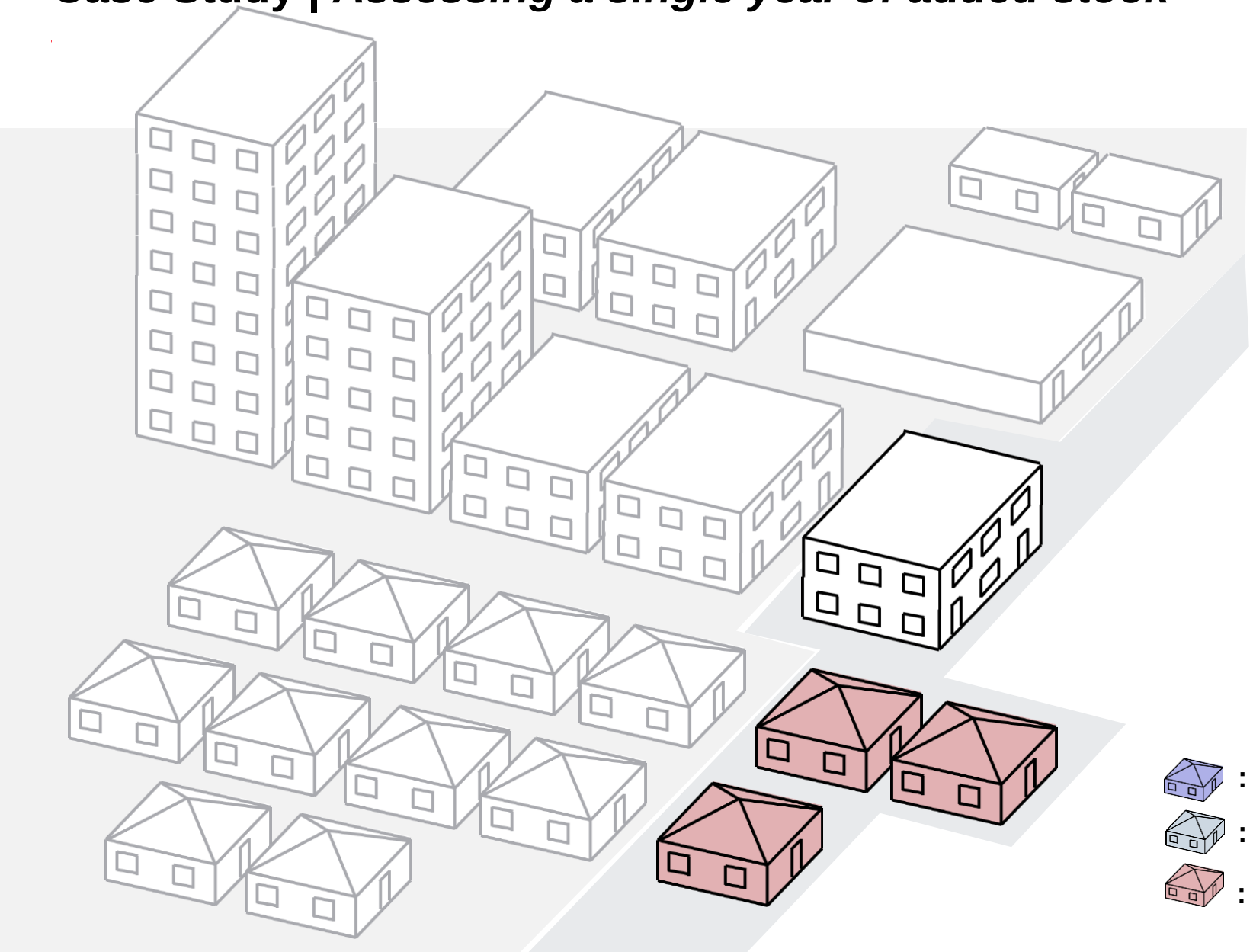

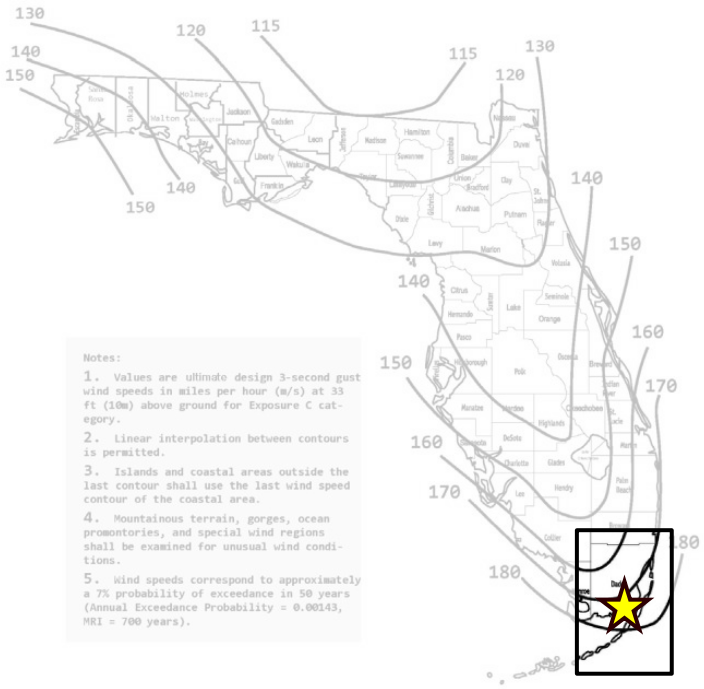

