CAE 465/526 Building Energy Conservation Technologies

Fall 2022

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Building Performance Metrics and Life-Cycle Analysis

Built Environment Research @ IIT

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PROJECT & EXAM

Project & Exam

- How was the first submission?

- Exam is next week:
  - Will be posted on Wednesday 11/02 at 6 am
  - Submit on Friday night, 11/04 at midnight

INTRODUCTION TO LIFE-CYCLE ASSESSMENT (LCA)

Intro to LCA

- Life-cycle analysis is ***defined*** as "*a methodology to evaluate the* environmental effects *associated with any given industrial activity from the initial gathering of raw materials from the earth until the point at which all residuals are returned to the earth*"

Environmental Solutions, 2005

Intro to LCA

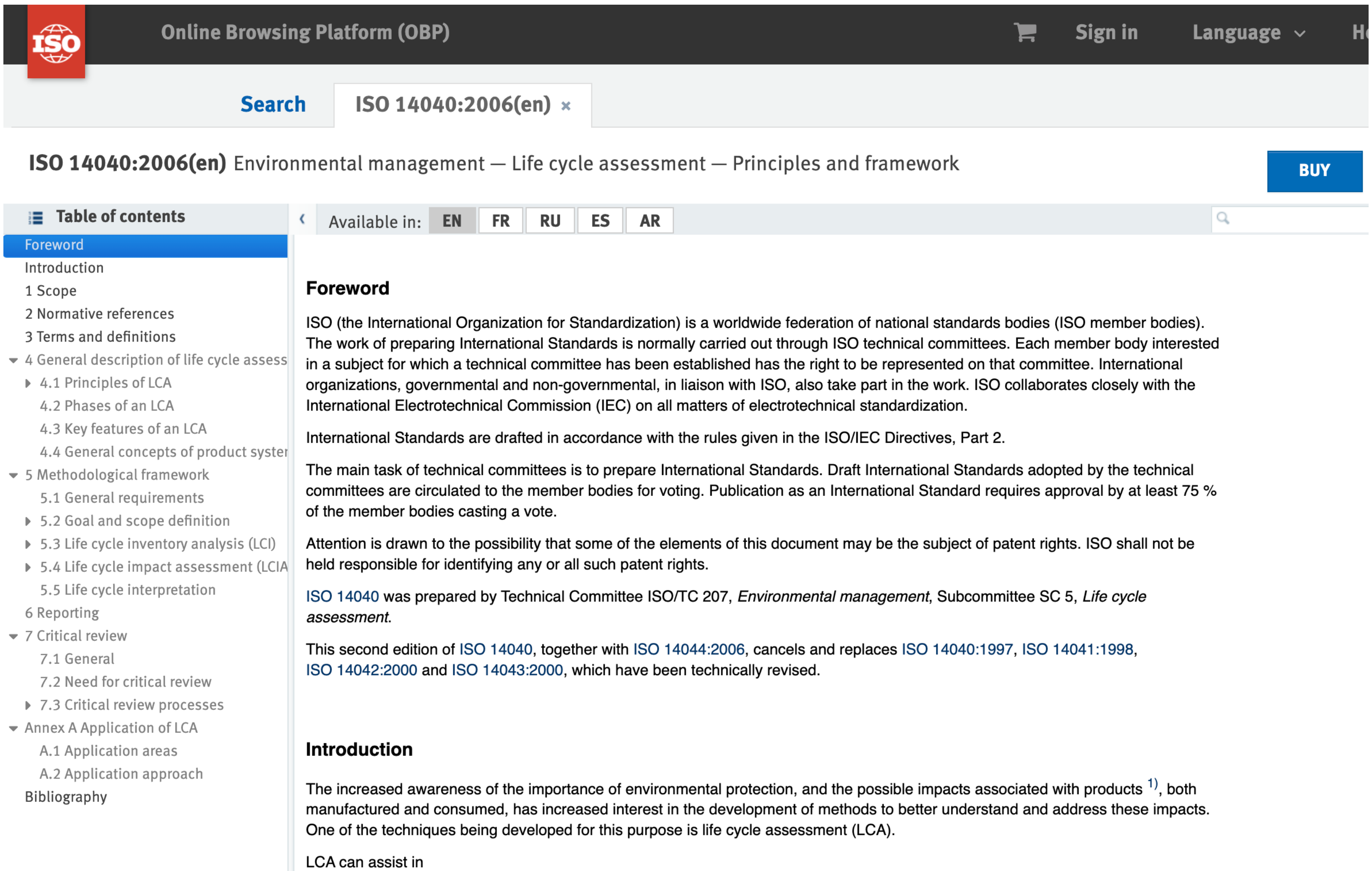
- LCA is known as:
  - ❑ Life-cycle assessment
  - ❑ Cradle-to-grave analysis

Intro to LCA

- In the context of buildings, the ***objectives*** are to:
  - Evaluate environmental burdens associated with a building
  - Assess the impact of the energy and materials used as well as wastes released to the environment
  - Identify and evaluate opportunities to affect environmental improvements

Intro to LCA

- Different standards exist (e.g., International Standards Organization (ISO))



Online Browsing Platform (OBP)   Sign in   Language

Search   ISO 14040:2006(en) ×

ISO 14040:2006(en) Environmental management — Life cycle assessment — Principles and framework   BUY

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Available in: EN FR RU ES AR

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 14040 was prepared by Technical Committee ISO/TC 207, *Environmental management*, Subcommittee SC 5, *Life cycle assessment*.

This second edition of ISO 14040, together with ISO 14044:2006, cancels and replaces ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000, which have been technically revised.

Introduction

The increased awareness of the importance of environmental protection, and the possible impacts associated with products [1)], both manufactured and consumed, has increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is life cycle assessment (LCA).

LCA can assist in

https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en

LCA PHASES

LCA Phases

- LCA usually has four phases of:
  - Goal and scope
  - Inventory analyses
  - Impact assessments
  - Interpretation

