Abstract

The building industry has attempted to reduce the impact of the design, construction and operation of buildings by replacing traditional technologies with sustainable technologies that have a reduced ecological, health and environmental life cycle impact. At present, the performance of sustainable technologies in buildings is generally not assessed holistically, but rather from a primarily single-issue perspective, e.g., only financially or only environmentally. Such an approach is limited in that it ignores the interaction of the technologies within the physical facility itself as expressed through life cycle costs, the impact on the surrounding environment, design objectives of the project and its stakeholders whose value systems may conflict. The primary goal of this work is to improve the understanding and decision making capabilities of the building industry and government when faced with decisions regarding investment and policy regarding sustainable building technologies. A secondary goal is to identify knowledge gaps in our understanding of sustainable technologies.

The thesis explores the unique characteristics of the building sector in terms of the stakeholders involved, the construction process, and the operation and maintenance of a building. The unique characteristics of the building sector influence the industry motivation towards sustainable construction, and thus sustainable construction, the characteristics of sustainable buildings and selected sustainable technologies are also described. The main barriers to improving the environmental performance of the building sector and incentives for the adoption of sustainable construction practices are introduced, and the value systems of various stakeholders involved in a construction project and the motivation for the adoption of sustainable technologies are discussed. An analytical framework is developed herein for the selection of appropriate
sustainable technologies in buildings and for assisting policy makers develop meaningful sustainable technology regulation, policy and incentives. Rooftop garden technology is used to demonstrate the application of the framework in hypothetical building examples. Benefits of the framework include a means to promote dialogue among stakeholders to reflect the diverse value systems involved in a building project and a logical structure for applying sustainability concepts and for assessing the relevance of technology to the project context, construction process and final product.
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CHAPTER 1  Overview and Summary

1.1. Background

The building sector has a significant impact on the environment. Building sector activities including the design, construction, operation, refurbishment and demolition of buildings have both direct and indirect impacts on the environment. These impacts include, but are not limited to, the consumption of natural resources, generation of solid waste, encroachment on sensitive habitats and ecosystems, and pollution of air, water and soil. These impacts are believed to affect the quality of life of both current and future generations. The building sector has recognized that good construction practices contribute to improved environmental performance and have defined sustainable construction as: “the creation and responsible maintenance of a healthy built environment, based on resource efficient and ecological principles” (CIB Publication 225, 1998). One avenue through which the building industry is initiating the application of sustainable construction practices is in the replacement of traditional technologies with “environmental” or “sustainable” technologies that have a reduced ecological, health and environmental life cycle impact. The terms “environmental” or “sustainable” technologies, are used interchangeably in this thesis, and in general are considered innovative in nature.

This thesis contributes to the development of improved analytical tools for the assessment and selection of appropriate environmental technologies in buildings. The application of the framework introduced herein is intended to stimulate dialogue, critical thinking, and
to contribute to informed, rational decision-making as it pertains to the selection of environmental technologies.

1.2. Motivation
The increased interest in the inclusion of sustainable construction practices in projects has resulted in the implementation of sustainable technologies to improve the environmental performance of a building. The selection and implementation of new technologies and techniques in a building project can have significant implications for long-term costs, performance, and owner/investor satisfaction. These sustainable technologies are typically installed prior to an evaluation of their full life cycle implications, which could adversely impact building performance in the long term or set back efforts to encourage the adoption of sustainable technologies. Currently, there is no comprehensive standard evaluation approach available to assist designers, policy makers and constructors to perform a holistic evaluation of a sustainable technology, which includes technical, social, environmental and economic measures. Some benefits of sustainable technologies are easily measured such as energy, water or wastewater savings while other benefits are subjective, intangible or indirect such as improvements to productivity and health, enhancement in reputation and reduction of peak energy demands. Therefore traditional evaluation approaches, including financial models, inadequately assess the performance of a sustainable technology. The framework is intended to assist decision makers in evaluating the performance of sustainable technologies with respect to multiple criteria rather than from a primarily single-issue perspective (e.g., only financially or only environmentally). A holistic approach allows decision makers to assess performance
relative to stakeholder objectives and consider the totality of influences on all systems and life cycle phases.

A fundamental issue related to the principles of sustainable construction is the appropriate selection of a technology to ensure that it meets the desired performance requirements. In short, a sustainable technology is not sustainable if it is inappropriate for the physical and social setting, which may manifest as prohibitive operations and maintenance requirements and lack of occupant support. Therefore a review of technology appropriateness with respect to a holistic set of evaluation criteria is the motivation of this thesis.

1.3 Objectives
This framework provides a systematic basis for identifying and evaluating the positive and negative technical, social, environmental and economic implications of innovative building technologies. Application of the framework is illustrated using the assessment of green roof technology for a multi-unit residential building. This technology has been selected because it demonstrates the multiple dimensions of a technology and the potential impacts on other building systems. The framework is offered as a guide in the systematic assessment of a technology but is not the decision making process itself. The thesis:

i. Discusses the characteristics of sustainable technologies and buildings and the barriers and incentives for their adoption;

ii. Reviews the current state-of-the-art in terms of technology assessment methods and frameworks available for evaluating new technologies in buildings;
iii. Explores the value systems of various stakeholders involved in a construction project and articulates the motivation for and implications of sustainable technology adoption in projects;

iv. Develops a framework for the technical, social, environmental and financial evaluation of environmental technologies and develops a set of indicators that could be used to guide multiple decision makers in evaluating a new technology;

v. Introduces the characteristics of green roof technology, which is the sustainable technology selected to demonstrate the application of the framework;

vi. Applies the framework through the evaluation of green roof technology with emphasis on how impacts differ depending on building context. The evaluation of technology performance in different building types is used to verify the framework and identify risks, benefits and challenges including issues of consensus and disagreement among decision makers; and,

vii. Concludes with a discussion of the broader applications of the framework.

1.4 Market transformation towards sustainable construction

The interest in sustainable construction is becoming more and more mainstream in the building industry with the increased market awareness, popularity and client interest in environmental issues. The rapid rise in membership, from 250 building professionals in 1999 to 3500 in 2003, in the U.S. Green Building Council (USGBC), a non-profit organization with the mandate to transform the construction marketplace and promote more environmental construction practices, is just one indication of the construction industries interest in sustainable construction (EDC, 2004a). The USGBC introduced the LEED® 2.1 Leadership in Energy and Environmental Design Green Building Rating
System, a consensus-based national standard for developing high performance, sustainable buildings (USGBC, 2004a). Owners and developers from all states in the United States, in Canada and 10 other countries have registered their intent to certify their buildings under the LEED® system (EDC, 2004b). Government entities are particularly motivated. In the United States for example, more than 15 states, cities and jurisdictions, have developed programs to promote sustainable construction and comprise greater than 47 percent of the total LEED® registered buildings (EDC, 2004c). Private developers are also interested in sustainable construction. For example, the developers of a new one billion dollar skyscraper under construction in New York City, the proposed second tallest building in the city, aim to create the world’s most “environmentally responsible” high-rise office tower (CEN, 2004). In order to promote new construction practices and technologies and improve building performance, both public and private entities offer financial and regulatory incentives. Incentives have included tax credits, grants for energy modeling, accelerated approvals, commissioning and related costs, preferred zoning considerations and direct financial subsidies. It is becoming increasingly clear that environmental protection has become a key political and socioeconomic issue.