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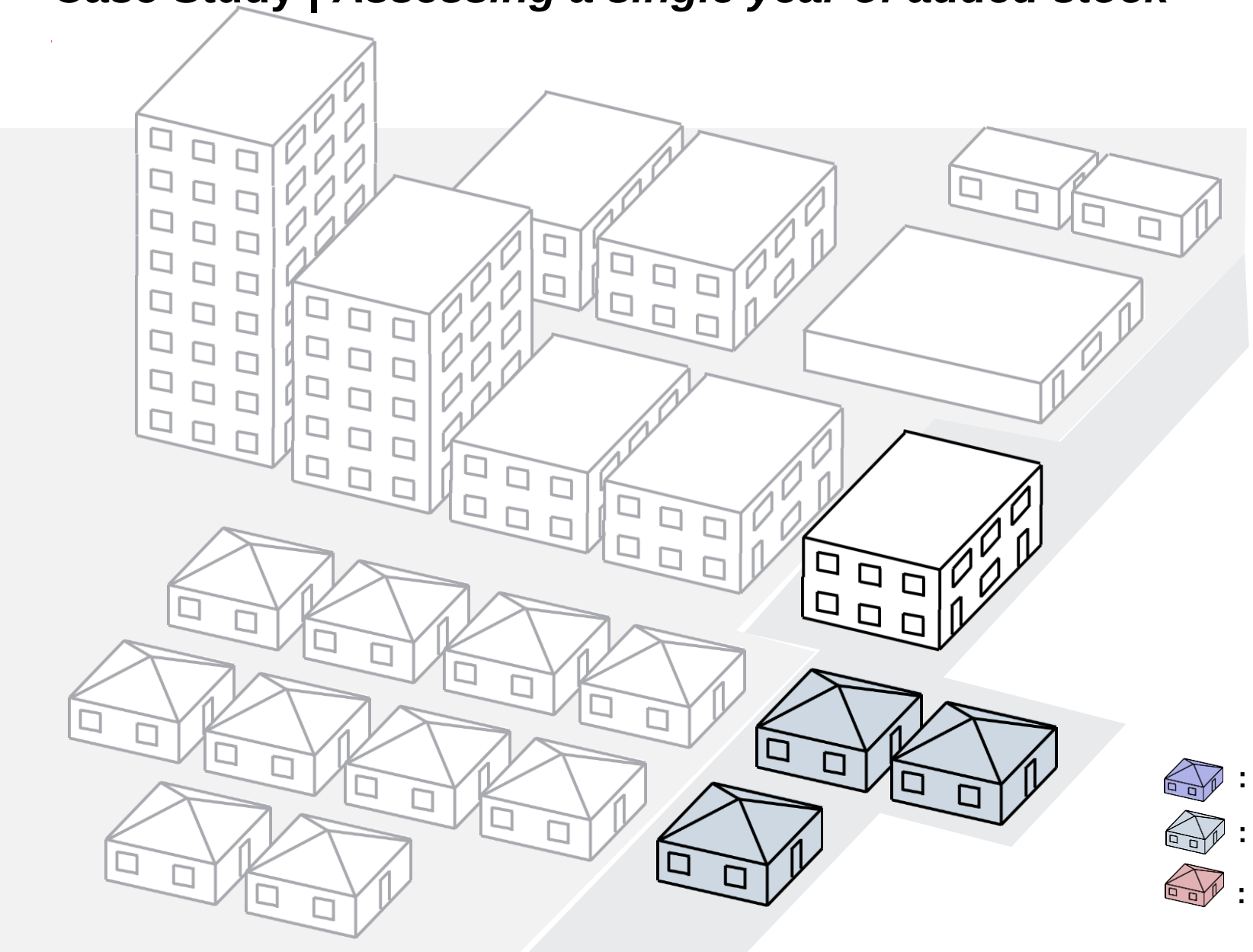

