CONSTRUCTION TECHNOLOGY

Modular Construction

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COLUMBIA | CBIPS
Center for Buildings, Infrastructure and Public Space

Outline

01

RELOCATABLE MODULAR BUILDINGS

Relocatable Modular Building

Definition

Modular Construction

Process in which a building is constructed off-site, under controlled plant conditions, then assembled on location.

Modular Construction Institute: https://www.modular.org/

- **Permanent Modular Construction**
- **Relocatable Modular Construction**

"Relocatable buildings are defined in the International Existing Building Code as partially or completely assembled buildings constructed and designed to be reused multiple times and transported to different building sites."

2020 Relocatable Modular Construction: https://growthzonesitesprod.azureedge.net/wp-content/uploads/sites/2452/2021/08/MBI-RB-annual-report-2020-FOR-DIGITAL.pdf

Relocatable Modular Building

Definition

Comparison of Permanent Modular Construction (PMC) and Relocatable Buildings (RB)

	Permanent Modular Construction (PMC)	**Relocatable Building(RB)**
Manufacturing Ratio/Rate of Recycling	60-70%/74%	80-90%/100%
Field Construction	Vertical installation piping, boilers, balcony ceilings, wall for evacuation, welding and bolt joints between modules, fireproofing, and exterior finish.	Electrical/equipment piping connections, bolt joints between modules
Exterior Finish	Installation of temporary scaffolding, exterior finish work	No external finishing work
Foundation	Non-recyclable	Recyclable
Elevator	Site construction	Elevator modularization
Junction between modules	Bolting, welding, wet work	Bolting, dry work
Waterproof	Breathable waterproofing paper on site	Units individually waterproofed
Usability	Permanent residence	Can be moved and reinstalled in another location

RELOCATABLE MODULAR BUILDINGS FOR A SHORT-TERM INTERNATIONAL EVENT: THE PYEONG-CHANG WINTER OLYMPIC GAMES
https://meridian-allenpress-com.ezproxy.cul.columbia.edu/jgb/article/15/3/3/444178/RELOCATABLE-MODULAR-BUILDINGS-FOR-A-SHORT-TERM

Relocatable Modular Building

Background

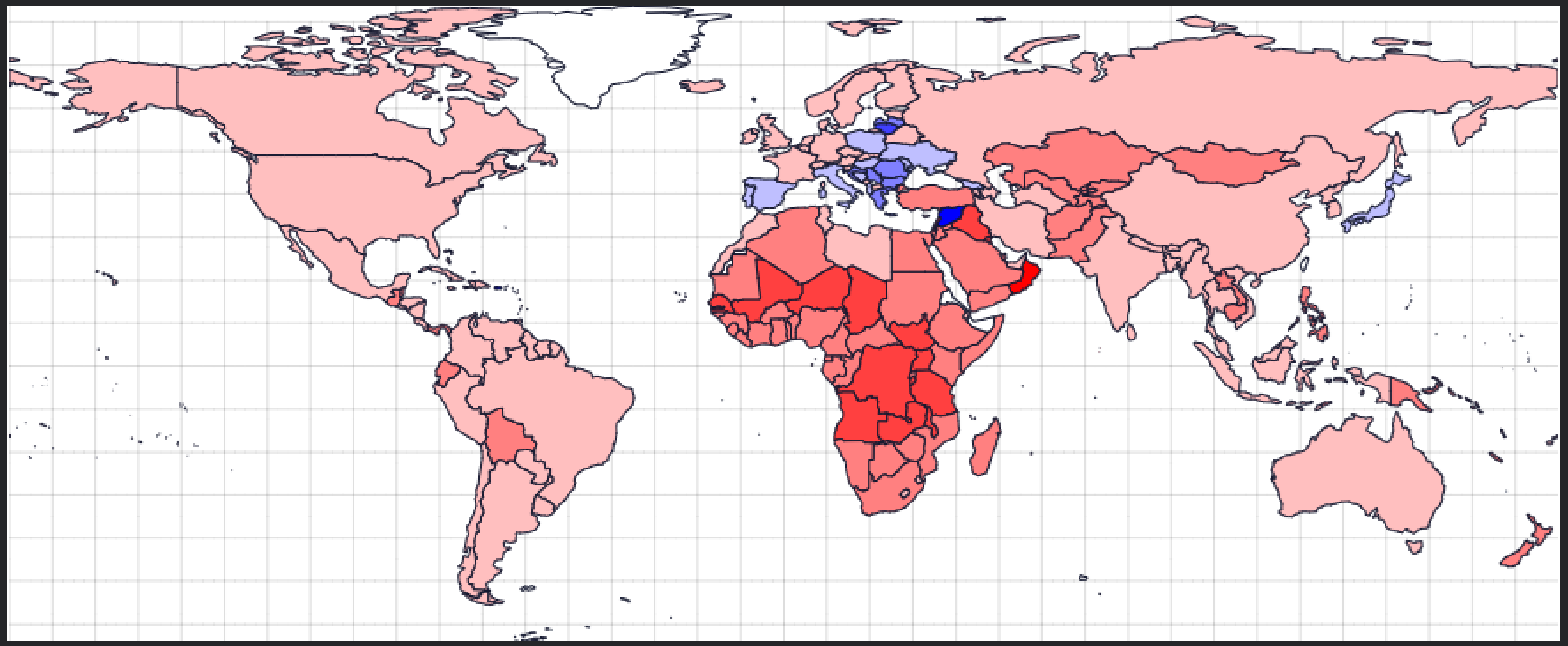
Trend

Due to megatrends such as urbanization and ageing of the population, different types of regions are facing different types of demographic challenge.

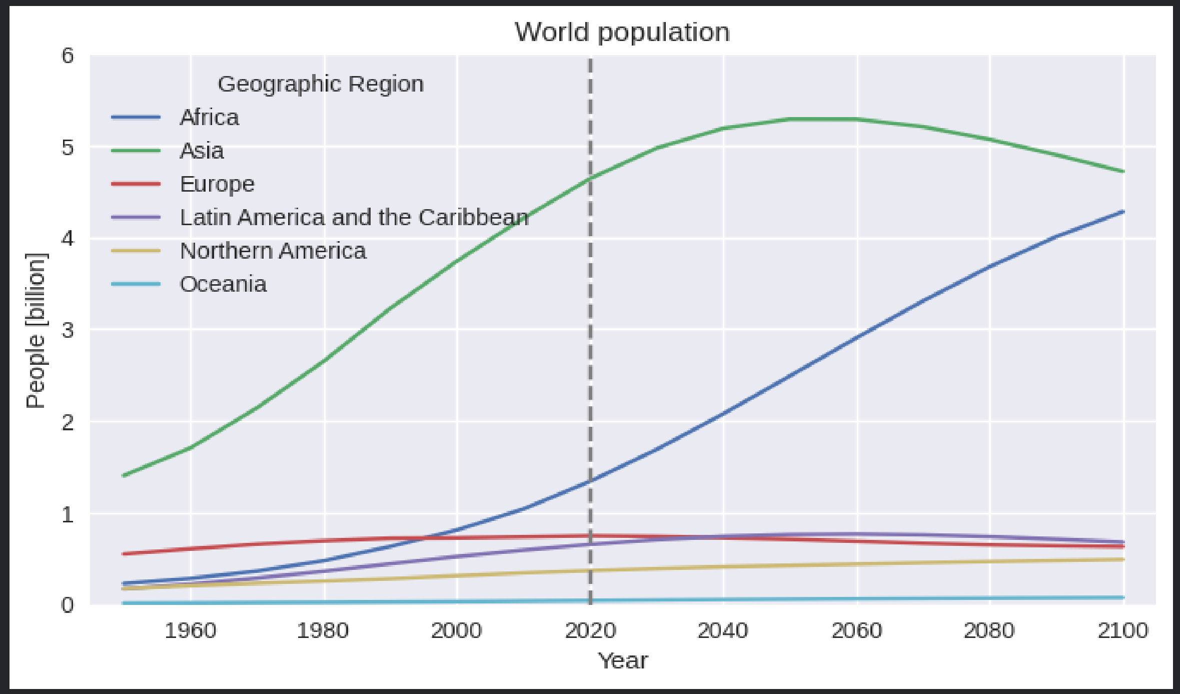
- Fast-paced demographic change
- Put a lot of pressure on the environment

Relocatable Modular Building offer one potential solution

Embodying circularity through usable relocatable modular buildings
https://www.proquest.com/docview/2173504215?accountid=10226&parentSessionId=v2uBhlNlm4%2FVlRId3QXmMsg9%2B56%2F3Cg9NH9XLsd6F8Q%3D&pq-origsite=summon



Population growth (annual %, 2015)
https://www.populationpyramid.net/hnp/population-growth/2015/



Factfulness, Straight Line Instinct & World Population
https://www.athoughtabroad.com/2020/04/19/factfulness-straight-line-instinct-world-population

Relocatable Modular Building

Problems

Disassemble

Transportation

- road and/or sea transportation
- every time building relocate

Design

- dimensional restrictions
- aesthetic quality

Regulation

- different laws and systems across states and countries
- ownership

Relocatable Modular Building

Case studies

Wing Aviation, LLC - Christians burg NEST (First Place)
Built by BMarko Structures, LLC.

Cole Starnes Abbotsford Temporary Housing Facility
Built by Metric Modular.

Residence Modular Hotel for winter Olympic
Built by POSCO A&C.

Relocatable Modular Building

Solutions

Disassemble → **Reversible Building Design**

Transportation → **Use already existing standards**

↕

Design → **Create a new size standard**

Regulation → Establish common regulations

02

REVERSIBLE BUILDING DESIGN

BAMB
BUILDINGS AS MATERIAL BANKS

Co-funded by the Horizon 2020 Framework Programme of the European Union

BUILDINGS AS MATERIALS BANKS

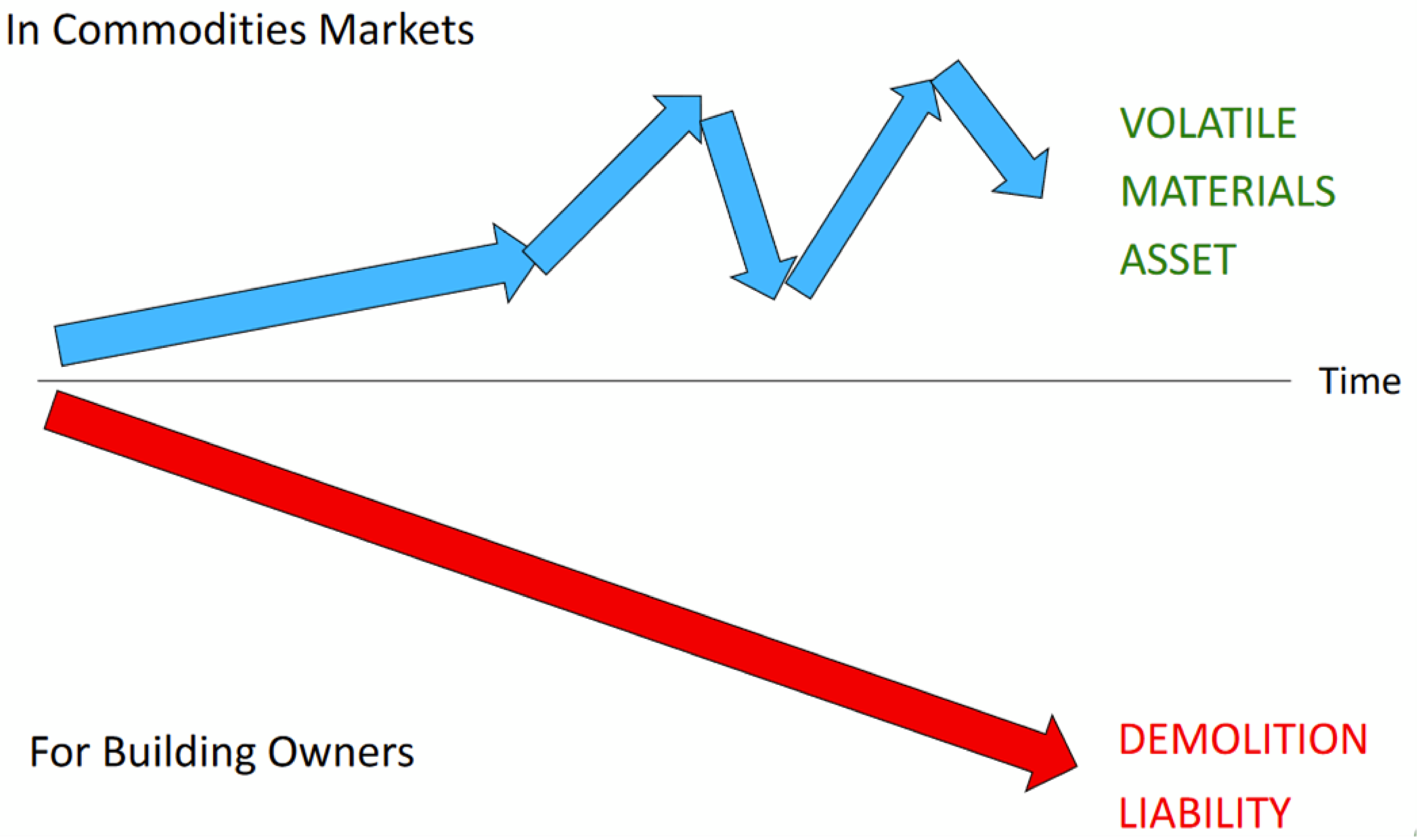
The influence of BAMB in shaping circularity the construction industry

- Starting date: 1st of September 2015
- 16 partners from 8 European countries

Caroline Henrotay - Brussels Environment

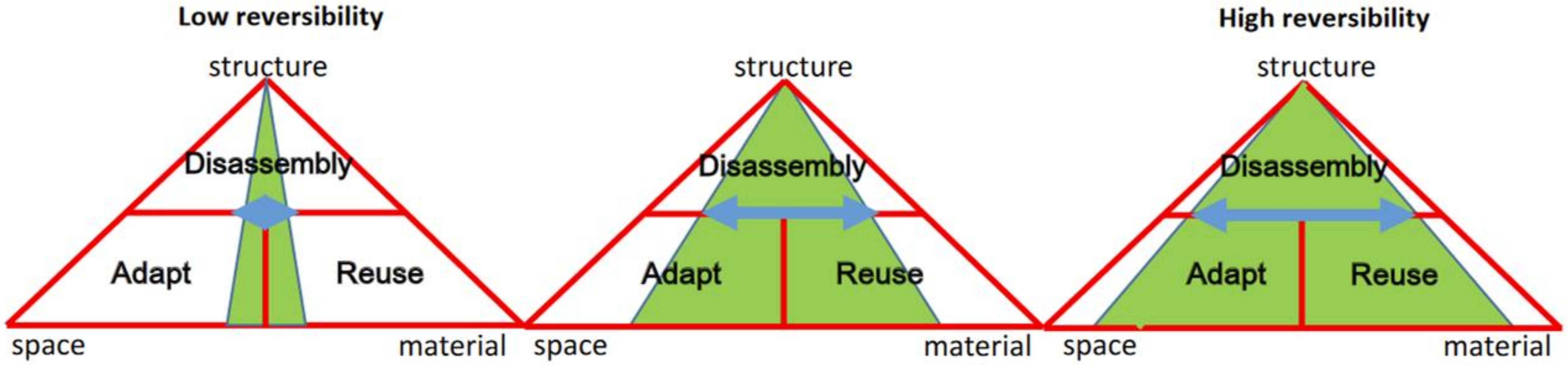
EPEA Nederland · brussels environment · bre · IBM · Ronneby Kommun · vito · Universiteit Twente. · Zuyd Hogeschool · VUB Vrije Universiteit Brussel · Sarajevo Green Design Foundation · Universidade do Minho · SundaHus · TUM · Aurubis · bam · Drees & Sommer

Materials Value in Commodities Markets vs. Buildings

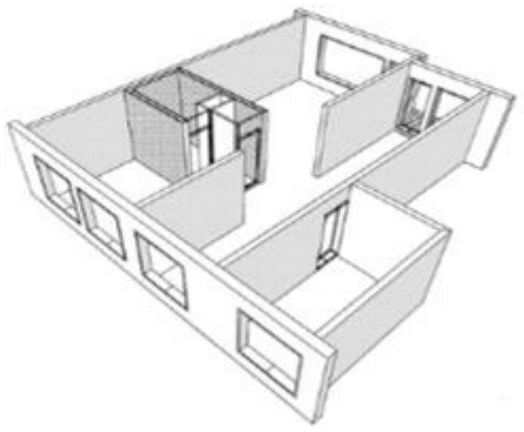


Hansen, Katja. How BAMB Supports Great Designs, Circular Economy In The Built Environment Launch Of The Bamb Stakeholder Network. Building As Material Banks (BAMB), 2016.

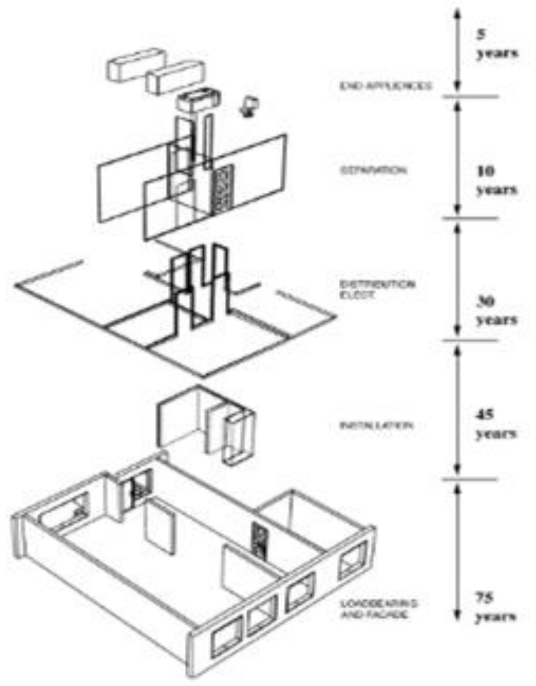
Reversible Building Design Framework



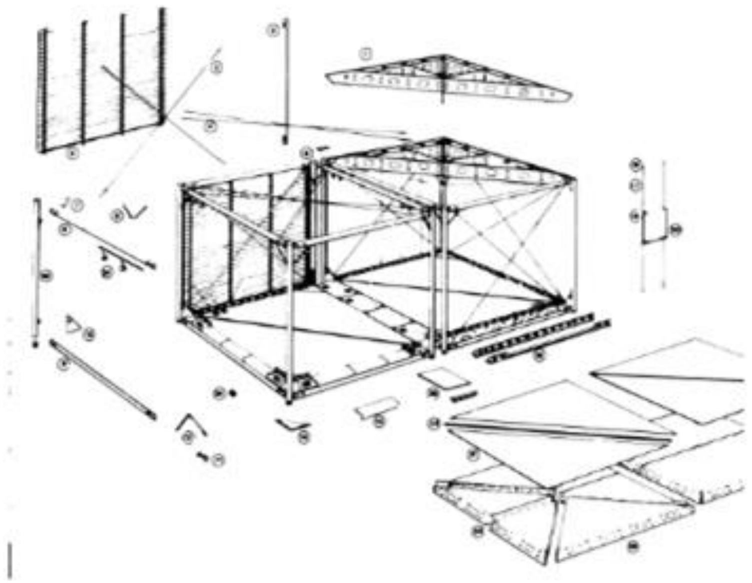
1 Fixed structure

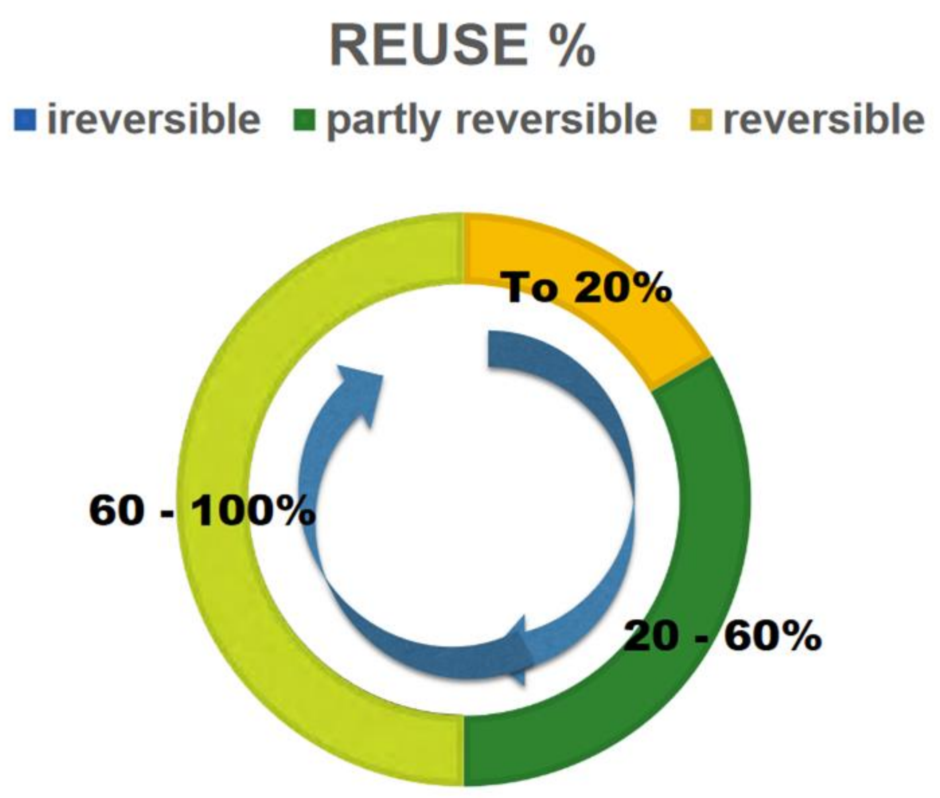


2 Partly reversible



3 Reversible structure





IRREVERSIBLE

- RP < than 0.3
- End of life options = RECYCLING/DOWN CYCLING.

PARTLY REVERSIBLE

- 0.2 < RP < 0.6
- End of life options = REPAIR, DIRECT REUSE, REMANUFACTURING.

