Webinar:
Building and Construction –
What are the missing hotspots?

Reducing Embodied Carbon: Options for Hong Kong

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Reducing Embodied Carbon: Options for Hong Kong

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Green Council Webinar on Building and Construction
- What are the missing hotspots?
23 February 2023

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- Received PhD from Stanford University 美國斯坦福大學取得博士學位

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- Over 300 peer-reviewed journal and conference papers **300**餘篇國際期刊及會議論文

Acknowledgement

- We would like to sincerely thank the support from ALL the collaborators, supporting organizations, and funding agencies (including RGC, ITC, CIC)!
- Thanks also go to the research group members who work hard at the behind.
- Collaboration is Welcome.

Carbon Neutrality by 2050 in Hong Kong

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THE TIME IS NOW

WE MUST TAKE ACTION

We must embark on a pathway to net zero greenhouse gas emissions to limit the temperature rise within 1.5°C above pre-industrial levels.

The October 2018 IPCC report Global Warming of 1.5°C highlights that global annual emissions need to be reduced to about half from the current levels by 2030 in order to limit global warming to 1.5˚C.

This goal will only be achieved if net emissions are reduced to zero by around 2050.

Hong Kong is committed to take action under the Paris Agreement. In 2017, Hong Kong released the Climate Action Plan 2030+ and committed to peak carbon emissions by 2020 and to reduce them by 26-36% from 2005 levels by 2030.

But we must agree a pathway to net-zero emissions for HK.

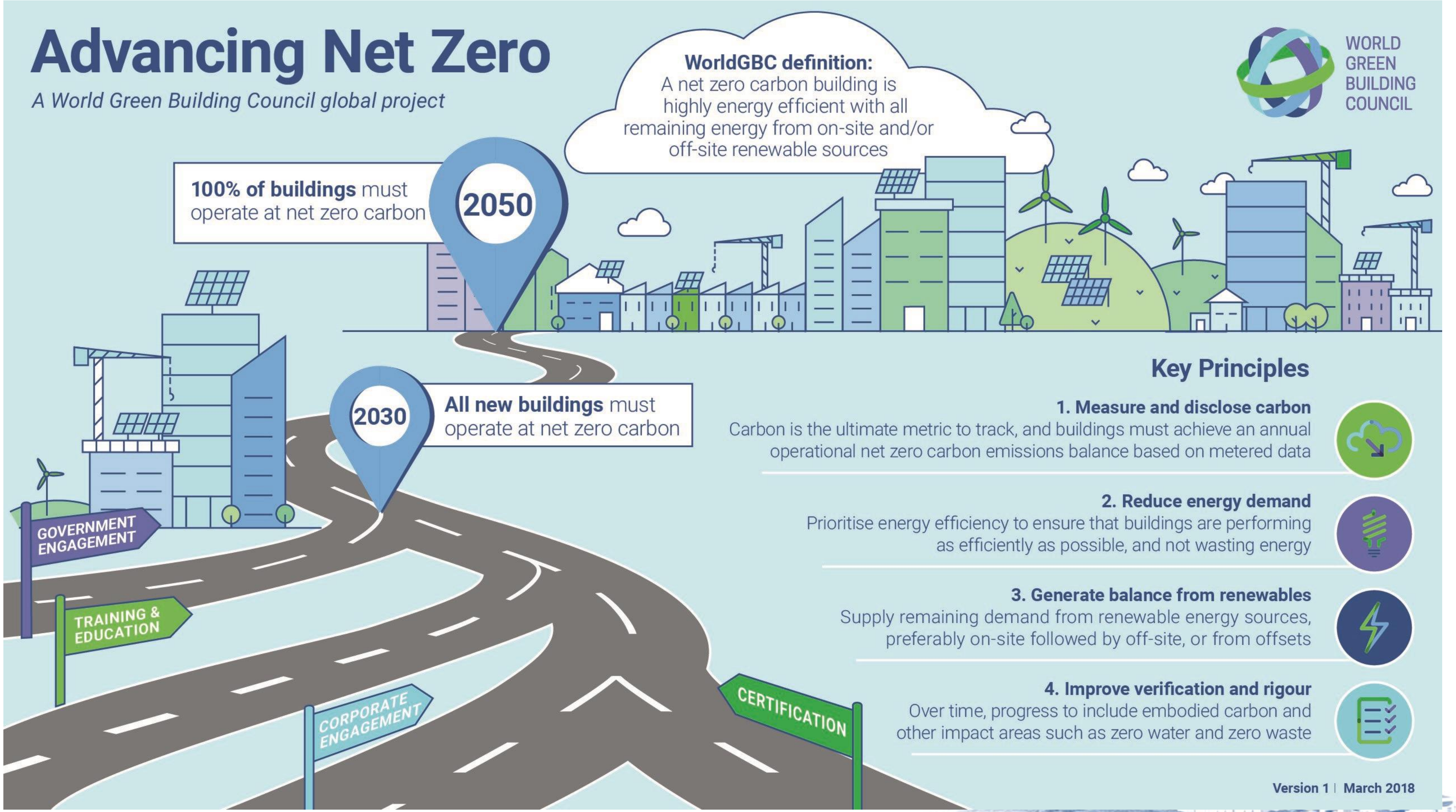
PATHWAYS TO NET ZERO CARBON EMISSIONS BY 2050

2020 2030 2050

HONG KONG 2050 IS NOW

(Source: https://www.hk2050isnow.org/)

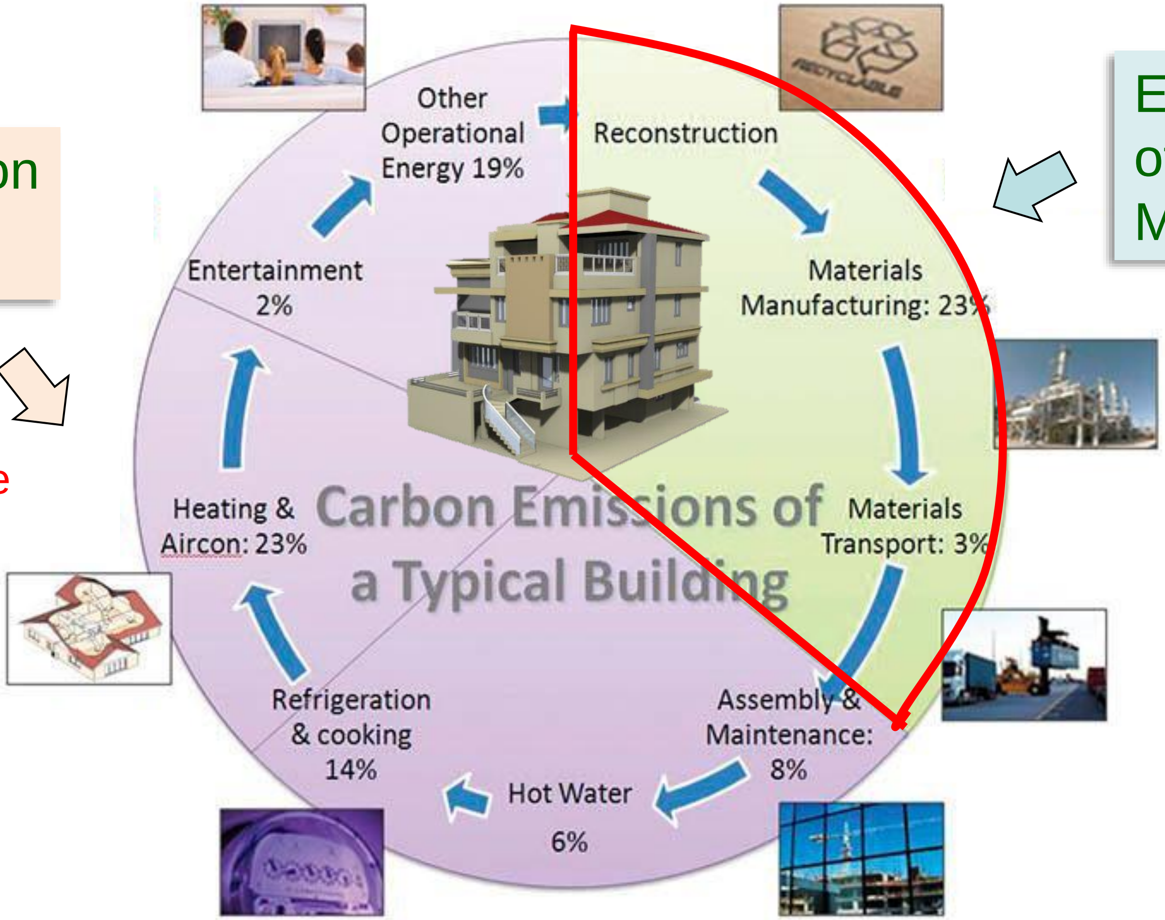
What is Net Zero?