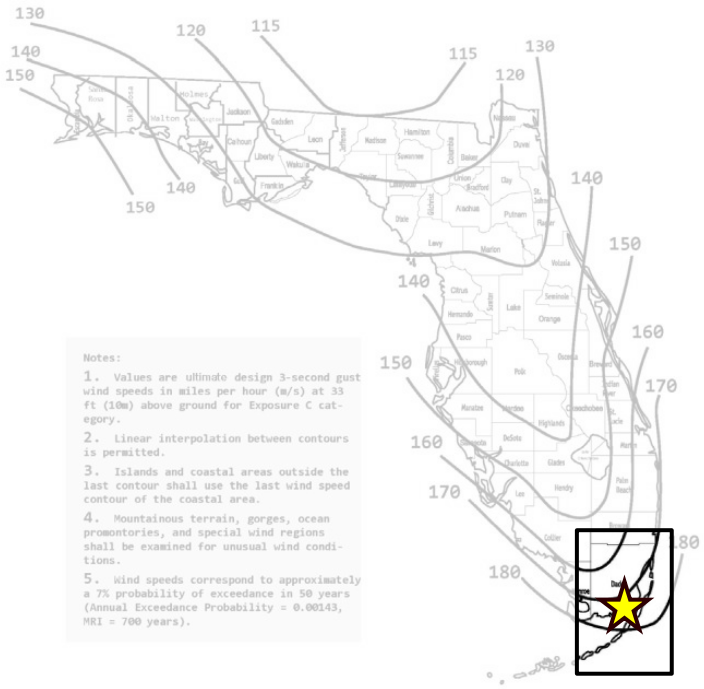

Ultimate Design Wind Speeds for Risk Category II

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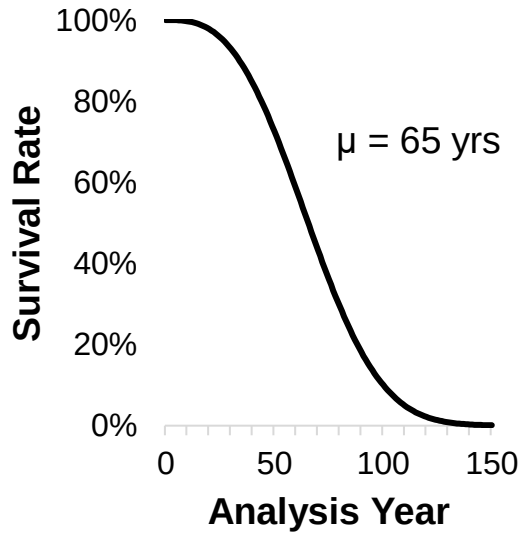
Case Study | *Assessing a single year of added stock*

: ‘Concrete’

: ‘Masonry’