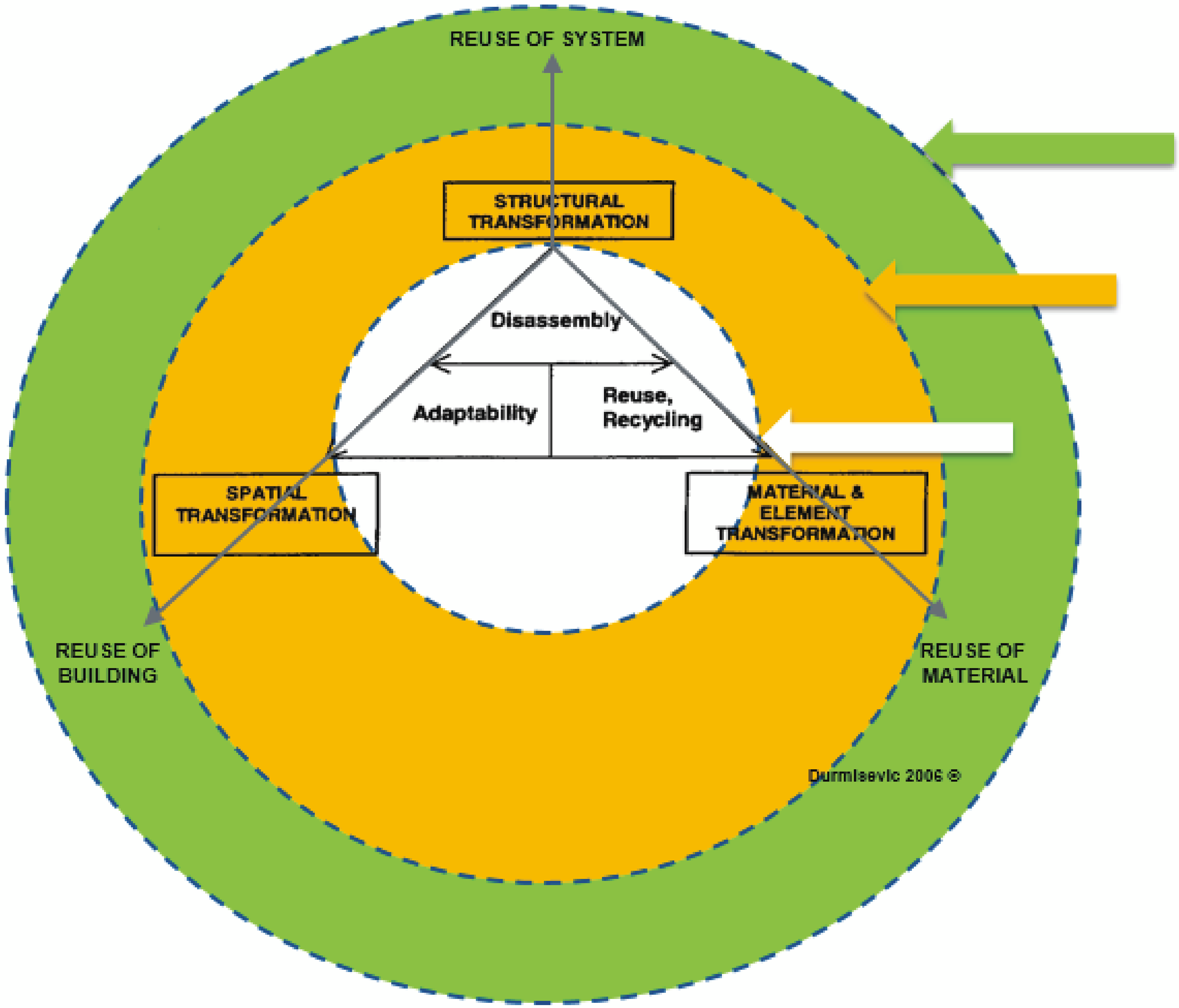
REVERSIBLE

- RP > 0.6
- DIRECT REUSE AND REPAIR of its parts the system can be RECONFIGURED AND UPGRADED

Durmisevic, Elma. Circular Economy in Construction. Design Strategies for Reversible Building. Building As Material Banks (BAMB).

Durmisevic, Elma. Potential of BAMB's Reversible Building Design Tools for the future of sustainable procurement. University of Twente/4D architects. 2019. https://www.bamb2020.eu/wp-content/uploads/2018/09/Durmisevic.pdf. Accessed 3/17/2022

Design Task is to guaranty long term value of buildings by **high transformation** and **reuse potential** of buildings and materials on three levels



Reuse potential
+
Transformation potential
=
Reversible buildings

Demolition = Design Mistake

THREE DESIGN DIMENSIONS OF REVERSIBLE BUILDINGS

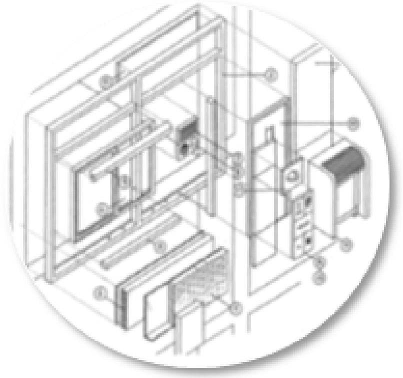
Elma Durmisevic, University of Twente

1

Reversibility of space

Adapt space

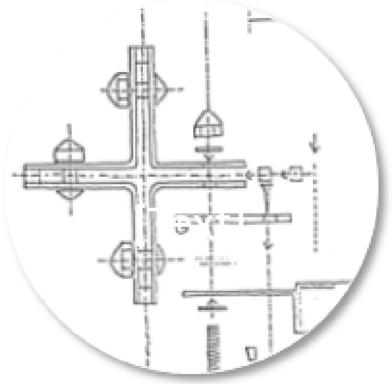
2



Reversibility of structure/

Reconfigure /upgrade structure

3

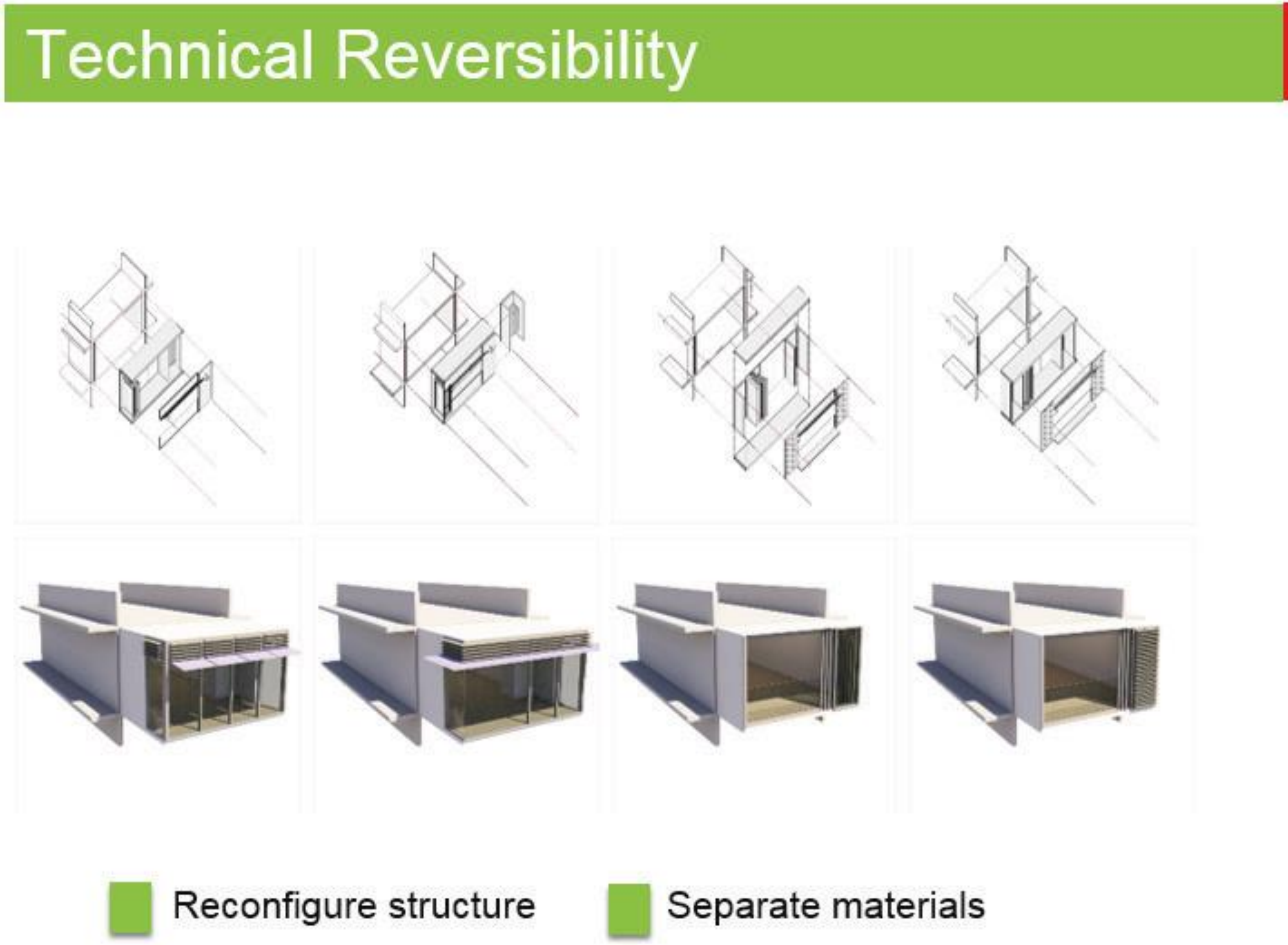


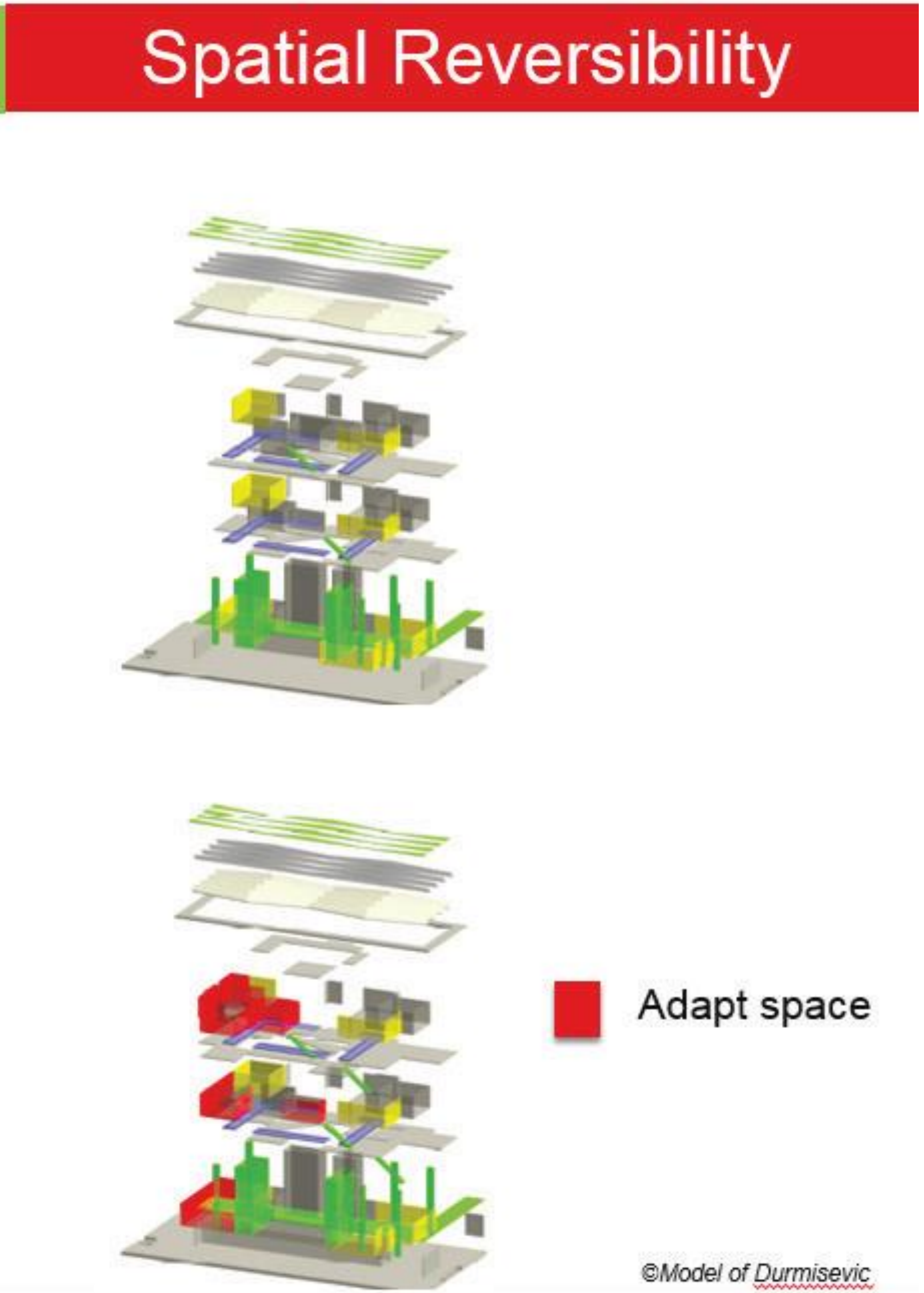
Reversibility of material/

Separate elements/ material

Durmisevic, Elma. Circular Economy in Construction, Design Strategies for Reversible Building. Building As Material Banks (BAMB),

REVERSIBLE BUILDING DESIGN





Durmisevic, Elma, Circular Economy in Construction, Design Strategies for Reversible Building, Building As Material Banks (BAMB).

Spatial Reversibility

- Dimension (Building Level)
- Position of Core Elements
- Building Level Disassembly
- Capacity of the core

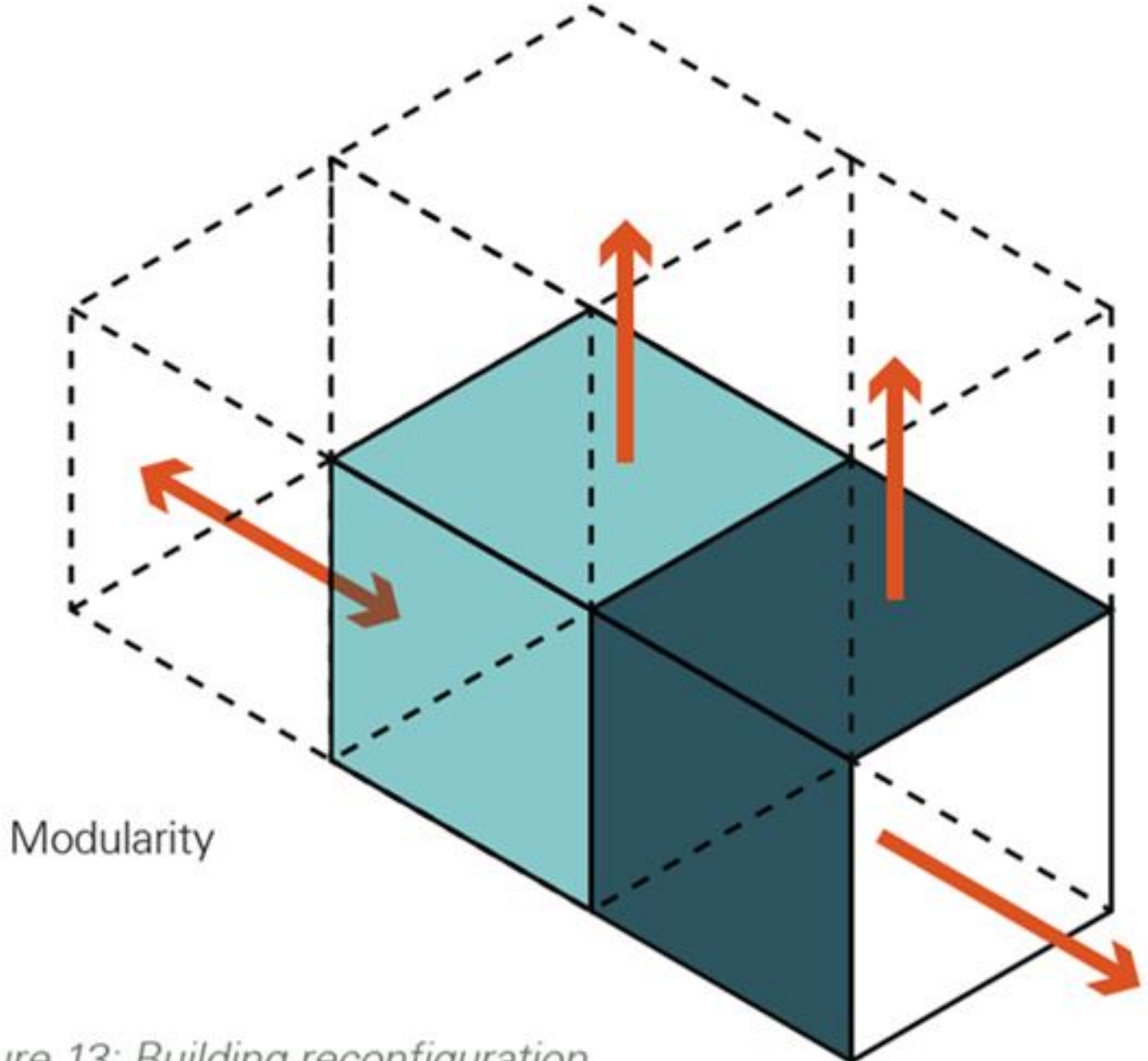


Figure 13: Building reconfiguration

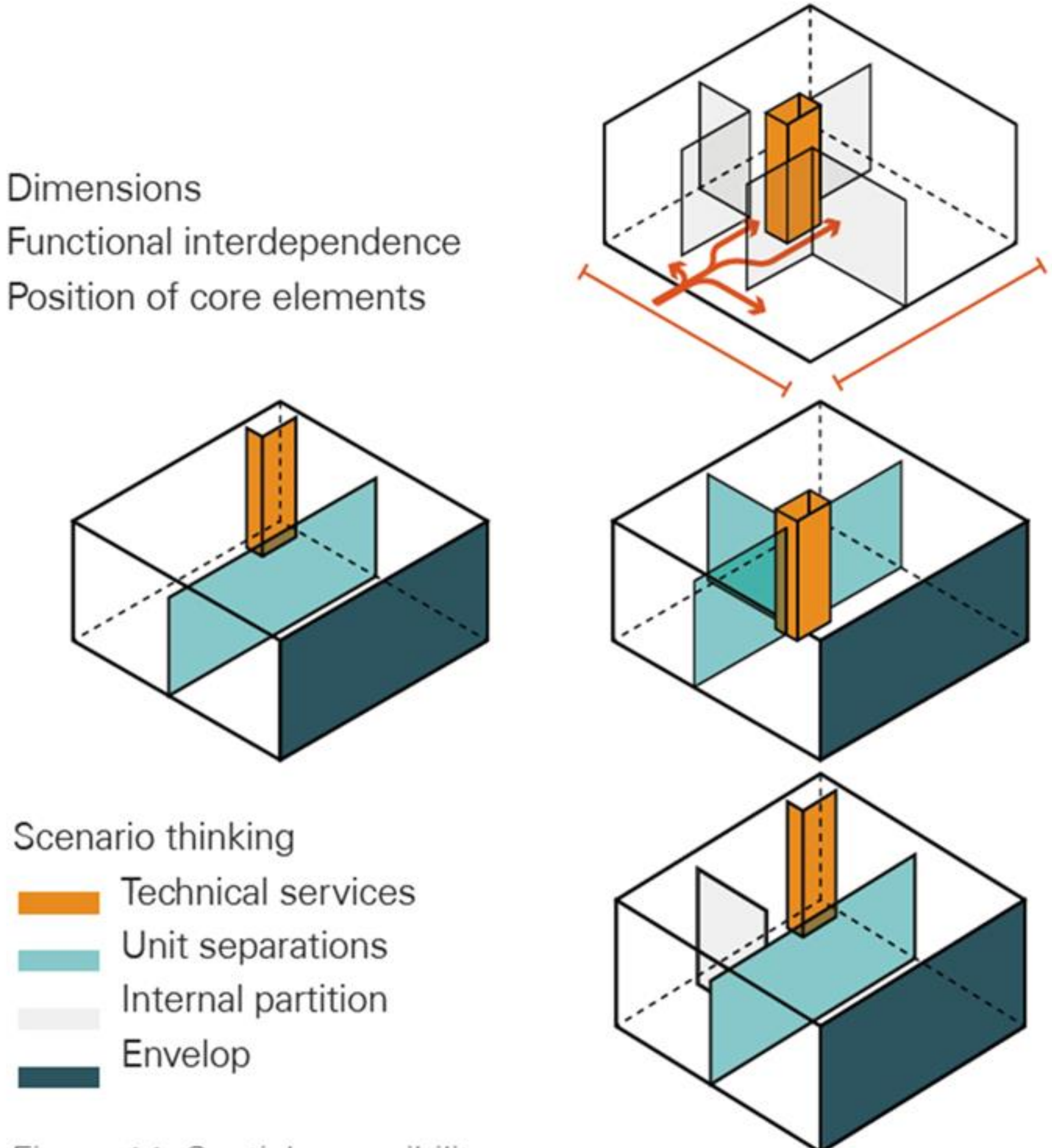
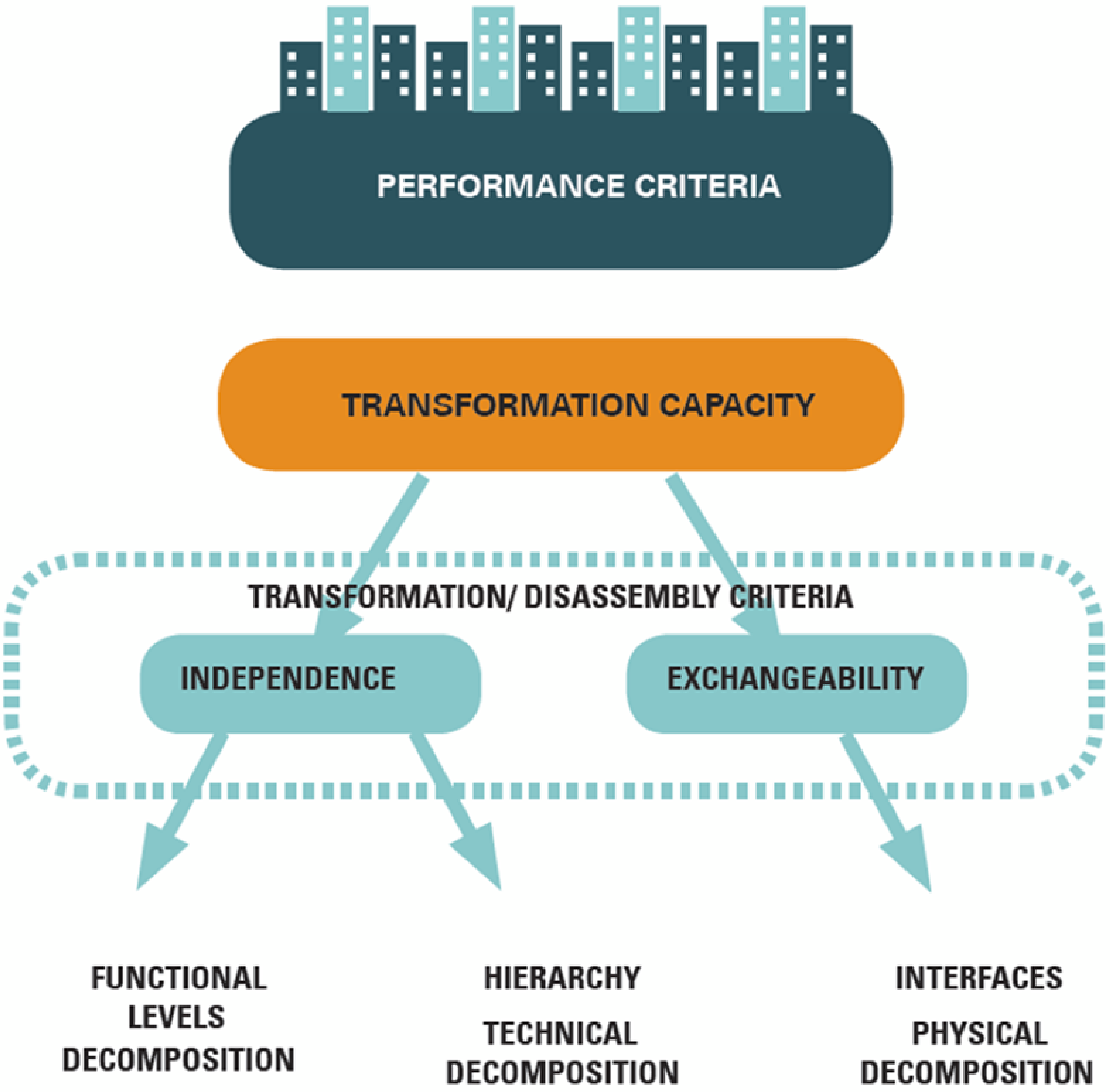


