Sustainable Infrastructure Design and Maintenance

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Abstract. Infrastructure are long-lasting products which have huge impacts on the environment during their whole lives. The design and subsequent maintenance of infrastructure should take into consideration long-term environmental and economic benefits. Through a systematic literature review this report presents the concept of sustainable infrastructure design and maintenance (SIDM), identifies the key factors during the application of SIDM, and introduces corresponding sustainability assessment tools. Particularly, a life cycle assessment approach is introduced in detail. Finally, an existing case related to the life cycle assessment method is demonstrated in order to assist the decision makers.

Keywords: Sustainable infrastructure · Environmental and economic benefits · Life-cycle assessment

1 Introduction

Nowadays, many developing countries in the world are experiencing a process of urbanization at an unprecedented scale and speed. This trend is expected to result in, by 2050, an additional 1.2 billion people who are projected to live in cities in Asia [1], as shown in Fig. 1. As urban population grows, not only will new cities and new urban districts need to be developed, but existing cities will also need to be retooled to improve livability.

Since infrastructure is central to development in developing countries, massive infrastructure construction is urgently required for ensuring the connectivity, productivity, efficiency and overall competitiveness. For instance, there are about 40 billion square meters of buildings in China and this figure will reach 70 billion square meters by 2020 [2]. However, the challenge of meeting massive infrastructure construction needs in the face of its significant impacts on environment, and dwindling resources [3]. It is estimated that approximately 80% of the total greenhouse gas (GHG) emissions come from cities, with 25% attributed to urban transportation, 32% to build environment, and an additional 5% to municipal solid waste. Urban transportation accounts approximately 20% for the global energy consumption, and building construction and operation responds to an additional 25% [4]. Therefore, design for sustainable infrastructure is an urgent task for the construction industry.

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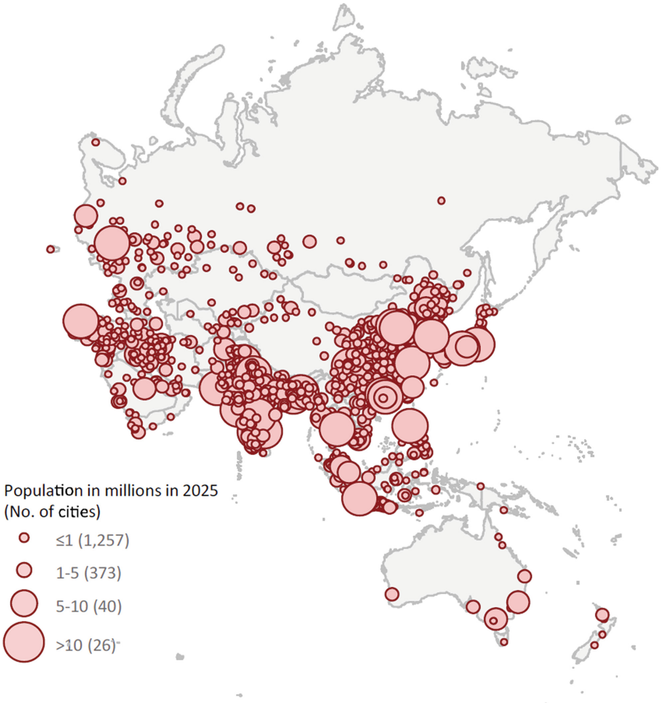

Fig. 1. An expected distribution of cities in Asia by population size in 2025 [1].

Sustainability is a concept of meeting the current need without jeopardizing the future generations' capability of meeting their own needs. It is an approach to meeting the current need with the future in mind. While this is a generally acceptable concept, there remain significant gaps on the approaches to operationalizing in many sectors of the economy especially in some developing countries where majority are struggling to make the ends meet. Although the approach to design is essentially traditional whereby the design focus is basically on functionality, cost and aesthetics [5]. The world bank statement that "As of 2000, about 80% of all government-owned water systems in small towns were nonoperational" is an eye opener and a good pointer to the need for a different approach. A new design approach that enables incorporation of technical, economic, institutional, environmental and socio-cultural factors into design is sustainable design. However, the current sustainability assessment system focuses mainly on the design stage. As a critical set of systems, infrastructure forms much of the foundation for quality of life and enables national development and progress. However, it also consumes vast material resources and energy [6]. Sustainable infrastructure design and maintenance (SIDM) considers the environmental influences of a building through its whole life, that is, from the initial construction process to the future operation stage of the building [7]. Thus, it is essential that the infrastructure be designed and maintained using the SIDM approach that consider social, environmental, and economic impacts over buildings' whole lives.