1.5 Definition of sustainable technologies and buildings

1.5.1 Sustainable buildings

In this thesis, a sustainable building or "green" building includes strategies, over and above traditional building practices, to reduce the ecological, health and environmental life cycle impact of construction activities and operations. The American Society of Heating Refrigeration and Air Conditioning Establishment (ASHRAE), an American professional organization for design professionals, best clarifies the term "green"
building in the ASHRAE Greenguide publication (Grumman, 2004) as a building that achieves high performance by focusing on the following aspects:

1. "Minimal consumption—due to reduction of need and more efficient utilization—of non-renewable natural resources, depletable energy resources, land, water and other materials as well. (Corollary to this is maximization of the effective use of renewable resources to meet building needs.)

2. Minimal atmospheric emissions having negative environmental impacts, especially those related to greenhouse gases, global warming, particulates or acid rain.

3. Minimal discharge of harmful liquid effluents and solid wastes, including those resulting from the ultimate demolition of the building itself at the end of its useful life.

4. Minimal negative impacts on site ecosystems.

5. Maximum quality of indoor environment, including air quality, thermal regime, illumination, acoustics/noise and visual aspects."

This definition is consistent with the definition of a “green” building made by other organizations. Some organizations define a “green” building with consideration of a broader range of activities outside the boundaries of the building envelope. The emphasis of a green building project as outlined in the Santa Monica Green Building Program (SMGBP, 2004) includes the following broader strategies:

1. Minimize material and resource use

2. Reduce human exposure to materials and fumes with adverse health implications

3. Maximize use of renewable energy
4. Use materials that are harvested from a sustainable source

5. Protect, restore and enhance the local environment

6. Promote non fossil fuel means of transportation

In Vancouver, British Columbia, there are a growing number of buildings that are considered sustainable or "green" including the CK Choi building and the Liu Centre at the University of British Columbia campus. Both buildings incorporate salvaged and recycled materials to reduce the amount of new materials used and include natural ventilation strategies to maximize energy savings and eliminate the need for large heating and cooling equipment. The CK Choi building was designed to use 40% less energy than the average building standard. The most notable environmental feature in this building is the inclusion of composting toilets that allow the building to operate independent of the city sewer. The Liu Centre is designed to have similar energy savings and the most notable environmental feature of interest is the high percentage use of high volume fly ash concrete as the primary structural and architectural feature. A fifty percent content of fly ash, a waste product that replaces cement in the concrete mix, translated into the saving of the creation of 33% CO₂ in the buildings construction.

There are numerous assessment methods available to determine whether a building is "green" or sustainable and these schemas are discussed in Chapter 2. Their adoption by both private and public sector is increasing. One strategy in attaining a green building is the implementation of sustainable technologies that perform advantageously in comparison with the traditional alternative with respect to economic, environmental or social criteria.
1.5.2 Sustainable technologies

Sustainable or environmental technologies are defined as available and potentially available technologies that may help decrease the human pressures on the environment or natural resources while providing a desired standard of living (Kraines and Wallace, 2003). The objectives of such technologies include, among others, maximizing operation efficiency, reducing waste and improving the environmental quality of the structure. These outcomes are viewed as elements of a “green” building. Examples of sustainable technologies introduced on demonstration green building projects and their primary associated environmental benefits relative to traditional alternatives include:

1. Wind Turbines  Reduction in fossil fuel consumption
2. Photovoltaic cells  Reduction in fossil fuel consumption
3. High volume fly ash concrete  Reduction in CO₂ emissions
4. Under floor air conditioning  Improved occupant comfort
5. Eco materials  Improved indoor air quality

A list of current environmental technologies and practices for commercial and multi-unit residential buildings is available at http://www.advancedbuildings.org/ and the following section describes each of these technologies. A description of green roof technology is provided and applied as a demonstration of the framework introduced in Chapter 2 and 3.
Wind Turbines

Wind turbines use the force of the wind, a renewable and clean fuel source, to generate power. The two types of power generators illustrated are: a vertical axis linear blade type (1.5kW) and a propeller type (0.4kW x 3). Wind turbines utilize a renewable energy source and can reduce utility bills by displacing the power normally supplied by an energy supplier. The advantages of wind power are that it is a domestic source of energy and no pollutants are released. Although wind power is the fastest-growing energy source in the world, it is not cost competitive with fossil fuel generating sources, requires a high initial investment and demand requirements may not be met because wind cannot be harnessed. Other disadvantages include the noise generated by rotor blades.

Photovoltaic (PV) Cells

Photovoltaic (PV) cells directly convert sunlight into electricity. PV cells can provide quiet, clean, efficient electrical energy from an energy source that is renewable. PV cells are expensive due to the high cost of producing the semiconductor material within the technology and the long payback period deters many building owners from investing in the technology.
High Volume Fly Ash Concrete (HVFAC)

Concrete, which is composed of cement, aggregate, water and additives, is one of the most commonly used building materials in the world. The production of cement results in high volumes of carbon dioxide emission (CO₂) a pollutant that contributes to climate change and ozone depletion. High volume fly ash concrete (HVFAC) has properties similar to a traditional concrete mix but replaces a higher percentage of the cement with flyash; a waste product from coal burning plants. Advantages of HVFAC include high sulphate resistance, ease of placement, low heat of hydration and long term strength gain. Although HVFAC is generally cheaper than the traditional alternative the longer setting time impacts the project schedule, and stronger forms are required which can offset or increase overall costs.

Figure 1.3 Sandhead Light station, HVFAC Construction

Underfloor Air Conditioning Systems (UAS)

The under-floor air-conditioning system (UAS) uses the same air-conditioning equipment as in conventional air-conditioning systems but differs in the method of air distribution. A conventional system supplies air from the ceiling level while UAS supplies air from floor level and returns to the air-handling unit from the ceiling. The advantage of UAS is that it moves air in the same direction as the thermal lift in the room and therefore facilitates the removal of heat from occupied areas and lowers energy consumption compared with the conventional overhead system. Other benefits include full flexibility in changes to office layout. The perceived risks of this technology are the lack of standards and codes, and documented case studies on performance, and the potential for higher capital costs.

Figure 1.4 Underfloor air conditioning system
Eco Materials

Design, construction and operation of buildings requires energy and material resources, and impacts the air quality, animal habitat and watersheds. The development and application of eco materials in construction projects is one approach to reduce the construction industry’s burden on the environment. Eco materials include materials, chemicals, resins and adhesives among others that promote reduction, reuse, and safety or enable easier separation and processing for recycling or reuse purposes. The benefits include reduced impact on the environment and improved indoor air quality for occupants in buildings because of the lower emission of fumes and materials that cause adverse health impacts. The disadvantage is the lack of documented performance of these products in a building that has a typical lifecycle of 50 years.
1.6 Benefits of sustainable construction

Sustainable construction, including the construction of “green” buildings, is primarily driven by concerns on reducing the impacts of the construction, operation, and maintenance of traditional buildings on both the local and global environment.