Figure 14: Spatial reversibility

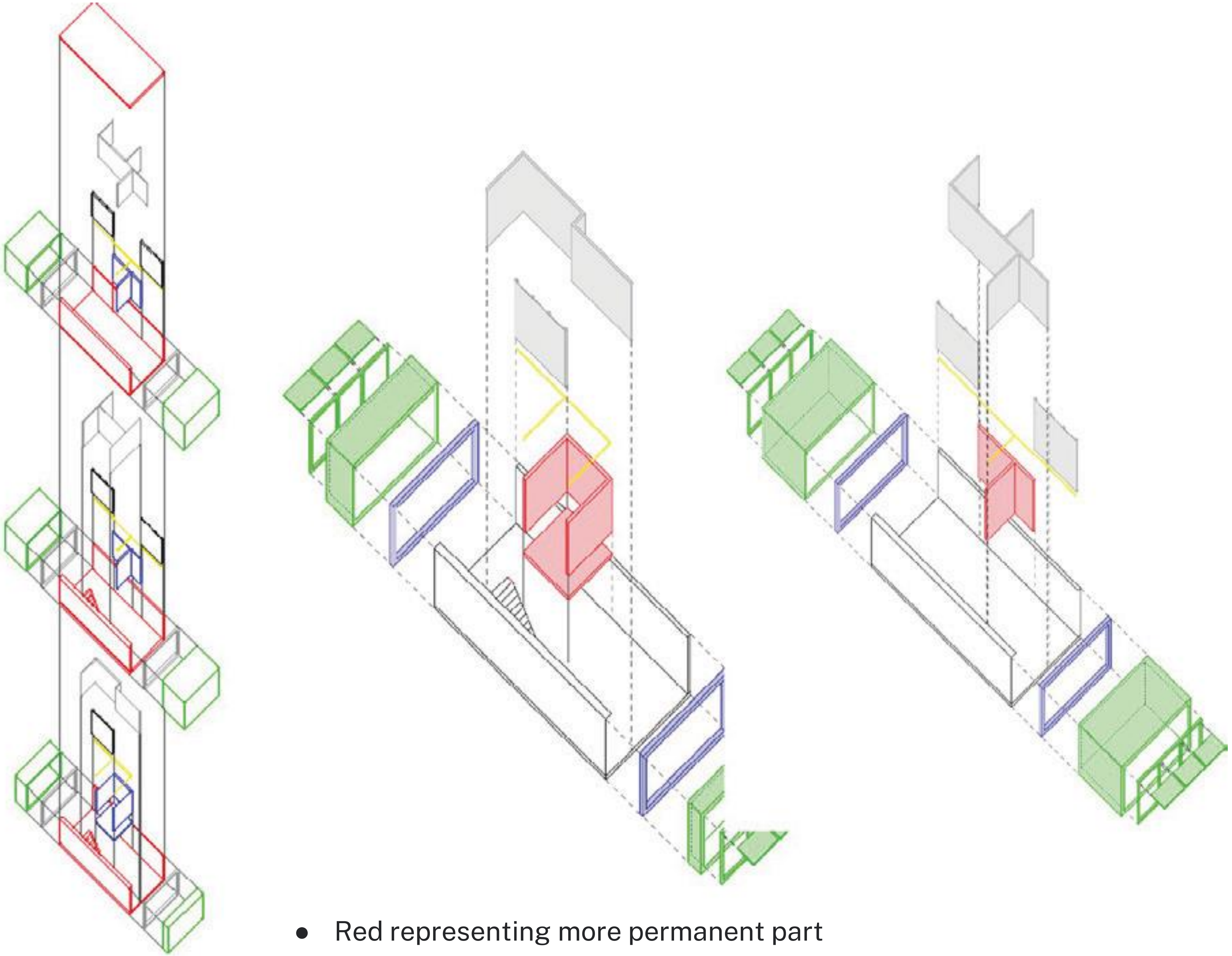
Testing Bamb Results Through Prototyping And Pilot Projects - D14 – 4 pilots built + Feedback report. Building As Material Banks (BAMB), 2019.

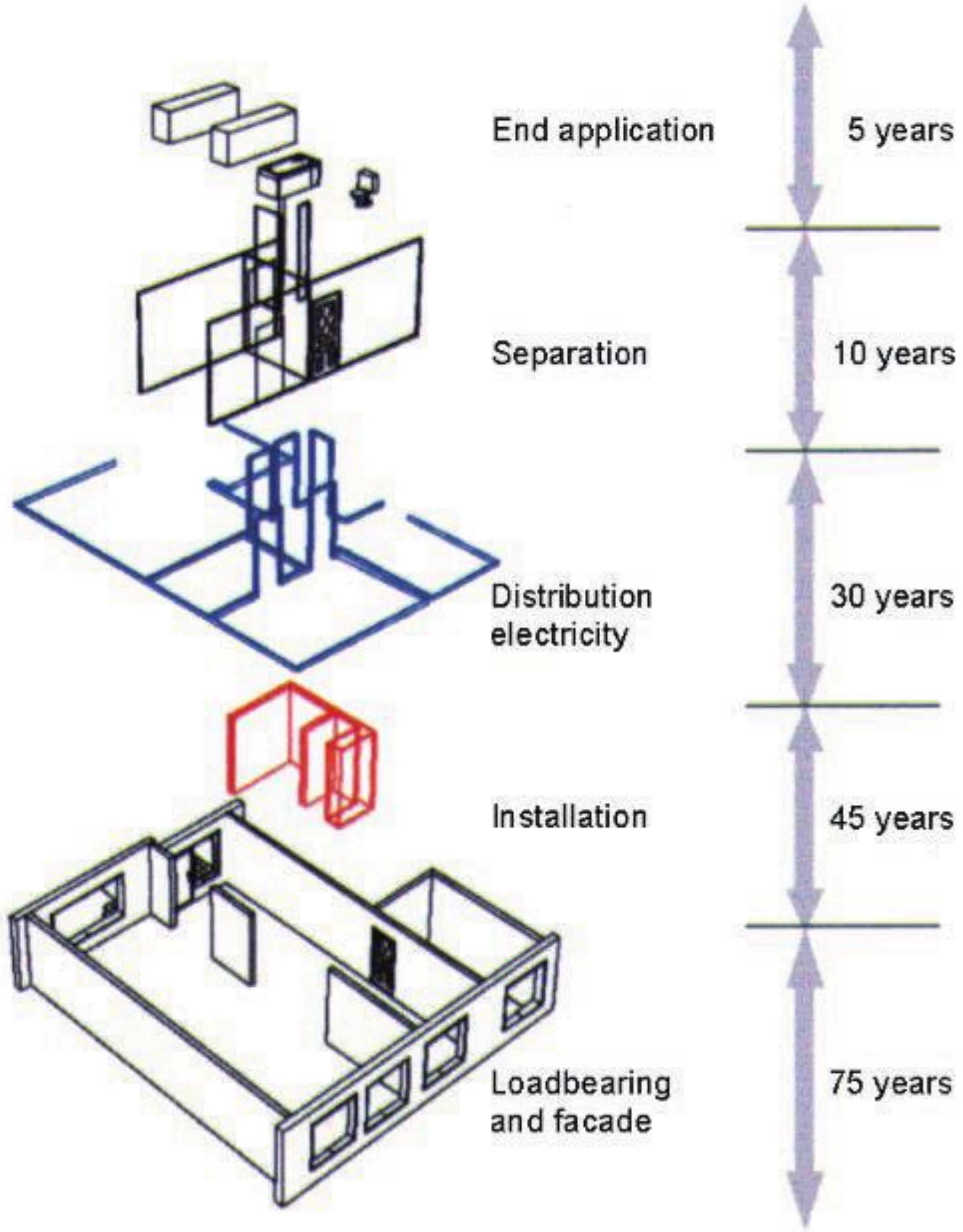
Technical Reversibility

- Functional decomposition
- Systematisation and clustering
- Hierarchical relations between elements
- Base element specification
- Assembly sequences
- Interface geometry
- Type of the connections
- Life cycle co-ordination in assembly/disassembly



Testing Bamb Results Through Prototyping And Pilot Projects - D14 – 4 pilots built + Feedback report. Building As Material Banks (BAMB), 2019.



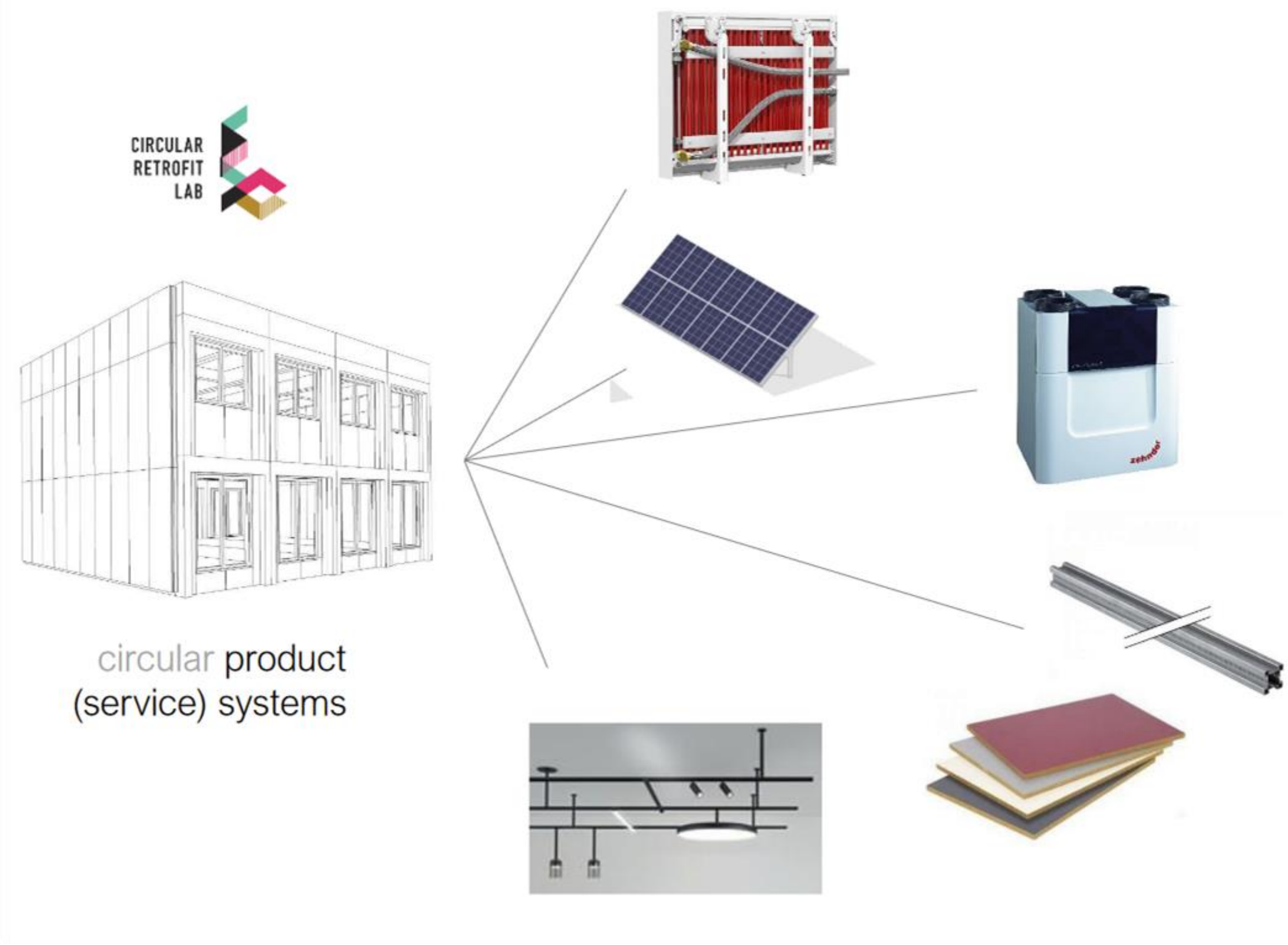


- Red representing more permanent part
- Green representing variable/ exchangeable parts of the structure
- Blue representing intermediary between the permanent and variable parts of the structure
- Gray represent replaceable infill elements

Durmisevic, Elma. Circular Economy in Construction, Design Strategies for Reversible Building. Building As Material Banks (BAMB),

CASE STUDIES: Circular Retrofit Lab

Type	Refurbishment, integration of transformed elements
Size	size: 180 m^2
Function	Exhibition and office space
Location	VUB Campus, Brussels, Belgium



General aims

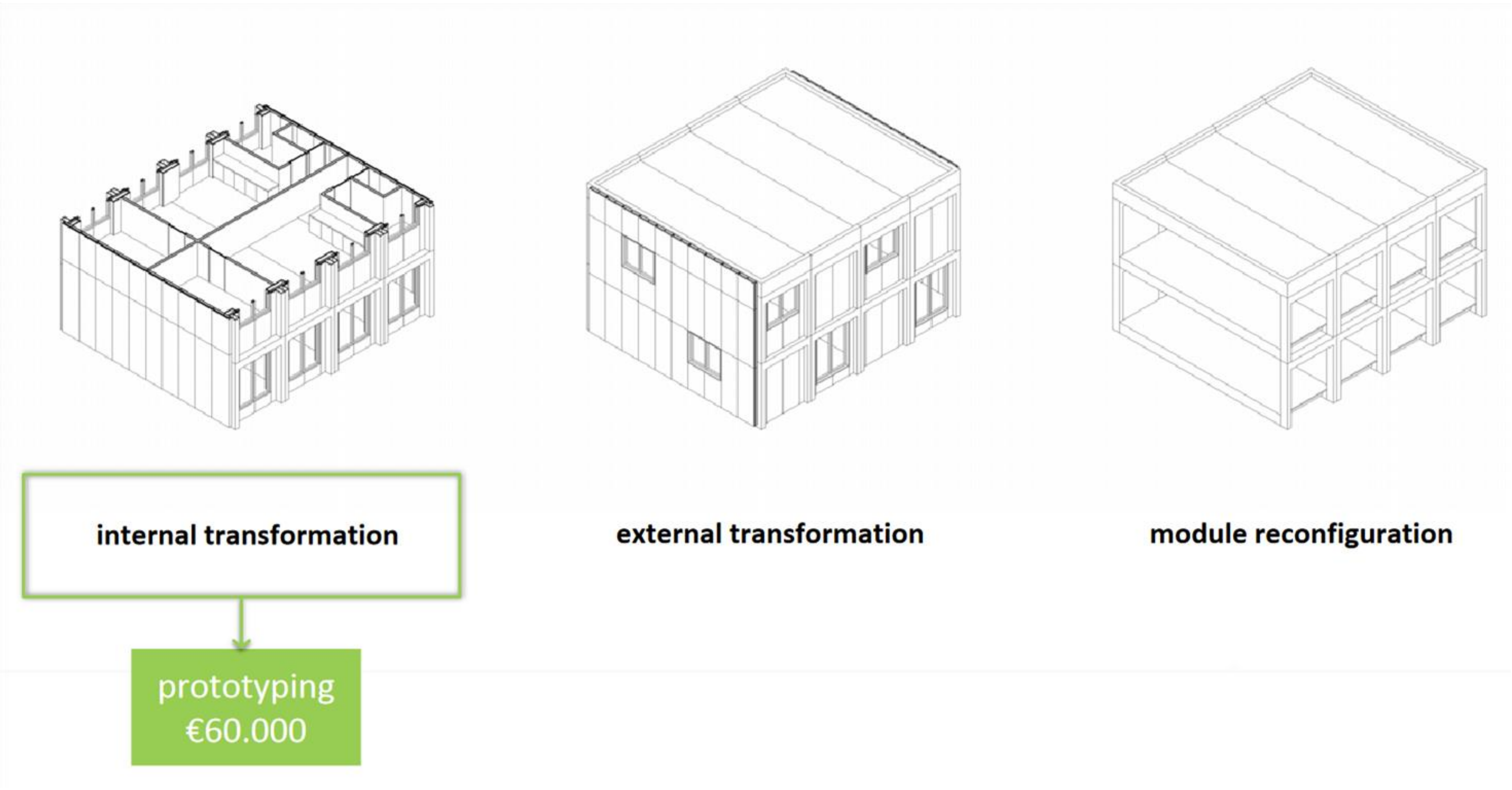
A catalyst for circular renovation

Demonstrator for reversible building principles

Collaborate with industry and test case for circular business models

Exemplary for other circular renovation experiments

Paduart, Anne., et al. Circular Retrofit Lab: A Brussels' Renovation Experiment on How to Re-design Existing Buildings Into Circular Buildings. 2018. Building as Material Banks. https://www.bamb2020.eu/wp-content/uploads/2018/06/Circular_Retrofit_Lab_-_A_Brussels__renovation_experiment_on_how_to_re-design_buildings_into_circular___05.06.18_web-2.pdf. Accessed 3/22/2022



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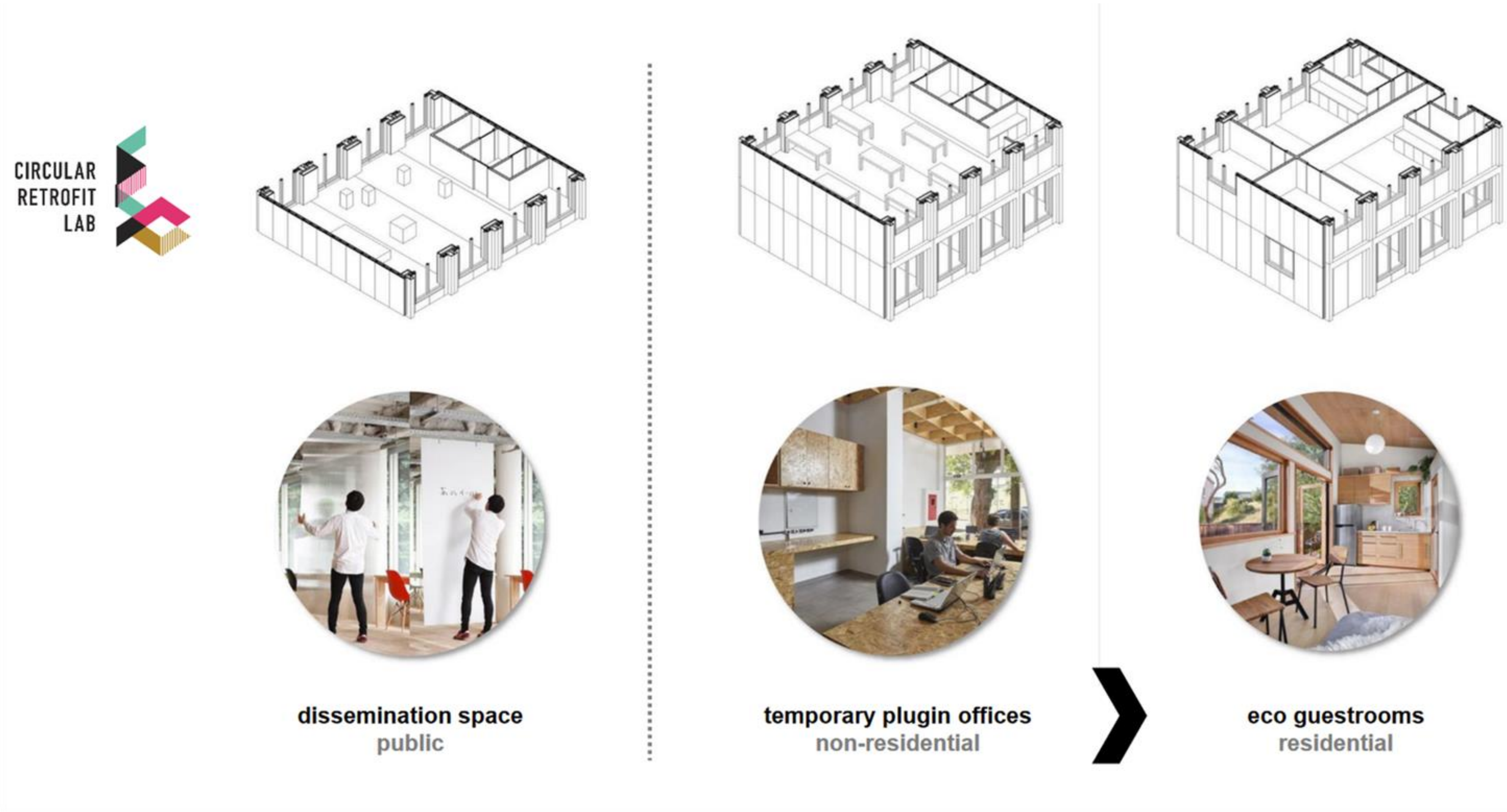

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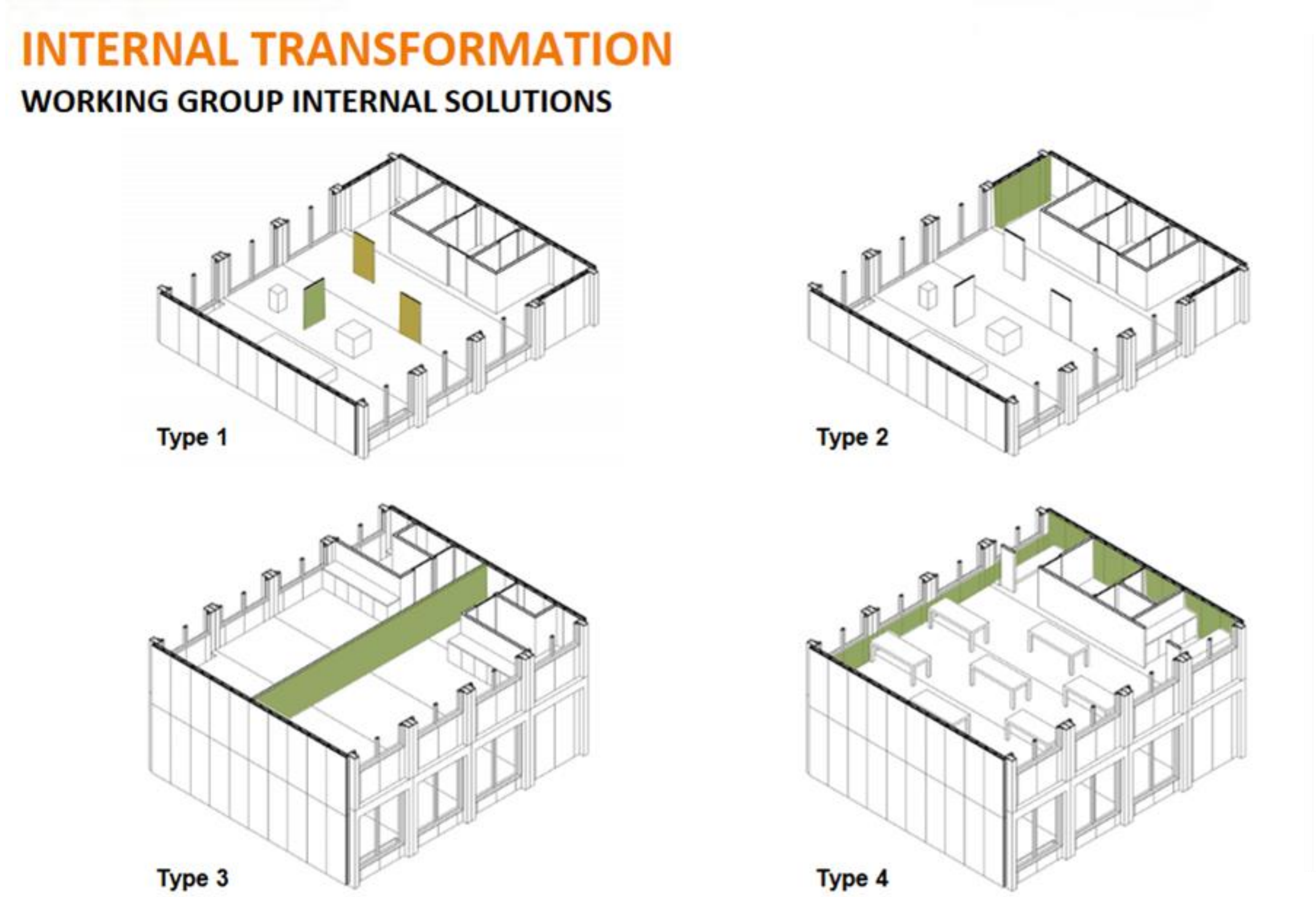