2 What Is Sustainable Infrastructure [8]

The **Global Commission on the Economy and Climate** defined Infrastructure as: structures and facilities that underpin power and other energy systems (including upstream infrastructure, such as the fuel production sector), transport, telecommunications, water, and waste management. It includes investments in systems that improve resource efficiency and demand-side management, such as energy and water efficiency measures. Infrastructure includes both traditional types of infrastructure (including energy to public transport, buildings, water supply and sanitation) and, critically, also natural infrastructure (such as forest landscapes, wetlands and watershed protection).

SIDM refers to infrastructure projects that are planned, designed, constructed, operated, and decommissioned in a manner to ensure economic and financial, social, environmental (including climate resilience), and institutional sustainability over the entire life cycle of the project. The guiding principles for each of the dimensions of sustainability is shown in Fig. 2.

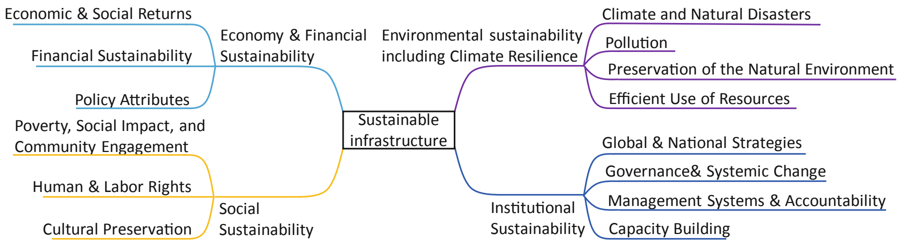

Fig. 2. The Four Dimensions of Infrastructure Sustainability [8].

2.1 Economic and Financial Sustainability

Infrastructure is economically sustainable if it generates a positive net economic return, considering all benefits and costs over the project life cycle, including positive and negative externalities and spillovers. In addition, the infrastructure must generate an adequate risk adjusted rate of return for project investors. Sustainable infrastructure projects must therefore generate a sound revenue stream based on adequate cost recovery and be supported, where necessary, by well-targeted subsidies (to address affordability) or availability payments (when users cannot be identified), or where there are large spillover effects. Sustainable infrastructure must be designed to support inclusive and sustainable growth and boost productivity and to deliver high-quality and affordable services. Risks must be fairly and transparently distributed to the entities most able to control the risk or to absorb its impact on the investment outcomes over the life cycle of the project.

2.2 Environmental Sustainability, Including Climate Resilience

Sustainable infrastructure preserves, restores, and integrates the natural environment, including biodiversity and ecosystems. It supports the sustainable and efficient use of natural resources, including energy, water, and materials. It also limits all types of pollution over the life cycle of the project and contributes to a low-carbon, resilient, and resource-efficient economy. Sustainable infrastructure projects are (or should be) sited and designed to ensure resilience to climate and natural disaster risks. Sustainable infrastructure often depends on national circumstances, where the overall performance will need to be measured compared to what could have been built or developed instead.

2.3 Social Sustainability

Sustainable infrastructure is inclusive and should have the broad support of affected communities - it serves all stakeholders, including the poor—and contributes to enhanced livelihoods and social well-being over the life cycle of the project. Projects must be constructed according to good labor, health, and safety standards. Benefits generated by sustainable infrastructure services should be shared equitably and transparently. Services provided by such projects should promote gender equity, health, safety, and diversity while complying with human and labor rights. Involuntary resettlement should be avoided to the extent possible and when avoidance is not possible, displacement should be minimized by exploring alternative project designs. Where economic displacement and relocation of people is unavoidable, it must be managed in a consultative, fair, and equitable manner and must integrate cultural and heritage preservation.

2.4 Institutional Sustainability

Institutionally, sustainable infrastructure is aligned with national and international commitments, including the Paris Agreement, and is based on transparent and consistent governance systems over the project cycle. Robust institutional capacity and clearly defined procedures for project planning, procurement, and operation are enablers for institutional sustainability. The development of local capacity—including mechanisms of knowledge transfer, promotion of innovative thinking, and project management—is critical to enhance sustainability and promote systemic change. Sustainable infrastructure must develop technical and engineering capacities as well as systems for data collection, monitoring, and evaluation, to generate empirical evidence and quantify impacts or benefits.