LCA Phases

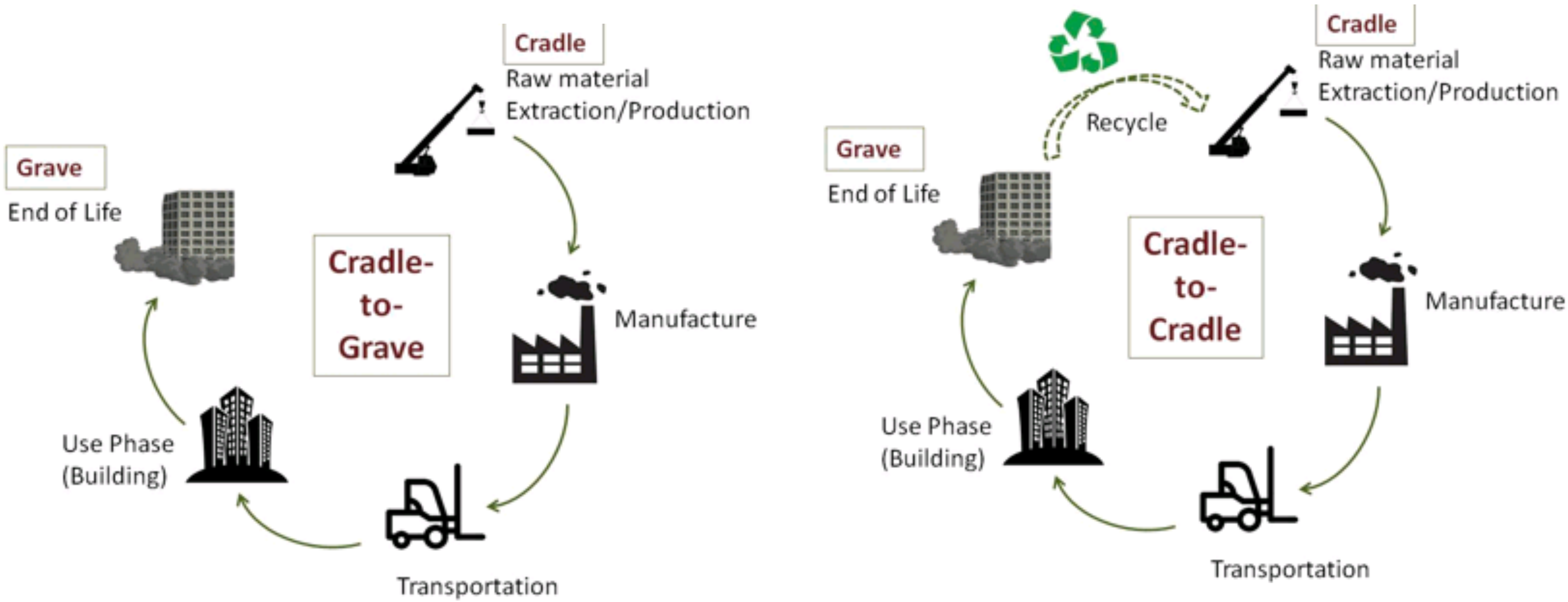
- The detailed description of the phases are:
  - Goal and scope definitions to identify purposes, audiences, and system boundaries
  - Inventory analyses known as LCI requires data collection and calculations to quantify materials and energy inputs and outputs of a building systems
  - Impact assessments phase evaluates the significance of potential impacts based on the LCI
  - Interpretation phase to evaluate findings and establish final conclusions and recommendations

LCA Phases

- In the context of buildings first the system boundaries need to be defined

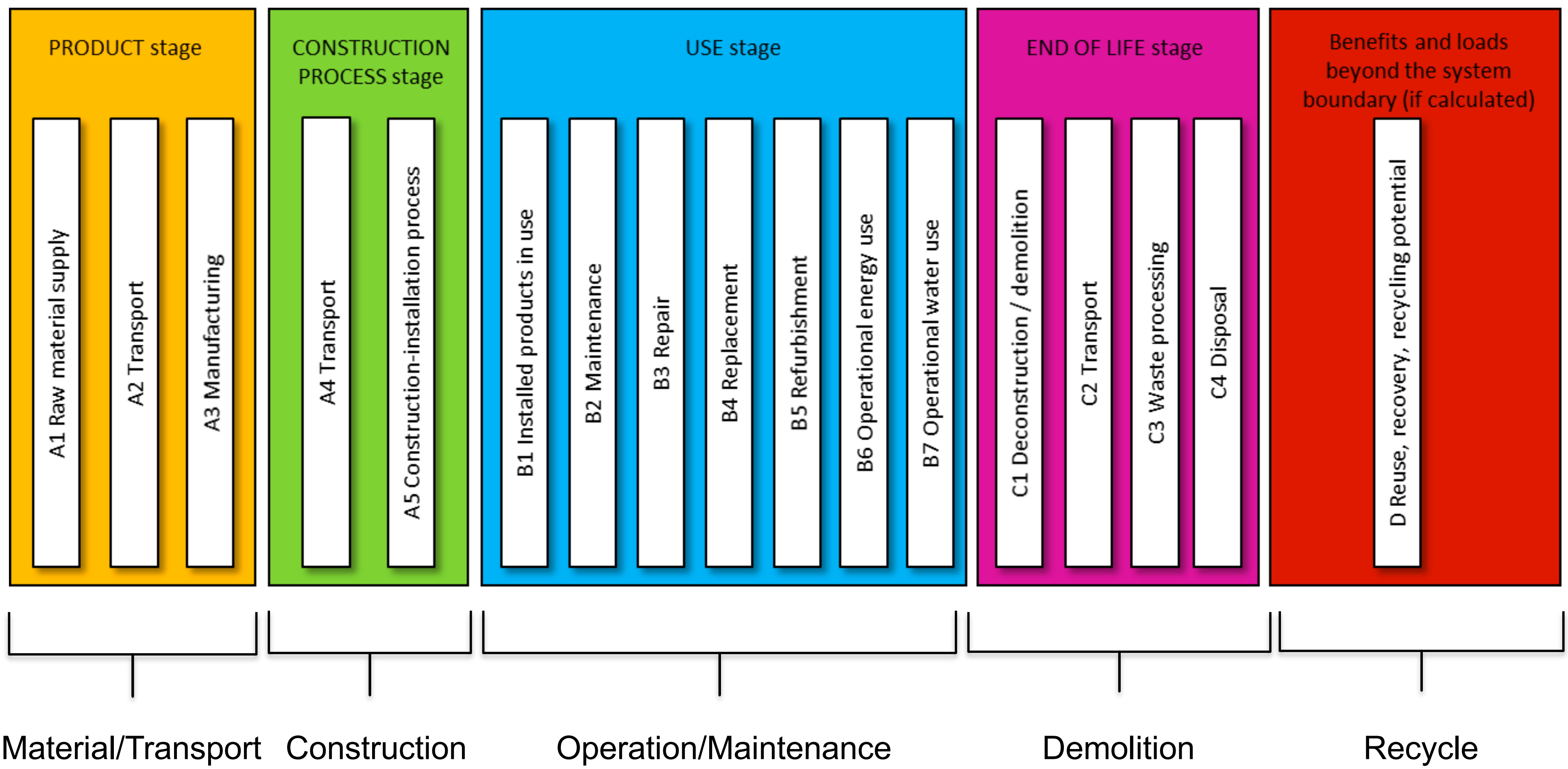
- Typical comprehensive building life-cycle assessment covers:
  - ❑ Material manufacture
  - ❑ Transportation
  - ❑ Construction
  - ❑ Operation
  - ❑ Maintenance
  - ❑ Demolition