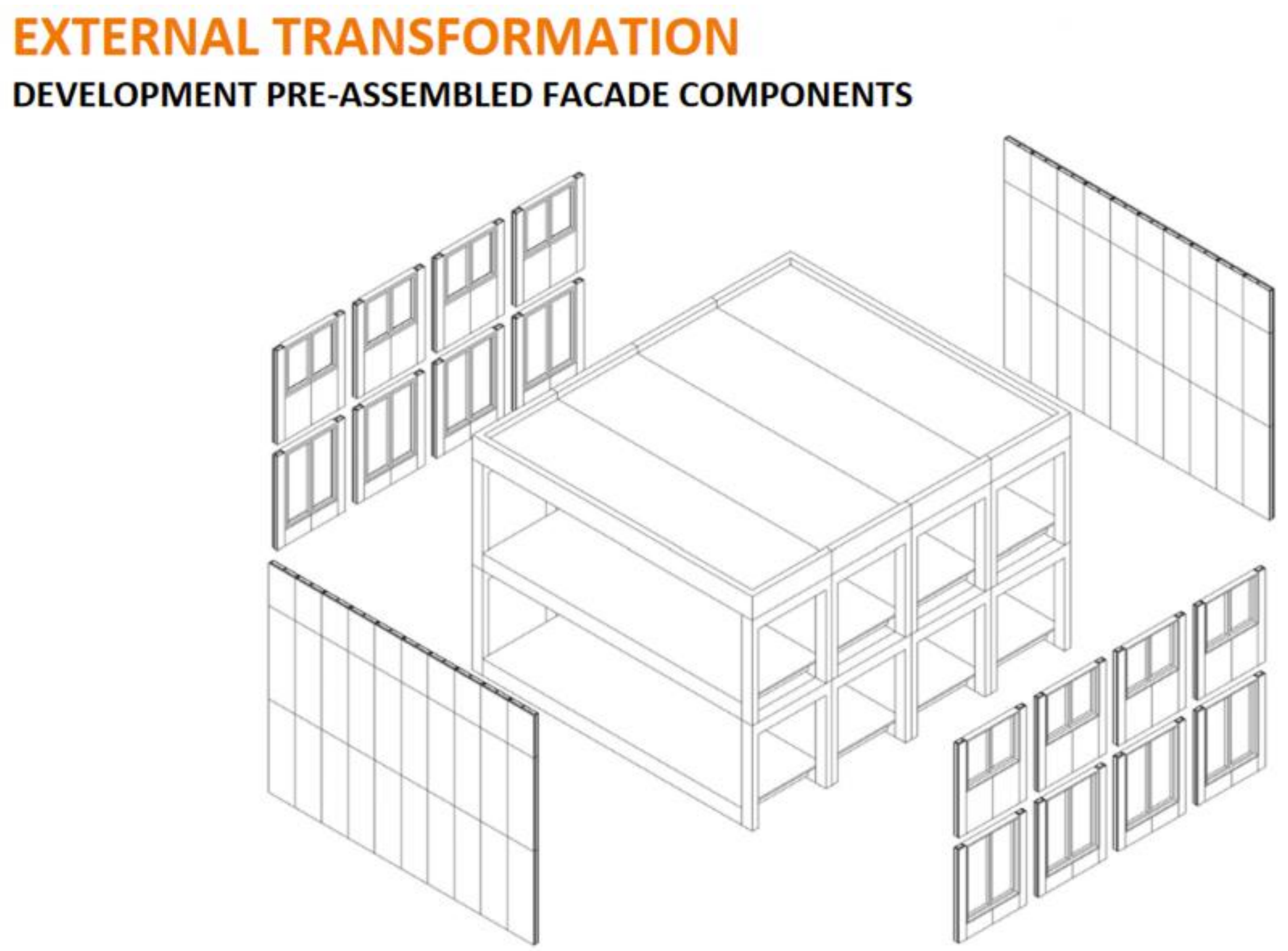

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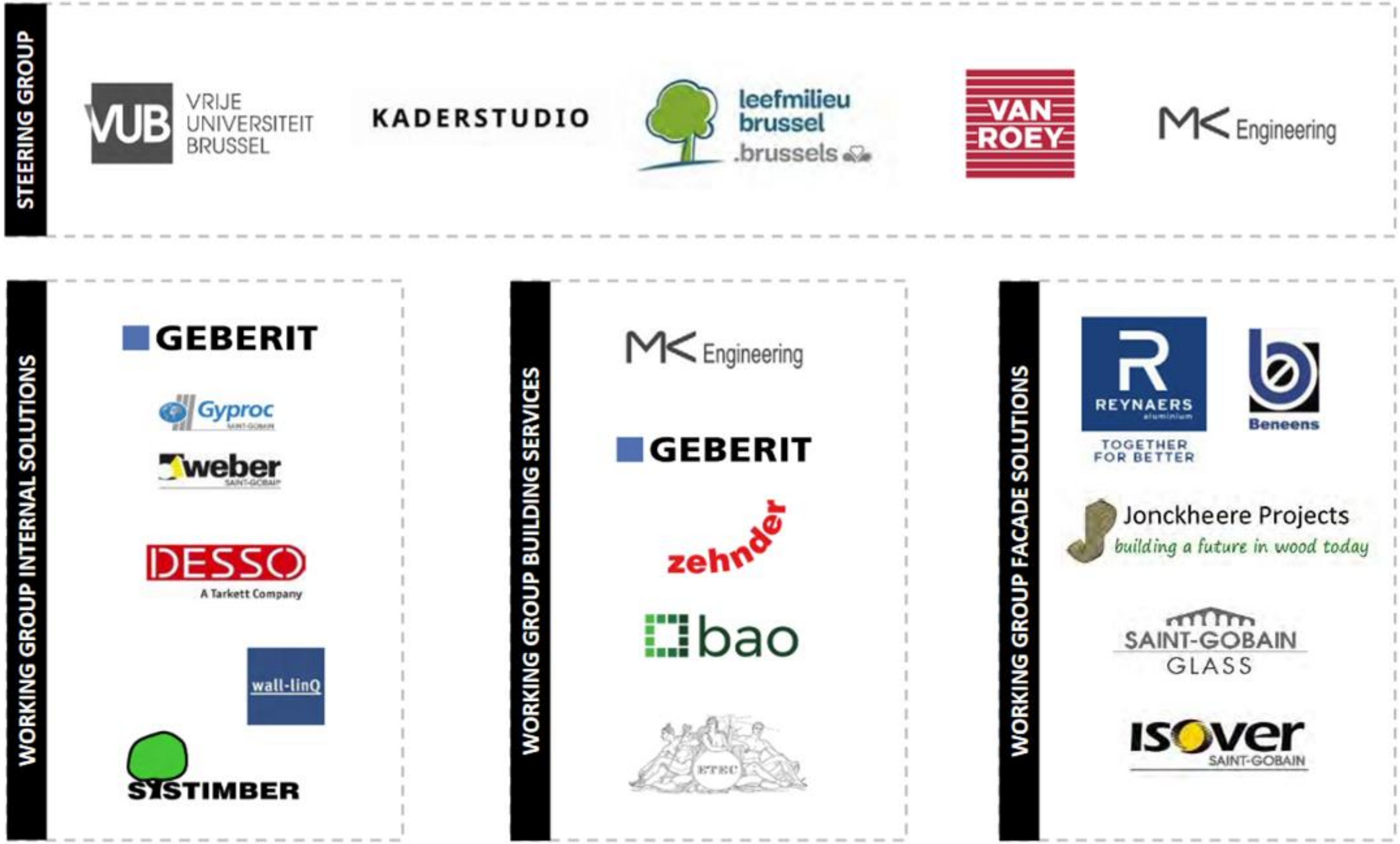
STAKEHOLDERS - PARTNERSHIPS



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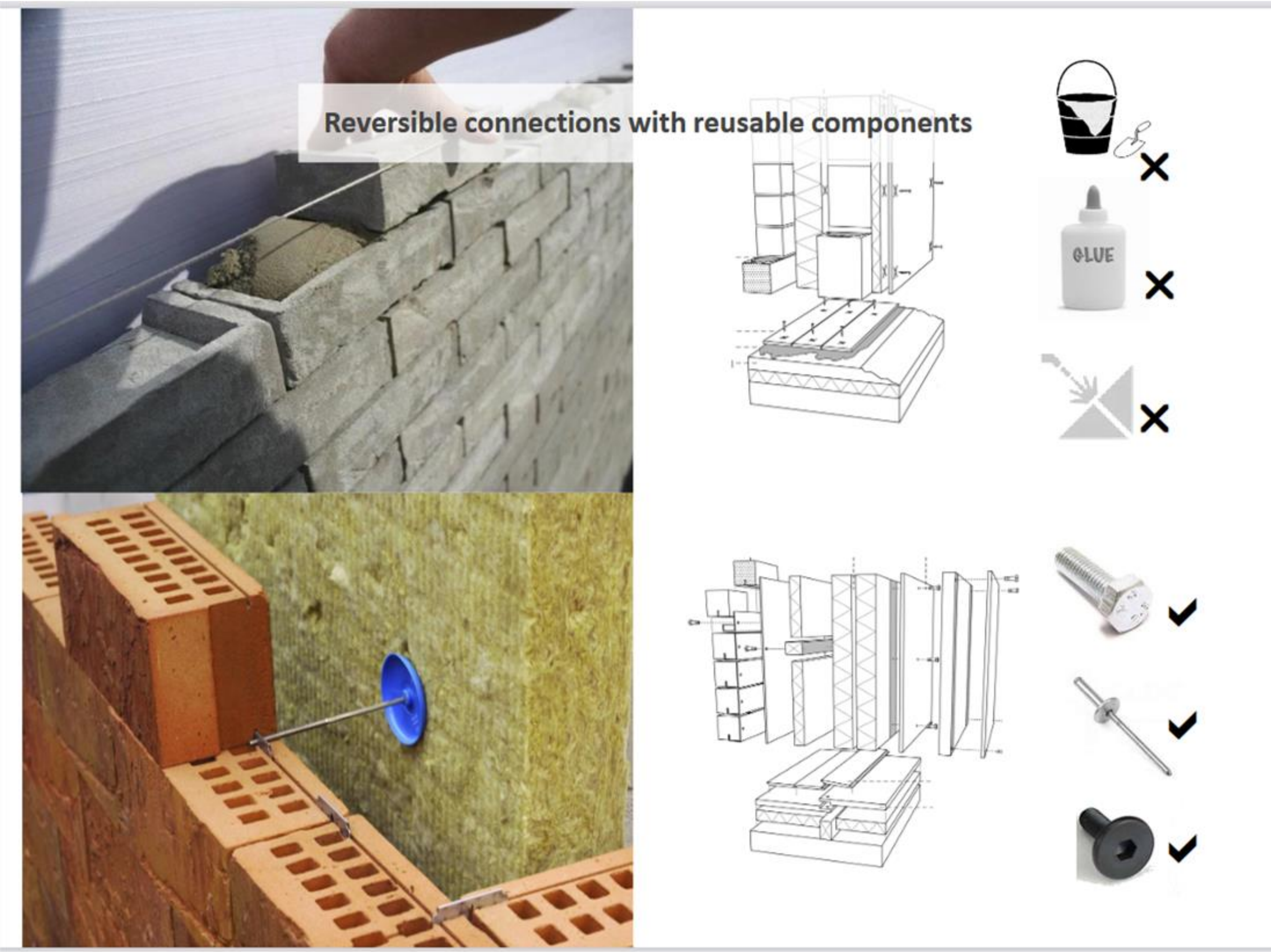

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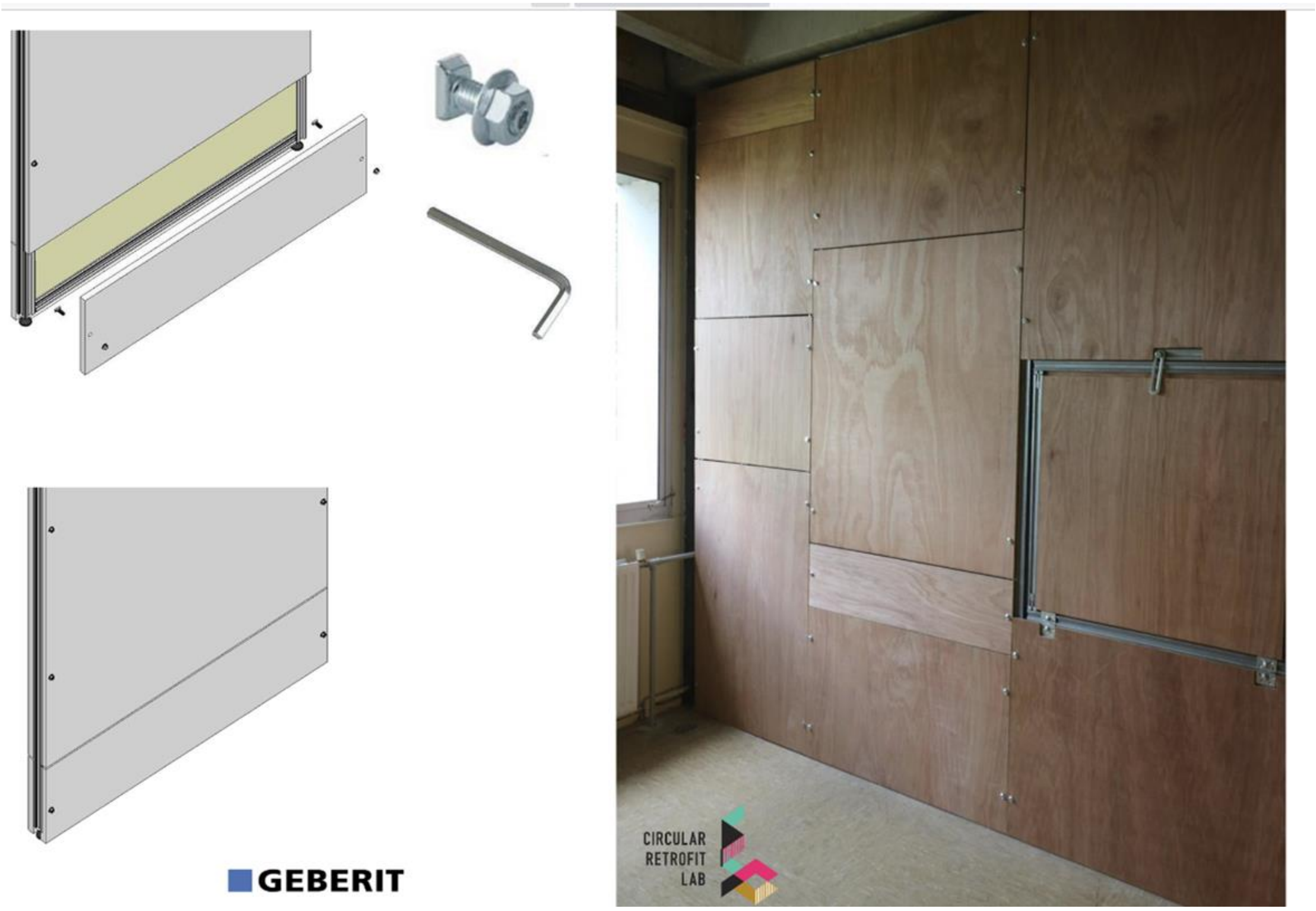