3 Leading Factors and Assessment Tools for SIDM

Infrastructure provision has considerable impacts on resource utilization, quality of the environment and overall quality of life. Infrastructure provision process should meet performance requirements in terms of economic, ecological and social aspects and that the design approach has to be in a way to harness technologies and meet human needs by working with nature, instead of solving problems at nature's expense. Thus, key design elements for sustainable infrastructure design should be identified for the application of SIDM in developing countries.

3.1 Leading Factors for SIDM [7]

To identify the key design stage factors that significantly influence the delivery of sustainable infrastructure, a systematic literature review was conducted by Nuramo and Haupt [9]. The results were found to be important toward delivery of sustainable infrastructure in the context of developing countries. Table 1 outlines refined 50 key elements and corresponding factors for sustainable infrastructure design.

3.2 Sustainability Assessment Toolkits [7]

The incorporation of the aforementioned factors for SIDM has brought sustainability issues to the forefront of infrastructure and building design, construction, and operations practice in the different countries. For example, the BRE Environmental Assessment Method (BREEAM) system is an integrated sustainability assessment tool used in the UK, which covers waste, water and energy, as well as transport, pollution, community engagement, the health and wellbeing of building occupants, the choice of material, enhancing biodiversity and building management. The BREEAM series can assess several types of buildings' design, including BREEAM Courts, Healthcare, Industrial, International, Multi-residential, Prison, Offices, Retail, Education, Communities and Bespoke.

The other sustainability assessment tool for buildings is The Code for Sustainable Homes [10] to be used in residential building designs in the UK covers the following areas:

(1) Energy efficiency/CO2.
(2) Water efficiency.
(3) Surface water management.
(4) Site waste management.
(5) Household waste management.
(6) Use of materials.
(7) Lifetime homes (applies to Code Level 6 only).

Another well-known sustainability assessment tool is Leadership in Energy & Environmental Design (LEED) [11] used mainly in the US. It covers new construction, existing buildings, commercial interiors, core and shell, schools, retail, healthcare, homes, and neighbourhood development. The checklist scoring system includes the following main aspects:

(1) Sustainable sites.
(2) Water efficiency.
(3) Energy and atmosphere.
(4) Material and resources.
(5) Indoor environmental quality.
(6) Innovation and design process.

Table 1. The main factors in sustainable infrastructure design and maintenance.

Factor 1: Material Selection
1. Prescribing low energy materials
2. Use of locally available materials
3. Use of durable/high-performance materials
4. Use of materials with low health risk and pollution
5. Material reuse
Factor 2: Economic Considerations
1. Cost/benefit analysis
2. Life cycle analysis
3. Cost efficiency
4. Bankability
Factor 3: Policy and Regulations
1. Presence of design sustainability regulatory requirements
2. Presence of sustainability rating systems
3. Inclusion of sustainability requirements in public project briefs
Factor 4: Social Considerations
1. Public/beneficiaries participation
2. Client participation
3. Accessibility of the infrastructure to the public including people with specific needs
4. Health and safety consideration for construction workers and the public during construction and operation stages
5. Security consideration during construction and use
6. Satisfaction of the public
7. Protection of cultural heritage
8. Protection of landscape, historical areas and archaeological sites
9. Risk analysis and disaster mitigation
Factor 5: Design and Project Management
1. Early contractors' involvement at design stage
2. Early suppliers' involvement at design stage
3. Selection of appropriate contract/project delivery type
4. Inclusion of sustainability related clauses in contract documents
5. Proper construction quality control procedure
Factor 6: Technical Considerations
1. Exhaustive site survey and ground investigation
2. Considering alternatives prior to proposing a solution
3. Multi-disciplinary integrated design team beginning from feasibility study stage
4. Meeting functional requirements and users' comfort
5. Robustness and less maintenance products
6. Completeness and clarity of design documents
7. Value engineering 8. Harmony with the surrounding environment

(*continued*)

Table 1. (*continued*)