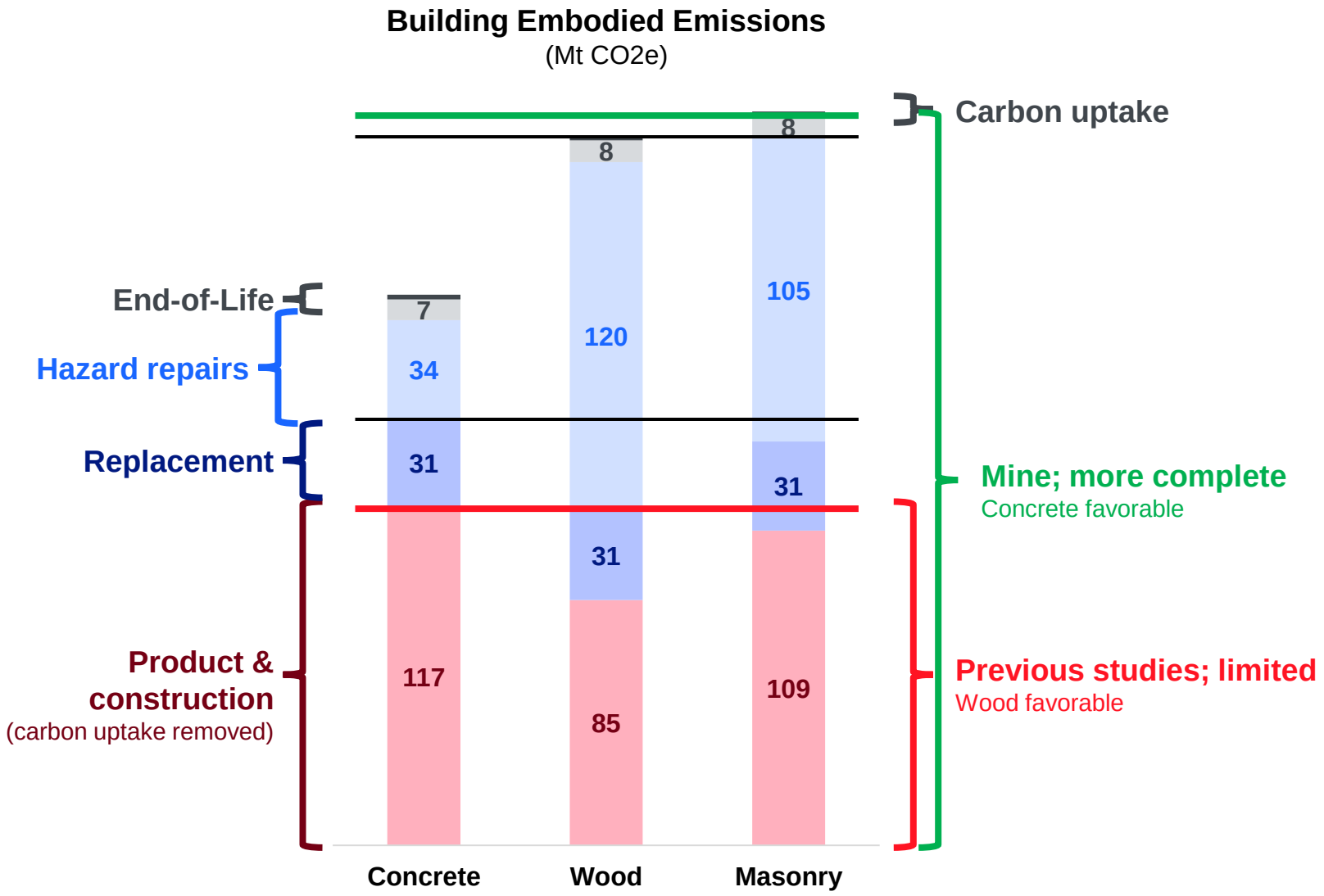
: ‘Wood’

Archetypes differ by ext wall core, otherwise equivalent



Concrete homes benefit from avoided damages, making up for initial difference

magnitude of expected damages vary widely by location



Eg tract in Miami-Dade, FL (mean of 5000 samples, 100 scenarios; median scenario)