Sustainable construction practices include goals to reduce resource consumption and pollution, and to enhance and preserve the natural environment. The reduction in the demand of energy, water and wastewater services results in a benefit to the community from the reduced demand of public infrastructure and their related capital, operation and maintenance costs.

According to a report by the Rocky Mountain Institute besides the environmental benefits, the improved indoor air quality and energy efficiency of a “green” building can result in an increase in employee productivity by between 6-16% (Romm and Browning, 1998), reduce absenteeism and improve morale. Strategies used in “green” buildings include increasing the ratio of filtered outside air, operable windows, access to natural light, specification of eco materials that release fewer and less harmful emissions, and protection of the air distribution systems during construction and performing a building flush-out prior to occupancy. Benefits to improving the indoor environment can result in significant savings to employers by means of reduced absenteeism and liability from lawsuits or claims over building related illness and to occupants through improved quality of life.
Direct financial benefits of “green” buildings can include lower operations and maintenance costs, free press, enhanced asset value, and higher retention and absorption rates. The installation of high performance systems can reduce the energy and water use and wastewater production relative to a traditional building and result in significant utility savings over the life of the project. It is not uncommon for a “green” building to have greater than 40% annual energy savings relative to the traditional alternative. Developers of “green” buildings often benefit from free press of their development with the accompanying opportunity to increase the marketability of the product and attract organizations with environmental priorities willing to pay a premium to lease a facility with environmental features and lower occupancy costs. Yates (2001) outlines how a business can benefit by implementing sustainable construction practices through the analysis of case study projects.

1.7 Why are all Canadian buildings not “green”?

Although there is a growing interest for sustainable construction practices and the installation of sustainable technologies, there are still barriers that hinder total market transformation. The construction industry is not free from liability due to construction defects and adverse environmental health impacts such as building envelope failures and related mould growth. Consequently, many decision makers are hesitant to adopt additional uncertainty associated with the performance and cost of a new technology, as well as to assume the responsibility or liability of failure. Even if one can assume that risks associated with life cycle performance can be accounted for in dollars, impact on schedule and reputation, the risks associated with the innovative nature of the technology (i.e., risks relative to technology failure or reduced performance with respect to such
issues as durability, mould and leaking) remain. A Canadian Mortgage and Housing Report (CMHC, 2002) summarizes the barriers for the implementation of innovative technologies in buildings:

There are many proven innovative technologies available to the residential construction industry, but even with modern and aggressive information dissemination techniques, it still requires 15 to 25 years for a new technology to be widely adopted by the industry. This means that, on average, the Canadian residential construction industry makes use of only some 50 per cent of the available quality enhancing or cost-cutting innovations at any given time. And half of this advantage happens only during the last five to six years of an innovation’s introductory period. The unique structural nature of the industry and limited resources pose inherent barriers to pursuing innovation adoption. The delay in uptake can limit advances in housing construction quality, cost efficiencies and environmental benefits.

It is apparent that there are opportunities to reduce the environmental impacts of the building sector; however, the unique characteristics of a building with respect to its long life (on average 50 years) and the sometimes conflicting objectives of primary stakeholders (owner, occupant, and builder) have created specific barriers that may impede environmental performance of this sector.

Aversion to up front capital costs, impact on project schedule, limited performance information and liability issues are other barriers to the adoption of sustainable construction practices and technologies. Decision makers may face budget or policy
constraints that restrict up front investment in sustainable technologies that may have a long payback period and incremental costs relative to the traditional alternative. A developer who sells the property upon completion is commonly motivated for a quick return on investment, and therefore has little incentive to implement technologies with incremental capital costs but long-term savings in operations and maintenance. Government entities create similar disincentives with policies that require technology investments that have a payback period of five to eight years or decisions that are based on the capital build budget for the construction that is distinct from the operations and maintenance budget. Occupants may not be willing to pay for environmental benefits to the community that they view as a free good, or for improved life cycle costs because they intend to occupy the building for a limited time. Design professionals and building officials may lack sufficient information regarding the efficacy and performance of a new technology to make knowledge based decisions and suggest modifications to applicable building codes. The results of a survey by the Development Center for Appropriate Technology about the effect of building codes on green-building practices confirm that building codes can be a barrier to the use of alternative building materials and methods where 65% of those surveyed said that they have chosen not to include a green alternative because they expected that it would not be approved.

Durability, robustness, operations and maintenance, interaction with other building components, and the affect on client investment criteria are just some of the factors to consider prior to making a technology recommendation. The additional time and therefore impact on schedule and money required to research, design and receive the
relevant approvals or performance equivalencies for innovative technologies relative to the traditional alternative is a disincentive for their implementation. Both public entities and design professionals are hesitant to recommend or approve a new technology and be liable in the event of failure.

1.8 Initiatives towards sustainable construction

1.8.1 Promoting sustainable construction with incentives

All building assessment tools developed so far do not address the fact that the objectives of policy makers may not always coincide with the profit maximizing goals of developers and designers (Chau et al., 2000), or indeed those of the end users who must invariably pay for any increased costs. Therefore, a number of public and private entities have begun to offer incentives to promote sustainable construction practices and the installation of sustainable technologies. Canadian federally, provincially and municipally funded financial incentives available for projects in British Columbia are available at www.greenbuildingsbc.com. The majority of funding available is for the adoption of technologies with energy savings relative to the traditional alternative. An example of a green building program offered by the City of Scottsdale Arizona is typical of what is offered by municipalities across North America, that is the provision of incentives such as the fast tracking of permits, lectures on green building strategies, and marketing of the firms that construct "green" buildings. Other cities, among others, offering similar programs include: New York City, New York; Austin, Texas; Portland, Oregon; San Jose, California; and Vancouver, British Columbia. The provision of incentives suggests that some sustainable technologies in their current form may be economically unattractive at the individual project level or that the environmental benefit of the
sustainable technology to society as a whole is valued greater than the cost of the incentive, and hence the need to subsidize it.

1.8.2 **Promoting sustainable construction with information**

Government policy measures have played a role in promoting sustainable construction in the supply of information through demonstration projects, design tools and performance results of new technology. The supply of information reduces the time required of design professionals to research a new technology and is an approach to control liability of technology failure. For a list of tools that are available to designers to assist in the design of a “green” building see Carlisle el. (2004). A comprehensive listing of “green” building case studies in North America is available at USGBC (2004b) and projects specific to British Columbia, Canada at Green Buildings BC (2004) to review the selection and performance of environmental technologies in the context of a whole building. In order to promote sustainable construction and transform the marketplace, many countries have developed building assessment methods to evaluate what constitutes a “green” building. A comprehensive list of building assessment methods and a relative comparison of each of their attributes is available at www.auspebbu.org. In the past few years the number of tools to aid design professionals has increased and the use of these tools is becoming more mainstream in the construction industry.