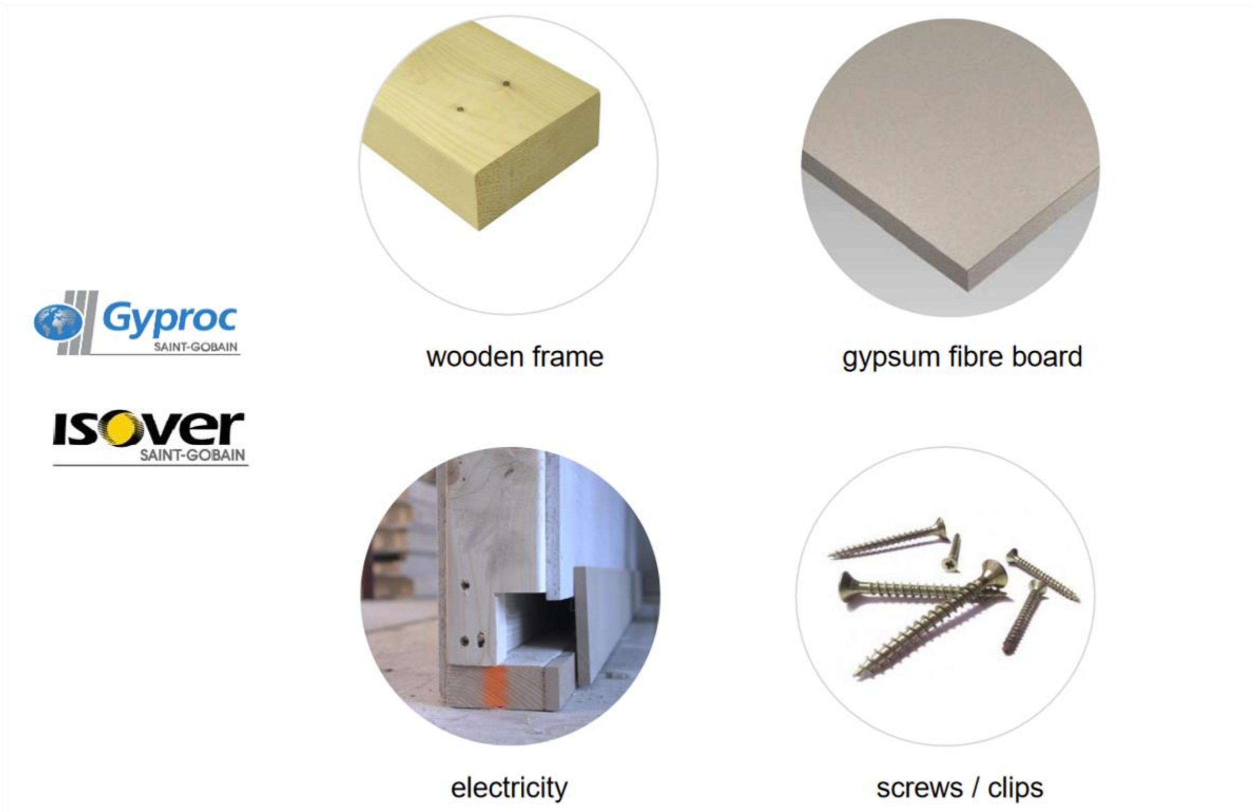

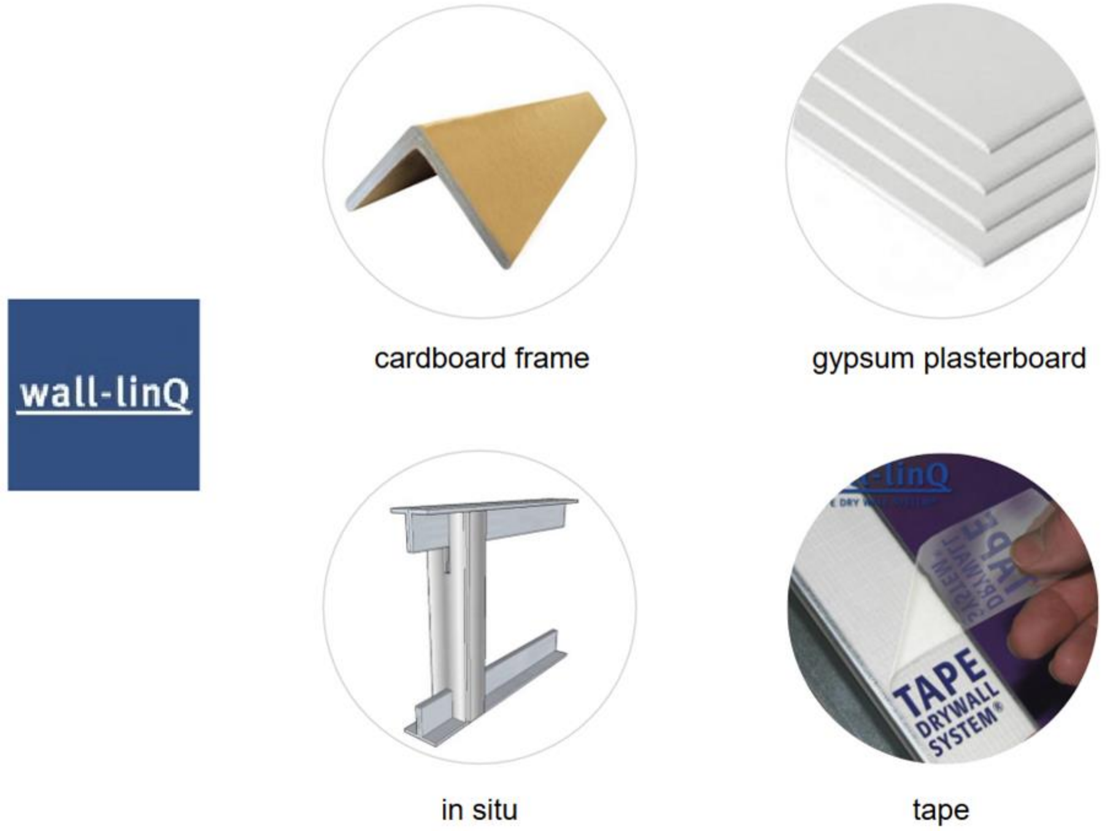

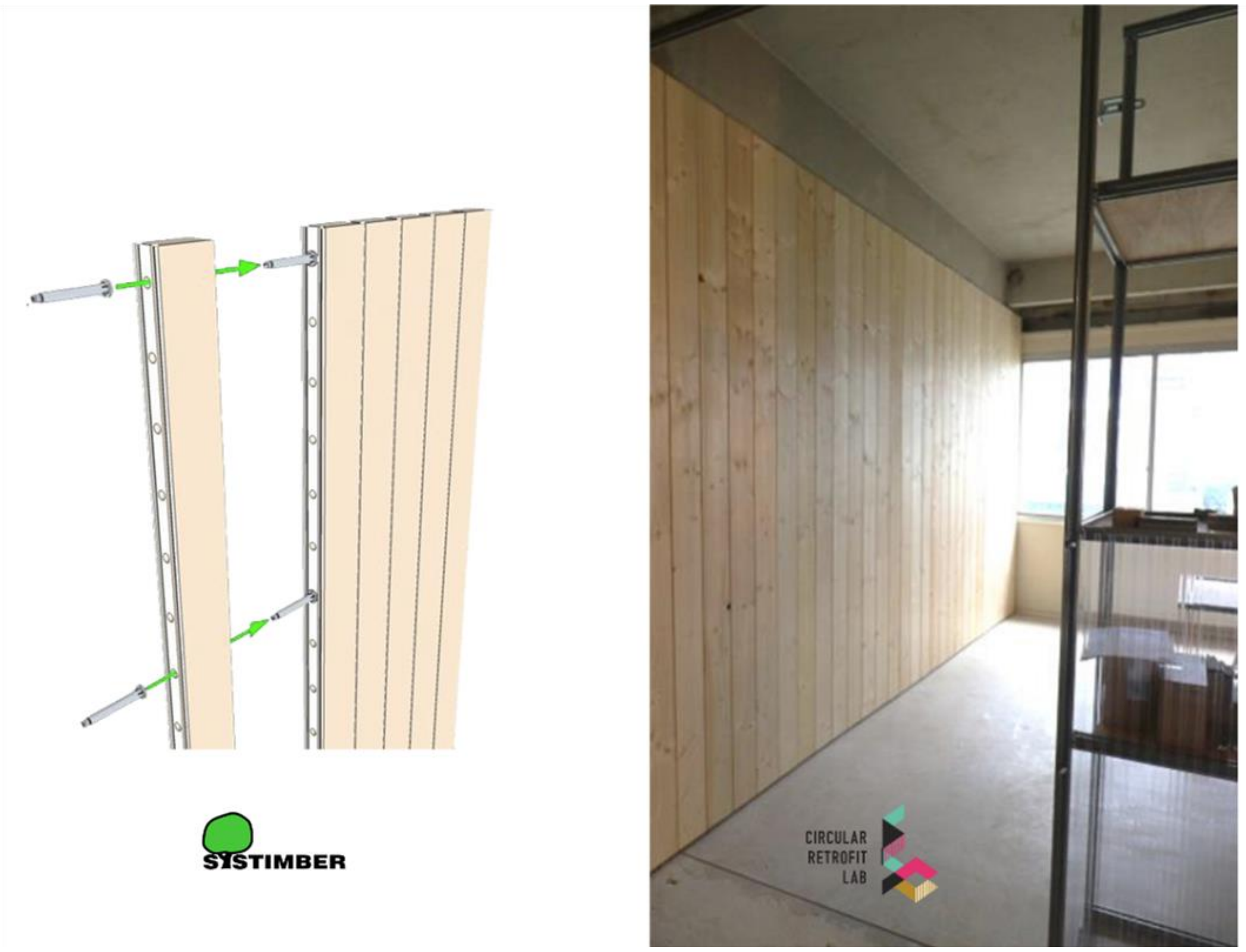

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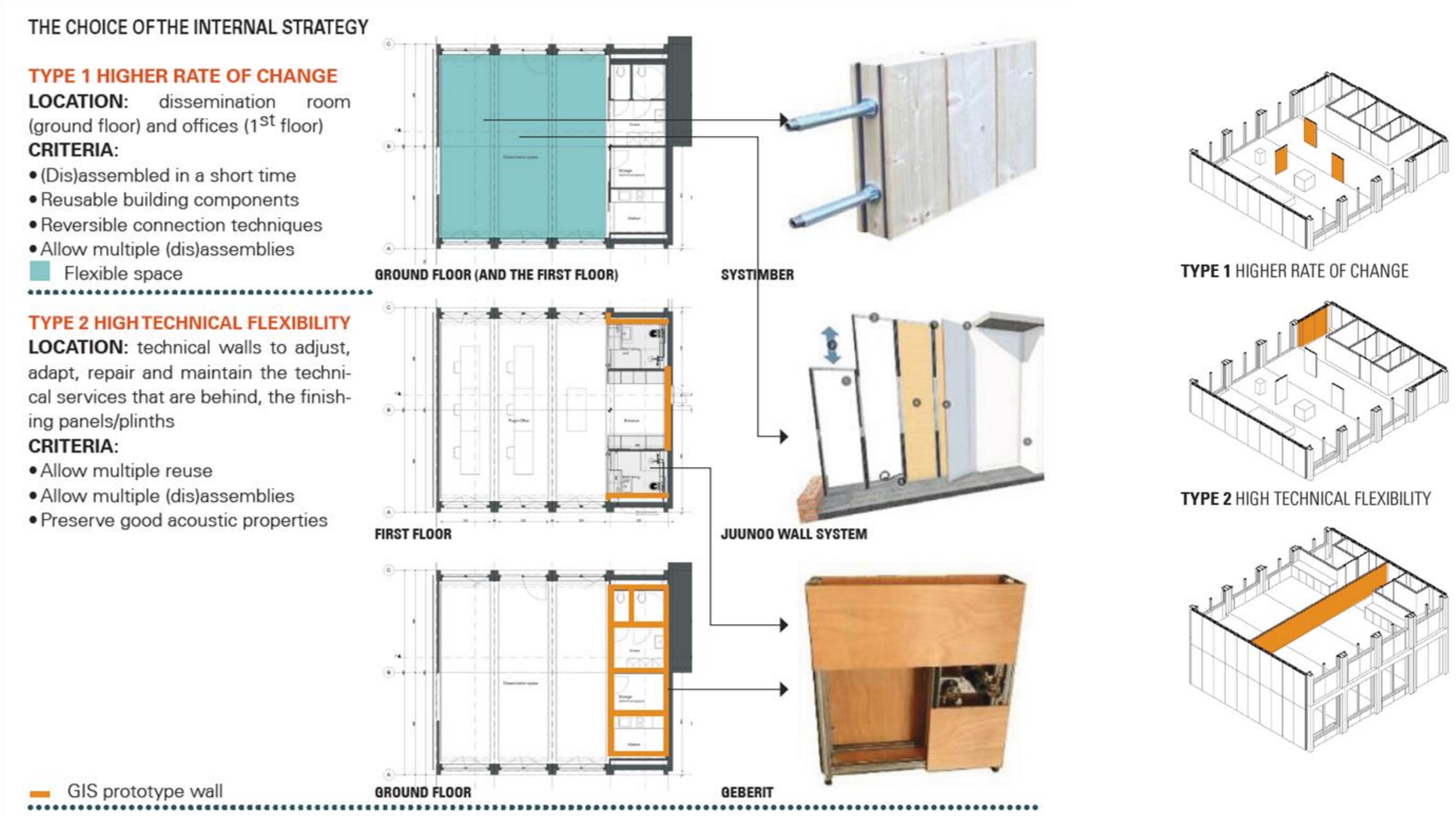

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TYPE 3 LOWER RATE OF CHANGE

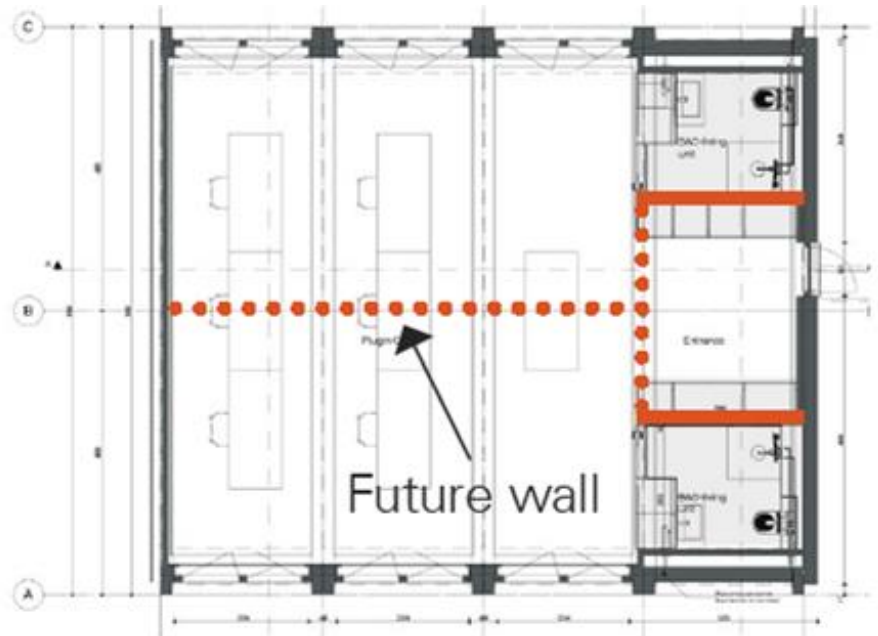
LOCATION: The partition walls between the two eco-guestrooms

CRITERIA:

- Comply with acoustic standards
- Comply with fire safety regulation
- Flexible integration of technical functions

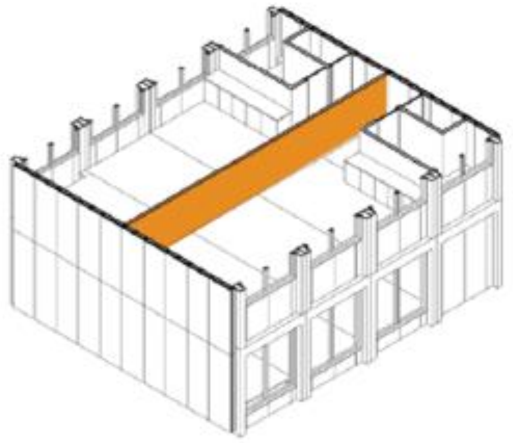
Saint-Gobain Dry-wall (fire rated)

BAO Living prefab module



FIRST FLOOR

GYPROC SAINT-GOBAIN FIRE SAFETY



TYPE 3 INTERMEDIATE RATE OF CHANGE

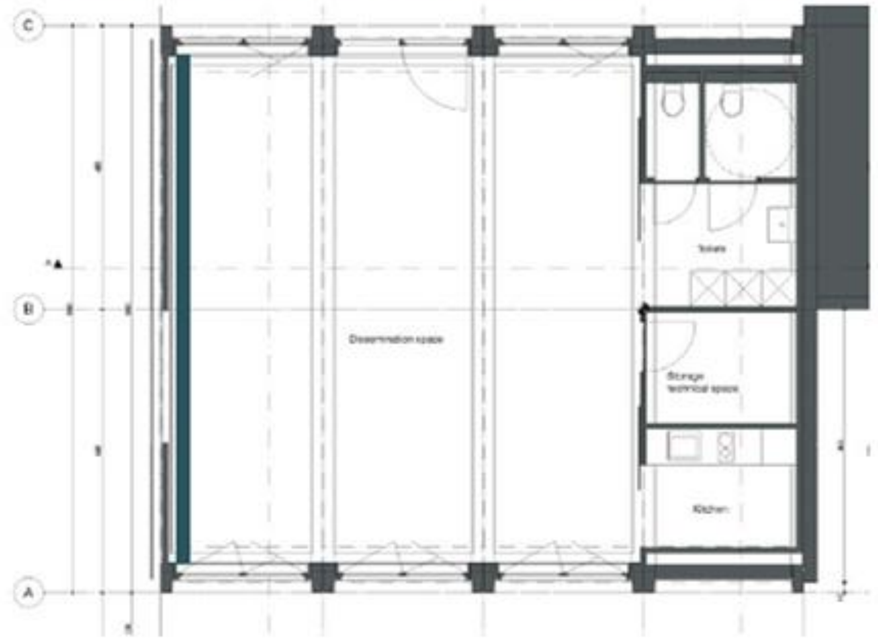
TYPE 4 LOW RATE OF CHANGE

LOCATION: The closed south facade and wall surfaces under the windows

CRITERIA:

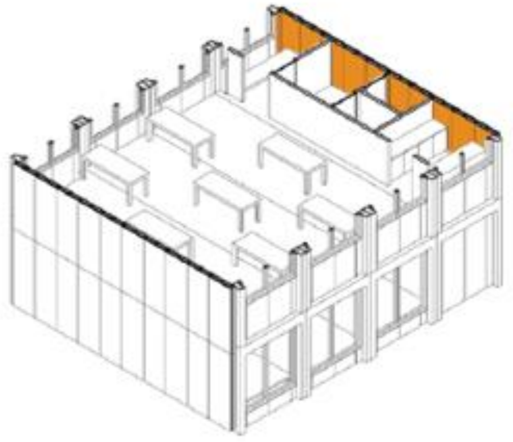
- a low environmental life cycle impact
- reuse of components at the end of functional life

Saint-Gobain prototype wall

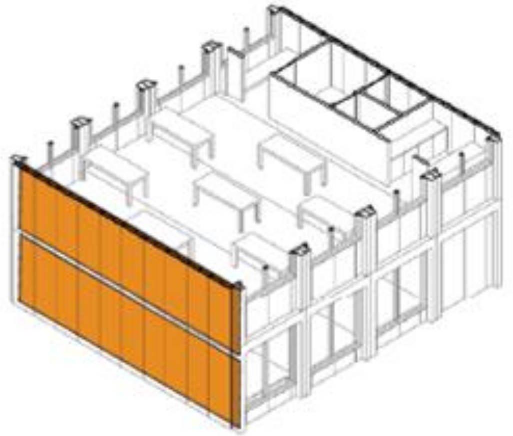


GROUND FLOOR (AND THE FIRST FLOOR)

GYPROC SAINT-GOBAIN CIRCULAR PROTOTYPE



TYPE 4 LOW RATE OF CHANGE



TYPE 4 LOW RATE OF CHANGE

Paduart, Anne., et al. Circular Retrofit Lab: A Brussels' Renovation Experiment on How to Re-design Existing Buildings Into Circular Buildings. 2018. Building as Material Banks. https://www.bamb2020.eu/wp-content/uploads/2018/06/Circular_Retrofit_Lab_-_A_Brussels__renovation_experiment_on_how_to_re-design_buildings_into_circular___05.06.18_web-2.pdf. Accessed 3/22/2022

Conclusion: Circular Retrofit Lab

- Pioneers' work
- Eco system per individual company needs to be defined for circular economy
- Design and engineering tasks for development of Transformable / reversible buildings are very intensive and cost much more time than design of traditional "linear" buildings. Standardisation of design process is needed
- Realization of transformable building requires different approaches to each segment of the building. This requires lot of new product development in the future.
- Industry is more and more aware of the need to change
- Need for business cases
- Experiments - scaling opportunities

Paduart, Anne., et al. Circular Retrofit Lab: A Brussels' Renovation Experiment on How to Re-design Existing Buildings Into Circular Buildings. 2018. Building as Material Banks. https://www.bamb2020.eu/wp-content/uploads/2018/06/Circular_Retrofit_Lab_-_A_Brussels__renovation_experiment_on_how_to_re-design_buildings_into_circular___05.06.18_web-2.pdf. Accessed 3/22/2022

Durmisevic, Elma. PRESENTATIONS & VISITS pilot projects BAMB – 13/10/2017. Building As Material Banks (BAMB), 2017.

03

Durability

Durability challenge of relocatable and reversible buildings

Current solutions for corrosion prevention

Novel Construction Material

Benefits

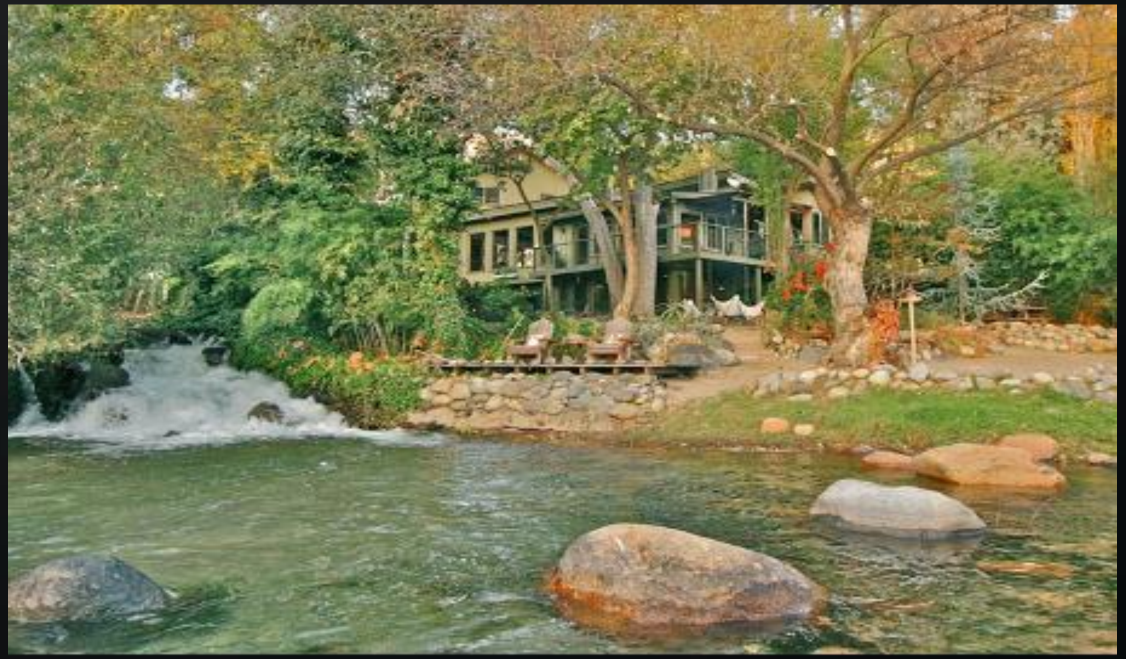
01 Durability challenge of relocatable and reversible buildings

- With the emerging technology of modular construction especially for relocatable buildings and reversible buildings, we could realize locating our modular units in different regions and reusing them multiple times.

- Besides regular locations of application, relocatable & reversible building plays an irreplaceable role in emergency/post disaster relief areas and other swing space. And reversible design of building achieves recycled 60%-90% building materials. The most significant feature is that it could be directly used or reconstructed in extreme environments, such as snow & ice regions, tropical rain forests and marine locations.

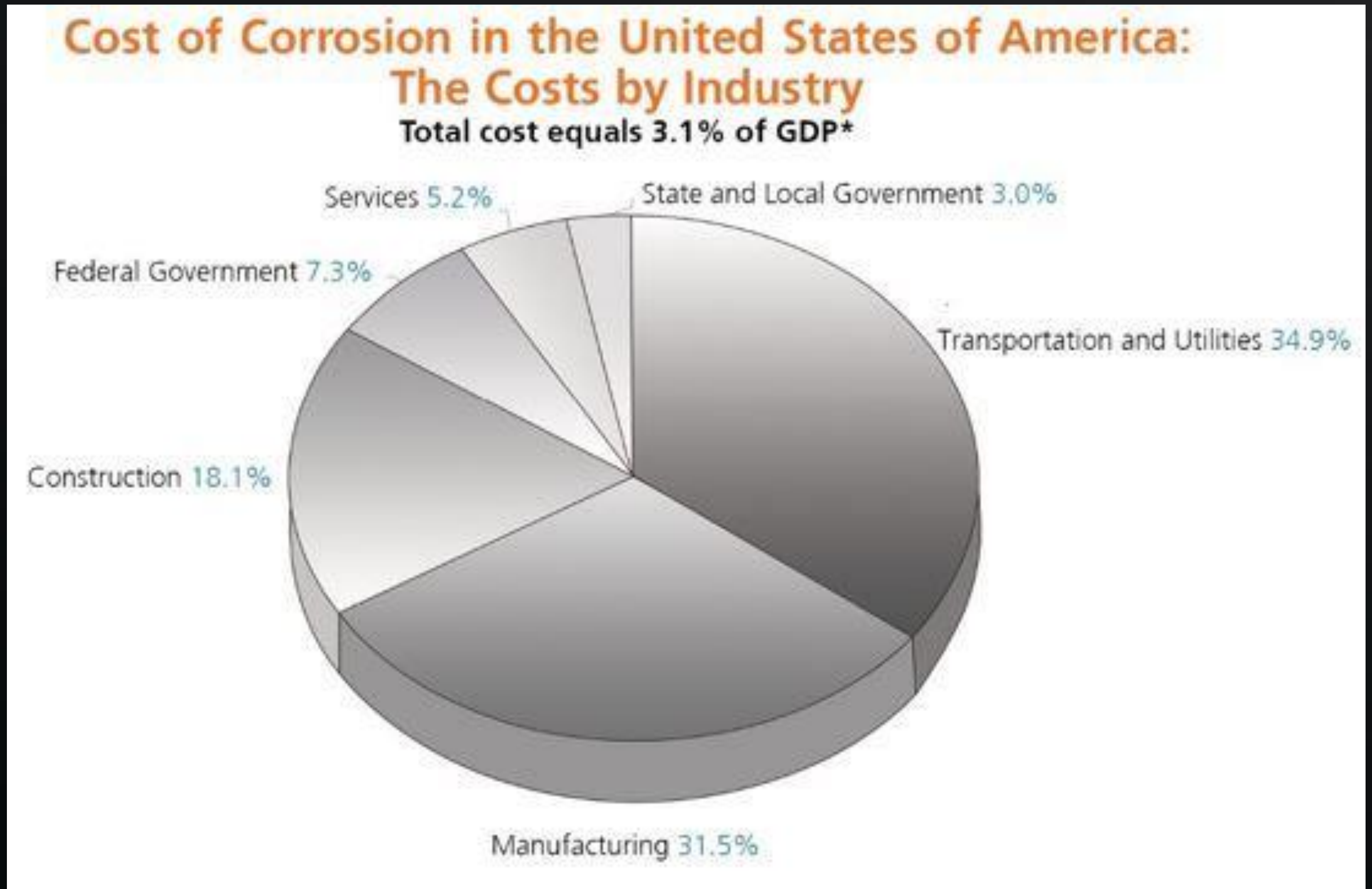
Tropical Rain forests

Snow & Ice regions



Marine locations

01 Durability challenge of relocatable and reversible buildings



Steel Corrosion

- Freeze–thaw cycle, Carbonation and Chloride ion attack, would accelerate the steel corrosion process and have a negative impact on buildings’ durability and cut down their service life significantly.
- Modular constructions mainly consist of steel which accounts for 60%-70% of total components. The excessive proportion of steel would induce high sensibility of corrosion causing substantive maintenance cost and inevitable negative impact on durability of modular buildings.

Overly Cost

- Total direct cost of corrosion in the United States is approximately $276 billion per year, which is 3.1% of the nation's gross domestic product (GDP). Construction and infrastructure industry accounts for 18.1% with $50 billion per year [1].
- Preventing the corrosion of steel in concrete structures subjected to various extreme environments are urgent problems to be solved.