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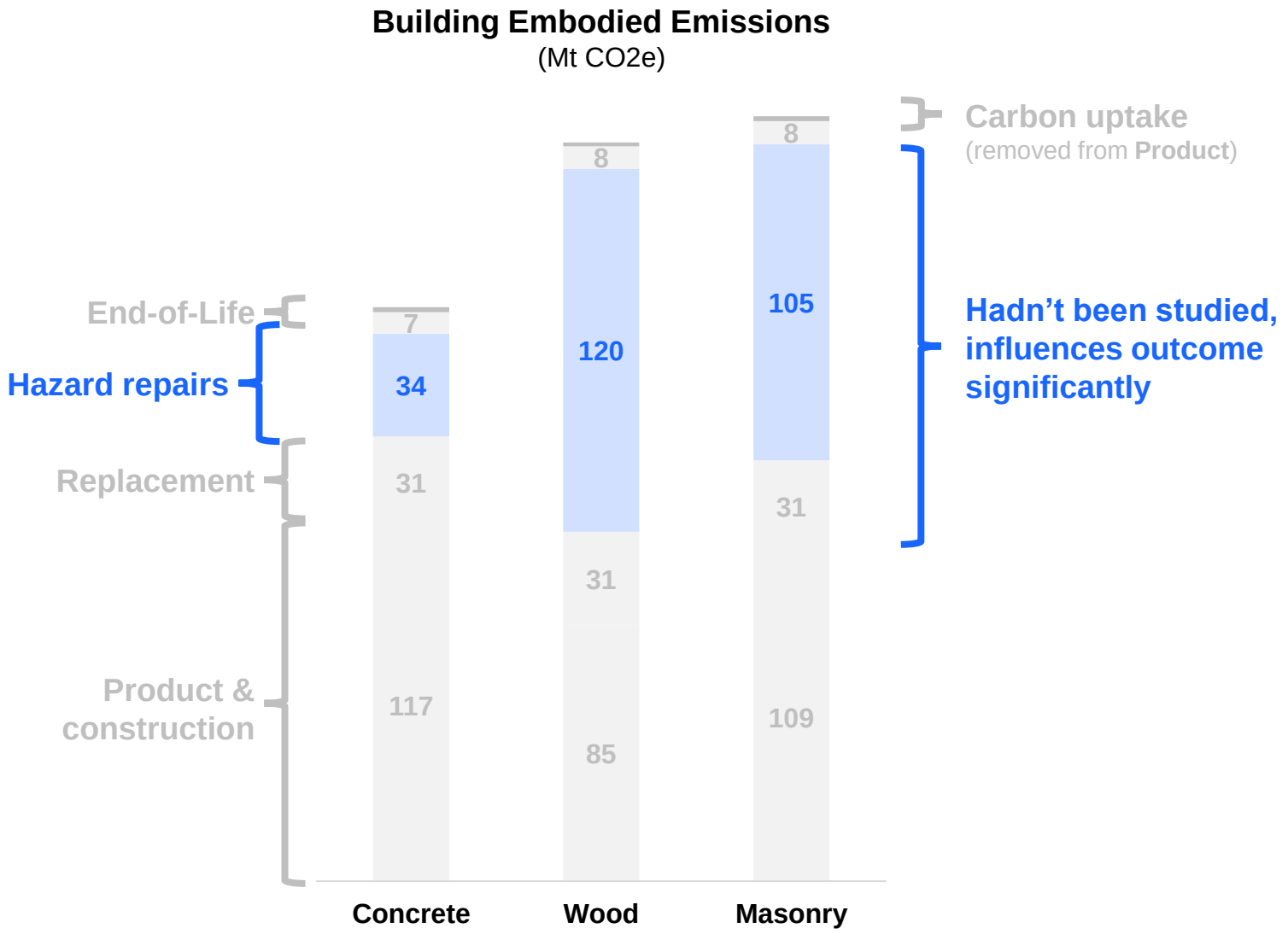