1.8.3 **Promoting sustainable construction with mandatory requirements**

Government entities are also starting to initiate sustainable construction programs and making mandatory requirements for buildings to be certified relative to building assessment methods. For example, the City of Vancouver was the first North American municipality to adopt the LEED® Silver protocol for 30 acres of a proposed development
project. Federal government entities including Public Works Government Services
Canada (PWGSC), the Canadian department responsible for the construction of federal
buildings, requires that all new or retrofit projects greater than 10,000m² aim to be
LEED® Gold Certified. The U.S. federal government entity, General Services
Administration (GSA), also requires that all new GSA building projects must meet
criteria for basic LEED® certification.

1.9 Value systems of key stakeholders

The design and construction of a multi-unit residential building is a complex process with
the involvement of multiple decision makers with various interests. It is common for the
values of direct stakeholders (i.e., developer, design professional, contractor, end user)
involved in a construction project to conflict. Conflicts can particularly heighten when
the interests of third party stakeholders (i.e., special interest groups, government) are
involved. Each stakeholder has different interests and the value they place on
performance measures in a technology evaluation process, and their decision whether or
not to implement the technology, may vary depending on their objectives. Project success
for some organizations such as a government entity or publicly shared company may
include environmental objectives as part of the primary decision criteria while other
organizations may be solely motivated by the bottom line. The framework introduced
herein serves to formalize the treatment of stakeholder value systems and the
performance measures impacted that are of interest in the decision making process of
technology adoption. The principal stakeholders involved in the selection of a new
technology and their value systems are described below and their perspective of green
roof technology is discussed in Chapter 3.
1.9.1 Policy Makers

The perspective of a policy maker is typically one that includes environmental goals as part of project success. In order to determine the societal impact of a policy on a local or global scale, it is necessary for policy makers to consider its cumulative effect over all projects of similar type or which are amenable to the technology being considered. Hence, output from the framework for a single project of a particular type becomes input into a larger decision framework that attempts to address the cumulative impact of incorporating a given technology on one segment of the building stock for a given region. If this impact is desirable and substantive, then government, using results from application of the framework, can identify policy instruments for encouraging the private sector to adopt the technology, if it is not justifiable in economic terms at the individual project level.

1.9.2 Government Organizations

With respect to building or commissioning the design and construction of facilities for its own use, government bodies or public sector organizations have a complex agenda to fulfill that requires them to be innovative and perform in an environmentally and fiscally responsible fashion. They may therefore see their facilities as playing a lead role in the introduction of new environmental technologies to the building industry, provided that a thorough evaluation shows promise for the technology. The primary objective of a government organization is that the cost of a building is within the capital budget and environmental objectives set out at project initiation were met.
1.9.3 Developers

The perspective of developers, who are investors in a project with the goal to sell the product to an owner/occupant or to operate and maintain it over the long term, is at the individual project level and adoption of a technology must be justified at this level. Some developers do not believe the investment in sustainable technologies is justified. Peter R. Smith, President of the New York State Energy Research and Development Authority pays developers $500 for each unit to install high efficiency appliances and said “If the developer is not going to live there or benefit from the lowered operating costs, then sometimes it is harder to persuade them to make the investment" (Greenclips, 2004). The developer determines project initiation, financing, form and function of the building, its delivery schedule, quality and sale, lease or rental terms. Environmental features may not be considered economical to include in a project where the primary objective is to maximize the net present value (NPV) of the project cash flow.

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Table 1.1 Multi Unit Residential Developer Interest in Sustainable Technologies.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Developer Interest</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building Structure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Buffer Zone</td>
<td>No</td>
<td>Not familiar with technology</td>
</tr>
<tr>
<td>Thermally Broken Balconies</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td>Airtight Drywall Approach (ADA)</td>
<td>Yes</td>
<td>Implemented on most projects</td>
</tr>
<tr>
<td>Mineral wool Based EIFS</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td>Spectrally Selective Glazings</td>
<td>N/A</td>
<td>Not residential</td>
</tr>
<tr>
<td>Low conductivity Window Frames</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td>Inert Gas Window Fills</td>
<td>No</td>
<td>Controversial, believe gas disappears with time</td>
</tr>
<tr>
<td>Warm edge Windows</td>
<td>N/A</td>
<td>Not familiar with terminology</td>
</tr>
<tr>
<td>Aerated Concrete</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td>Transparent Insulation</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td>Engineered Wood Products</td>
<td>Yes</td>
<td>Selective, typically finger jointed studes</td>
</tr>
<tr>
<td>High Volume Fly Ash Concrete</td>
<td>Yes</td>
<td>Interested in pursuing further</td>
</tr>
<tr>
<td><strong>Finishes and Furnishings</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straw Particleboard</td>
<td>No</td>
<td>Hard to find, not a typical available product</td>
</tr>
<tr>
<td>Low emission adhesives</td>
<td>Maybe</td>
<td>Interested in pursuing further</td>
</tr>
<tr>
<td>Formaldehyde-free MDF</td>
<td>Maybe</td>
<td>Interested in pursuing further</td>
</tr>
<tr>
<td>Linoleum Flooring</td>
<td>Yes</td>
<td>Subjective, typically no because residential and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>higher end product utilized</td>
</tr>
<tr>
<td><strong>Heating and Cooling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water loop Heat Pumps</td>
<td>No</td>
<td>Not very interested in these technologies since</td>
</tr>
<tr>
<td></td>
<td></td>
<td>each is considered an aggressive solution with a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long pay back period</td>
</tr>
<tr>
<td>Radiant Heating and Cooling</td>
<td>Maybe</td>
<td></td>
</tr>
<tr>
<td>Low Nox Burners</td>
<td>No</td>
<td>Expensive</td>
</tr>
<tr>
<td>Comb. Space and Water Heaters</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Recuperative Gas Boilers</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Direct Contact Water Heaters</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Geothermal Heat Pumps</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td><strong>Plumbing and Water Heating</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cisterns/Rainwater Harvesting Sys</td>
<td>No</td>
<td>Rainwater harvesting is of interest</td>
</tr>
<tr>
<td>Grey water Recycling</td>
<td>No</td>
<td>Cant’ find interest &amp; potential health concern</td>
</tr>
<tr>
<td>Grey water Heat Recovery</td>
<td>No</td>
<td>Payback period is too long</td>
</tr>
<tr>
<td>Solar Hot Water Pre heaters</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>Wastewater Treatment</td>
<td>No</td>
<td>No comment</td>
</tr>
<tr>
<td><strong>Load Management</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Automation Systems</td>
<td>No</td>
<td>Application is of interest</td>
</tr>
<tr>
<td><strong>Electricity Production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cogeneration</td>
<td>N/A</td>
<td>Commercial application for each of these</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>N/A</td>
<td>electricity production options</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Building Integrated Photovoltaics</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Site Services</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced grass paving systems</td>
<td>No</td>
<td>Debate on the resistance of the system over time</td>
</tr>
<tr>
<td>Roof Top Garden</td>
<td>Yes</td>
<td>Installed a small trial size roof garden on a project</td>
</tr>
<tr>
<td><strong>Motors and Equipment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Energy Elevators</td>
<td>No</td>
<td>Too expensive</td>
</tr>
</tbody>
</table>
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residential high-rise project. A description of the interaction of the technology with other building systems (enclosure, substructure, superstructure and mechanical) and life cycle phases follows and demonstrates both the complexity of the technology and the tangible and intangible impacts.