Carbon Emissions of a Typical Building

Operational Carbon of Building

- Electricity (Energy) Use
- Fuel Mix
- Renewable Energy Generation



Embodied Carbon of Construction Materials

- Material Use
- Raw Materials and Production of Materials
- Transportation of Materials

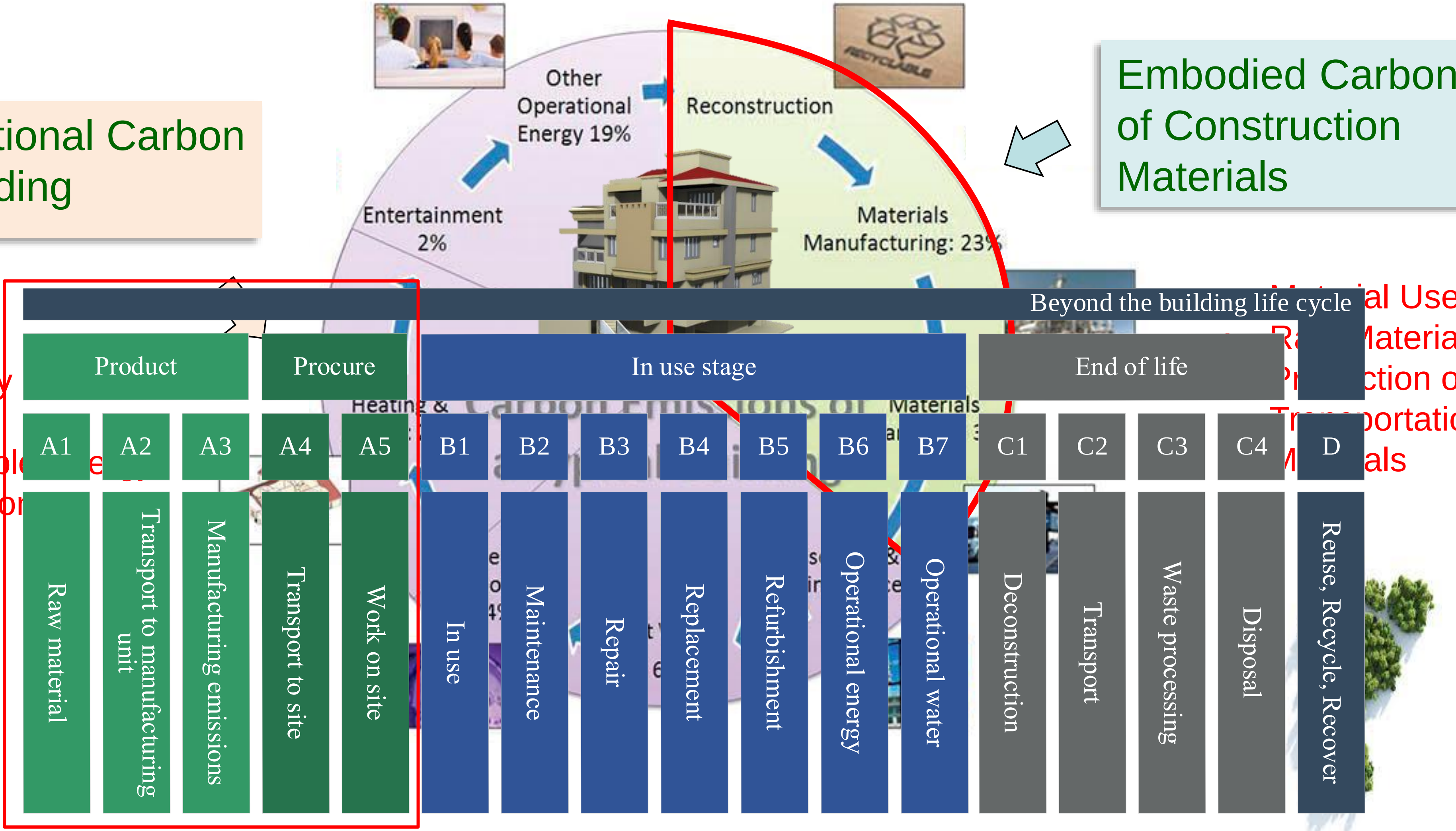
“Reducing Embodied Carbon: Options for Hong Kong” – Jack Cheng (HKUST)

Carbon Emissions of a Typical Building

Operational Carbon of Building

Embodied Carbon of Construction Materials

- Electricity
- Fuel Mix
- Renewabl
  Generatio

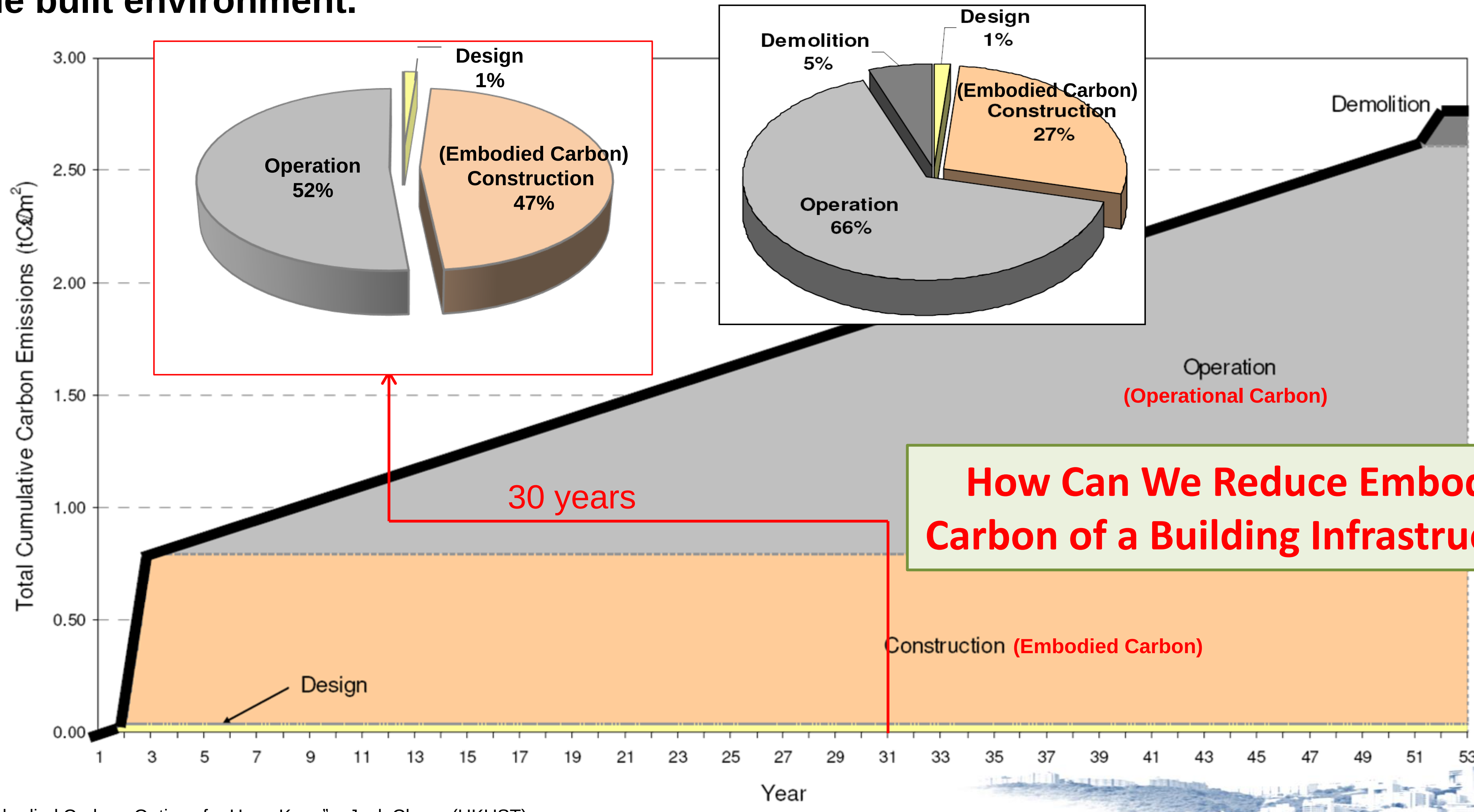


Upfront Embodied Carbon

"Reducing Embodied Carbon: Options for Hong Kong" – Jack Cheng (HKUST)

Carbon Footprint of a Typical Building over Life Cycle

- **Reducing embodied carbon can significantly lower the life cycle CO_2-e emissions from the built environment.**



How Can We Reduce Embodied Carbon of a Building Infrastructure?