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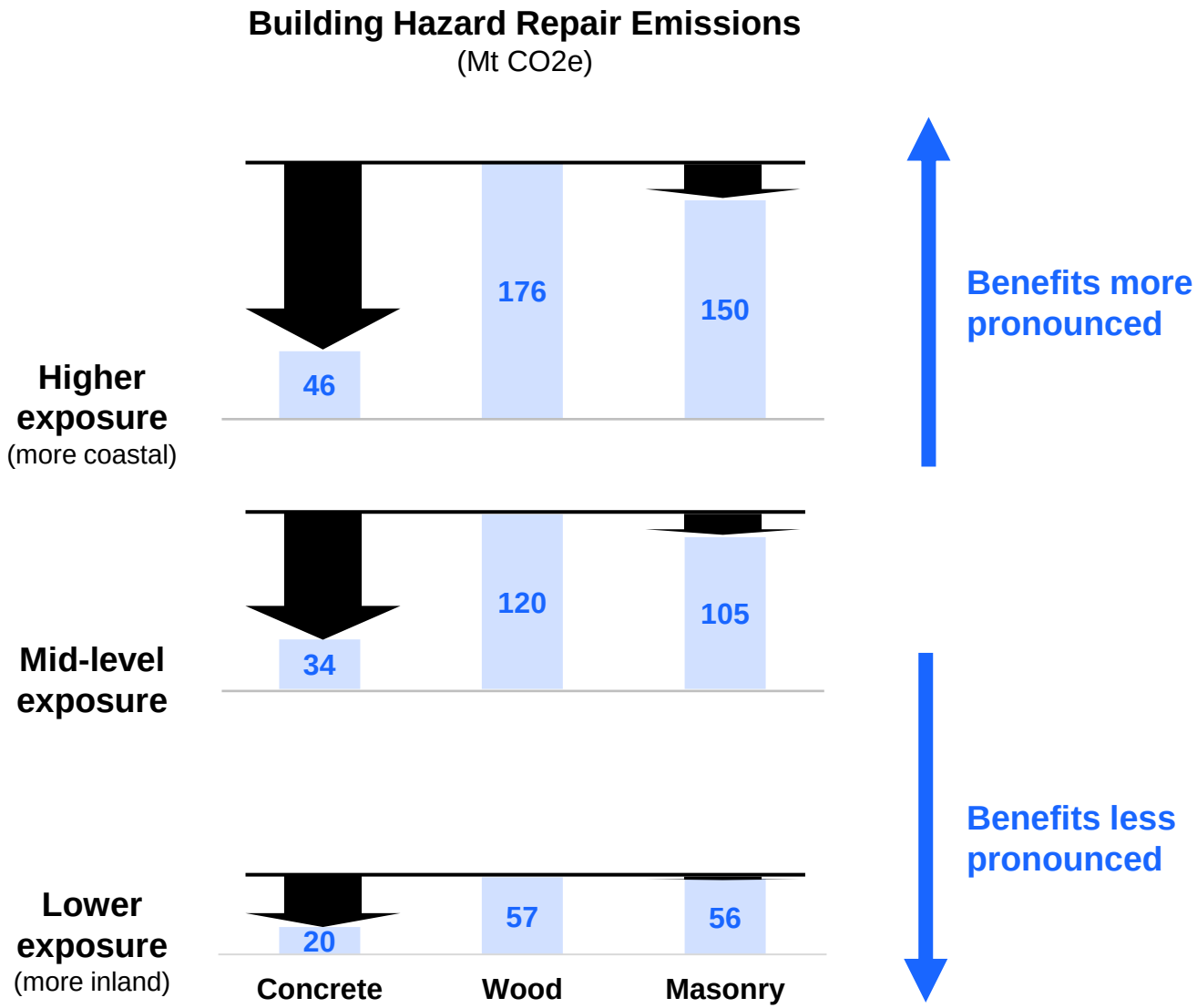
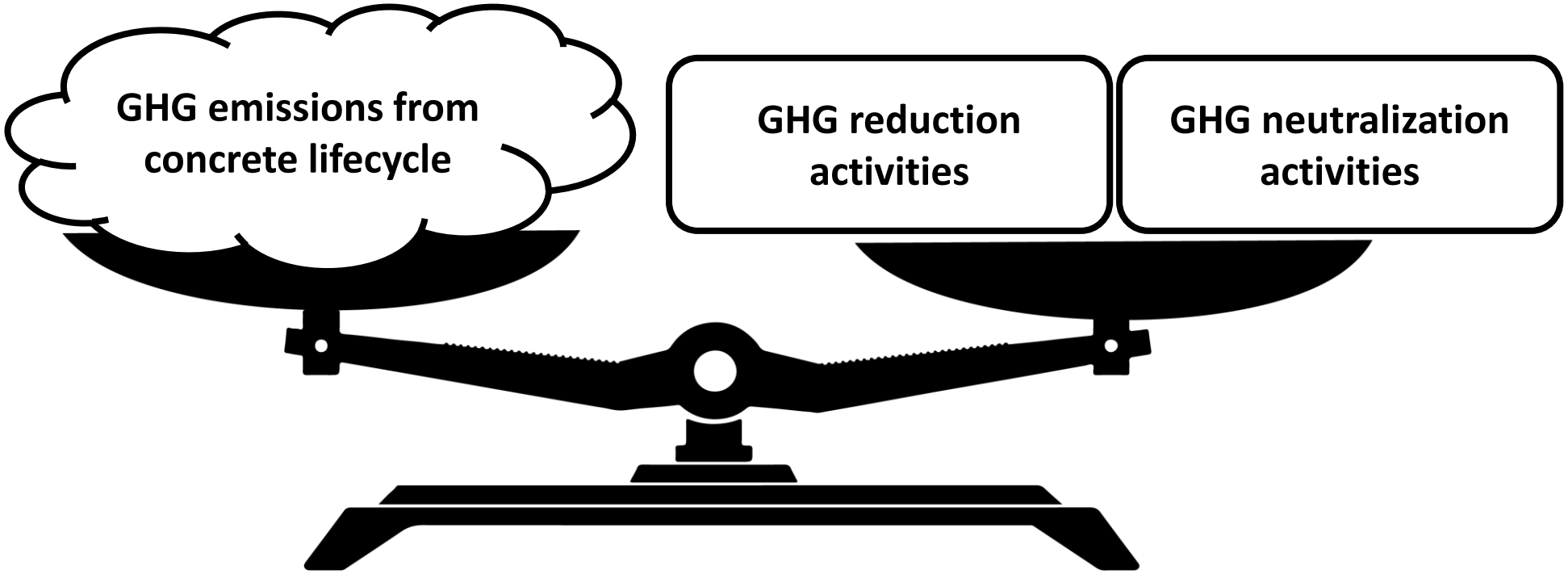