LCA Phases



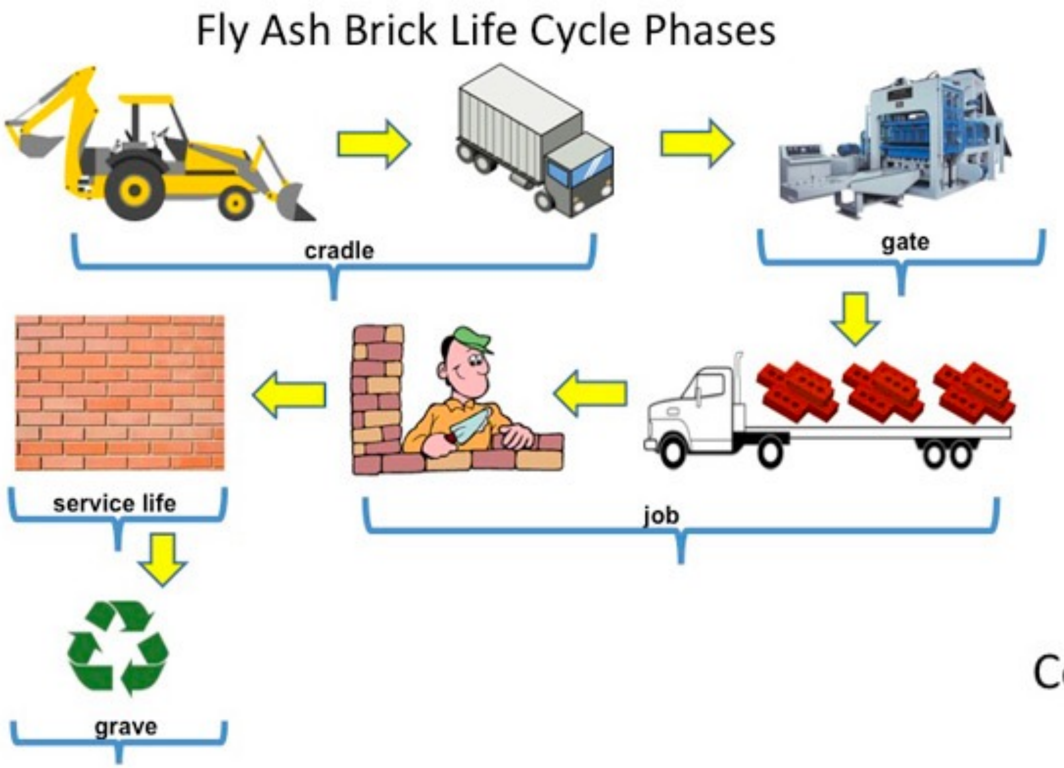
http://www.archecology.com/2017/05/31/life-cycle-assessment/

LCA Phases



https://www.branz.co.nz/cms_display.php?sn=415&st=1&pg=16913

LCA Phases



https://continuingeducation.bnpmedia.com/courses/calstar-products/life-cycle-assessment-of-building-products/5/

CLASS ACTIVITY

Class Activity

- We will do the actual class activity in the next lecture. Meanwhile, in the context of building retrofit, consider an energy efficiency measure and complete the phases

LCA REQUIREMENTS

LCA Requirements

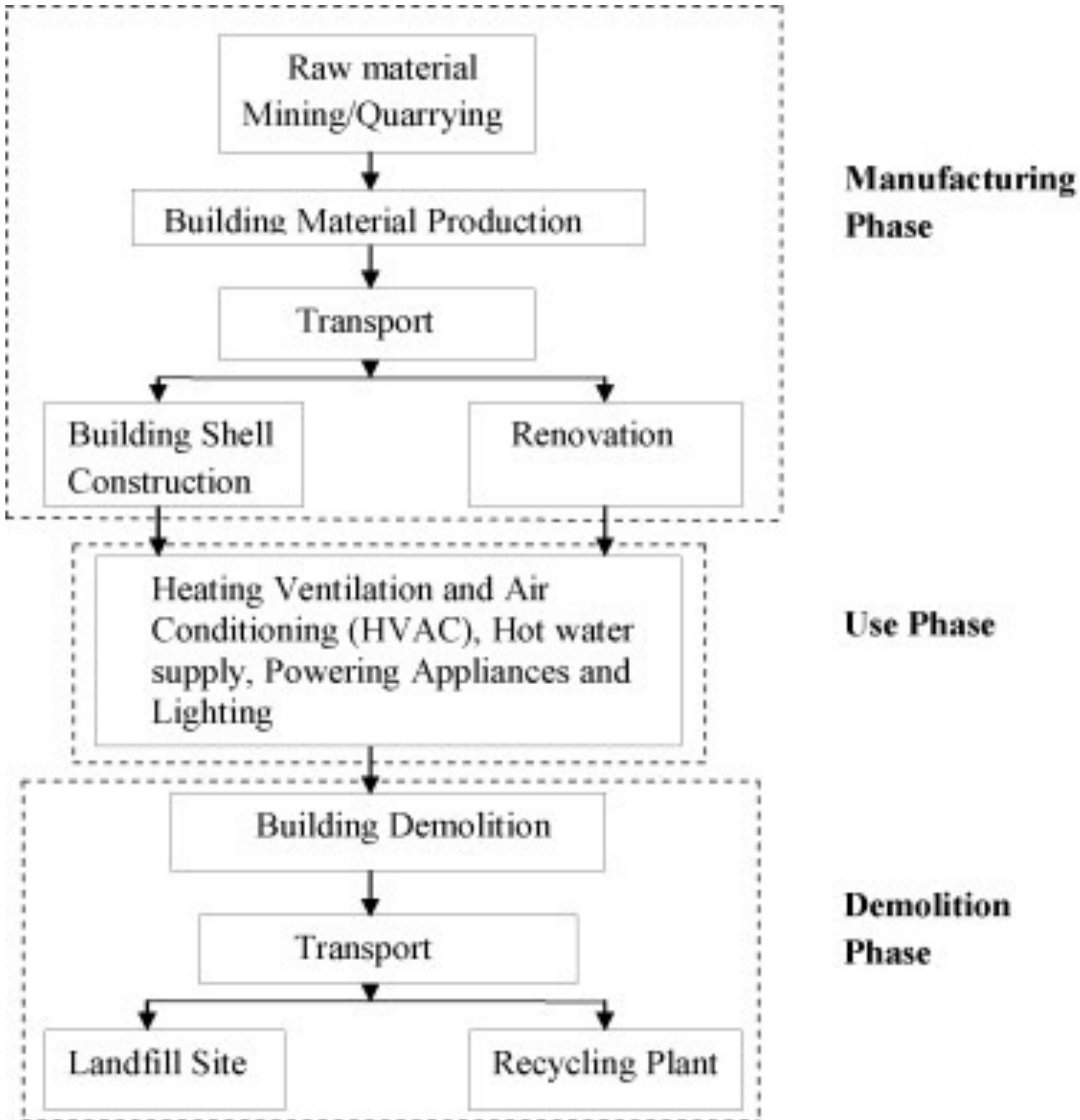
- Characteristics:
  - ❑ Heavy data requirements
  - ❑ Time-consuming and costly
  - ❑ Great flexibility in designing system boundaries
  - ❑ Flexibility in analysis objectives

LCA Requirements

- LCA analysis can cover different aspects such as:
  - Energy -> “Life-cycle energy analysis”
  - Cost -> “Life-cycle cost analysis”
  - Environmental impact -> “Life-cycle environmental impact analysis”

BUILDING LIFE-CYCLE ENERGY ANALYSIS

Building Life-Cycle Energy Analysis



Building Life-Cycle Energy Analysis

- Manufacture phase includes manufacturing and transportation of building materials and technical installations used in erection and renovation of the buildings:
  - ❑ Material extraction
  - ❑ Transportation to manufacturing plant
  - ❑ Manufacturing
  - ❑ Transportation of products
  - ❑ Installation and construction process