Factor 7: Environmental Considerations
1. Mitigating effects of natural disasters and climate change 2. Climate resiliency (resistant to climate change) 3. Ensuring efficient energy utilization both during construction and operation phases 4. Optimizing uses of natural resources 5. Optimizing site potentials (land use) 6. Uses of less energy during construction and operation 7. Waste minimization/design optimization
Factor 8: Design Professionals and the Design Process
1. Awareness of clients about sustainability 2. Awareness of designers about sustainability 3. Knowledge and experience of designers 4. Skill of designers 5. Appropriating adequate time for design 6. Reasonable financial compensation for design work 7. Presence of design guidelines/procedures for sustainable infrastructure 8. Proper coordination among designers from different disciplines 9. Willingness of designers to implement sustainability design concept and practices in their designs

The Waste and Resources Action Programme (WRAP) recycle content toolkit is designed by the WRAP [12] in order to increase the amount of recycled content incorporated into buildings. It includes some 3000 building components recycle content that estimates for new build and existing buildings. In the IPCC fourth assessment report Metz [13] suggested key mitigation technologies and practices by seven sectors.

(1) **Energy supply** - improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power.
(2) **Transport-more fuel** - efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorized transport; land-use and transport panning.
(3) **Buildings** - efficient lighting and day lighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycle of flu orientated gases.
(4) **Industry** - more efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO2 gas emissions and a wide array of process specific technologies.
(5) **Agriculture** - improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH4emissions; improved nitrogen fertilizer application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency.

(6) **Forestry** - forestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use.
(7) **Waste** - landfill methane recovery; waste incineration with energy recovery composting of organic waste-controlled wastewater treatment; recycling and waste minimization.

The advantages and disadvantages of those sustainable design tools are listed in Table 2. Other resources for generating sustainable design solutions include BRC [14], Constructing Excellence [15], SEEDA [16], The Carbon Trust [17], UK Government Office of Government Commerce [18]. There are an enormous number of literature and sustainable design tools providing numerous sustainable design options for designers to choose; however not all of them can be implemented in practice. In the current industrial environment, the application of sustainable design solutions in a project is limited by the affordability and risks the investors willing to take in practice. The opinions of the practitioners are crucial to the final decision. Therefore, the key factor that influence the practice of the sustainable infrastructure design and maintenance should be clarified.

Table 2. The advantages and disadvantages of some main sustainable assessment tools [7].

Tool name	Advantages	Disadvantages
BREEAM	Covers a wide range of design aspects	Serves the UK public non-commercial buildings. Limited sustainable design options
Code for sustainable home	Higher standard requirements on energy efficiency. Request zero carbon for new houses on level 6	Limits to residential projects only. Limited sustainable design options
LEEDs	Covers various types of buildings	Exclude waste management. Limited sustainable design options
WRAP recycle content tool	Building breaking down into components in order to select the high recycle content building materials for projects. Suitable for all types of buildings	Focuses on only the recycle content aspect of sustainable design. Limited sustainable design options
IPCC	Includes new considerations such as industry, agriculture and forestry, etc.	Just a general guidance for sustainable design. Limited sustainable design options

4 Life Cycle Assessment

The existing sustainable design tools are designed for the general guidance of building design. These sustainable design tools for buildings mostly focus on the environmental impact of the buildings and the capital cost of the design options. However, the life cycle costs, and the practitioners' opinion have been neglected, even they are just as equally important as the environmental impact. Buildings are long-lasting products; the design of buildings should practically reduce the life cycle costs and improve the sustainability of the buildings.

In this aspect, life cycle assessment is the best tool to combine both the long term environmental and the economical evaluations of building designs. Life cycle assessment also includes economic and risk evaluations in analysis. The key economic analysis is life cycle costing, which is a technique to estimate the overall costs of design options during the economic life of the building. In order to compare the long-term economic performance of the design options, life cycle costing should be included in strategic designs because the economic concerns drive the decision makers may be sometimes more than the other concerns. There are many cost models that have been developed to estimate life cycle costs such as NHS hospital buildings [19] running cost for building element [20], noise barrier wall selection [21, 22], and water supply system [5, 23].

4.1 Procedure for SIDM Using Life Cycle Approach

Generally, life cycle design is a multi-stakeholder's collaborative approach. It may involve the qualitative evaluation from practitioners and the quantitative data from technical engineers and quantity surveyors. Various parties involved in the assessment process allow the tool taking into consideration not only the long-term environmental and economic impacts of the building design option but also the feasibility evaluation of the practitioners. Their data are finally integrated into a single measurement to rank the design options. The integrated tool includes the following steps:

(1) Generating sustainable building design options through literature review.
(2) Feasibility assessment by practitioners through educational workshops.
(3) Technical analysis on life cycle costs and risk levels of design options by technical experts.
(4) Multi-criteria decision-making process to combine multiple evaluations by direct weighting method.