Chapter 3 includes a comprehensive assessment and application of the framework. The framework is applied to compare green roof technology performance in wood frame low-rise and concrete high-rise multi-unit residential buildings. From a communication perspective the framework is intended to provide a means for all levels of decision-makers to share their concerns and findings and promote dialogue to foster appropriate risk allocation at the outset of a project or before use of the technology is mandated. Consequences of the technology implementation, performance and uncertainty over the life of the project are assessed through interviews with project stakeholders; a public authority, developer and architect to both enrich the framework and assess potential issues of consensus and disagreement. Performance objectives impacted by implementation of a green roof technology that are of significant interest from the perspective of a stakeholder with profit maximization objectives are presented. A set of indicators is introduced to develop order of magnitude estimates of performance measures. The results of this analysis reflect the diverse value systems of the stakeholders involved in a building project and the relevancy of the decision context, such as building type, in the selection of technologies. It was found that the performance of green roof technology was dependant on the building context and objectives of the decision maker.
Finally, the concluding chapter (Chapter 4) presents a summary of findings and key recommendations for future research. These are directed toward enhancing the sustainable technology evaluation framework and assisting building sector stakeholders in selecting appropriate sustainable technologies in building projects and improving the policy development process. A selection of websites considered useful to researchers looking at technology evaluation and sustainable construction practices is presented in Appendix A. The framework results from consultation with industry professionals evaluating green roof technology is presented in Appendix B and finally a list of performance measures used in the framework and definitions is presented in Appendix C.
1.11 Bibliography


CHAPTER 2

Assessing the performance of sustainable technologies for building projects

2.1 Introduction

The construction, operation and the maintenance of buildings have a significant impact on the environment. The Buildings Group, one of the Research and Development groups of the CANMET Energy Technology Centre (CETC 2002), estimates the building industry consumes more than 50% of Canada’s primary resources, is currently responsible for 35-40% of total national energy consumption and generates 25% of the country’s solid waste. Recognizing that good construction practices contribute to sustainable principles, sustainable construction was first defined by Kibert at the First International Conference on Sustainable Construction in 1994 as: “the creation and responsible maintenance of a healthy built environment, based on resource efficient and ecological principles” (CIB Publication 225 1998). Technology is defined for the purpose of this paper as materials, components or systems of a building that contribute to its function and design requirements. One avenue through which the building industry is initiating the application of sustainable development principles in the design, construction and operation of buildings is in the replacement of traditional technologies with technologies that have a reduced ecological, health and environmental life cycle impact. Sustainable technologies include, but are not limited to, green roofs, high volume fly ash concrete or grey water recycling systems; see http://www.advancedbuildings.org/ for a list of current environmental technologies and practices for commercial and multi-unit...
residential buildings. The terms “environmental” and “sustainable” technologies are used interchangeably in this paper, and in general are considered innovative in nature. This paper contributes to the development of improved analytical tools for the assessment and selection of appropriate environmental technologies in buildings. The application of the framework introduced in this paper is intended to contribute to informed decision-making as it pertains to the selection of environmental technologies. Throughout this work we take the position that potential users (e.g. owners, designers, etc.,) of environmental technologies are forward thinking or have long-term business objectives after sales. We therefore characterize their objectives as profit satisficing rather than profit maximizing because they make tradeoffs between profit maximization and other criteria such as long term reputation, which in turn can create future opportunities.

The selection and implementation of new technologies and techniques in a building project can have significant implications for long-term costs, performance, and owner/investor satisfaction. It is necessary that technology selection decisions be based on a clear understanding and proper evaluation of the full range of implications associated with it. Many managers in engineering and architecture choose to intuitively derive such decisions using their own perceptions of established professional practice and organizational history (deMonsabert et al. 2003). This method of decision analysis is common not only for design professionals but also for other stakeholders involved in the construction of a building. The approach is problematic not only because individuals may introduce bias because decision making is based on only one issue but also because the
process is not systematic in terms of considering the totality of influences on all systems and life cycle phases.

Currently, designers, regulators and constructors interested in adopting environmental technologies in the residential market have no comprehensive evaluation approach to review their technical feasibility, social, environmental and economic implications at the project level. An effective evaluation tool for green building technologies is needed because traditional models, such as financial models, inadequately assess the subjective benefits associated with these technologies (Sawers 1998). The framework introduced in this paper is of direct interest to both private and public sector entities involved in assessing environmental technologies, owners, and developers, as well as to policymakers in framing legislative incentives. Its purpose is to provide an evaluation method to assist decision makers in systematically identifying and evaluating the implications and relative merits of environmental technologies from a holistic perspective. Due to increased interest in sustainable project delivery, there has been considerable pressure to install environmental technologies in buildings prior to evaluation of their full life cycle implications, which could create problems in the long term or set back efforts to encourage the adoption of sustainable technologies. Application of the framework is intended to contribute to improved decision making and the rational selection of new environmental technologies and techniques, by addressing project performance from environmental, social, economic and technical perspectives. Its use is illustrated by way of the assessment of green roof technology for a multi-unit residential building. However, the framework is applicable to any type of building (residential, commercial, institutional,
industrial). Green roof technology has been selected because it demonstrates the multiple dimensions of a technology and the potential impacts on other building systems.

The remainder of this paper is structured as follows. First, we present a brief discussion of the increasing interest in sustainable construction and the motivation for the adoption of environmental technologies in projects. Next, we review the current state-of-the-art in terms of technology assessment methods and frameworks available to evaluate new technologies in buildings. The framework envisioned for the technical, social, environmental and financial evaluation of environmental technologies from multiple perspectives is then described, followed by its application to the evaluation of green roof technology with emphasis on how impacts differ depending on the decision context. The paper concludes with a discussion of the broader applications of the framework.

2.2 Motivation for sustainable construction

The installation of environmental technologies in buildings is becoming more and more common with the increased market awareness, popularity and client interest in green buildings and design. In response to growing public interest and awareness, there has been an ever increasing number of reference documents produced to guide decision makers in the creation, design and construction of buildings with improved environmental performance which are referred to as green buildings. Numerous building assessment methods have been developed for use in the construction industry with the primary objective being to increase market demand for green buildings. Benefits cited by Bosch and Pearce (2003) of such buildings include energy, water and other resource savings over the building life cycle, and the opportunity to reduce capital infrastructure
costs and environmental liability and impact. Other benefits observed by Bosch and
Pearce are that green buildings improve academic performance and student behaviour in
schools, increase employee satisfaction, productivity, health, and retention, and reduce
absenteeism in the workplace. Sustainable technologies that are focused on maximizing
operation efficiency, reducing waste and improving the environmental quality of the
structure are viewed as elements of a green building.