01 Durability challenge of relocatable and reversible buildings

Category	Relocatable buildings' Service life	Permanent / Traditional buildings' Service life
Foundations	**50 years**	**50 years**
Building structure	**10-15 years**	**50+ years**
Interior finishes	**5-10 years**	**5-10 years**
Roofing systems	**20 years**	**20 years**
Mechanical systems	**20 years**	**20 years**
Electrical and plumbing systems	**25 years**	**25 years**

- Relocatable buildings have an average service life of up to 10-15 years [2]. Comparing to permanent or traditional constructions which have 50+ years service life, relocatable buildings have a below-average service life because of steel corrosion effect under its changing use circumstances including snow regions, tropical rainforest and marine locations [3].

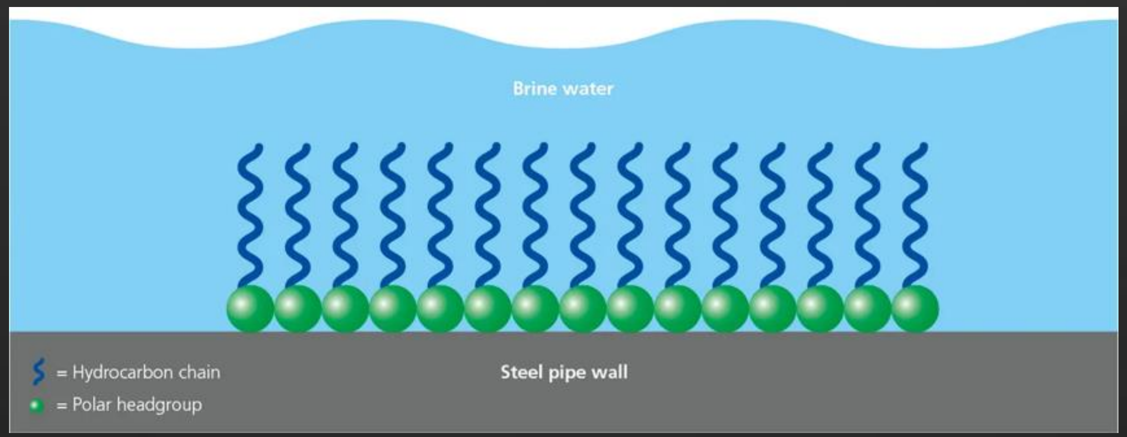
- Short service life hinder the development and wide application of modular construction. Therefore, it is reasonable to find a way enhancing its capability of corrosion resistance and extending its service life.

- The reversible design of modular construction has similar problems and situations. Both the reuse environment and deconstruction process will have a negative influence on the service life of its components. In other words, reversible design could be meaningful only when the service life of the building is prolonged and then recycling more building materials can be realized.

02 Current solutions for corrosion prevention

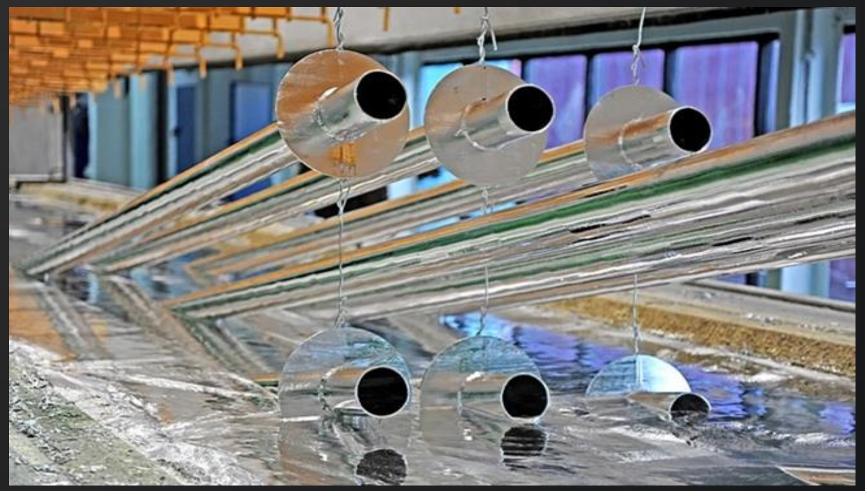
Metal Plating

- Electroplating
- Electroless
- Hot dipping



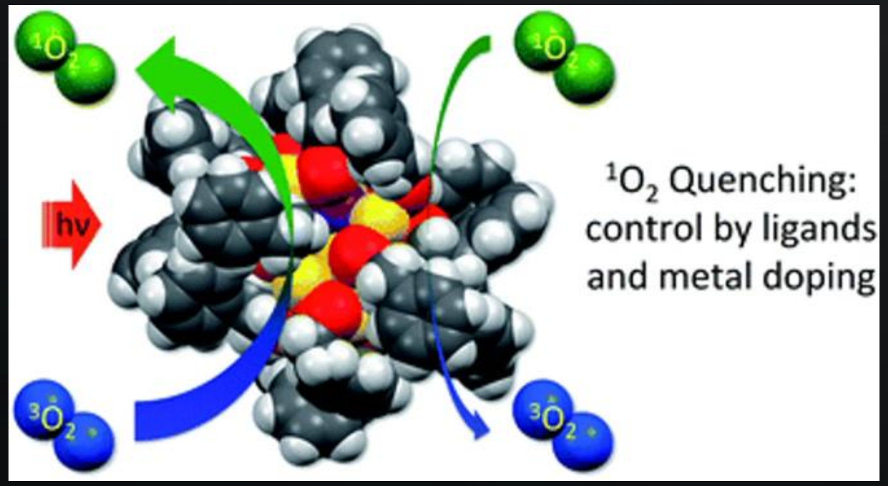
Corrosion inhibitors

Corrosion inhibitors are chemicals applied to the surface of the metal that react with the metal or the surrounding gases to inhibit or suppress the electrochemical processes that lead to corrosion.



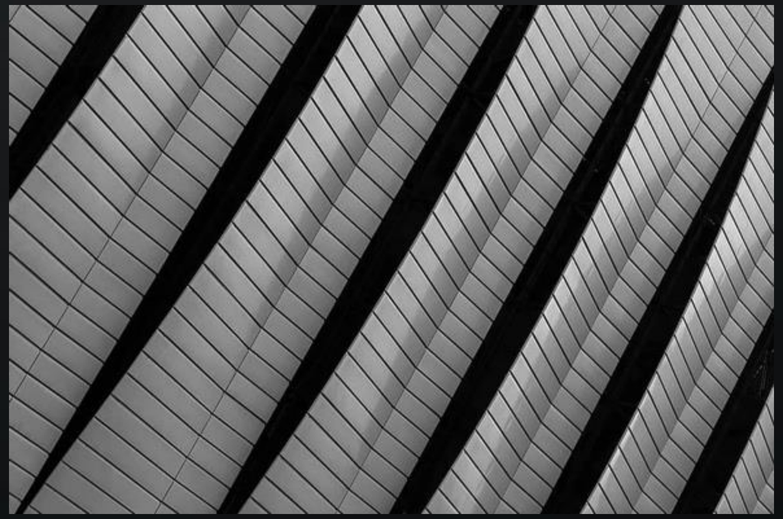
Sacrificial coatings

A coat of a metal that is likely to oxidize is added on the surface of the metal you want to protect.



Metal Plating

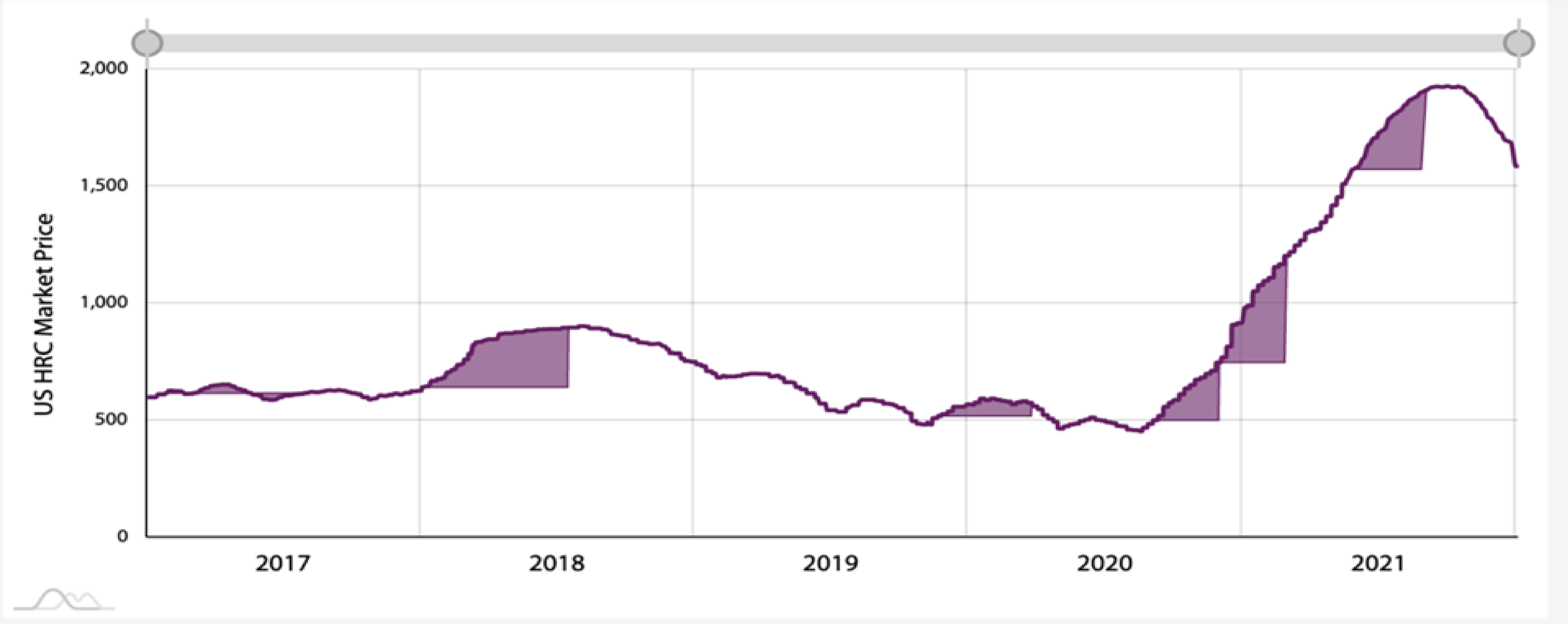
By controlling the environment, we can prevent or reduce the rate of corrosion. Reduce exposure to moisture while complex alternatives include controlling the oxygen, sulfur, or chlorine levels in the environment around the metal.

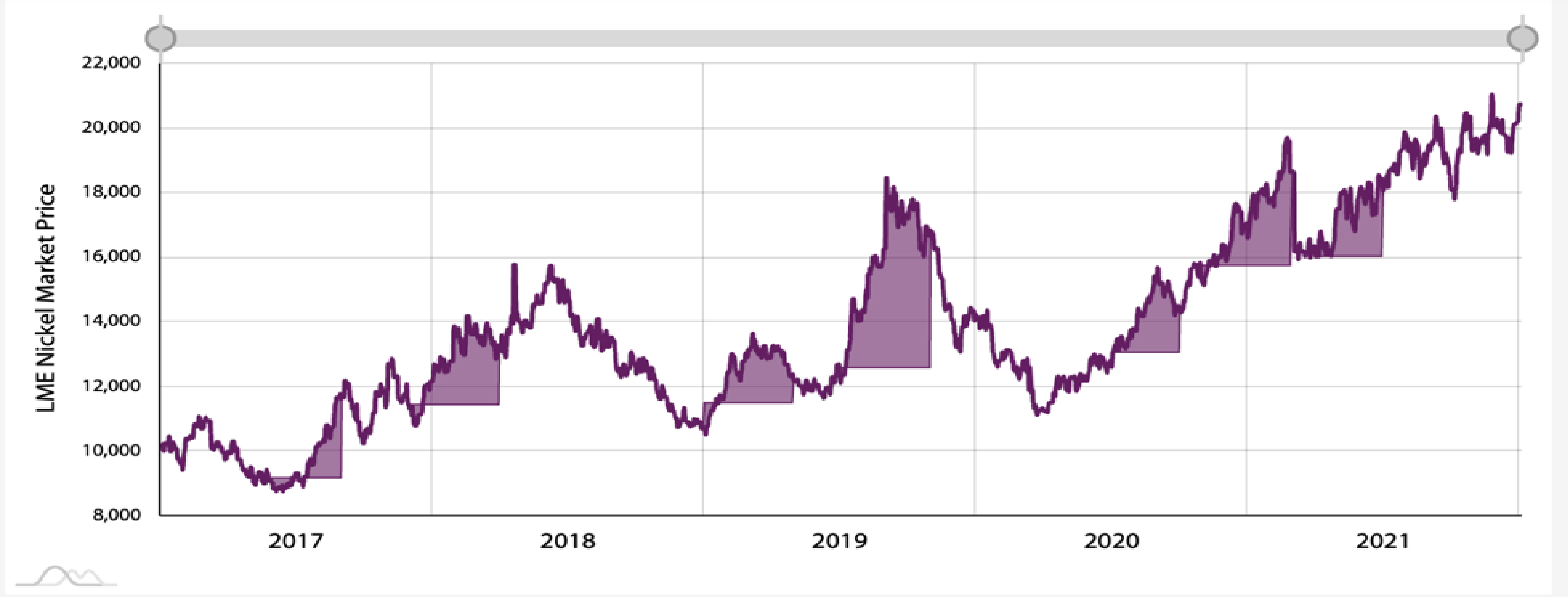


Modifying the design / Using stainless steels

Adding Nickel or other rare metal into the steel processing progress.

02 Current solutions for corrosion prevention





Carbon steel & Stainless Steel

- Traditional methods greatly increase the cost of construction because of expensive protective materials. For instance, using stainless steel, comparing to the carbon steel, stainless steel has a much higher selling price, which is about 3-4 times as expensive as carbon steel on average.

- As a rare metal and main component of stainless steel, nickel is a derivative financial investment tool, and its market price fluctuation is greatly affected by the financial market. With the risk of today's geopolitics, the supply of Nickel decreased dramatically, and the market price skyrocketed.

- The current market price of nickel (stainless steel) is nearly 11 times of HRC (carbon steel) and the gap between them is likely to widen further because of geopolitical factors.

- Current solutions of steel corrosion prevention could not meet the demand of a cheap and effective method in order to enhance the durability of modular buildings.

03 Novel Construction Material - TDA

- ## Steel protective coating

A fresh coat of **TDA (Rubber) paints** will enhance the appearance of the metal structure and prevent corrosion because they act as a barrier that prevents the metal's chemical structure from interacting with environmental compounds like water and oxygen that result in corrosion.

Applying a **rubber powder coat** is another effective method of corrosion prevention. Rubber powder can be obtained by cutting TDA into powder with particle size of 0.180-0.425mm. The powder coat applied on the surface of the metal is heated to form a smooth protective film. For metal sheets, rubber powder coat can also help to prevent corrosion to some extent and also hide imperfection caused by contact with the rollers at the mills.

Mix proportions of rubber concrete (kg/m^3).

Rubber concrete	Cement	Sand	Aggregate	Water	Rubber
RC-0	337	506	607	135	0
RC-10		455			37
RC-20		405			74

- ## Concrete

The mix proportions of rubber concrete are listed in Table 1, rubber particles was used to replace 0%, 10% and 20% of sand under the same volume. The rubber particles used in the concrete belong to broken rubber powder, particle size is 1-2 mm.

The low-permeability and cracking-resistance characteristics of rubber demonstrate its potential to delay chloride ion penetration and corrosion-induced cracking from the perspective of material properties. Therefore, the goal to extend the service life of modular units is achieved.

- ## Foundation

Normally half of the foundation is below the surface water level, which is the most vulnerable part to steel corrosion and the most important element affecting the durability of the structure. Same with the second point, in order to enhance the foundation’s resistance of steel corrosion, we use rubber concrete to replace traditional vulnerable construction materials.

04 Benefits

Reduce cost

- Replace stainless steel with carbon steel +TDA powder coating.
- Replace sand under the same volume in cement, 20%-25% capital expenditure would be saved.
- TDA are discarded materials with low price.
- With simple processing of cutting TDA into different sizes, the cheap and flexible construction material gained.

Environmental-Friendly

- Recycle more discarded tires and the global waste tire problem will be resolved.

Enhance the durability

- More resisted to steel corrosion and be more stable.
- Impede the process of chloride ions attacking internal steel bar.
- With TDA, the modular construction service life would possibly extend to 50-60 years.

High project flexibility

- Carbon steel with TDA powder coating, a substitution of stainless steel with Nickel reduce the geopolitical risks and financial market impact on modular industry.
- It could reduce potential risks from upstream suppliers and increase its project flexibility.

04 CASE STUDY

Flying Sales Center

Reversible & Relocatable Modular Building




Poly · The Sky Garden - Modular Detachable Sales Center

- Location: Fujian, China
- Project size: 294 square meter
- Function: Real Estate Sales Center

- Project Background: Adjacent to two arterial roads and surrounded by villages in the city
- Dilemma/Problem of traditional sales center:
  - Temporary Use vs. High Investment
  - Long waiting time

- Owner: Poly Developments and Holdings
- Design Company: HYP-ARCH Design Consultant
- Modular Service Provider: Unitised Green Prefab

- R&D Period: Oct 2017 - Oct 2019
- Fabrication: Start on Oct 5, 2019
- Transportation: Nov 12, 2019
- Onsite Construction: 5 days (Nov 14 - 18, 2019)

Photography by © Inter-mountain

https://www.archiscene.net/commercial/poly-·-futuristic-modular-boxes/

Interview with Liu Qidong

CEO of Unitised Green Prefab

优积科技
UNITISED GREEN PREFAB

Columbia University | CBIPS Research
Modular Construction Group
Mar 20, 2022

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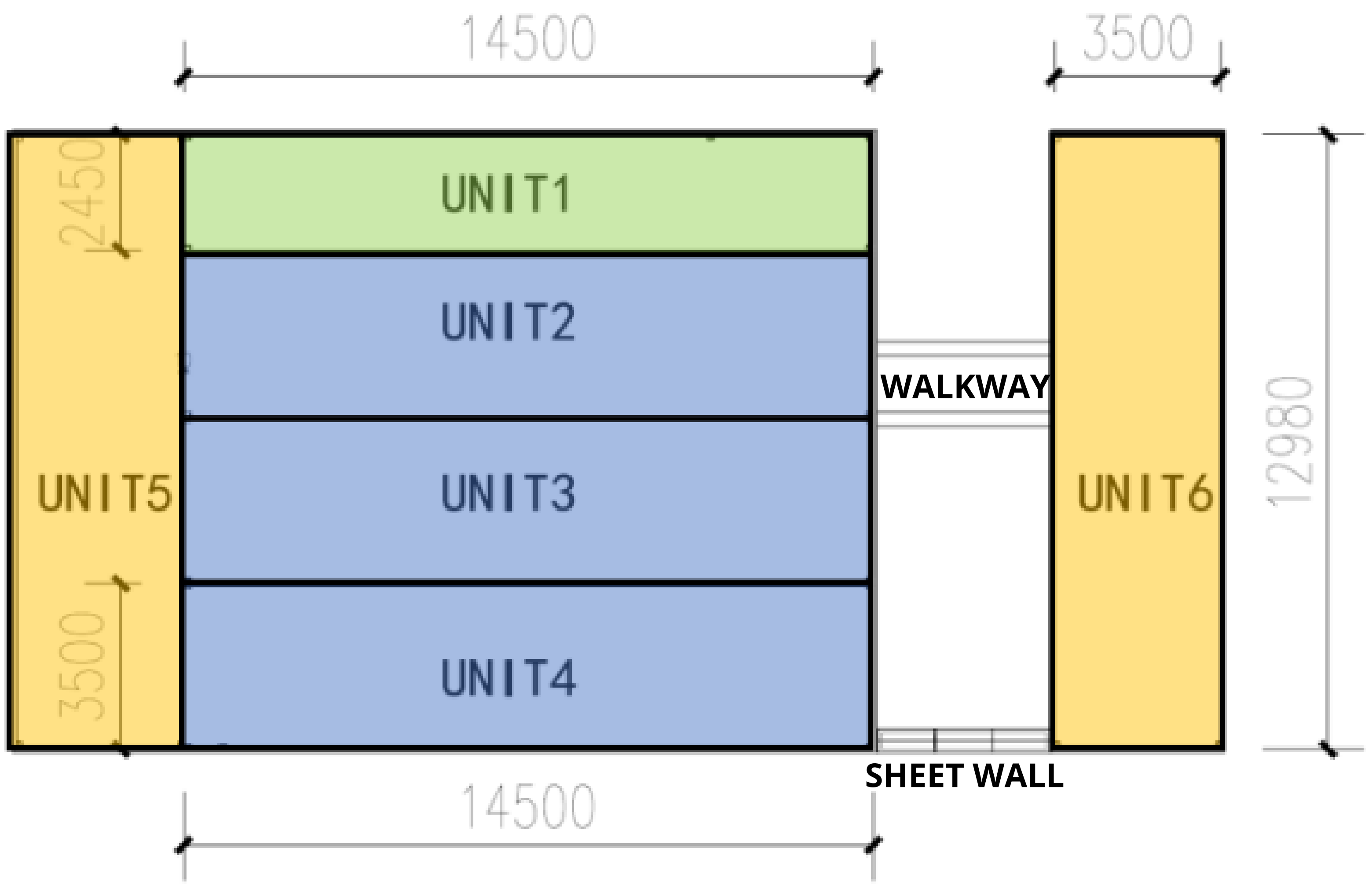
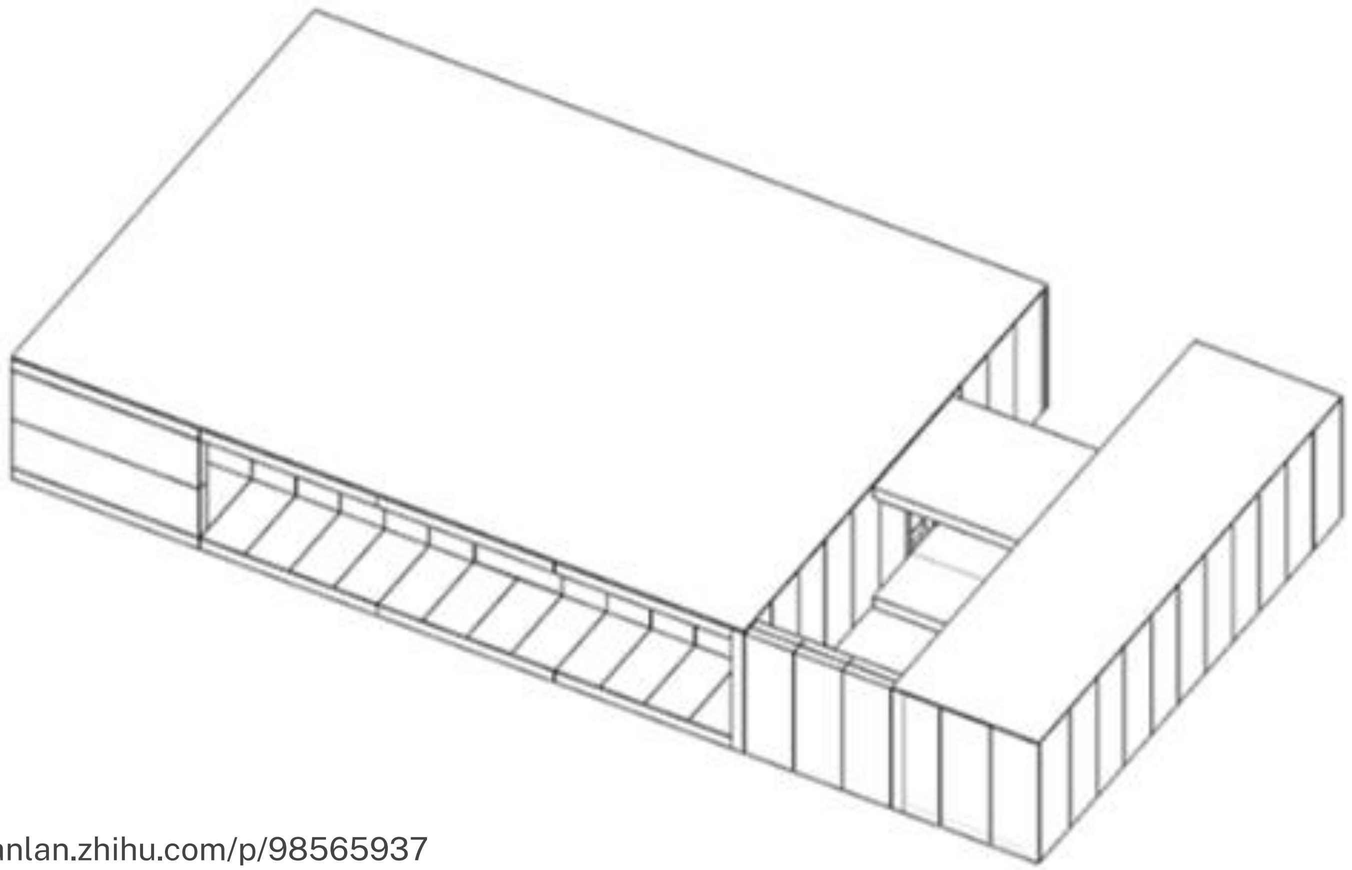
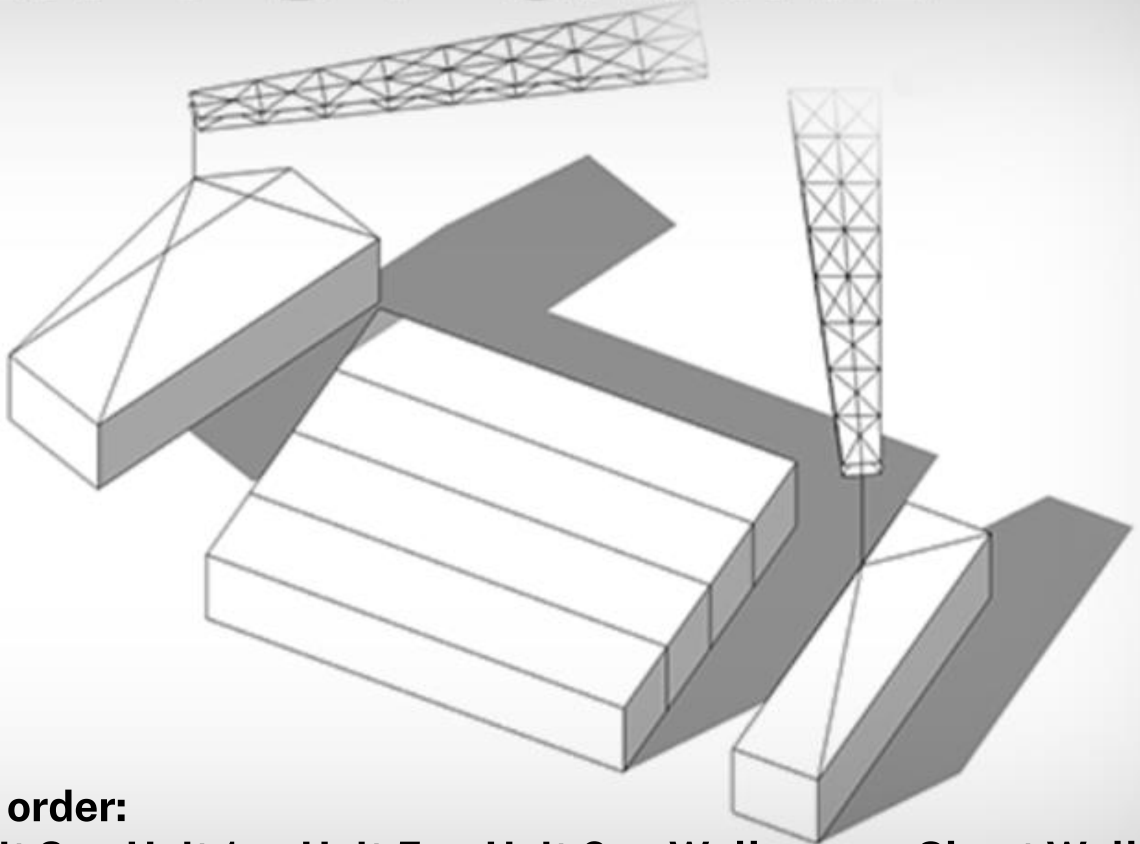