Building Life-Cycle Energy Analysis

- Operation phase encompasses all activities related to the use of the buildings, over its life span. These activities include maintaining comfort condition inside the buildings, water use and powering appliances:
  - Use
  - Maintenance
  - Repair
  - Replacement
  - Rehabilitation or retrofit
  - Energy consumption
  - Water consumption

Building Life-Cycle Energy Analysis

- Demolition phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants:
  - ❑ Destruction and demolition
  - ❑ Transportation
  - ❑ Reuse and recycling management
  - ❑ Final disposal

Manufacturing Phase

- Life-cycle energy (LCE) is defined as:

$$LCE = EE_i + EE_r + OE + DE$$

- ❑ EE_i: Initial embodied energy of the building
- ❑ EE_r: Recurring embodied energy of the building
- ❑ OE: Operating energy in the life span of the building
- ❑ DE: Demolition energy

Manufacturing Phase

- **Embodied energy** is defined as “the energy utilized during manufacturing phase of the building”

- Embodied energy is the energy content of all the materials used in the building and technical installations, and energy incurred at the time of erection/construction and renovation of the building:

  - ❑ Initial embodied energy
  - ❑ recurring embodied energy

Manufacturing Phase

- **Initial embodied energy** is the energy incurred for initial construction of the building:

$$EE_i = \sum m_i M_i + E_c$$

- ❑ EE_i: Initial embodied energy of the building
- ❑ m_i: Quantity of building material (i)
- ❑ M_i: Energy content of material (i) per unit quantity
- ❑ E_c: Energy used at site for erection/construction of the building

Manufacturing Phase

- **Recurring embodied energy** is defined as the sum of the energy embodied in the material, used in the rehabilitation and maintenance:

$$EE_r = \sum m_i M_i \left[\left(\frac{L_b}{L_{mi}} - 1\right)\right]$$

- ❑ EE_r: Recurring embodied energy of the building
- ❑ L_b: Life span of the building
- ❑ L_{mi}: Life span of the material (*i*)

Operation Phase

- **Operating energy** is the energy required for maintaining comfort conditions and day-to-day maintenance of the buildings. It includes:
  - ❑ HVAC
  - ❑ Domestic hot water
  - ❑ Lighting
  - ❑ Receptacles

Operation Phase

- **Operating energy** is defined as:

$$OE = E_{OA} L_b$$

- ❑ OE: Operating energy in the life span of the building
- ❑ E_{OA}: Annual operating energy
- ❑ L_b: Life span of the building

Demolition Phase

- **Demolition energy** is the energy at the end of buildings' service life, energy is required to demolish the building and transporting the waste material to landfill sites and/or recycling plants

$$DE = E_D + E_T$$

- DE: Demolition energy
- E_D: Energy incurred for destruction of the building
- E_T: Energy used for transporting the waste materials

Building Life-Cycle Energy Analysis

- Most of the case studies show:
  - ❑ Operating energy has major share (80–90%) in life cycle energy use of buildings
  - ❑ Embodied energy (10–20%)

Life cycle energy analysis of buildings: An overview. T. Ramesh, et al. Energy and Buildings, v42, 2010, 1592-1600.

LCA Tools

- For example, energy simulation tools, e.g. DesignBuilder and IES, have plugin for “One Click LCA” to prepare documents for:
  - ❑ BREEAM
  - ❑ LEED

	IESVE														One Click LCA				
	Location & Transport				Sustainable Sites			Energy & Atmosphere			Indoor Environmental Quality			Integrative Process	Life Cycle Assessment				
LEED Version	Surrounding Density & Diverse Uses	LT5	LT7	Green Vehicles	Open Space	Rainwater Mgmt	Heat Island Reduction	EAPreq2	EA2	EA6	Thermal Comfort	Daylight	Quality Views	Energy	MRc1	MRc2	MRc3	Pilot Credits*	Total Credits
LEED v4	4	5	1	1	1	3	3	18	3	2	1	3	1	1	5	2	2	2	58

http://www.iesve.com/software/breeam?utm_source=Integrated%20Environmental%20solutions&utm_medium=email&utm_campaign=10057284_OCL%20Faculty%20Follow%20Up%20for%20Bldg%20Sim%2C%20Nov%2018%2C%20CEN%20SOF&utm_content=breeam&dm_i=WN3,5ZK90,M743BC,NGRXW,1#bree

BUILDING LIFE-CYCLE ENVIRONMENTAL IMPACT ANALYSIS

Building Life Cycle Environmental Impact Analysis

- Life-cycle Environmental assessment:
  - ❑ Greenhouse effect or global warming, ozone depletion, acidification, eutrophication, photochemical smog.
  - ❑ Estimated using software (SIMAPRO, ECOBAT, LEGEP, BEES, ATHENA)

- Recommendation: select a database whose inventory of construction materials suits the reality of the area or region of the building

**Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment 44 (2009) 2510-2520.*

Building Life Cycle Environmental Impact Analysis

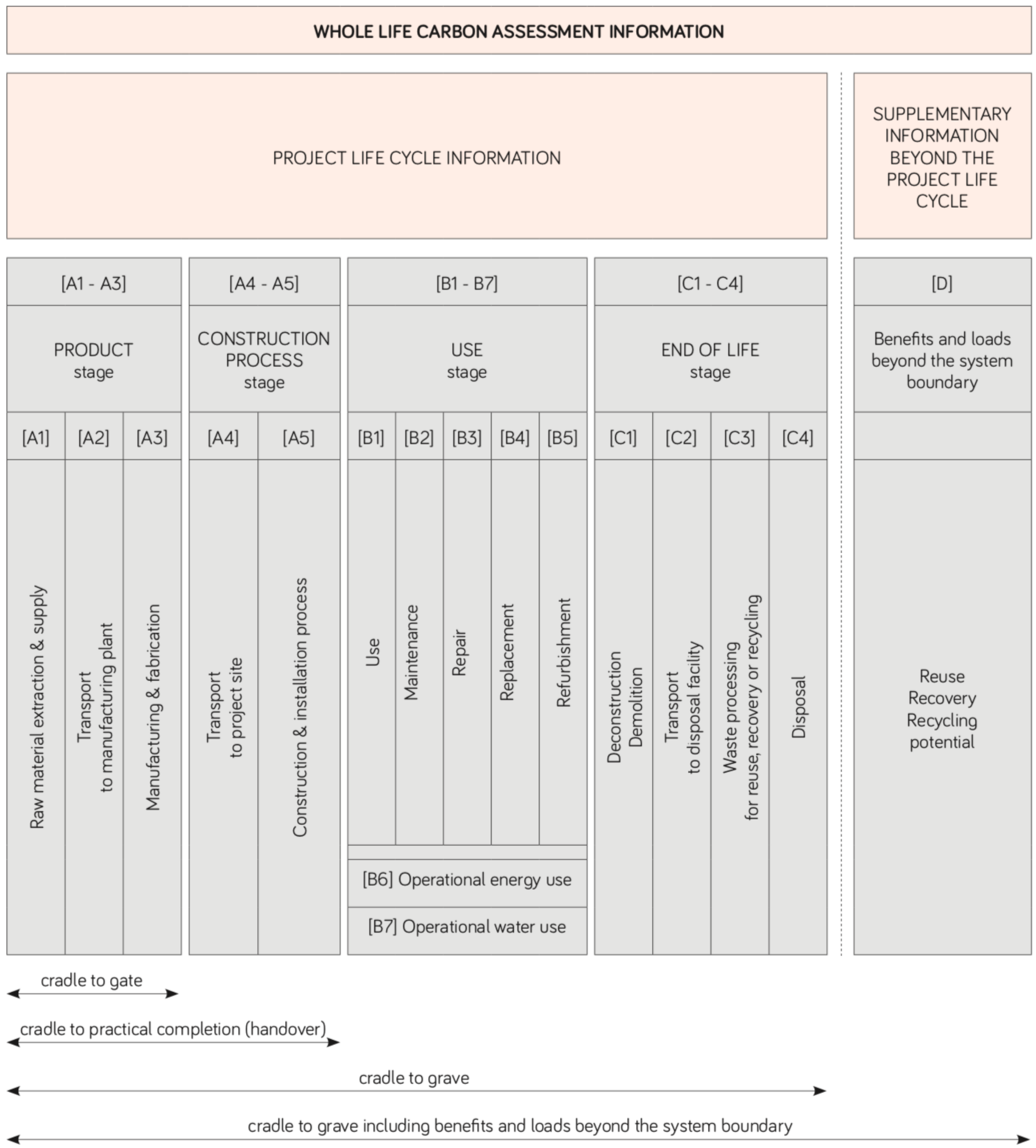
- Environmental impact categories estimated
  - ❑ Global warming potential (GWP)
  - ❑ Ozone depletion potential (ODP)
  - ❑ Acidification potential (AP)
  - ❑ Nitrification potential (NP)
  - ❑ Solid waste generation