"Reducing Embodied Carbon: Options for Hong Kong" – Jack Cheng (HKUST)

Overview

- Background
- Reduction of Embodied Carbon by Building Materials
- Reduction of Embodied Carbon by Building Design
- Reduction of Embodied Carbon by Low Carbon / Energy Construction
- Summary

Reduction of Embodied Carbon by Building Materials

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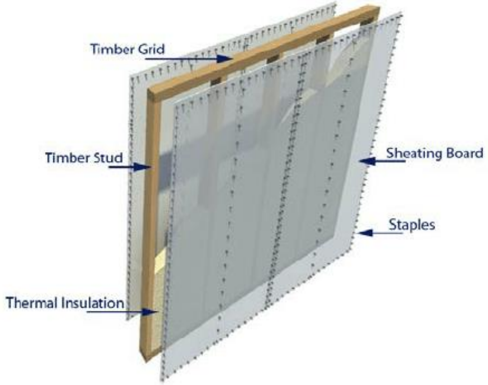
- **Concrete:**
  - Optimized mix design (e.g. workability, strength, aesthetics)
  - Supplementary cementitious material (SCM) substitution: PFA (up to 25-35% cement replacement), GGBS (up to 35-75% cement replacement), Silica Fume (up to 5-10% cement replacement)
  - Carbon capture and utilization and storage (CCUS) technology
  - Carbon curing and capture technology

Fly ash GGBS

- **Steel:**
  - Electric arc furnace (EAF) vs. Blast furnace – basic oxygen furnace (BF-BOF)
  - Recycling contents



- **Timber:**
  - Timber composite building component
- **Green Procurement:**
  - Selection of sustainable materials (e.g. with recycled contents)
  - Procurement of materials from sustainable (and nearby) sources

Pilot Study on One Taikoo Place

- Developer: **Swire Properties**
- 48-storey office tower (completed in 2018)
- Reinforced concrete (RC) using a core-frame structure
- Steel outriggers are constructed near mid-level
- A triple Platinum (WELL, BEAM Plus and LEED)

(Gan, V.J.L., Li, X., Lo, I.M.C., Tse, K.T., Cheng, J.C.P., Chan, C.M., Ho, P., Lai, A., Law, J., Kwok, R., and Yau, R. (2020) "Automatic measurements of carbon emissions from building materials and construction for sustainable structural design of tall commercial buildings." *Proceedings of the 8th International Conference on Innovative Production and Construction (IPC 2020)*, Hong Kong, China, 7-8 December 2020.)

Pilot Study on One Taikoo Place

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- **Other indirect emissions significantly outweighs** direct emissions (from energy combustion on-site) and energy indirect emissions (from electricity use)
- **Embodied carbon of major building materials** (concrete, rebar) accounts for the majority (90.4%) of the total emissions

Table: Breakdown of carbon emissions for One Taikoo Place

Scope of carbon measurement	Carbon emissions (kg CO_2-e)	Percentage contribution (%)
Scope (1) – Direct emissions	103,168	0.1%
Scope (2) – Energy indirect emissions	2,490,996	3.6%
Scope (3) – Other indirect emissions	67,354,114	**96.3%**
3.1 Embodied carbon of major building materials	63,237,196	**90.4%**
Concrete	22,816,249	32.6%
Rebar	36,912,115	52.8%
Structural steel	2,644,164	3.8%
Glass and timber	864,669	1.2%
3.2 Carbon emissions from transportation of major building materials	3,993,942	5.7%
Concrete	537,197	0.8%
Rebar	3,116,832	4.5%
Structural steel	166,836	0.2%
Glass and timber	173,077	0.2%
3.3 Carbon emissions due to waste disposal, sewage water treatment	122,975	0.2%
Total carbon emissions	**69,948,279**	**100.0%**

(Gan, V.J.L., Li, X., Lo, I.M.C., Tse, K.T., Cheng, J.C.P., Chan, C.M., Ho, P., Lai, A., Law, J., Kwok, R., and Yau, R. (2020) "Automatic measurements of carbon emissions from building materials and construction for sustainable structural design of tall commercial buildings." *Proceedings of the 8th International Conference on Innovative Production and Construction (IPC 2020)*, Hong Kong, China, 7-8 December 2020.)

Pilot Study on One Taikoo Place

- **Formulations for Carbon Measurement**

Embodied Carbon of Building Materials

$$E_1 = \sum_{i=1}^{I} V_i CE_i + \sum_{i=1}^{I}\sum_{j=1}^{J} Q_i D_{i,j} CE_j$$

Carbon Emissions from On-site Fuel and Electricity Consumption

$$E_2 = \sum_{e=1}^{E}\sum_{c=1}^{C} E_{ec} CE_e$$

Total Embodied Carbon (in kg CO_2-e/m^2)

$$E_T = [E_1 + E_2 + E_3 + E_4] \cdot A^{-1}$$

Construction floor area

Carbon Emissions due to Waste Disposal

$$E_3 = \sum_{l=1}^{L} R_l \cdot CE_d$$

Carbon Emissions due to Fresh Water Consumption and Sewage Treatment

$$E_4 = W \times (f_1 + \varepsilon f_2)$$

(Gan, V.J.L., Li, X., Lo, I.M.C., Tse, K.T., Cheng, J.C.P., Chan, C.M., Ho, P., Lai, A., Law, J., Kwok, R., and Yau, R. (2020) "Automatic measurements of carbon emissions from building materials and construction for sustainable structural design of tall commercial buildings." *Proceedings of the 8th International Conference on Innovative Production and Construction (IPC 2020)*, Hong Kong, China, 7-8 December 2020.)

Sample Emission Factors

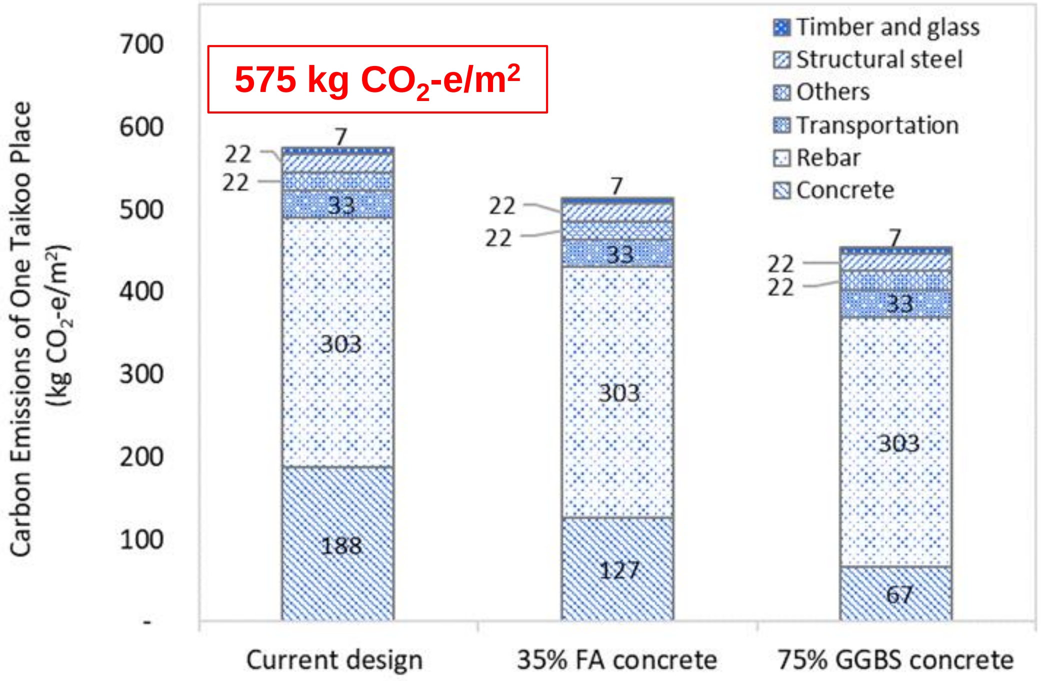
Materials	Emission factor	Unit	Description
Rebar (BF-BOF) – 100% Recycled	0.84	kgCO_2-e/kg	Localized to Hong Kong context according to the literature
Rebar (BF-BOF) – 13% Recycled	2.07	kgCO_2-e/kg	
Structural steel (BF-BOF) – 10% Recycled	2.16	kgCO_2-e/kg	
Concrete (G20/20D)	262	kgCO_2-e/m^3	First-hand data (HKUST)
Concrete (G30/20D 125mm)	222	kgCO_2-e/m^3	Carbon emission factors provided by the main contractor
Concrete (G35/20D 125mm)	230	kgCO_2-e/m^3	
Concrete (G45/10D 125mm)	280	kgCO_2-e/m^3	
Concrete (G45/20D 125mm WP with Caltite)	272	kgCO_2-e/m^3	
Concrete (G45/20D 125mm)	257	kgCO_2-e/m^3	
Concrete (G45/20D 200mm)	295	kgCO_2-e/m^3	
Concrete (G60/20D 200mm)	295	kgCO_2-e/m^3	
Concrete (G60/20D 200mm WP with Caltite)	326	kgCO_2-e/m^3	
Concrete (G80/20D 200mm)	271	kgCO_2-e/m^3	
Glass	1.20	kgCO_2-e/kg	First-hand data (HKUST)
Timber-Plywood for Formwork	1.97	kgCO_2-e/kg	ICE Database (Hammond et al., 2011)