LIFT BY CRANE



Lifting and assembly order:
Unit 4 → Unit 3 → Unit 2 → Unit 1 → Unit 5 → Unit 6 → Walkway → Sheet Wall

https://zhuanlan.zhihu.com/p/98565937
https://www.archiscene.net/commercial/poly-·-futuristic-modular-boxes/
http://www.uedmagazine.net/ued_content_473_473_13583.html

Unitised Green Prefab - Crowne Plaza Hotel Extension at Singapore Changi Airport (Video)

Unitised Green Prefab - Manufacturing Conditions

- Factory Location
    - Preferred distance between the factory and the site < 300 km

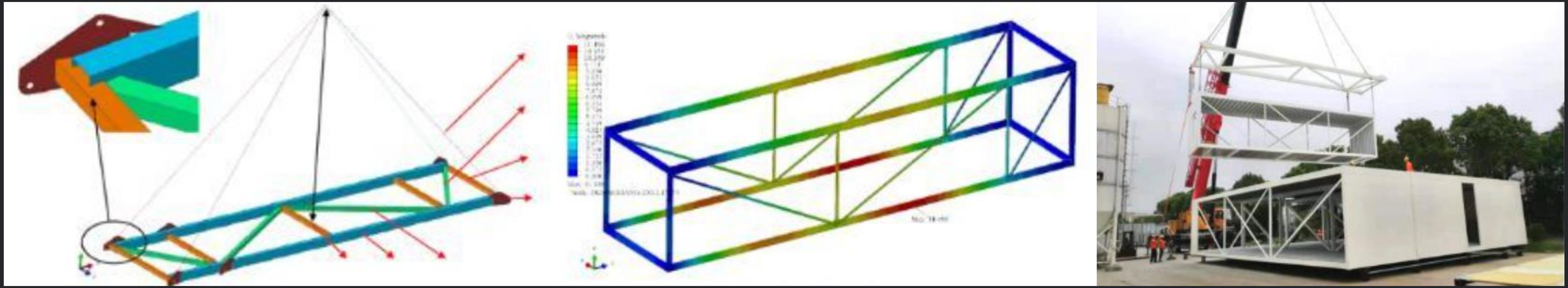
- Productivity
    - Singapore Crowne Plaza Hotel Extension Project - 4 finished modules per day (Shanghai, China | 2016)
    - 8 finished modules per day (Langfang, China | Present)

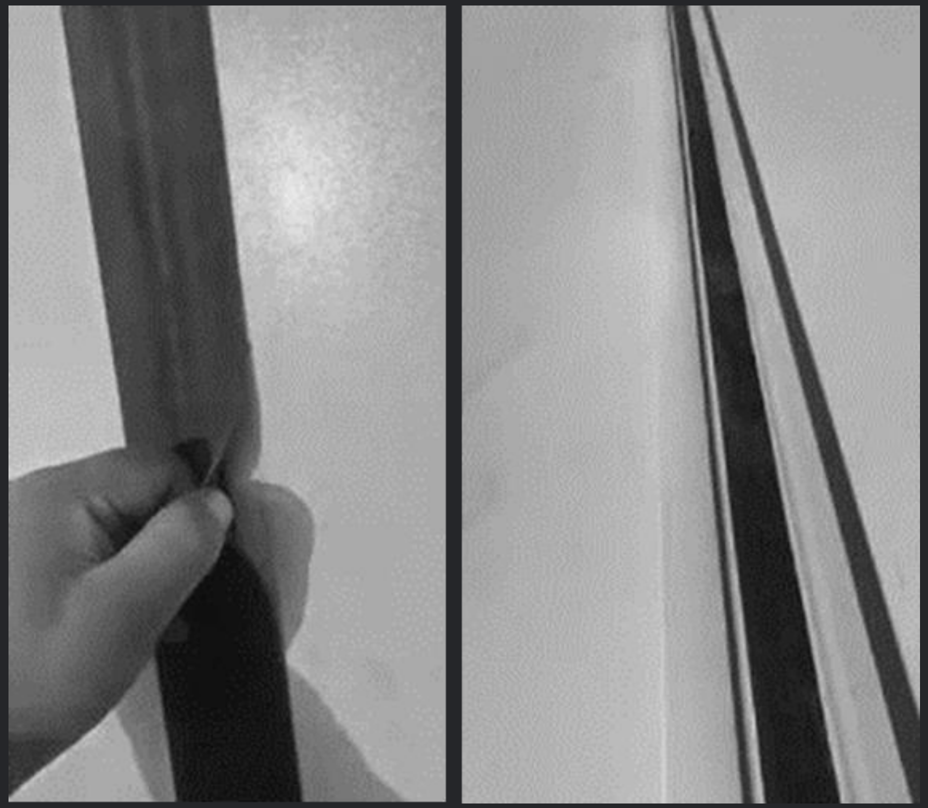
- Automatic Level
    - Unmanned production of steel structure and some components (Present)
    - Challenge: Full automation requires too much investment

Liu, Qidong. Personal interview. 20 Mar. 2022.

Poly · The Sky Garden - Modular Detachable Sales Center

- Spreader for Lifting





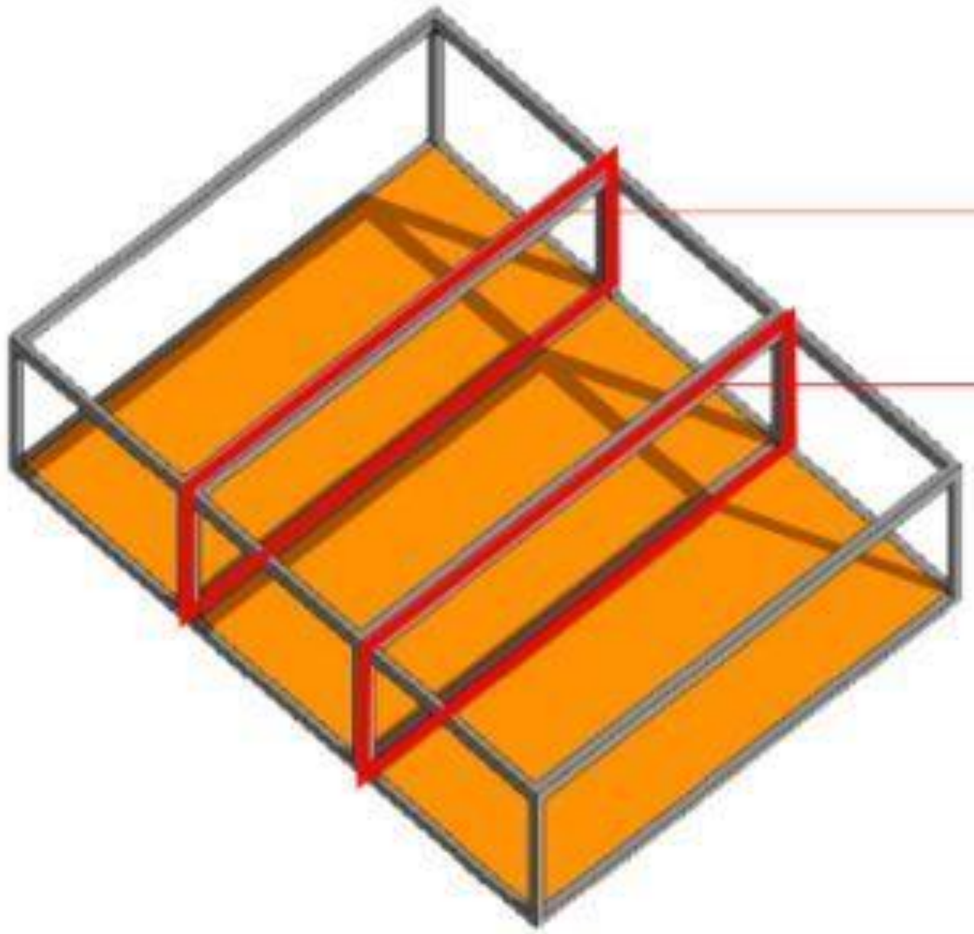
- Module Design & Installation
  - 10 mm Preserved between Modules as Expansion Joint
  - Waterproofing Membrane & Seal Strip Laying in Joints

- Foundation: 25-35mm Thick Plain Concrete Slab + Steel Pile

https://zhuanlan.zhihu.com/p/98565937

Poly · The Sky Garden - Modular Detachable Sales Center

- Detach Process



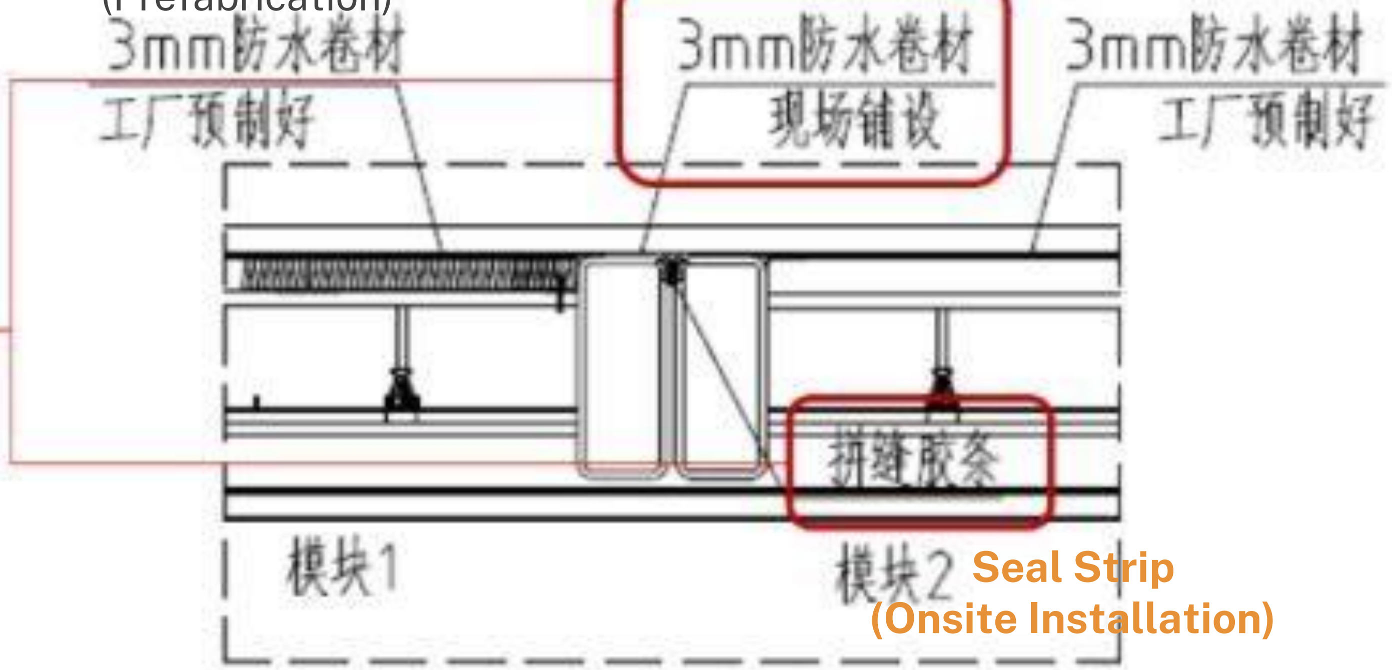
箱体拆装位置示意图

Disassembly and Assembly Positions

拼接现场需铺设防水卷材及拼缝胶条的位置，也是拆卸时需要拆除的部分，施工工艺简单，可以达到快速拆装的目的。

Simple and Rapid Processes

The location, at which the waterproofing membrane and the seal strip were required for connecting modules, is also the part that needs to be removed when disassembling.



拆装部分防水节点示意图

Disassembly Joints Plan

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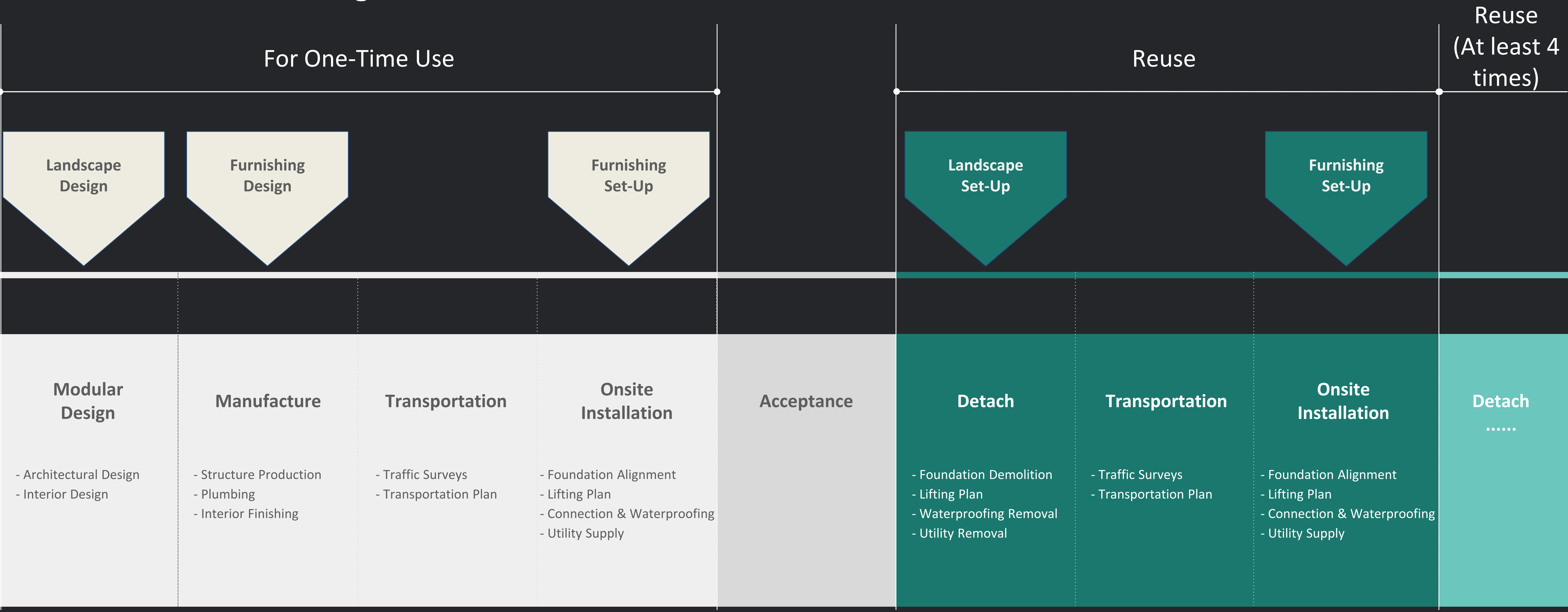
Poly · The Sky Garden - Modular Detachable Sales Center

- Reuse Processes Diagram



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Reversible & Relocatable Design Considerations

★ Convenience
★ Economy
★ Maintenance

- 5 mm Seam Reserved between Panels
  - Increase tolerance for dimensional errors
  - Reduce material wear during detachment

- Replaceable Outer Cover
  - Look completely new
  - Adaptable to different styles

- Lightweight and Less Deformable Material with High Assembly Rate
  - Make transportation easier
  - Reduce material loss when reusing

Replace Building Skin

Metal

Glass

Stone, Ceramic, Concrete Panel

Polycarbonate Panel

Plywood

Liu, Qidong. Personal interview. 20 Mar. 2022.