Although the construction industry in its broadest sense (owners, developers, designers,
contractors, etc.) is traditionally conservative in adapting new technologies (Kua and Lee
2002), the increased interest in environmental building assessment tools has provided
impetus for the employment of sustainable technologies. In the United States for
example, more than 15 states, cities and jurisdictions, have developed green building
programs. Public and private entities offer financial and regulatory incentives to make
building green more attractive including tax credits, grants for energy modeling,
commissioning and related costs, preferred zoning considerations and expedited permit
reviews (USGBC 2003a). Jurisdictions in Canada appear to be following suit, indicating
that environmental protection has become a key political and socioeconomic issue. The
provision of incentives suggests that some sustainable technologies in their current form
may be economically unattractive at the individual project level or that the environmental
benefit of the sustainable technology to society as a whole is valued greater than the cost
of the incentive, and hence the need to subsidize it.
All building assessment tools developed so far do not address the fact that the objectives of policy makers may not always coincide with the profit maximizing goals of developers and designers (Chau et al. 2000) or indeed those of the end users who must invariably pay for any increased costs. The application of sustainable construction by both the private and public sector helps meet the policy goals of public entities because they have a commitment to protecting the environment, improving the quality of life and promoting sustainability in the community. For example, green roof technology can reduce ambient urban temperatures therefore mitigating the urban heat island effect. Reducing the urban heat island effect directly contributes to reduced ozone creation and in turn reduced human health costs associated with smog. This benefit would be of primary interest to public entities who are responsible for public safety and not necessarily to individual firms whose interests rest in profit satisficing. Public entities appear to benefit the most of all the stakeholders involved from the adoption of sustainable technologies in building projects. Therefore, sustainable technologies may be desirable from the perspective of society due to their superior environmental performance relative to their traditional alternatives, but they may be undesirable from the perspective of an individual firm who may have conflicting objectives.

The construction industry is not free from crises that include liability due to construction defects and adverse environmental health impacts such as building envelope failures and related mould growth. Consequently, many decision makers are hesitant to adopt additional uncertainty associated with the performance and cost of a new technology, as well as to assume the responsibility or liability of failure. Even if one can assume that
risks associated with life cycle performance can be translated and accounted for in dollars, impact on schedule and reputation, the risks associated with the innovative nature of the technology remain, i.e., risks relative to technology failure or reduced performance with respect to such issues as durability, mould and leaking.

2.2.1 Building technology assessment tools

As the construction industry has become increasingly aware of the environmental impact of buildings, much work has been carried out over the last decade to develop environmental assessment methods to evaluate buildings over their life cycle. The UK Building Research Establishment Environmental Assessment Method (BREEAM) developed in 1990 is the world’s most widely used means of reviewing and improving the environmental performance of buildings (Building Research Establishment 2002). It is the source of inspiration for the development of many building assessment models around the world. In the USA, the US Green Building Council (USGBC) introduced the LEED® 2.1 Leadership in Energy and Environmental Design Green Building Rating System™ for the assessment of new and large renovations of institutional, commercial and high-rise residential projects (USGBC 2003b). The Canadian Green Building Council (CaGBC) is currently developing a national LEED™ Canada tool, an adaptation of the USGBC LEED® to Canada. In Hong Kong, the Building Environmental Assessment Method (HK-BEAM) has been developed based on a modification of BREEAM. A model created to measure building performance relative to a range of environmental criteria is the Green Building Tool (GBTool). It was developed as part of the international cooperative of 20 countries for the Green Building Challenge Process to test the performance of building designs in each country (Green Building Information
Centre 2004). Other countries, including France, Australia, Norway, Sweden and the Netherlands have been creating their own assessment systems. The metrics of each of these building assessment methods focus on environmental performance, primarily during building operation, for example energy use, water use, green house gas emissions, and stormwater runoff (Cole 2000). While important, such metrics constitute only a subset of the concerns of those that design, construct, operate and maintain buildings and who warrant performance.

Although these assessment models attempt to evaluate the environmental performance of buildings, there are very few studies in North America that quantify the actual lifecycle benefits and costs of a building technology at the project level. This can be attributed to the lack of comprehensive data and methods available to value externalities such as the reduced ecological, health and environmental life cycle impacts associated with green buildings. The David and Lucille Packard Foundation (2002) reports the life cycle costs of six designs that increase in increments of “greenness” as assessed by the design team. The study highlighted the change in cost measured by net present value (NPV) and the effect on construction schedule for each building type. Given the state-of-the-art at the time, the findings are that both cost and schedule are impacted negatively and external costs to society are impacted positively with each increment of “greenness”. The report prepared for the Portland Energy Office evaluates the first cost and life cycle costs associated with changing the original design of three city buildings in order to qualify under the LEED® approach (Xenergy, Inc., SERA Architects 2000). The costs and benefits of the green options are assessed from the perspective of the city as the direct
operator/owner of the buildings. The costs and benefits from a societal perspective, which include air pollution and health impacts, are also assessed. The study finds that the original construction cost would have increased for two of the three buildings by 0.3% and by 1.3% for the other building and the lifecycle costs to the city would have decreased for each building relative to the base building. One recommendation highlighted in the study includes the development and implementation of incentives to encourage green building practices because of the perceived long-term benefits to the city and society at large. The report to the State of California Sustainable Building Task Force is the most definitive cost benefit analysis of green building ever conducted (Kats et al. 2003). The study accounts for not only the direct financial benefits to the building owner/operator such as energy, waste and water savings but also the benefits to the state of California as a whole that are relatively uncertain and difficult to measure including productivity and health benefits. Even though this is the most comprehensive compilation of valuations of green building benefits and costs, the report highlights the limitations in available data and analysis. In addition, the importance of identifying adverse interactions with green building technologies and the need to create corresponding risk management reduction protocols to mitigate risks is identified. All three studies show that green buildings incur a “green premium” above the costs of standard construction and that the benefit is greatest for public entities because they have an explicit responsibility to be concerned with broader societal goals. The primary findings of these studies indicate that construction of green buildings results in both incremental costs to the project and benefits to society as a whole.
There are a number of reasons for so few reports on the benefits and costs of green buildings. In part, this is due to the inherent ambiguity and uncertainty associated with quantifying their benefits. Some benefits are easily measured such as energy, water and wastewater savings while other benefits such as improvements to productivity/health and reduction of energy peak demands are less predictable. Our knowledge is still incomplete and especially so when trying to predict performance. Becker (1999) notes that despite the vast knowledge accumulated in the fields of ergonometrics, human needs, human factors engineering, architectural design, structural analysis, building physics, energy analysis, building materials and durability analysis, this knowledge is not applied systematically during the building process. Policy makers therefore face a fundamental dilemma today in matching the sustainable development goals that benefit society as a whole with the available data and information to substantiate their green building policies.

The evaluation of new systems and technologies has been approached from several individual points of view, such as financial, environmental or technical. Sawers (1998) applies decision matrices as a methodology for designers to compare among design alternatives so that subjective factors such as competitive advantage, improved management information or strategic alignment are included in the analysis in addition to the objective economic criteria traditionally considered. Although the approach does not identify project objectives, it illustrates how attributes can be structured into a value hierarchy where each attribute is weighted according to its importance relative to other attributes from the perspective of the stakeholders. A methodology to identify
technologies that have the greatest impact potential on a building program by Chang et al. (1988) may be of interest to owners of large building inventories. This paper illustrates a preliminary screening step to filter out innovative technologies with little benefit to the owner from further analysis based on the cost/benefit, risk and feasibility impact assessment approach introduced. Chao and Skibniewski (1998) introduce a fuzzy logic based risk-incorporating approach in which they identify the need to address the inherent aspect of risk associated with replacing an existing technology with a new one. The traditional approach compares and selects alternatives with financial models (Russell and Arlani 1981).