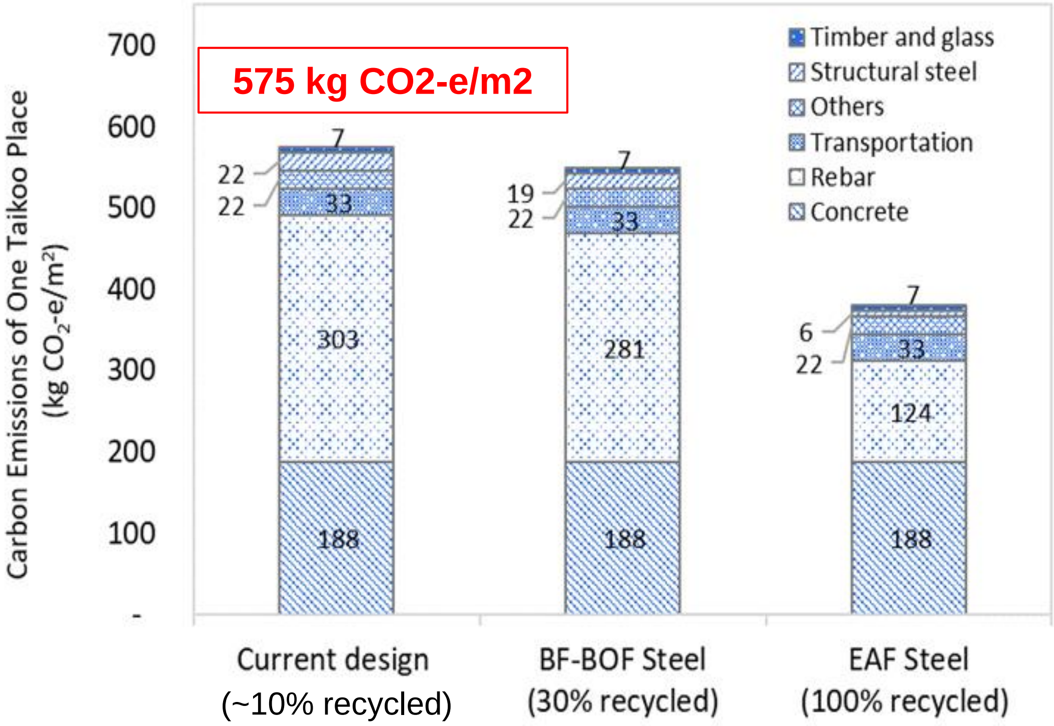
Energy source	Emission factor	Unit	References
Electricity-CLP	0.54	kgCO_2.e/kwh	CLP,2017
Electricity-HKE	0.79	kgCO_2.e/kwh	HKE,2017
Towngas	2.82	kg/unit	HKEPD & HKEMSD, 2010
Diesel	2.617	kgCO_2.e/l	HKEPD & HKEMSD, 2010
LPG	1.679	kgCO_2.e/l	HKEPD & HKEMSD, 2010
Kerosene	2.432	kgCO_2.e/l	HKEPD & HKEMSD, 2010
Petrol Oil	2.707	kgCO_2.e/l	HKEPD & HKEMSD, 2010

Pilot Study on One Taikoo Place

- **Recommendations**

Mix Design with/without Substitutional Materials*	Characteristic Strength (MPa)		
	C30	C40	C50
100% OPC	295±30	335±30	365±20
65% OPC + **35% FA**	200±19	227±19	265±13
25% OPC + **75% GGBS**	108±9	120±9	130±6





- **35% FA concrete** reduces the embodied carbon 514 kg CO_2-e/m^2 **(11% reduction)**
- **75% GGBS concrete** minimizes carbon emissions to 454 kg CO_2-e/m^2 **(21% reduction)**
- **BF-BOF steel (max. 30% scrap)** reduces embodied carbon by **4%** to 549 kg CO_2-e/m^2
- **100% recycled EAF steel** reduces **34%** of the embodied carbon (to 380 kg CO_2-e/m^2)

(Gan, V.J.L., Li, X., Lo, I.M.C., Tse, K.T., Cheng, J.C.P., Chan, C.M., Ho, P., Lai, A., Law, J., Kwok, R., and Yau, R. (2020) "Automatic measurements of carbon emissions from building materials and construction for sustainable structural design of tall commercial buildings." *Proceedings of the 8th International Conference on Innovative Production and Construction (IPC 2020)*, Hong Kong, China, 7-8 December 2020.)

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Reduction of Embodied Carbon by Building Design

- Low carbon design (geometry, orientation, location, etc.)
- Architectural design optimisation and buildability (Digitalization helps)
- Reducing embodied carbon of MEP system
- Design for Manufacturing and Assembly (DfMA)
- Design for deconstruction
- Low carbon material specifications

Integrating BIM with Engineering Analysis Tool for Low Carbon Building Design

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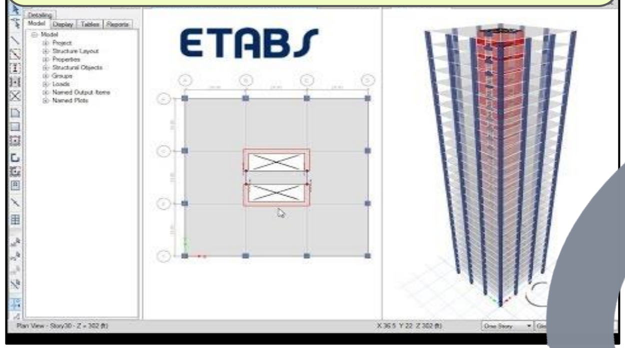
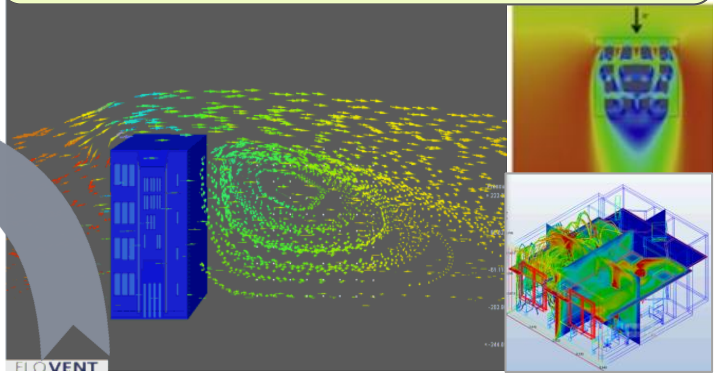
Structural analysis & design optimization



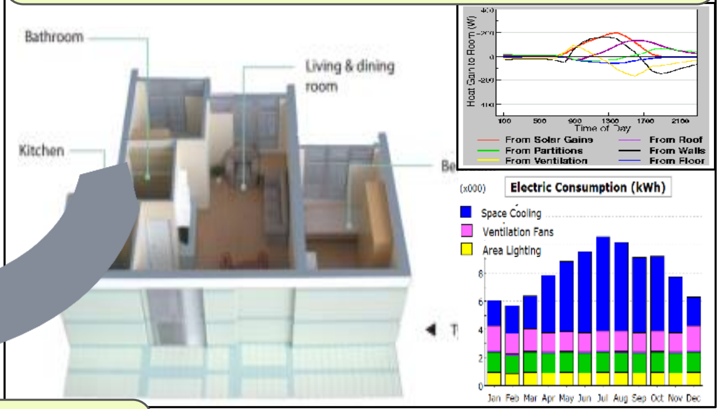
Wind effects on tall buildings & computational fluid dynamics (CFD)