Eg tracts in Miami-Dade, FL (mean of 5000 samples, 100 scenarios; median scenario)

Why is Carbon Uptake important?

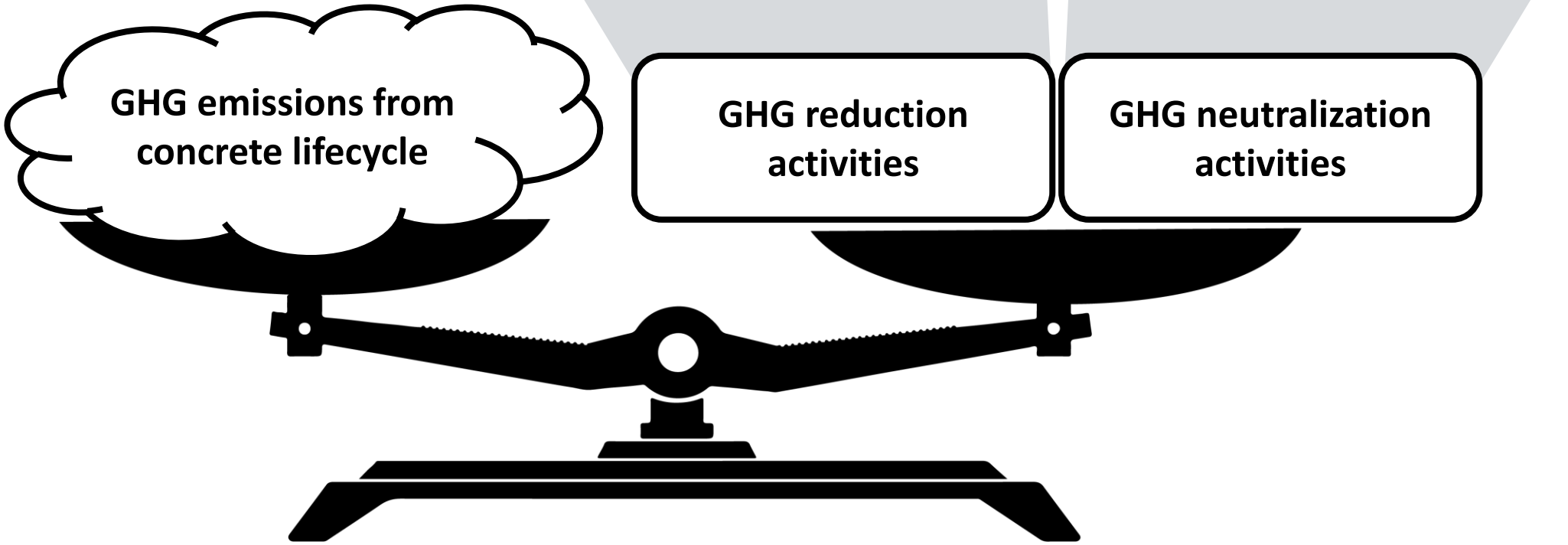


Carbon Neutrality

Why is Carbon Uptake important?