Building Life Cycle Environmental Impact Analysis

- For example, UK government recommends three scopes
  - ❑ Scope 1 (Direct emissions)
    - Have direct control on the emission activity (e.g. owned boilers, vehicles, furnaces)
  - ❑ Scope 2 (Energy indirect)
    - Does not have direct control on the emission activity with the on-site facility but responsible for the purchase or consumption (e.g. purchased electricity, steam, heat)
  - ❑ Scope 3 (Other indirect)
    - Does not have direct control on the emission activity with the on-site facility and not within the Scope 2 responsibly (e.g. purchased materials)

Embodied and whole life carbon assessment for architects, RIBA, 2017

Building Life Cycle Environmental Impact Analysis



Embodied and whole life carbon assessment for architects, RIBA, 2017

BUILDING LIFE-CYCLE COST ANALYSIS (LCCA)

Building Life-Cycle Cost Analysis

- Similar to the building projects, there are different phases of in the calculation of LCCA:
  - ❑ Capital “initial” cost
  - ❑ Transportation cost
  - ❑ Fuel cost
  - ❑ Operational cost
  - ❑ Maintenance and repair cost
  - ❑ Demolition “resale or salvage” cost
  - ❑ Finance cost
  - ❑ Non-monetary cost (e.g. rebates, taxes)

One time

Recurring

One time

Recurring

Depends

Building Life-Cycle Cost Analysis

- What's the purpose of LCCA?

"Select viable alternatives that may have high initial costs but low operational and maintenance costs"

- Examples are:
  - ❑ Glazing
  - ❑ Efficient HVAC systems

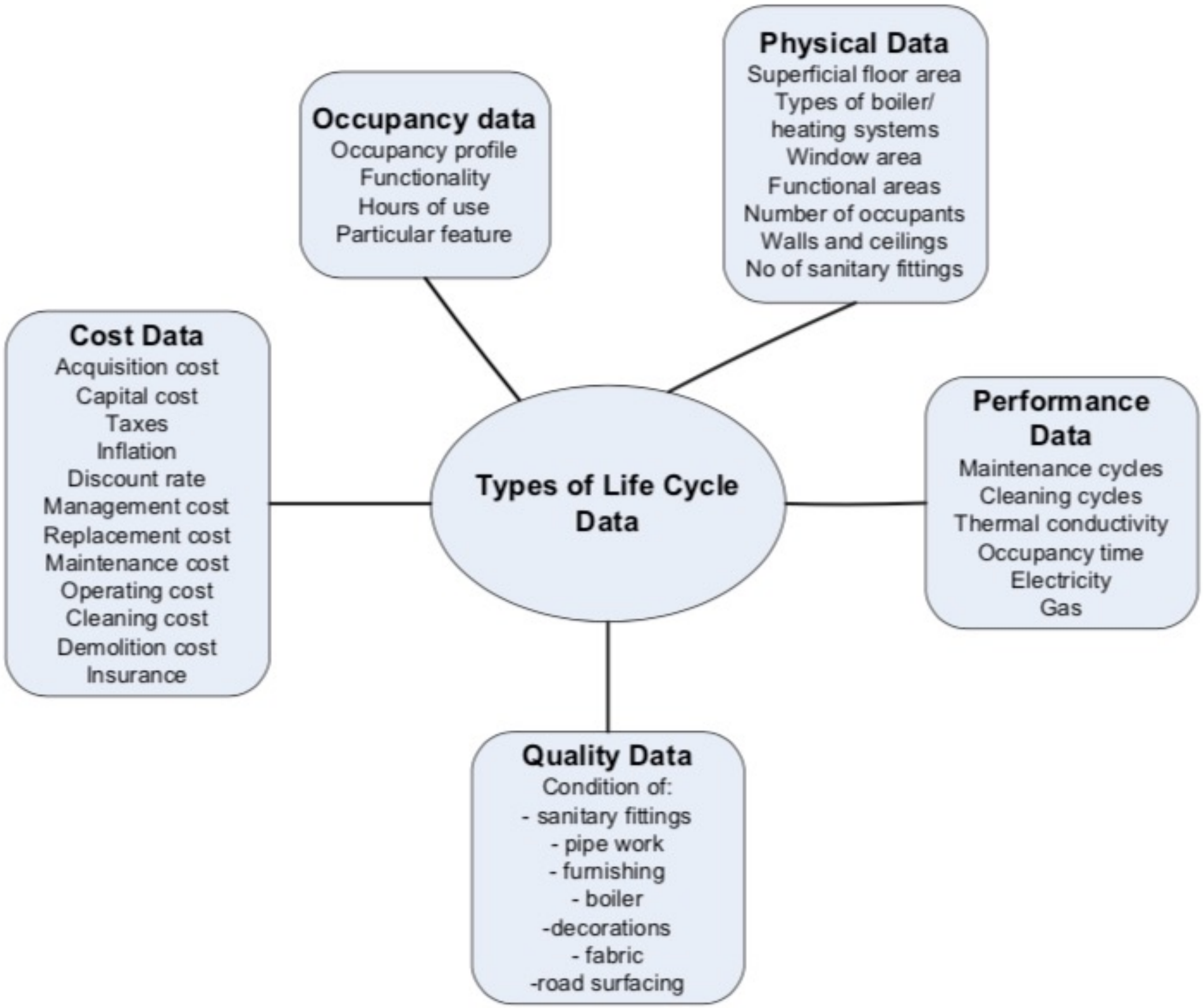
Building Life-Cycle Cost Analysis

- What are the examples of alternatives:
  - ❑ Different types of systems and components
  - ❑ Various efficiency
  - ❑ The choice of repair or replacement
  - ❑ Consideration of all alternatives