Integrated design platform using Building Information Modeling (BIM)

Low carbon materials & sustainable procurement

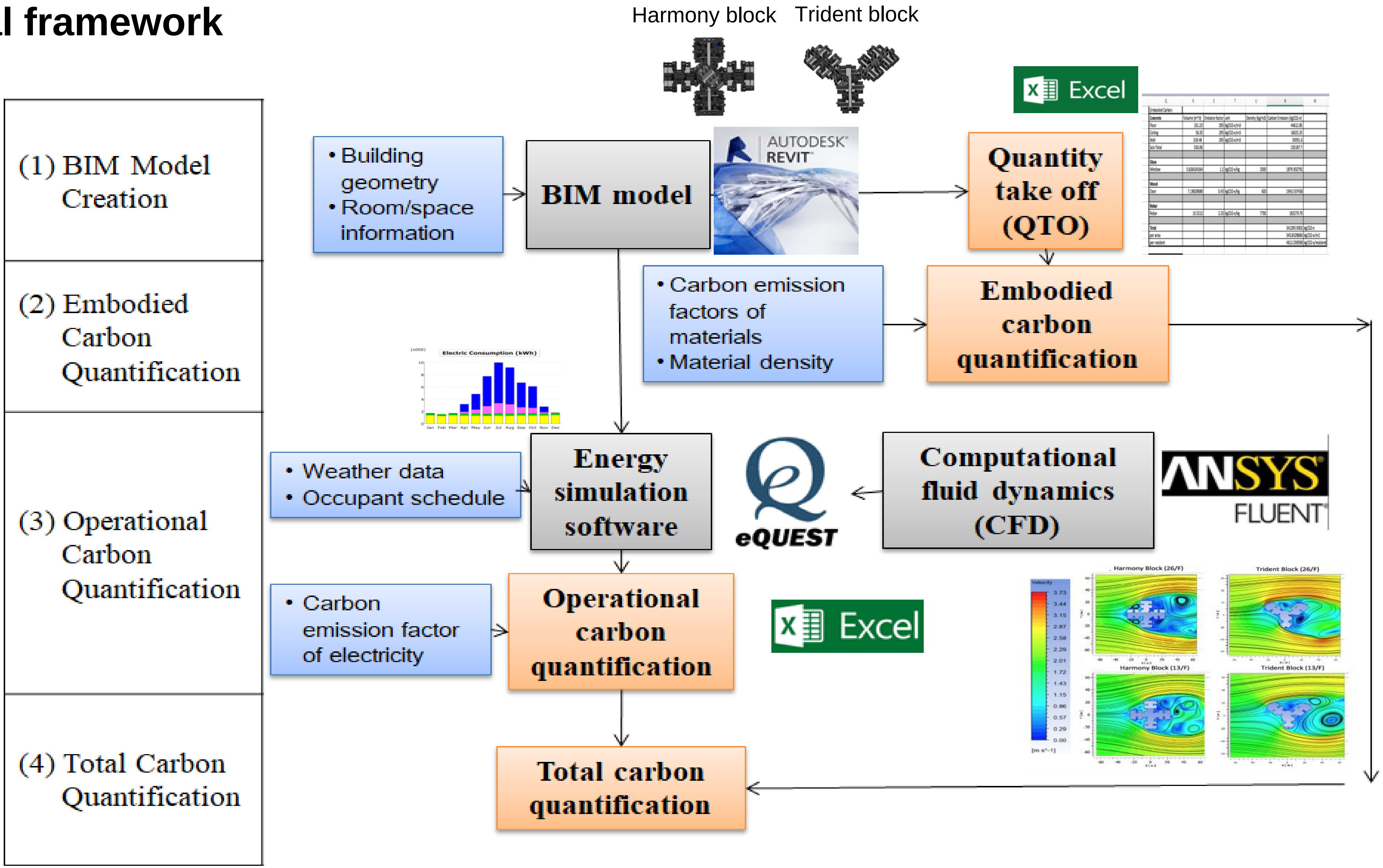
Building energy simulation & thermal analysis



Daylighting and shadow analysis, View analysis, Cost analysis, etc.

BIM-based Lifecycle Energy/Carbon Simulation

General framework



(Source: Gan, V.J.L., Deng, M., Tse, K.T., Chan, C.M., Lo, I.M.C.*, and Cheng, J.C.P.* (2018). "Holistic BIM framework for sustainable low carbon design of high-rise buildings." *Journal of Cleaner Production*, 195, 1091-1104)

Evolutionary Optimization for Design of High-rise Residential Buildings

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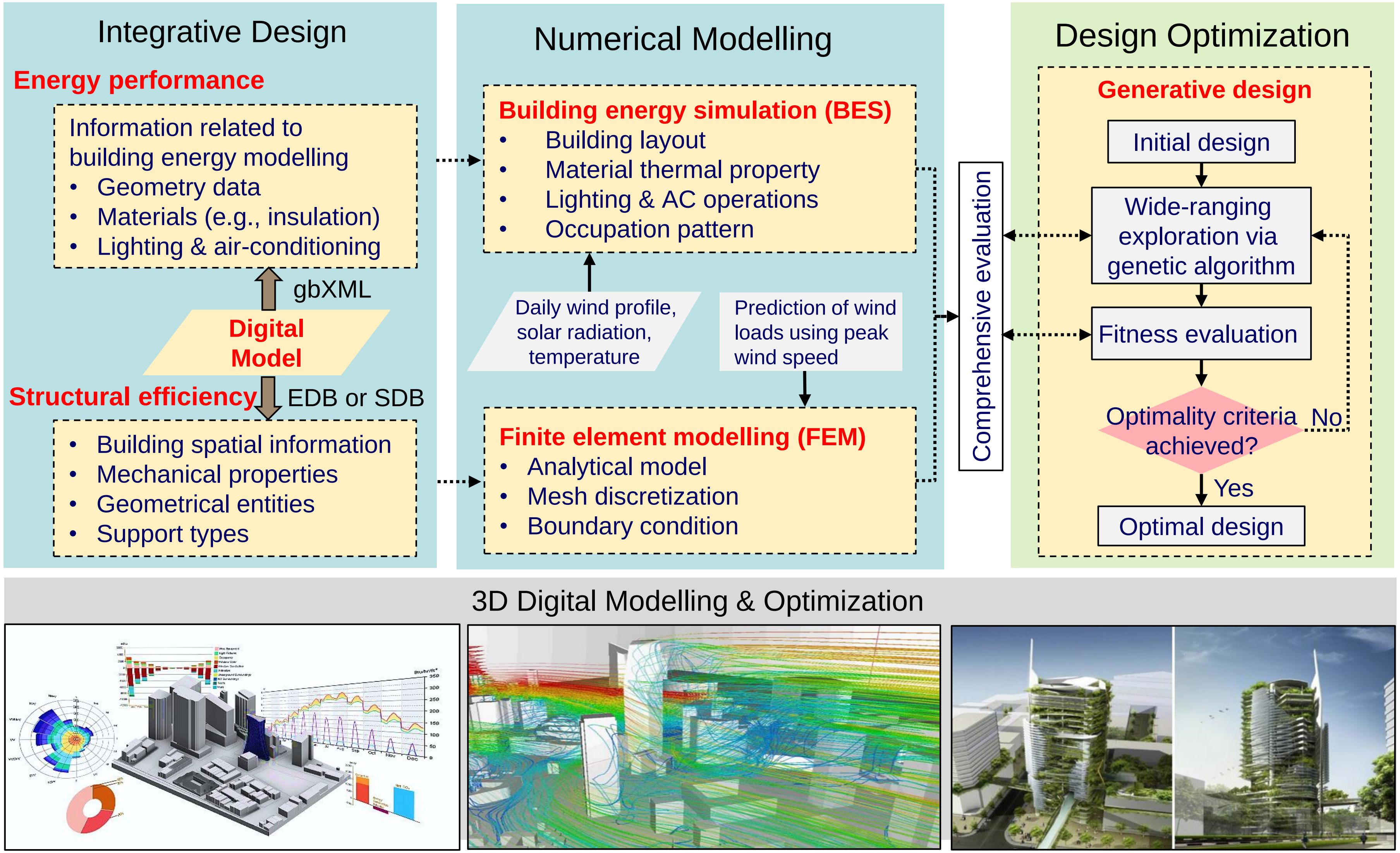


(Gan, V.J.L., Lo, I.M.C., Tse, K.T., Wong, C.L., Cheng, J.C.P., and Chan, C.M. (2019) "BIM-based integrated design approach for low carbon green building optimization and sustainable construction." *Proceedings of the 2019 ASCE International Conference on Computing in Civil Engineering (i3CE)*, Atlanta, GA, USA, 17-19 June, 2019.)