Many solutions, e.g.:
- Optimize design,
- Increase SCMs,
- …

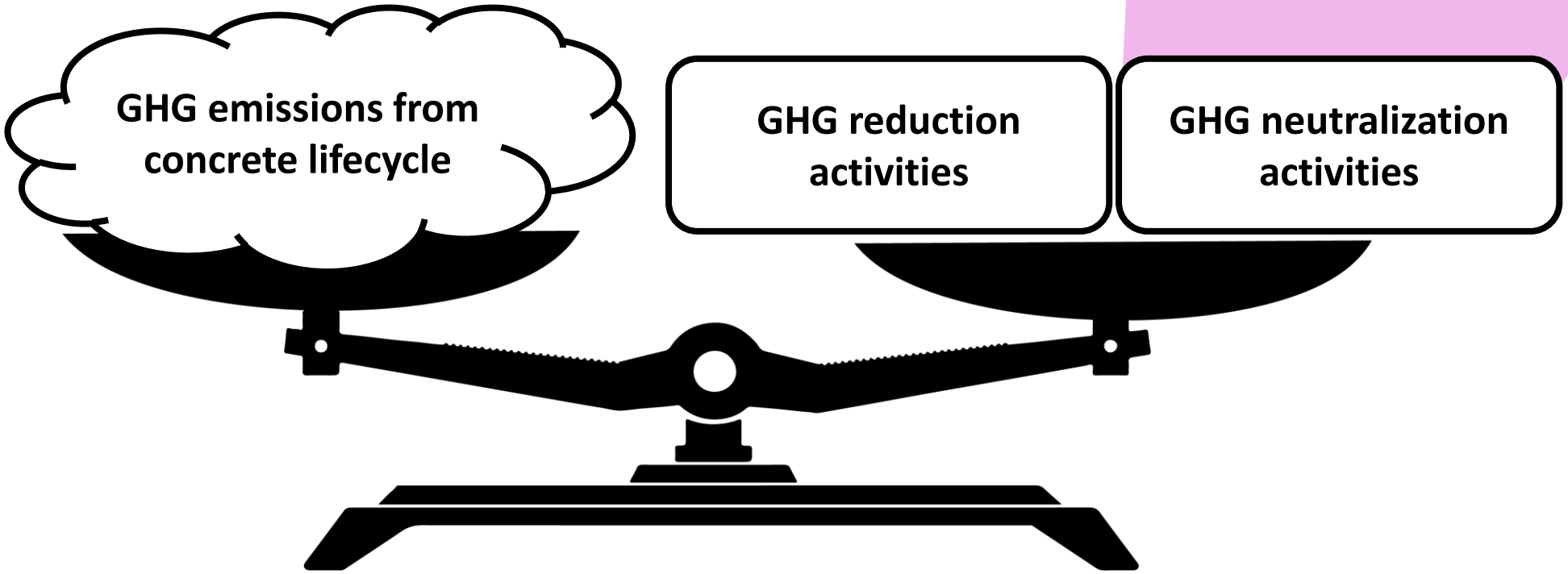
Expensive solutions, e.g.:
- CCS,
- CCU,
- …



Carbon Neutrality

Why is Carbon Uptake important?

Potential for carbon sequestration through Carbon Uptake



Carbon Neutrality

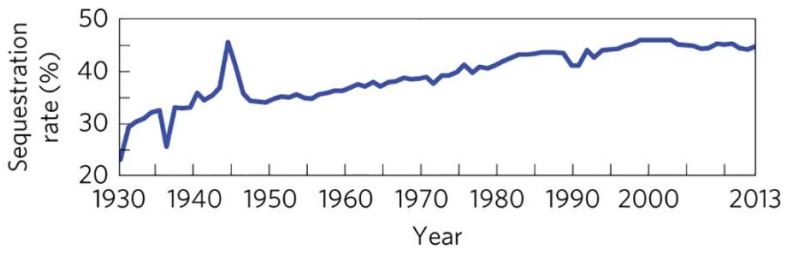
Motivation and Research Gap

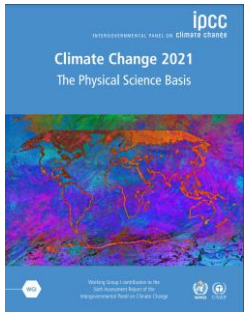
Contribution of carbon uptake to the neutralization of cement GHG emissions (Uptake perc) was reported in different ways:

- IPCC example 1 (for reporting national inventories)
- IPCC example 2 (for global contribution)
- EPD and LCA for product-level calculation

- Non-linear response of the uptake to the lifetime may result in a significant divergence when focusing on different accounting systems

IPCC example 1





Chapter 5, Section 5.2: "*The uptake of CO2 in cement infrastructure (carbonation) offsets about one half of the carbonate emissions from current cement production.*"

IPCC example 2

"In addition, documentation should be provided to illustrate that emission reductions from recarbonation are only reported in the year in which recarbonation occurs …"