Three classification systems, by Becker (2002), Lutz et al. (1990), and Foliente et al. (1998), were developed based on the assumption that the technical performance of all building systems can be described by a list of technical attributes. Table 2.1 is a compilation of the attributes identified by these authors. The methodology by Becker (2002) is a performance-based approach that evaluates and identifies faults of innovative materials, systems and details. She asserts that existing standards and regulations, which are based on traditional conventional building practices, are inadequate for the formal assessment of new systems that facilitate accelerated construction methods. The technical criteria identified pertain to safety, serviceability, integrity, tightness, durability of building components and building details and health, comfort and serviceability of building spaces. A comprehensive list of corresponding performance requirements is also available in Becker (2002). The approach identifies whether the Ministry of Construction and Housing of Israel can implement the system to produce a building that meets the
minimal performance requirements considered as essential for proper living conditions. The performance based investigation process offers evaluators the opportunity to reveal drawbacks of the new technology and develop solutions prior to implementation or identify economic feasibility and inherent risks of the technology. Lutz et al. (1990) applies his methodology to the evaluation of a new exterior enclosure building system where all technical sub-attributes applicable are evaluated relative to each subsystem such as the finish, wall, insulation, door and window. The evaluator notes all potential interactions that arise to determine which of the technical sub-attributes of the innovative technology are relevant to review with respect to each subsystem. Similar to the approach by Lutz et al. (1990) the Performance Matrix developed by Foliente et al. (1998) evaluates each of the attributes relative to building systems of the whole building. The approach is performance-based and it is noted that the attributes given are not comprehensive but one version of the Performance Matrix. Environmental attributes are introduced in this methodology. The framework for sustainable technology performance evaluation introduced in this paper is consistent with the matrices of Foliente et al. (1998) and Lutz et al. (1990) because they recognize the importance of building interactions in technology evaluation.

Specific sustainability criteria such as the minimization of material and resource use and the protection, restoration and enhancement of the local environment are not explicitly accounted for as attributes in Table 2.1. Baetz and Korol (1995) develop an evaluation process to compare technical alternatives from a sustainability perspective to address the concern that professionals designing for sustainability are required to understand more than traditional engineering economics, technical, health and safety issues in the
comparison of project alternatives. The list of sustainability criteria developed, based on principles of natural ecosystems, includes: integration, synergy, simplicity, input and output characteristics, functionality, adaptability, diversity and carrying capacity. These qualitative criteria are intended to stimulate engineers to consider issues that may not be considered in a traditional engineering analysis, which typically involves solely technical and financial issues. An alternative environmentally based approach is the identification of the environmental impact of buildings and their components. A summary of selected environmental assessment tools and methods for the selection and comparison of building products based on metrics including economic and environmental criteria is compiled by Jönsson (2000).

Interest by the insurance and risk management communities has resulted in literature related to risk management and insurance loss reduction for building technologies and techniques that use energy more efficiently or supply renewable energy (Vine et al. 1998; Mills 2003a; Mills 2003b). The fundamental barriers associated with the implementation of these specific technologies and their insurance loss-prevention benefits are addressed in this literature. Insurance agencies interests in energy efficiency and renewable energy are motivated by (1) loss prevention benefits (2) benefits from facility energy management and (3) an interest in maintaining a reputation as forward thinking relative to their competitors (Mills 2003a). An energy efficient technology with loss-prevention benefits is the installation of energy efficient windows, which reduce energy loss, the likelihood of breakage due to fire and enhanced occupant comfort (Mills 2003a). Selected barriers identified by Mills (2003c) to increased insurer involvement in the
implementation of these specific technologies are the lack of quantitative documentation of benefits, adverse side-effects of improperly applied technologies, regulatory hurdles to innovation and rate changes, adversarial history between environmentalists and industry, and the perception that efficiency is being used as a 'Trojan horse' by climate change advocates. The insurance industry has identified the need for better quality assurance, greater sophistication in the application of advanced technologies and greater adherence to codes and standards (Mills 2003c). Therefore although sustainable technologies are implemented to maximize environmental performance of a structure it is seen as dangerous to adopt a new technology without assessing its technical feasibility, integration within the structure and existing systems and effect on the basic project principles i.e., risk, cost, quality and schedule.

2.3 Technology evaluation framework

Our framework is intended to be a valuable tool that will help design professionals, regulators and government entities evaluate a technology's performance over the life of a project. It represents an integration and extension of previous work by others (Becker 2002), (Lutz et al. 1990), and (Foliente et al. 1998). From a communication perspective the framework provides a means for all levels of decision-makers to share their concerns and findings. As well, it helps to promote dialogue amongst different stakeholders to foster appropriate risk allocation at the outset of a project or before use of the technology is mandated.

At the operational level, professionals working in the architectural and engineering disciplines must make decisions on whether to recommend a new technology or not. The
request for adoption of a new technology could be initiated by the client, internally within
the organization or at the request or directive of a government entity. The framework
provides a logical structure for applying sustainability concepts and relevancy of the
technology to the construction process and final product. Further, before government
mandates the use of a new technology for sustainability purposes either through code
provisions or through permit requirements, or structures incentives for the adoption of a
new technology, a comprehensive assessment of the performance of the technology and
implications for its intended usage should be carried out. The framework provides a tool
for doing so.

Our framework, utilized from the individual project perspective, is founded upon four
guiding principles.

1. A building system is considered not as an isolated entity, but as a system possibly
   having implications on other systems within the building as a whole.

2. The framework must be capable of reflecting the diverse value systems
   (performance measures of interest and relative weightings) of the stakeholders
   involved in a building project.

3. The uncertainties and risks inherent in the technology being evaluated, whether
   novel or long standing, must be explicitly considered.

4. Performance over the total life cycle of a building project must be considered.

With respect to the foregoing, it is noted that a considerable amount of client
dissatisfaction can arise despite the exercise of explicit quality control with respect to a
particular technology, because reasons for underperformance often relate to the total
building performance rather than to the individual components and materials (Ang and Wyatt 2001). The evaluation process of a new technology or technique must therefore be seen as part of an integrated approach to building design and construction. Also, the values of direct project stakeholders may conflict (i.e., developer, designer, contractor, end-user), and these conflicts may be exacerbated when the interests of third party stakeholders (i.e., government, various interest groups) are taken into account. Conflicting value systems of an organization and society may result in different decisions on whether or not to implement a new technology. For example, an organization’s primary decision criteria for technology selection may be based on its impact on the project budget while environmental benefits, which may be of primary interest to the public entities, are secondary decision criteria. Formal treatment of a broad range of performance measures and values systems could serve to lessen conflicts through mutually agreed upon trade-offs, or assist in setting rational policies regarding the adoption of new technologies.