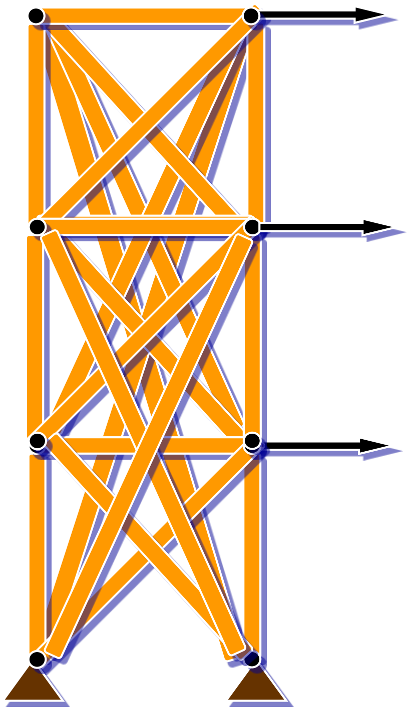
Evolutionary Optimization for Design of High-rise Residential Buildings

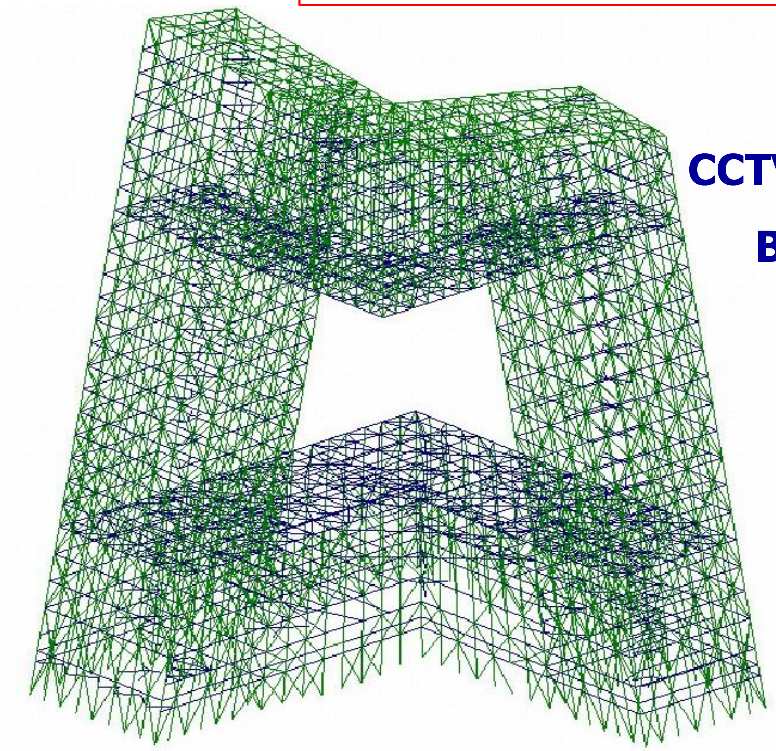
➔ Generative Design

Large-scale discrete structures

⬇

Ground structure approach





CCTV Tower, Beijing

No. of bracing = **12**

Possible combinations of bracing topologies = $2^{12} = 4096$

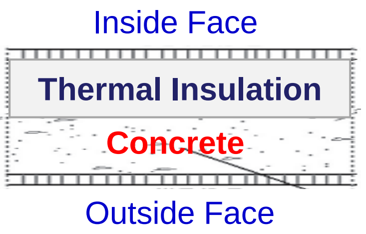
No. of bracing = **5000+**

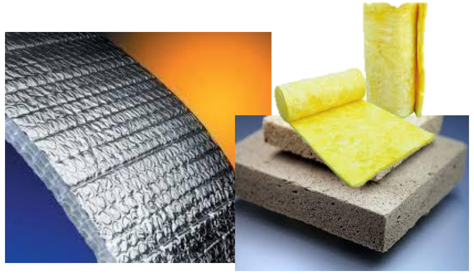
Possible combinations of bracing topologies $> 2^{5000}$

❖ **Topology optimization for high-rise discrete structures:**

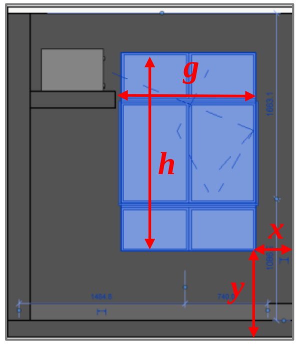
- **Spatial arrangement and connectivity of the structural components** to **optimally distribute materials** in the computational domain

Optimization of Material Selection for Building Envelope Design

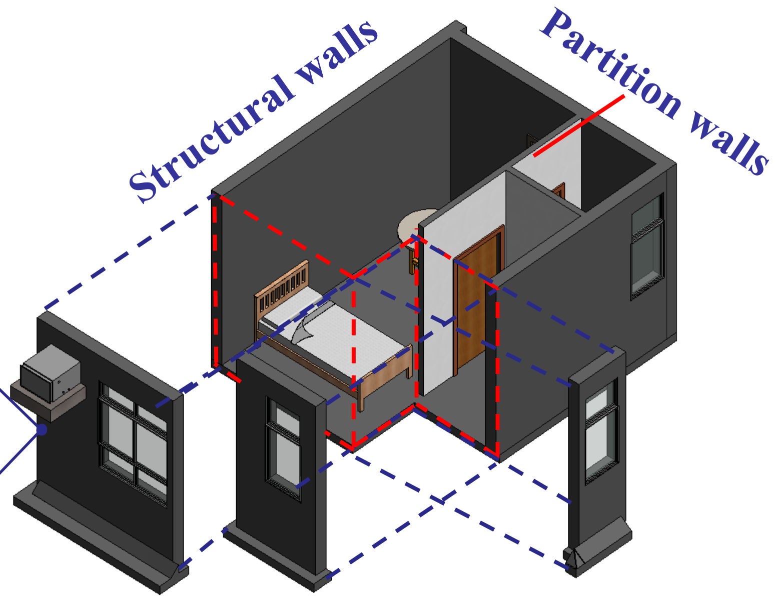




Insulation materials



Window glasses

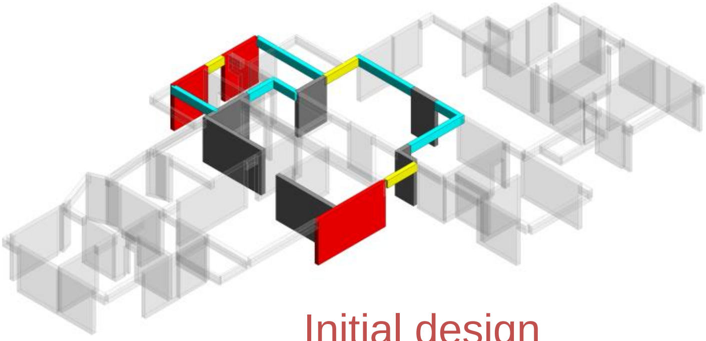


Precast panels

Design variables	Impact on TEC (x)	Variable type	
Insulation material	$\sum L/k$	Discrete variable	$\boldsymbol{\delta}$
Insulation material thickness	$\sum L/k$	Discrete variable	$\boldsymbol{\beta}$
Window type	$\gamma_{transmittance}$	Discrete variable	$\boldsymbol{\varepsilon}$
Window area	A_w	Discrete variable	g, h
Window location	$\gamma_{transmittance}$	Discrete variable	x, y

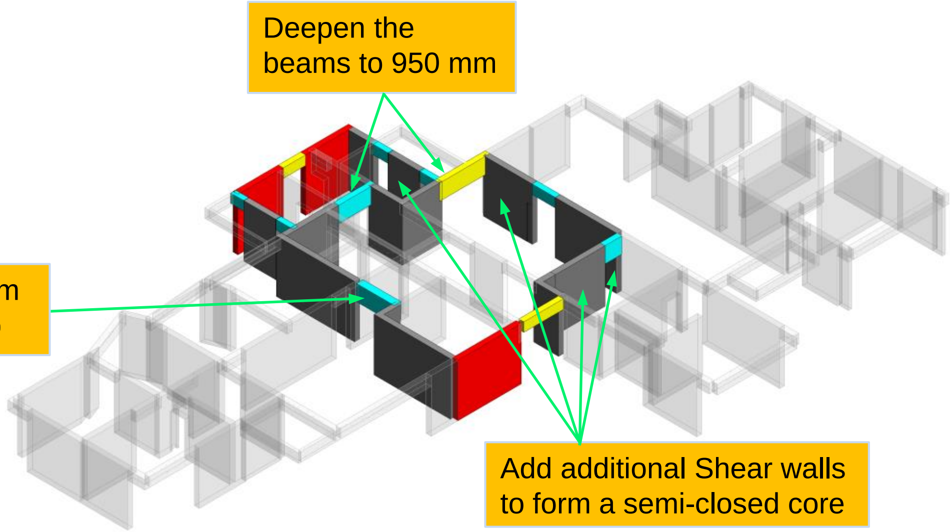
BIM-based Structural Members Redistribution