Building Life-Cycle Cost Analysis

- Why do we use LCCA?
  - ❑ Requirements of federal and states or private sectors
  - ❑ Evaluation of alternatives suggested by the ASHRAE Energy Codes
  - ❑ Beneficial for the calculation of Return of Investment (ROI)

Building Life-Cycle Cost Analysis



Energy Simulation and Life Cycle Costs, Estimation of a Building's Performance in the Early Design Phase

Building Life-Cycle Cost Analysis

- Steps for LCCA are:
  - ❑ Establish clear objectives (e.g., cost or IEQ)
  - ❑ Determine metrics (total cost or payback years)
  - ❑ Identify the base case and alternatives (alternatives may have different paybacks)
  - ❑ Gather cost data
  - ❑ Perform the analysis

Building Life-Cycle Cost Analysis Tools

- Early stage design construction costs should follow supported industry formats:
  - ❑ UNIFORMAT II (ASTM) mostly in the US and Canada
  - ❑ Levels 1 and 2 NRM1 (RICS) mostly in the UK

NISTIR 6389

NIST U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis

Robert P. Charette
Harold E. Marshall

https://arc-solutions.org/wp-content/uploads/2012/03/Charette-Marshall-1999-UNIFORMAT-II-Elemental-Classification....pdf

Capital Cost

- Capital costs for HVAC equipment more difficult than other mass-produced items. Special considerations:
  - Various size of equipment
  - Optimal design and cost

Capital Cost

- Capital cost is calculated as:

$$C = C_{ref}\left(\frac{S}{S_{ref}}\right)^{m}$$

- ❑ C: the cost at size S
- ❑ C_{ref}: the cost at a reference size S_{ref}
- ❑ m: the exponent varies between 0.5 – 1 (~0.6 recommended)
- ❑ This software is a good resource:
  http://www.hcbcentral.com/hcb/hcb.htm

Capital Cost

- It is important to consider the concept of "unit operations", meaning to group certain portions of a project.

- The components of unit operations are "unit assemblies" are itemized, priced, and plotted by size of unit operation. For example:
  - ❑ Unit Operation = Boiler
  - ❑ Unit Assemblies = Burner, air intake, flue, shut of valves, piping, fuel supply, expansion tank, water make up valves, deaerator

Fuel Cost

- Consider energy rates for
  - ❑ Electricity
  - ❑ Natural gas
  - ❑ Steam
  - ❑ Chilled water

Fuel Cost

- Type of rates for electricity
  - ❑ Flat rates
  - ❑ Tiered
  - ❑ Demand response
  - ❑ Time of Use (TOU)

Maintenance and Life Cost

- Examples of maintenance and operational costs:
  - Labor (e.g., technician to see the HVAC system)
  - Services
  - Supplies (e.g., air filter replacement)
  - Repair (e.g., repairs beyond warranty)

Maintenance and Life Cost

- Different sources are:
  - ❑ Building Owners, and Managers Association International (BOMA): https://www.boma.org/
  - ❑ RSMeans: https://www.rsmeans.com/
  - ❑ National Institute of Buildings Sciences: https://www.wbdg.org/design-objectives/cost-effective/utilize-cost-value-engineering
  - ❑ Open BIM Cost Estimator: http://open-bim-cost-estimator.en.cype.com/open_bim_cost_estimator_method_used.htm

Maintenance and Life Cost

Subsystem Categories		Average Life Cycle
1a.	Roofing – Tile	80 years
1b.	Roofing – Metal, Concrete	50 years
1c.	Roofing – Membrane, Built-up, Shingle, Bitumen, Foam	20 years
2a.	Building Exteriors, Doors, and Windows (Hard)	80 years
2b.	Building Exteriors (Soft)	20 years
3.	Elevators and Conveying Systems	25 years
4.	HVAC – Equipment and Controls	20 years
5.	HVAC – Distribution Systems	40 years
6.	Electrical Equipment	30 years
7.	Plumbing Fixtures	30 years
8.	Plumbing – Rough-in	50 years
9.	Fire Protection Systems	40 years
10.	Fire Detection Systems	20 years
11.	Built-in Specialties and Equipment	25 years
12.	Interior Finishes	15 years

Maintenance and Life Cost

- Examples of life expectancies are:

Equipment Type	Median Service Life (Years)
DX air distribution equipment	>24
Chillers, centrifugal	>25
Cooling towers	>22
Gas hot water boiler, steel	>22
Pneumatic electronic controls	>7
Portable electric hot water heaters	>21

Heating and cooling of buildings book

Building Life Cycle Cost Analysis Example

ASHRAE Owning and Operating Cost Database
Equipment Life/Maintenance Cost Survey
ASHRAE Research Project 1237-TRP

- **Database Main Page**
  - Project Summary
  - Preferences
- **Model Your Building**
- **Service Life Data**
  - by System Type
- **Maintenance Cost Data**
  - by All Options
  - by Region
  - by State
  - by BOMA Class
  - by Function
  - by Size
- **HVAC Equipment List**
- **Related Documentation**
- **Download Database**
- **Submit HVAC Data**

ASHRAE: Service Life and Maintenance Cost Database

The purpose of this database is to provide current information on service life and maintenance costs of typical HVAC equipment. Engineers depend on accurate owning and operating data to make decisions involving the life cycle and functionality of buildings. However, lack of sufficient up-to-date data makes it difficult to provide a solid basis for those decisions. Previous efforts to collect data through traditional survey methods have produced less than acceptable results.

See more details of goals of this project here: here

Main Features:

- **Equipment Service Life Evaluation** (here): Creates both lists and summaries of service life data customized to match specific criteria.
- **HVAC Maintenance Cost Evaluation** (here): Creates both lists and summaries of maintenance data customized to match specific criteria.
- **Submit HVAC Data** (here): The database is open for public data submissions. Registration is required.

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www.ashrae.org/database

Building Life Cycle Cost Analysis Example

- ASHRAE data is collected through RP-1237:

Air Distribution Equipment	Total	Currently in Service							Replaced						
		No. of Units	Equipment Age (years)						No. of Units	Age at Removal (years)					
			Mean	Median	Std Dev	95% C.I.	Maximum	Minimum		Mean	Median	Std Dev	95% C.I.	Maximum	Minimum
Air handling unit, constant volume	209	182	22	20	10.3	1.5	43	3	27	47	52	8.0	3.0	52	26
Air handling unit, dual duct	15	5	34	34	7.4	6.5	42	22	10	27	27	0.5	0.3	27	26
Air handling unit, multizone	208	178	20	20	5.9	0.9	31	3	30	64	64	0.0	n/a	64	64
Air handling unit, variable air volume	831	819	17	18	6.2	0.4	35	0	12	18	19	2.7	1.5	20	12
Air handling unit, variable volume, variable temperature	61	61	16	17	9.0	2.2	31	1	0	n/a	n/a	n/a	n/a	n/a	n/a
Fan coil unit	2452	1252	6	5	3.8	0.2	25	3	1200	52	52	0.0	n/a	52	52
Heat pump, air-to-air	161	25	16	17	3.4	1.3	17	0	136	12	12	0.4	0.1	17	12
Heat pump, water-source	1234	1129	17	18	6.0	0.4	24	1	105	17	17	0.2	0.0	17	16
Packaged DX unit, air-cooled	32	32	12	14	5.9	2.0	24	3	0	n/a	n/a	n/a	n/a	n/a	n/a
Packaged DX unit, rooftop	164	131	11	9	6.6	1.1	22	0	33	21	20	2.8	0.9	27	14
Packaged DX unit, water-cooled	187	177	14	17	9.0	1.3	32	1	10	22	22	0.0	n/a	22	22
Split DX system	129	129	16	16	1.1	0.2	21	12	0	n/a	n/a	n/a	n/a	n/a	n/a
Total	**5683**	**4120**	**14**	**16**	**5.9**	**0.2**	**43**	**0**	**1563**	**45**	**52**	**1.1**	**0.1**	**64**	**12**
AHUs Total	**1324**	**1245**	**18**	**18**	**7.0**	**0.4**	**43**	**0**	**79**	**46**	**52**	**4.7**	**1.0**	**64**	**12**
DX Units Total	**1907**	**1623**	**16**	**18**	**6.2**	**0.3**	**32**	**0**	**284**	**15**	**17**	**1.0**	**0.1**	**27**	**12**

Building Life Cycle Cost Analysis Example

- ASHRAE data is collected through RP-1237:

Cooling Equipment	Total	Currently in Service							Replaced						
		No. of Units	Equipment Age (years)						No. of Units	Age at Removal (years)					
			Mean	Median	Std Dev	95% C.I.	Maximum	Minimum		Mean	Median	Std Dev	95% C.I.	Maximum	Minimum
Chiller, absorption, indirect-fired, single-stage	6	6	35	35	0.0	n/a	35	35	0	n/a	n/a	n/a	n/a	n/a	n/a
Chiller, air-cooled reciprocating	9	8	6	7	4.2	2.9	15	1	1	11	11	n/a	n/a	11	11
Chiller, air-cooled rotary (screw)	8	8	8	5	9.4	6.5	29	2	0	n/a	n/a	n/a	n/a	n/a	n/a
Chiller, centrifugal	234	200	15	17	7.7	1.1	35	0	34	28	27	4.3	1.4	52	7
Chiller, water-cooled reciprocating	7	7	18	14	10.9	8.1	32	3	0	n/a	n/a	n/a	n/a	n/a	n/a
Chiller, water-cooled rotary (screw)	7	5	9	13	5.5	4.8	13	3	2	23	23	4.8	6.6	23	23
Total	**271**	**234**	**15**	**16**	**7.6**	**1.0**	**35**	**0**	**37**	**27**	**25**	**4.2**	**1.3**	**52**	**7**
Centrifugal Chiller Total	**234**	**200**	**15**	**17**	**7.7**	**1.1**	**35**	**0**	**34**	**28**	**27**	**4.3**	**1.4**	**52**	**7**

Building Life Cycle Cost Analysis Example

- ASHRAE data is collected through RP-1237:

	Total	Currently in Service							Replaced						
		No. of Units	Equipment Age (years)						No. of Units	Age at Removal (years)					
			Mean	Median	Std Dev	95% C.I.	Maximum	Minimum		Mean	Median	Std Dev	95% C.I.	Maximum	Minimum
Boiler, electric hot water	4	4	16	19	7.6	7.5	22	5	0	n/a	n/a	n/a	n/a	n/a	n/a
Boiler, cast iron	18	12	23	22	9.3	5.3	32	1	6	33	34	1.0	0.8	34	31
Boiler, steel fire-tube, forced draft, hot water	18	10	11	9	6.8	4.2	20	4	8	14	10	6.1	4.2	25	10
Boiler, steel fire-tube, forced draft, steam	10	10	34	35	8.5	5.2	43	20	0	n/a	n/a	n/a	n/a	n/a	n/a
Boiler, steel fire-tube, natural draft, hot water	12	11	14	14	4.0	2.4	21	9	1	15	15	n/a	n/a	15	15
Boiler, steel water-tube, forced draft, hot water	27	24	12	3	14.0	5.6	42	1	3	18	16	0.9	1.0	21	16
Boiler, steel water-tube, forced draft, steam	3	3	34	35	1.2	1.3	35	33	0	n/a	n/a	n/a	n/a	n/a	n/a
Boiler, steel water-tube, natural draft, hot water	47	35	13	15	11.2	3.7	37	0	12	17	17	2.9	1.6	23	11
Total	**139**	**109**	**17**	**17**	**10.2**	**1.9**	**43**	**0**	**30**	**19**	**17**	**4.7**	**1.7**	**34**	**10**
Steel Gas-Fired Boilers Total	**117**	**93**	**16**	**15**	**10.4**	**2.1**	**43**	**0**	**24**	**16**	**16**	**5.2**	**2.1**	**25**	**10**