Dunmade et al. [5] reported an approach to lifecycle design and sustainable management of Nigerian water infrastructure. Figure 3 is an illustration of various sustainable design concepts that need to be harmonized for a sustainable water supply infrastructure design. These design concepts include Design for Assembly and Disassembly, Design for simplicity and reliability, Design for manufacturing and remanufacturing, Design for Cost, and Design for Reuse and Upgrading. Furthermore, sustainable material selection for the system's hardware manufacturing, resource consumption minimization during system operational life as well as lifecycle extendibility are other things that would need to be put into consideration in the process of designing the water infrastructure for sustainability. This would ensure that sustainability is incorporated at the design, manufacturing, utilization and end-of-life management stages of the water supply facility's lifecycle. In designing a water supply system for sustainability, the energy requirement of the system and the source(s) of the energy need to be assessed and factored into the design. This is necessary in order to ensure availability and reliability of the requisite energy for the water system operation.

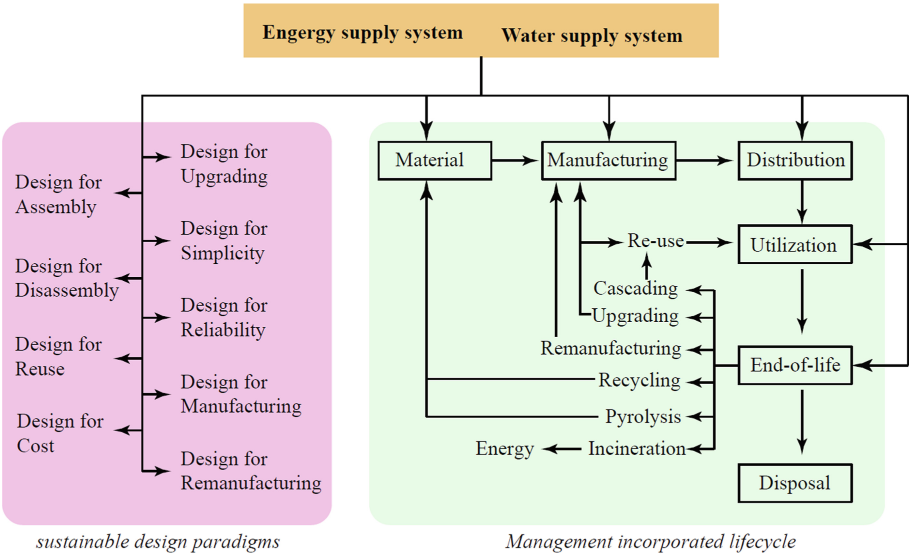

Fig. 3. An illustration of where sustainability can be incorporated [5].

Figure 4 is an illustration of the lifecycle design and sustainable management framework developed as a result of the study. It is a multi-stakeholder's collaborative approach. An application of the lifecycle design and sustainable management-based water supply infrastructure development model would start with the assemblage of coalition partners. Their first assignment would be to identify credible water needs of the community and to articulate their groups' interests in the project. The next step involves making arrangement for how the needs will be addressed. This would be achieved through an evaluation of existing policies suitability and possible reformulation of such policy to facilitate incorporation of innovative approach if/when necessary. This is expected to be followed by an assessment of water sources and their conditions in the locality, utilizable options, required energy and affordability. The next step would be generation of conceptual designs and applying various lifecycle design concepts (DFXs) on the conceptual designs. DFX refers to design for X where X could be material (DFMt), modularity (DFMd), assembly (DFMA), manufacturability (DFMf), disassemblability (DFD), maintainability (DFS), use and reuse (DFUR), upgradability (DFUG), remanufacturability (DFRm), recyclability (DFR), energy efficiency (DFEE), minimum residue (DFMR) and so on. Each conceptual design is then evaluated in turn for environmental friendliness by using E-LCA.