- The structural members in the interior sub-system interact closely with the members in the perimeter sub-system to form a semi-closed core, as follows:



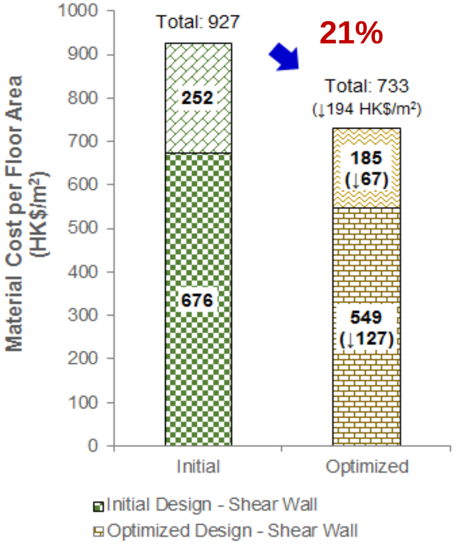
Initial design
(without closed core)

Shear Walls (Interior Sub-system)
Beams (Interior Sub-system)
Shear Walls (Perimeter Sub-system)
Beams (Perimeter Sub-system)



Add a coupling beam (400 mm * 950 mm)

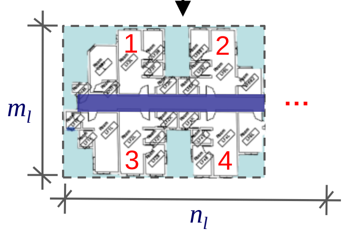
Optimized design
(with a semi-closed core)



(Collaboration with CM Chan)

BIM-based Module Layout Design Optimization

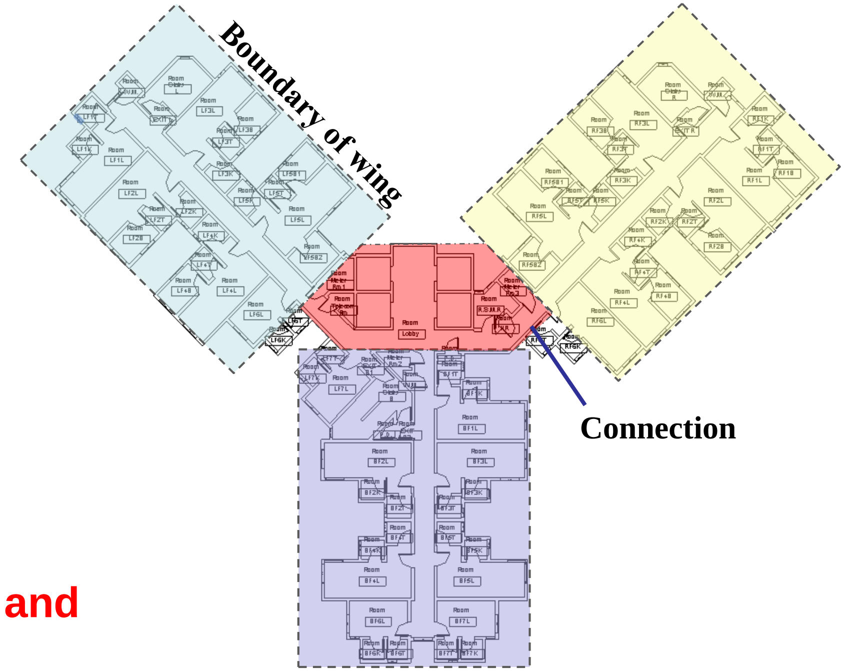
- **Combination of modular flats for each wing**



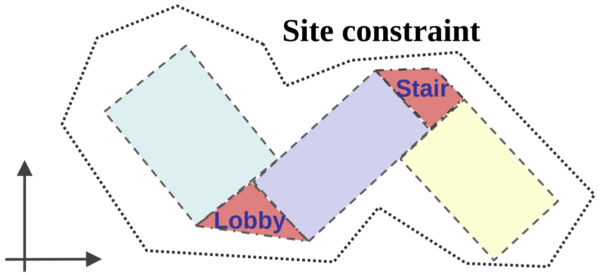
$$\sum_{l=1}^{L} F_w^l = F_w^1 + F_w^2 + \cdots + F_w^L$$

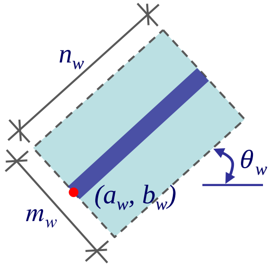
Design constraints for wing:

- Topology
- Dimension of wing



- **Geometric combination of wings and connections**





$$\tau = \sum_{w=1}^{W} \sum_{l=1}^{L} F_w^l + \sum_P Z_p \quad \text{wherein} \sum_{l=1}^{L} F_w^l \in [m_w, n_w, a_w, b_w, \theta_w]$$

6 Design Constraints

Design constraints for entire layout:

- Site constraint
- Number of occupant
- Accessibility (distance between stair and flat)
- Building shape (area and side aspect ratio)

➔ Generative Design

(Source: Gan, V.J.L., Deng, M., Tse, K.T., Chan, C.M., Lo, I.M.C.*, and Cheng, J.C.P.* (2018). "Holistic BIM framework for sustainable low carbon design of high-rise buildings." *Journal of Cleaner Production*, 195, 1091-1104)

Generative Design

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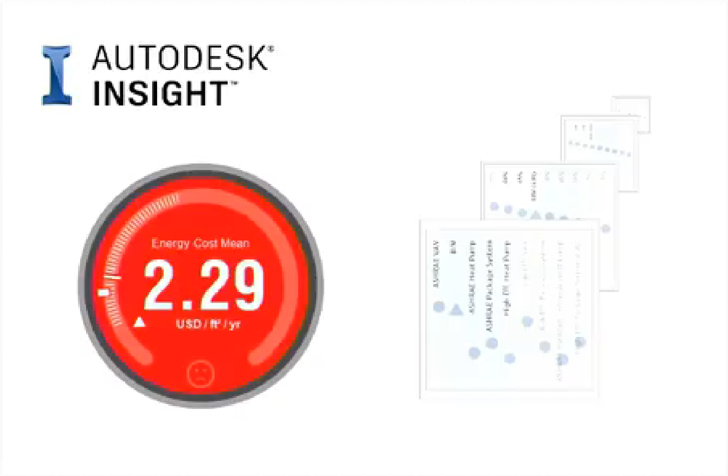

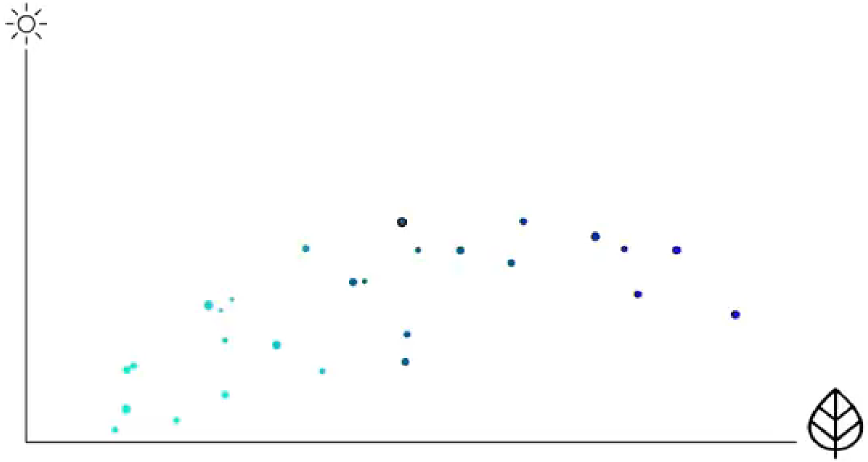

https://www.facebook.com/AutodeskUniversity/videos/894002928069438/

Overview

- Background
- Reduction of Embodied Carbon by Building Materials
- Reduction of Embodied Carbon by Building Design
- Reduction of Embodied Carbon by Low Carbon / Energy Construction
- Summary