PRESENT VALUE

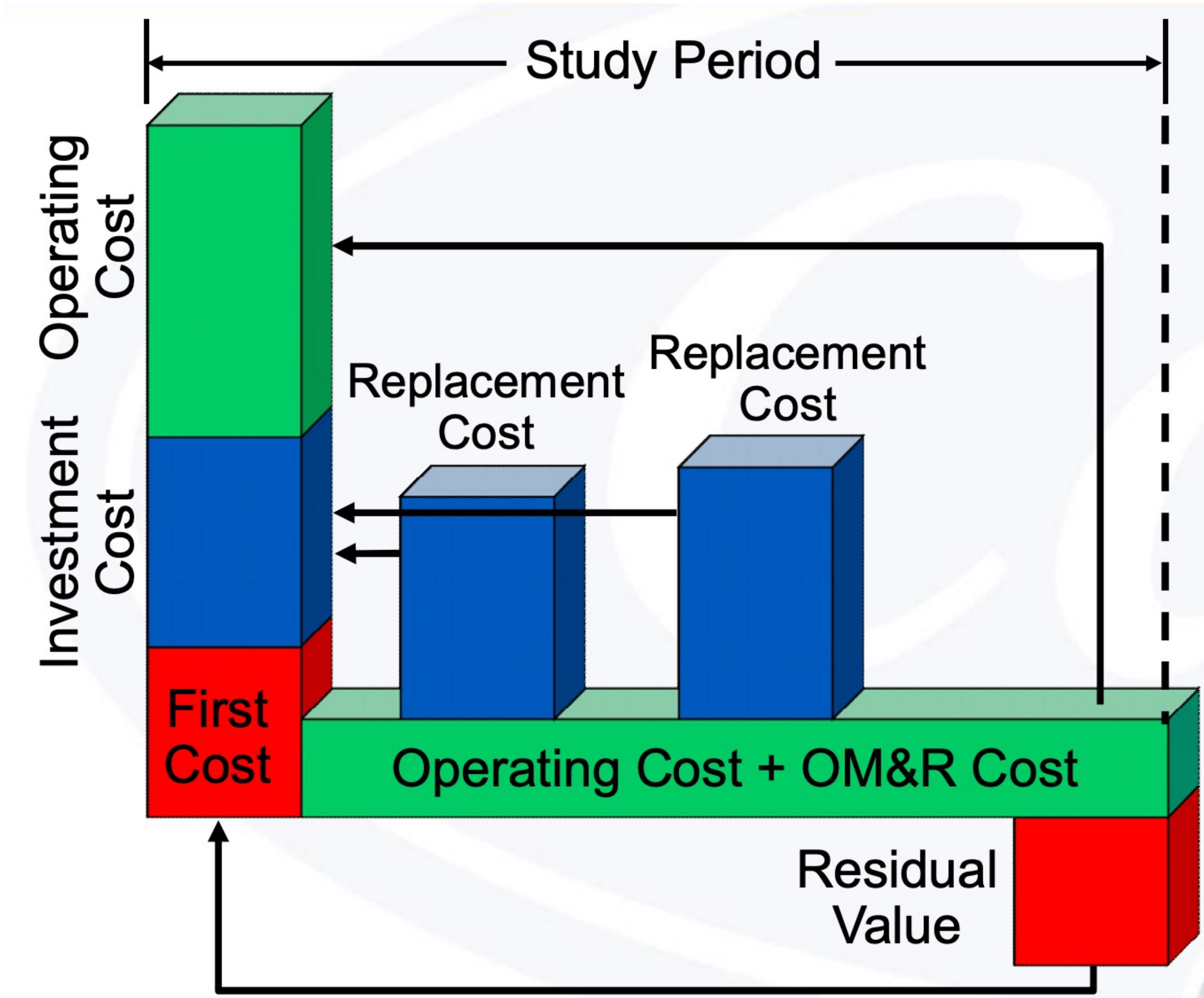
Present Value

- **Present value** (PV) or present discounted value is a future amount of money that has been discounted to reflect its current value, as if it existed today.
- The present value is always less than or equal to the future value

$$PV = \frac{C}{(1+i)^n}$$

- ❑ C: is the future amount of money that must be discounted
- ❑ n: is the number of compounding periods between the present date and the future date
- ❑ i: is the interest rate for one compounding period

Present Value



http://siglercommercial.com/wp-content/uploads/2017/12/TDP-903C_v1.0_Life-Cycle-Costing-CF.pdf

Net Present Value

- **Net present value** (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows of the same entity:

$$NPV\ (i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

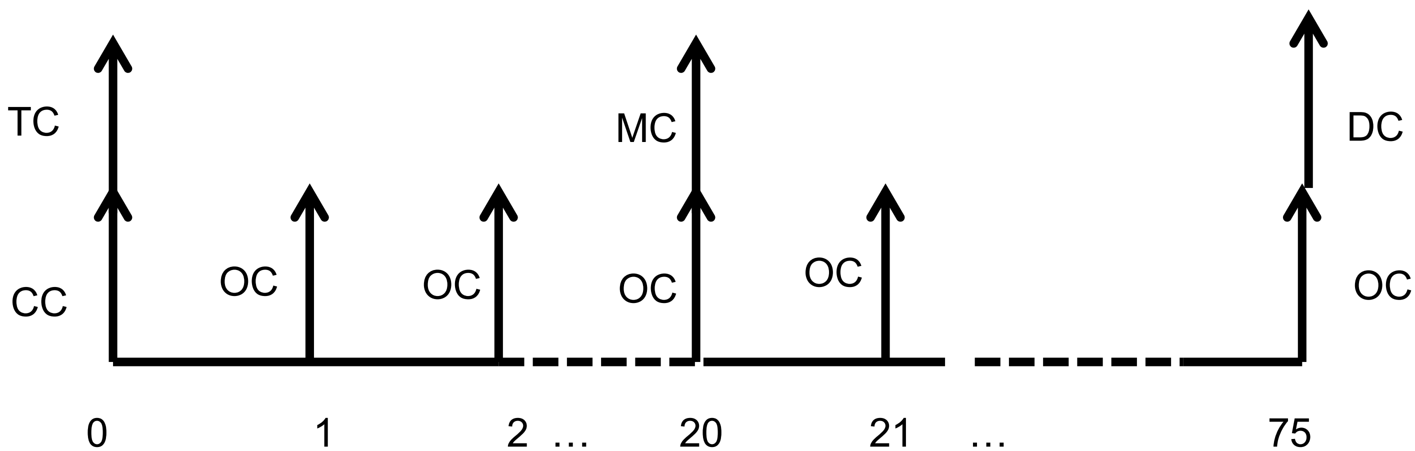
- t: The time of the cash flow
- i : The discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk.); the opportunity cost of capital
- R_t: The net cash flow i.e. cash inflow – cash outflow, at time t

Net Present Value

If...	It means...	Then...
NPV > 0	the investment would add value to the firm	the project may be accepted
NPV < 0	the investment would subtract value from the firm	the project should be rejected
NPV = 0	the investment would neither gain nor lose value for the firm	We should be indifferent in the decision whether to accept or reject the project. This project adds no monetary value. Decision should be based on other criteria, e.g., strategic positioning or other factors not explicitly included in the calculation.

Net Present Value

- Draw the cash flow:



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Whole-building life-cycle analysis with a new GREET® tool: Embodied greenhouse gas emissions and payback period of a LEED-Certified library

Hao Cai [a,*], Xinyi Wang [a], Ji-Hyun Kim [a], Arathi Gowda [b], Michael Wang [a], John Mlade [c], Scott Farbman [d], Luke Leung [b]

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GREET Training

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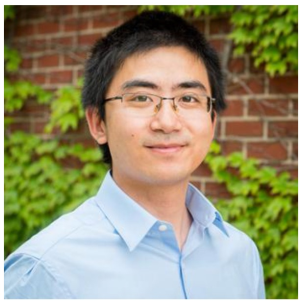
GREET Training

Argonne NATIONAL LABORATORY RESEARCH



Hao Cai

Group Leader, Materials Life Cycle Analysis

Biography

Hao Cai is an environmental and energy systems analyst examining life-cycle energy and environmental impacts of the production and use of transportation fuels and vehicle technologies. Dr. Cai specializes in characterizing air pollutant emissions of stationary sources and light-duty and heavy-duty vehicles, in analyzing energy efficiency and greenhouse gas emissions of the power sector and petroleum and natural gas systems, and in assessing the energy use, greenhousegas emissions, and air pollutant emissions of biofuel production systems. Much of Cai's work is incorporated into Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET^{TM}) model, which has more than 23,000 users worldwide.

Research Expertise and Interests

- Life-cycle Analysis of Transportation Fuels and Vehicle Systems
- Environmental Analysis of Fossil Fuel Systems
- Sustainability Analysis of Biofuel Supply Chains and Production Technologies

Argonne NATIONAL LABORATORY RESEARCH

Jarod Cory Kelly

Principal Energy Systems Analyst

Biography

Dr. Kelly examines the sustainability of energy and transportation systems as a research engineer at Argonne National Laboratory. His recent studies have considered the environmental implications of battery electric vehicle adoption and the supply chain variance associated with the production of lithium-ion batteries in different regions of the world. This work found that there are significant opportunities to reduce various pollutant emissions associated with battery production through locational variation. His work has also characterized breakeven substitution ratios for material substitution in vehicle light weighting efforts. He received his BS in mechanical engineering from the University of Oklahoma and his MS and PhD in mechanical engineering from the University of Michigan.