Cost Estimation of Modular Construction

05

01 Cost Estimation Process

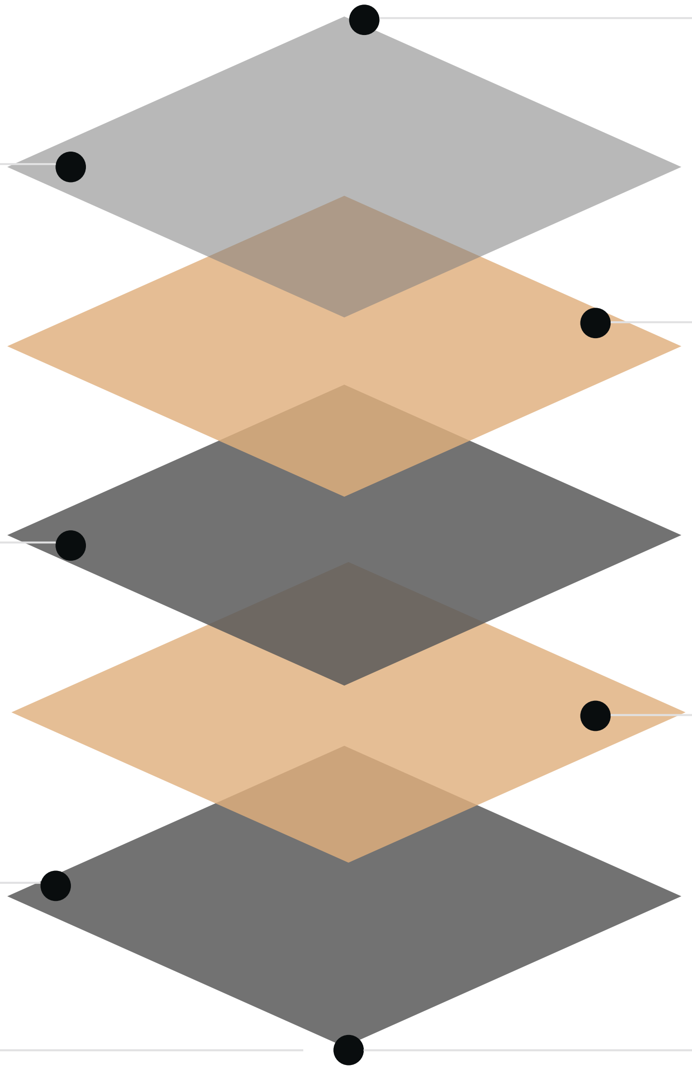
Step 1 : Customizing work items

Define a breakdown of representative work items which account for more than 95% of cumulative ratio of total project cost, when items listed in the order of high cost

**Add additional phase (Fabrication, Transportation and Installation)*

Step 2 : Selecting work items for fabrication

Determine modularization ratio of each work items according to criteria and objectives



Step 3 : Calculating weight of modules

Module weight(W_M)

$W_{PAUs} = W_{ET} + W_{SSU} + W_{PU}$

$W_{PARs} = W_{SSR} + W_{PR}$

Step 4 : Estimating Fabrication cost

Fabrication cost

$= W_M \times N_{\frac{MHr}{Ton} for\ Fab.} \times F_{L_{off-site}} \times F_{P_{off-site}} \times AR_{off-site}$

Step 5 : Estimating Transportation cost

Transportation cost

$= W_M \times Dis. \times N_{\$USD/(Km \cdot Ton)_{Trnas.}}$

Step 6 : Estimating Installation cost

Installation cost

$= W_M \times N_{MHr/Ton_{Inst.}} \times F_{P_{on-site}} \times AR_{on-site}$

Step 7 : Quantifying probability and impact of factors

Define Probability of occurrence and Impact of factors as probabilistic distribution

**Use Bernoulli distribution for probability and Triangular distribution for impact of factors*

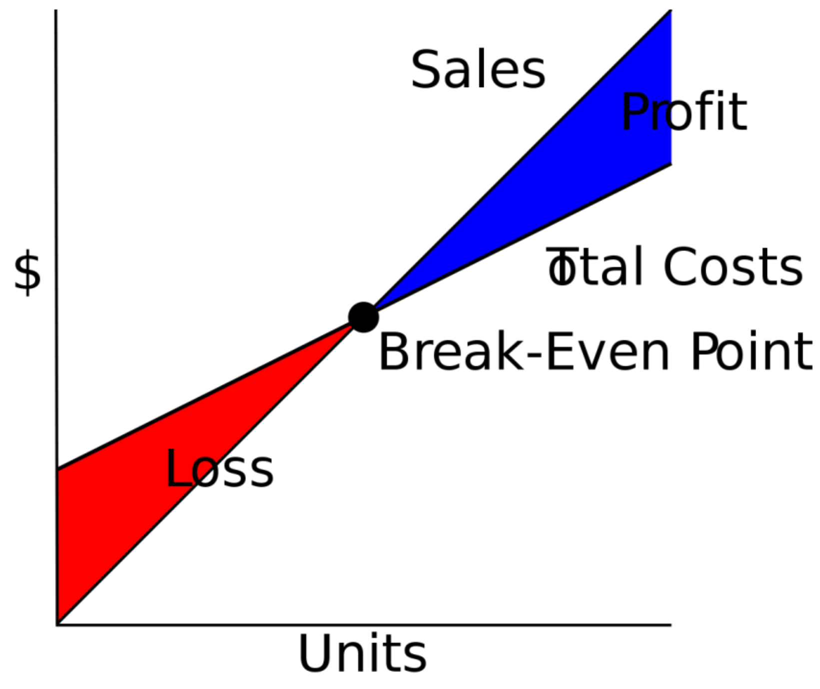
Step 8 : Using Monte-Carlo simulation

Project phase and Work items cost

$$= \sum_{i=1}^{n} C_i + \sum_{j=1}^{m} C_j \times 1 + (P_j \times I_j)$$

(Choi et,al., 2021)

02 Break-Even Point



Break Even Units Formula

$$\text{Break Even Units} = \frac{\text{Fixed Costs}}{\text{SP} - \text{VC}}$$

SP = Selling price per unit
VC = Variable cost per unit

Fixed Cost

- Factory (1 story 30000FT) $3,389,900
- Manufacturing Equipment(4) $5,400,000
- Land Preparation $1,250
- Maintenance $2,000
- Renting fee to store the onsite module $5,000
- Road Closure $10,000

Variable Cost

Work Item	Description	Conventional construction (UD$/S.F)	Modular construction (US$/S.F)
Project duration	–	20 months	16 months
Division 1.1	Indirect cost	$19.57	$13.21
Division 1.2	Construction equipment (crane and trucks)	$1.17	$5.38
Division 2	Earth working and	$7.55	$7.55
Division 4	Masonry	$5.4	$3.06
Division 5	Steel structure framing	$0.96	$26.44
Division 6	Millwork and carpentry	$9.97	$7.97
Division 7	Roofing and siding	$12.19	$14.62
Division 8	Doors and windows	$7.90	$6.79
Division 9	Interior finishes	$24.44	$21.77
Division 10	Specialties	$1.31	$1.12
Division 11	Equipment	$2.69	$2.23
Division 12	Furnishings	–	–
Division 13	General building items	–	–
Division 15	Mechanical systems	$26.31	$23.67
Division 16	Electrical systems	$13.69	$12.32
Division 17	Design fee	$11.79	$12.00
Total Cost/S.F		**$195.39/S.F**	**$173.31/S.F**

+

- Transportation $10.63

03 Calculation

Fixed Cost ($)		
Factory (1 story 30000SFT)	$ 338,9900.00	
Manufacturing Equipment (4)	$ 540,000.00	
Land Preparation	$ 1,250.00	
Maintenance	$ 2,000.00	
Renting fee to store the onsite modul	$ 5,000.00	
Road Closure	$ 1,000.00	
Total	**$ 3,939,159.00**	
Variable Cost ($/S.F.)		
Indirect cost	$ 13.21	
Construction Cost	$ 160.10	
Transportation	$ 10.63	
Total	**$ 183.94**	49,120,000
Selling Price	$ 200.00	
Break Even Point (SFT)	2425277.09	
Break Even Point (Unit/800SFT)	307	

Break Even Units Formula

$$\text{Break Even Units} = \frac{\text{Fixed Costs}}{\text{SP} - \text{VC}}$$

SP = Selling price per unit
VC = Variable cost per unit

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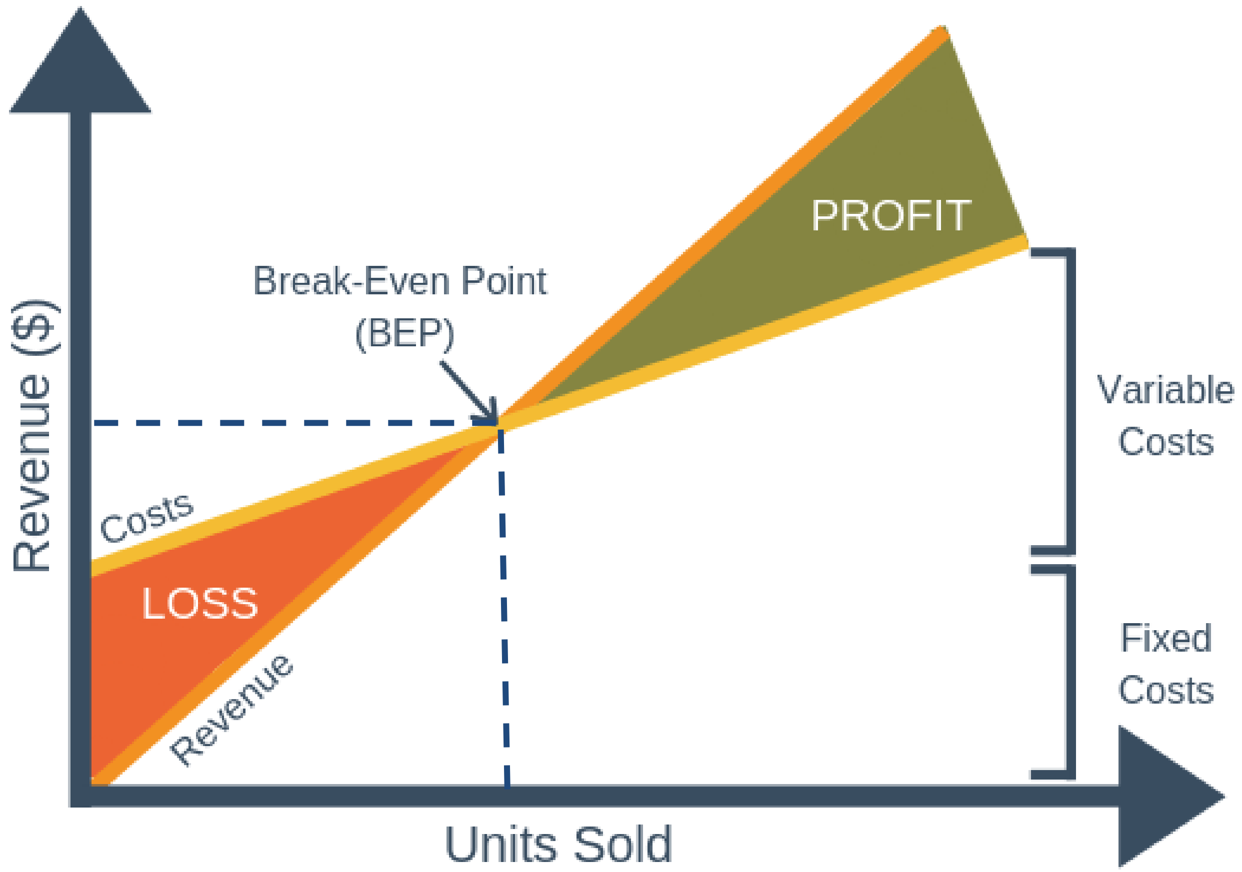
$$\text{BEP} = \frac{3{,}939{,}159}{200 - 183.94} = 2{,}425{,}277 = 307 \text{ Units}$$

Break-Even Analysis



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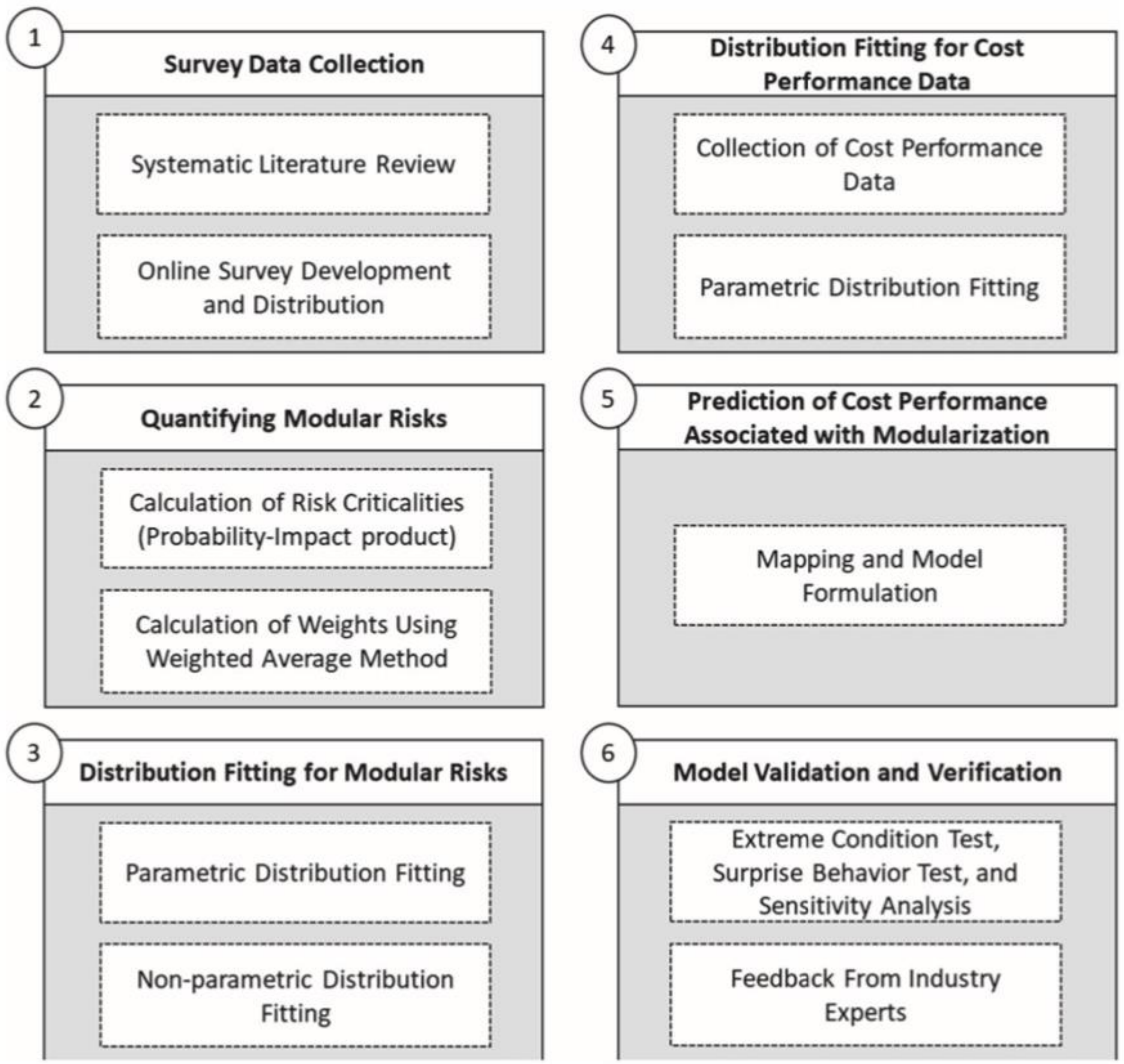
04 Risks Affecting Cost



(Nabi et,al., 2021)

Table 1. Modular risk factors

Risk ID	Description
R1	Increased onsite and offsite labor costs
R2	Increased overhead/site preliminary costs
R3	Poor supervision efficiency/costs
R4	Increased transportation costs
R5	High initial (capital) costs
R6	Increased installation and assembly costs
R7	Increased crane and equipment costs
R8	Increased design and engineering costs
R9	Increased cost of materials and modules
R10	Inconsistent cash-flow
R11	Inability to achieve economy of scale
R12	Poor construction activity sequencing/management
R13	Site disruptions and delays
R14	Inclement weather conditions
R15	Long transportation lead times
R16	Increased design and engineering lead times
R17	High shutdown times due to commissioning and testing
R18	Decreased capacity of quality control
R19	Inefficient quality assurance procedures at the manufacturing plant
R20	Rework
R21	Lack of experienced and capable manufacturers/suppliers
R22	Poor aesthetic quality
R23	Geometric variability of modules
R24	Safety accidents/injuries
R25	High workplace congestion
R26	High exposure to hazards
R27	Poor safety planning and communication
R28	Low onsite/offsite productivity
R29	Inability to incorporate modern technologies
R30	Limited capacity to handle and lift equipment
R31	Limited capacity of infrastructure and transportation mode
R32	Poor site attributes and logistics
R33	Shortage of stakeholders' experience
R34	Shortage of skilled and experienced laborers
R35	Incompliance with environmental standards/regulations
R36	High material consumption and waste
R37	Low energy efficiency
R38	Incompliance with green practices
R39	Low level of standardization
R40	Unanticipated field changes
R41	Late design changes
R42	Unsuitability of design for modularization
R43	Low repetitivity in design
R44	Challenges related to restricted tolerances and interfaces
R45	Lack of adequate collaboration and communication
R46	Cultural resistance to change and innovation
R47	Contractual risks and disputes
R48	Unsuitability of project delivery method
R49	Legal and regulatory challenges
R50	Issues related to project permitting

Table 6. Quantified characteristics of modular risks

	Likelihood of occurrence, L		Impact on cost, IC		Cost risk rating, RR_C		
ID	Mean	SD	Mean	SD	Mean	SD	Rank
R1	2.81	1.36	3.40	1.12	10.25	7.03	17
R2	3.29	1.01	2.79	1.09	9.88	5.92	23
R3	2.48	1.15	2.96	1.34	8.27	6.49	37
R4	3.50	1.15	3.44	1.07	12.63	6.58	6
R5	3.54	1.22	3.27	1.27	12.48	7.70	7
R6	2.85	1.20	3.04	1.11	9.38	6.02	30
R7	2.33	1.19	3.23	1.22	8.23	6.55	38
R8	2.98	1.26	2.88	1.31	9.88	7.02	22
R9	3.00	1.07	3.08	1.27	9.81	5.93	26
R10	2.96	1.32	3.17	1.15	10.31	6.97	15
R11	2.83	1.12	3.54	0.92	10.67	5.81	14
R12	3.13	1.14	3.54	1.13	11.88	6.48	10
R13	2.92	1.03	3.27	1.07	9.81	5.29	25
R14	2.81	1.39	3.23	1.24	10.17	7.52	19
R15	2.79	1.17	3.29	1.15	9.85	6.51	24
R16	3.23	1.24	2.98	1.18	10.13	6.51	20
R17	2.40	1.12	2.90	1.08	7.42	5.20	44
R18	2.25	1.14	2.96	1.35	7.52	5.88	42
R19	2.63	1.04	3.00	1.09	8.40	5.25	36
R20	2.58	0.96	3.48	1.20	9.60	5.92	27
R21	2.75	1.30	3.44	1.15	10.04	6.74	21
R22	2.69	1.06	2.77	1.13	8.17	5.22	39
R23	2.69	1.22	3.08	1.07	8.71	5.78	31
R24	2.35	1.23	3.02	1.47	8.02	6.84	40
R25	2.77	1.28	2.85	1.11	8.65	6.16	32
R26	2.19	1.14	2.38	1.21	6.29	6.12	48
R27	2.25	0.89	2.94	1.33	7.00	4.49	45
R28	2.73	1.05	3.27	1.12	9.52	5.66	28
R29	2.52	1.17	2.94	1.28	8.42	6.13	35
R30	2.17	1.04	3.17	1.15	7.52	5.20	43
R31	2.21	0.99	3.00	1.01	6.88	4.18	46
R32	3.75	0.93	3.46	1.11	13.60	6.58	3
R33	3.13	1.33	3.50	0.99	11.69	7.14	11
R34	3.50	1.15	3.92	1.01	14.50	7.11	1
R35	2.06	1.00	2.83	1.36	6.50	5.34	47
R36	2.44	1.11	2.96	1.13	7.79	5.41	41
R37	1.85	0.85	2.19	0.96	4.65	3.83	50
R38	2.15	1.01	2.35	1.02	5.29	3.68	49
R39	2.35	1.18	3.15	1.35	8.46	6.35	34
R40	3.00	1.17	3.58	1.11	11.13	6.25	12
R41	3.52	1.17	3.67	1.19	13.69	7.36	2
R42	3.33	1.31	3.75	1.10	13.17	7.46	4
R43	2.92	1.01	3.35	1.02	10.31	5.07	16
R44	3.15	0.99	3.63	1.08	12.00	6.34	9
R45	3.23	1.12	3.52	1.05	12.15	6.81	8
R46	3.15	1.30	3.06	1.28	10.92	7.51	13
R47	3.42	1.18	3.44	1.17	12.65	7.05	5
R48	2.58	1.03	3.08	1.13	8.60	5.52	33
R49	3.04	1.03	3.10	1.08	10.19	6.45	18
R50	2.98	1.12	2.92	1.09	9.44	6.43	29

Note: SD = standard deviation.

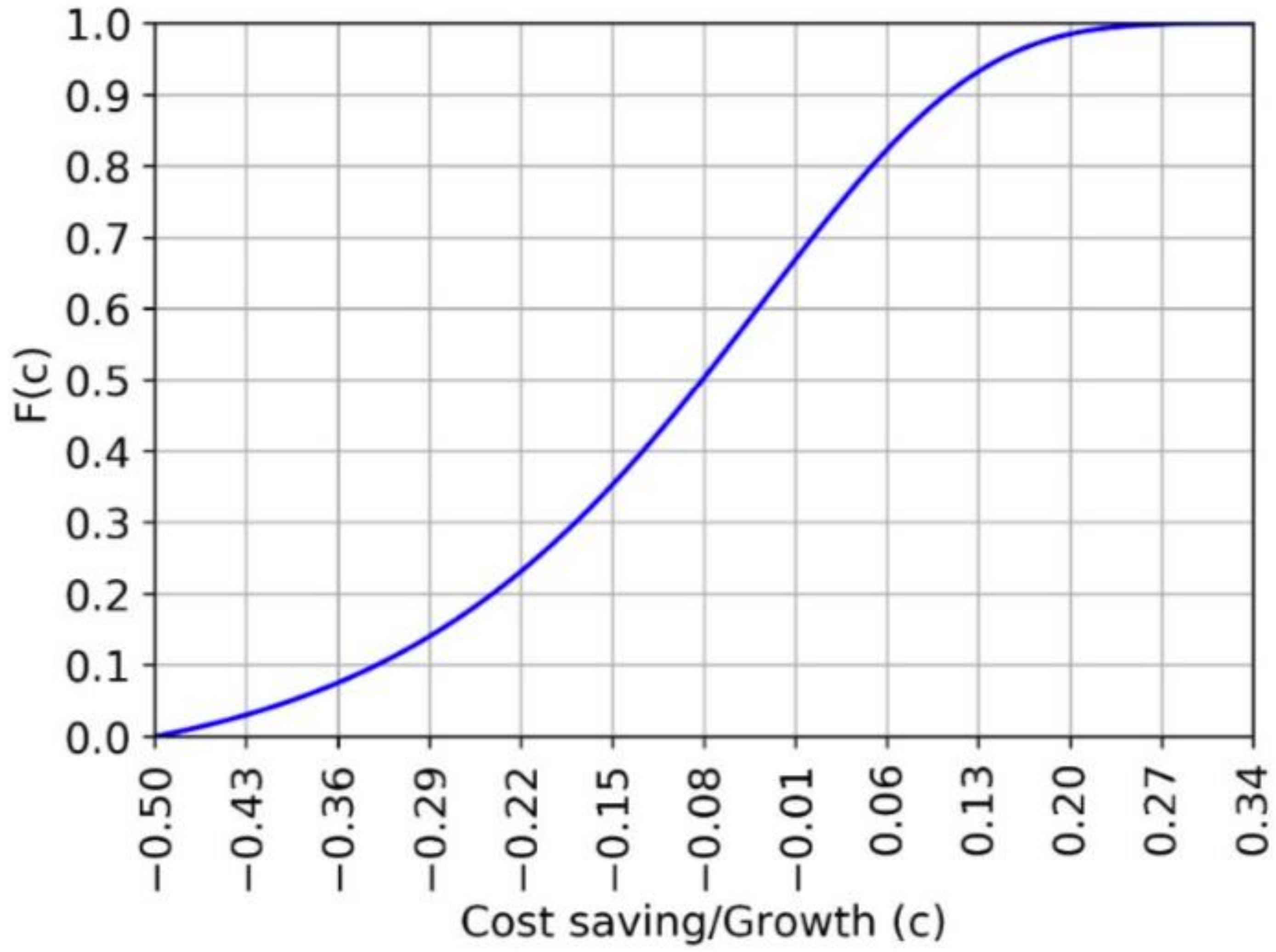
04 Risk Quantitive Analysis

$$\bar{F} = \sum_{i=1}^{50} W_i \times F_i(\mathrm{RR})$$

where Wi = weight of modular risk i;

Fi(RR) = value of fitted cumulative distribution function for modular risk i evaluated at point RR specified by the project team.

The cost saving or growth associated with the adoption of modularization in the project is retrieved such that F(c) = F ,where F(c) is the fitted distribution function for the cost performance data.



(Nabi et,al., 2021)

Major Problems Analyzed

- Shortage of skilled and experienced labors
- Increased Transportation
- Late design changes
- Poor site attributes and logistics
- Unsuitability of design for modularization
- Contractual risks and disputes.

Thank you!

Mar 23, 2022

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