Reduction of Embodied Carbon by Low Carbon / Energy Construction

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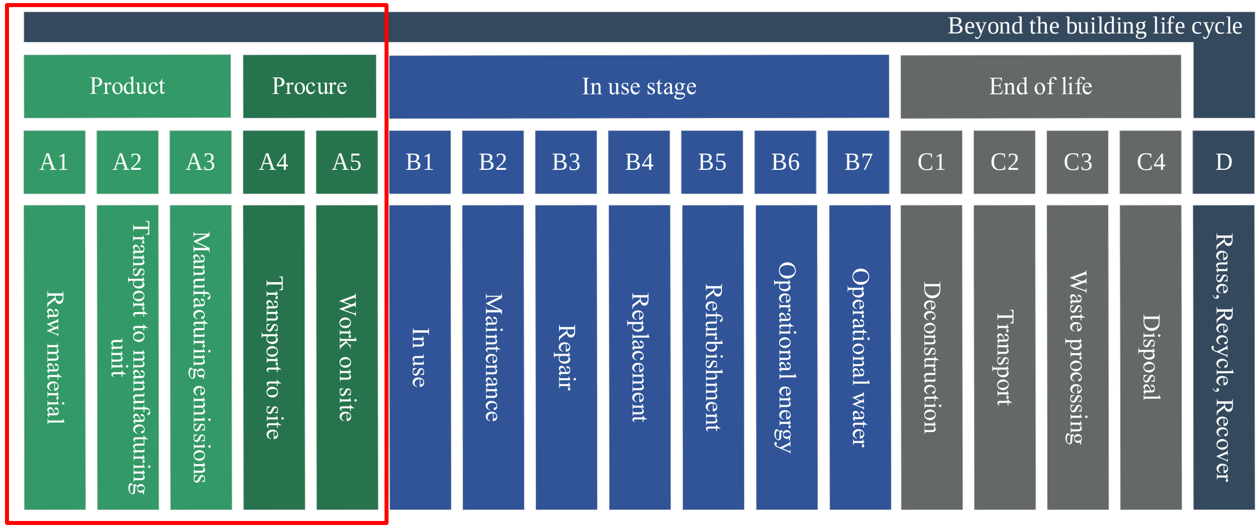
- **Transport to the Site**
  - Logistics planning and optimization
  - Selection of lower energy transport (e.g. electric or hydrogen trucks or lower carbon shipping power)
  - Low carbon fuels (e.g. B5, B10, electricity, hydrogen)

- **Site Operations**
  - Energy source
  - Construction methods
  - Energy efficiency
  - Water and waste generation



Upfront Embodied Carbon

Overview

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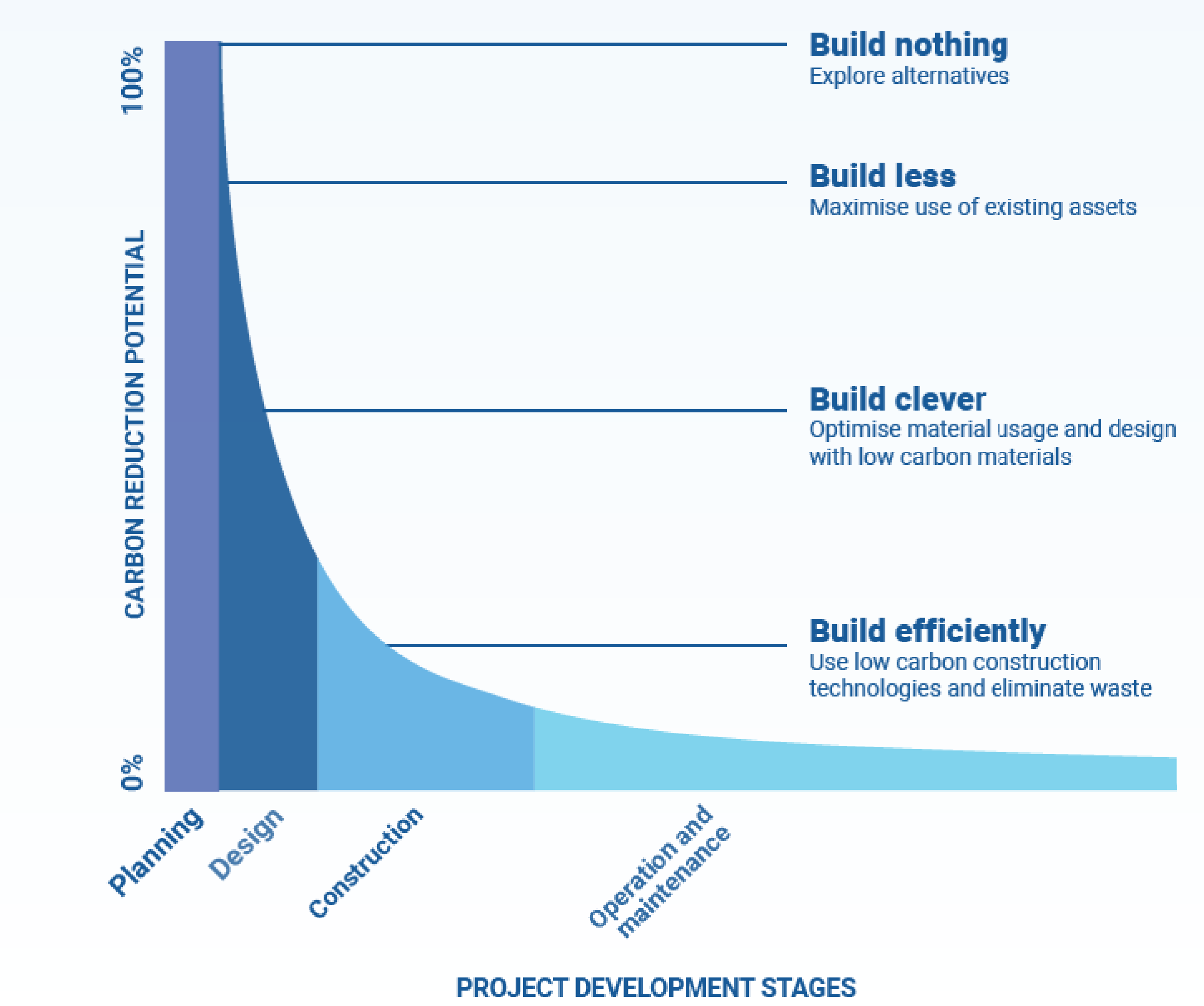
Carbon Reduction Potential



(Source: *Bringing Embodied Carbon Upfront*, World Green Building Council, 2019)

Establishment of Local Embodied Carbon Inventory Databases for Construction Materials

We cannot manage if we do not measure

- **Embodied carbon values are region-specific.**

Region	Construction Life Cycle Inventory (LCI)	Institution	System Boundary
Swiss	**Ecoinvent**	Swiss Centre for Life Cycle Inventories	Gate-to-gate
Europe	**ELCD** (European reference Life Cycle Database)	European Union	Cradle-to-gate
United Kingdom	**ICE** (Inventory of Carbon and Energy)	University of Bath, UK	Cradle-to-gate
China	**CLCD** (Chinese reference Life Cycle Database)	Sichuan University, China; IKE Environmental Technology Co. Ltd	Cradle-to-gate
Korea	**Korea LCI Database**	Korea Institute of Industrial Technology	Cradle-to-gate
Hong Kong	**ECO-CM Database**	Dept. of Civil and Environmental Engineering, HKUST	Cradle-to-site; C-to-G; G-to-G

- An **embodied carbon database** for construction materials can provide
  - A benchmark for green material selection and carbon label development.
  - A basis for prediction and estimation of carbon footprint.
  - An environmentally friendly and low-carbon construction industry.

Carbon Baseline and Reduction Targets

LONDON
ENERGY
TRANSFORMATION
INITIATIVE

LETI Embodied Carbon Primer

	Baseline	Best practice 2020	Best practice 2030
Domestic	800 $kgCO_2/m^2$	<500 $kgCO_2/m^2$	<300 $kgCO_2/m^2$
Non-domestic	1000 $kgCO_2/m^2$	<600 $kgCO_2/m^2$	<350 $kgCO_2/m^2$

- **Set local embodied carbon baseline**
  - (For reference) Non-residential: 800 kg CO2-e/m2 CFA
  - (For reference) Residential: 1000 kg CO2-e/m2 CFA
- **Set local embodied carbon target**

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Reducing Embodied Carbon: Options for Hong Kong

THANK YOU!

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Green Council Webinar on Building and Construction
- What are the missing hotspots?
23 February 2023