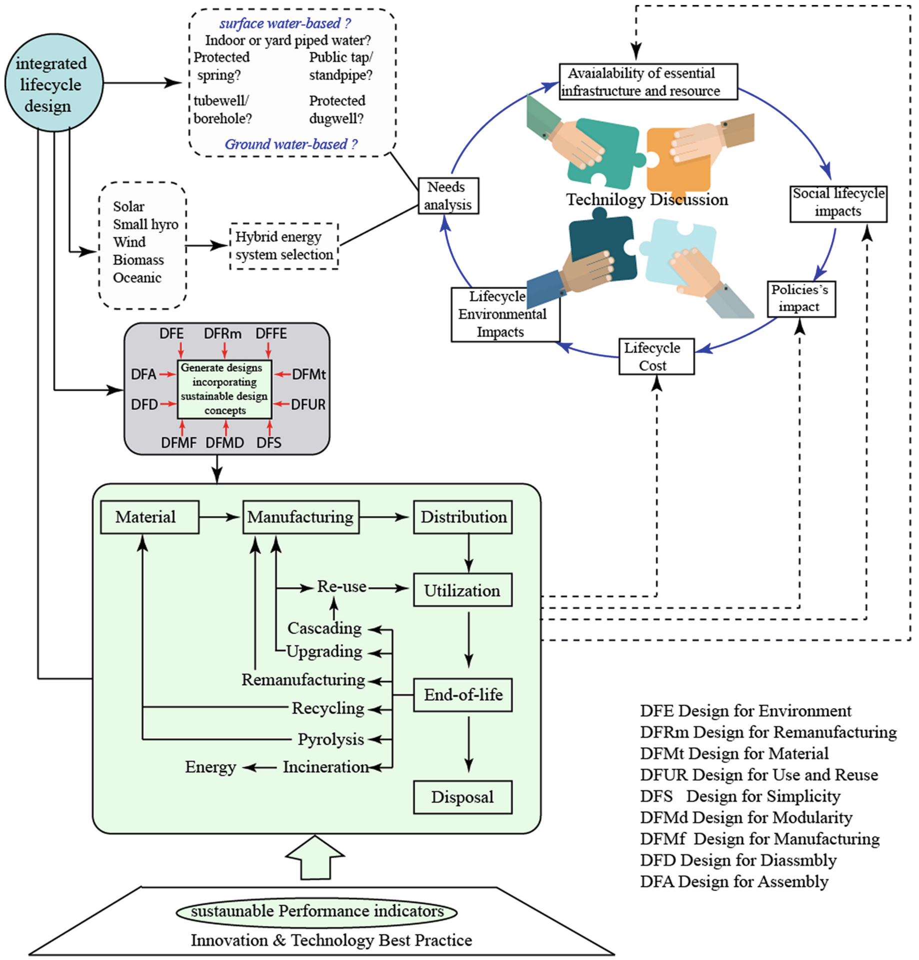

Fig. 4. An illustration of Lifecycle design and sustainable management based water supply system infrastructure [5].

4.2 Possible Challenges for Life Cycle Approach to SIDM

Without doubt, a comprehensive, life cycle approach to sustainability focused design will be difficult to implement. Significant challenges quickly come to mind; Some of the challenges include the current lack of sustainable design knowledge, and the degree of willingness to learn the new approach. Other challenges include the huge cost whenever new project would have to be undertaken in their region and how to wean them from personal aggrandizement and take ownership of the new system. Overcoming these challenges would require tact, consistency and patience in the process of educating the "unruly stakeholders" and managing incidences along the collaborative sustainable design and development process.

It should also bear in mind that the transition from conventional approaches to life cycle design may take very long time. And this shift required the collaboration of many academic disciplines, such as architecture, engineering, mechanics, and statistics, with contributions from economics (economic loss modeling and costing) and public policy (building codes). The transition to life cycle design for sustainability will require substantially more collaboration among academics, practitioners, and policymakers, and will draw from the diverse fields of biology, chemistry, and sociology for the proper establishment of ecosystem carry capacities and social norms. On a positive note, the rate at which collaborative thinking and research have moved from theory to practice has accelerated greatly in Europe.

5 Conclusions

Infrastructure are long-lasting products which have huge impacts on the environment during their whole lives. The design and subsequent maintenance of infrastructure should take into consideration long-term environmental and economic benefits. The selection of sustainable design options for building projects depends not only on the technical issues but also on economic and political concerns of the decision makers.

This report presents the concept of SIDM, and the assessment tools for SIDM. Among the existing assessment tools, the life cycle assessment tool is the best one, which combined feasibility study, life cycle costing, environmental evaluation, and risk analysis in the design decision.

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