It was necessary to understand the viewpoints and motivations of the potential users of the framework in its creation. The perspective of a policy maker must be one that facilitates both project success and sustainability. In order to determine the societal impact of a policy on a local or global scale, it is necessary for policy makers to consider its cumulative effect over all projects of similar type or which are amenable to the technology being considered. Hence, output from the framework for a single project of a particular type becomes input into a larger decision framework that attempts to address the cumulative impact of incorporating a given technology on one segment of the
building stock for a given region. If this impact is desirable and substantive, then government, using results from application of the framework, can identify policy instruments for encouraging the private sector to adopt the technology, if it is not justifiable in economic terms at the individual project level. With respect to building or commissioning the design and construction of facilities for its own use, government bodies or public sector organizations have a complex agenda to fulfill that requires them to be innovative in nature and perform in an environmentally and fiscally responsible fashion. They may therefore see their facilities as playing a lead role in the introduction of new environmental technologies to the building industry, provided that a thorough evaluation shows promise for the technology. The perspective of developers, who are investors in a project with the goal to sell the product to an owner/occupant or to operate and maintain it over the long term, is at the individual project level and adoption of a technology must be justified at this level. Thus, the performance variables that come into play for decision making are dependant on the viewpoint taken – all are accommodated in the framework presented.

All parties involved in implementing an innovative technology for a building project incur the risk of technology non-performance and related consequences. Given the considerable time and cost pressures faced by the construction industry coupled with the extreme difficulty posed by a lack of data for predicting long term performance of a new building technology as a function of its interface with other technologies, operating environment and maintenance policy, there can be considerable uncertainty surrounding one or more of the performance measures for the technology. Consequently, it is
imperative that such uncertainties be quantified to the extent possible for the total project life cycle for key performance measures, and risks appropriately allocated, assuming they are bounded. A framework that assists design professionals in evaluating a new technology from various perspectives including potential risks will therefore aid in performing the care and diligence required by their profession.

Two assumptions underlie the development of the framework as presented herein. First, in developing the technology framework, we have focused mainly on multi-unit residential housing, from low rise to high rise buildings because they represent a significant portion of the construction market in the building sector. Nevertheless, the framework is generally applicable to almost any building type. Second, we assume that a comparator is available in the form of a ‘standard solution’, or the currently generally accepted state-of-the-art. The comparator consists of the costs and benefits associated with this solution, along with corresponding performance measures (i.e., energy consumption, durability, etc.) Later, when we demonstrate application of the framework to an example, for phase one of the framework, we will assume that preliminary screening of the example technology has been done in terms of technical and regulatory feasibility (i.e. will it work and will it be permitted), and that sufficient tradeoffs between incremental costs and benefits exist thus warranting more intense scrutiny of the technology.

Underlying the framework are three constructs: (a) a three dimensional structure that treats the physical systems/components that make up a building project (the x axis) major
phases that comprise the life cycle of a project (the y axis), and the spectrum of quantitative and qualitative performance measures, grouped by class, that describe how a project, or component of a project will behave (the z axis); (b) a hierarchical structure of performance measures that corresponds to the z axis in (a), which captures the behaviour of the technology directly within the context of the individual project, plus its impact on the surrounding environment; and a value system in terms of the weights accorded to the various performance measures, including the decision makers aversion to risk; and, (c) a cash flow model that treats all incremental benefits and expenditures over the project’s life cycle, or time frame of interest of the decision maker. Complementing these constructs are the normal design and analysis tools used to forecast performance parameters (e.g., computation of energy consumption, sizing of components, estimation of costs, etc.).

Figure 2.1 presents the 3-D structure of physical component versus life cycle phase versus performance measure class and component. Each applicable ‘cell’ in this figure requires that the class of performance measure or individual measure within a class be assessed for the corresponding building system/component and life cycle phase. The granularity of this figure changes as one moves from preliminary screening to detailed assessment of a technology. For example, initially one would focus on the systems affected at the overall system level, but in a more detailed assessment, a system would be broken down into its various components in order to allow a more detailed examination of the interaction of the technology with building components. This is illustrated later in
Figure 2.3 when an example dealing with green roof technology is provided to illustrate application of the framework.

Table 2.2 contains a partial list of the performance measures we believe should be considered. They are organized first by class (e.g., technical, economic, environmental, etc.), then by individual measure within a class. Each performance measure can be further characterized as to the nature of its impact on the physical component/life cycle phase being considered (+/-) and on the surrounding environment/infrastructure (+/-), its significance in terms of decision making (critical, non-critical), how it is measured (e.g., pass/fail), degree of uncertainty, and whether it is a tier 1 or tier 2 measure. A tier 1 measure is a basic performance measure derived as a function of the physical properties of the technology or component affected by the technology, and overall project context; a tier 2 measure is derived from tier 1 measures and other design parameters, and relates mostly to economic measures such as capital cost, life cycle cost, etc. Tier 2 measures provide a means of synthesizing a number of metrics across one or more life cycle phases and building systems into a single measure. Thus, the measures cannot be considered to be independent of one another when making the final decision. The listing provided in Table 2.2 incorporates many of the measures suggested by others (Table 2.1), and as presented, is incomplete in terms of the full spectrum of measures that could be employed. Depending on the perspective of the user, different weights can be assigned (not shown in Table 2.2) to the various performance measures, thus capturing the user's value system. What is important, however, is that the assessment of each performance metric be made as objectively as possible, and as noted by way of the suggested
properties of performance measures, in some cases, considerable uncertainty surrounds the forecast value of a performance measure, and the formal treatment of risk in its estimation should be considered. Finally, when evaluating performance measures such as life cycle cost that incorporate other measures dealing with technical, economic, and time performance (e.g. energy consumption, system capacity, unit costs, inflation rate), consideration of the timing of the flows of benefits and costs is vital. Thus, Figure 2.2 shows the third construct in the form of an abstracted cash flow diagram that spans all phases of the project life cycle. Shown on this diagram are duration (t) and overlap (f) factors (f = 1 corresponds to no overlap of the current phase with the next phase, f = 0 corresponds to total concurrency) that may be affected by the adoption of a technology, and hence its attractiveness. The increment in cash flow in each phase (pre-tax and after-tax) is determined by assessing which components of the project are affected, and for each phase, summing all contributing flows to achieve the total incremental flow for that phase. Both direct and indirect costs should be included (including increments to insurance, etc.) Depending on the viewpoint of the decision maker, not all phases shown may be considered in assessing the technology.

Application of our framework involves a multi-phase process. The first phase deals with preliminary screening, and involves an evaluation at a relatively aggregated or coarse level both in terms of the physical systems affected (i.e. one does not drill down to the individual component level), and performance measures considered. Use is made of order of magnitude estimates and pass/fail judgements for critical decision criteria to see if the technology holds promise in terms of technical and regulatory feasibility, and
incremental costs and benefits. If the technology successfully passes through this screening phase, then more detailed analysis along with some preliminary design is undertaken, and a broader spectrum of performance measures is considered. The evaluator follows a series of filters to screen the technology to determine whether it should be eliminated from further consideration based on its’ associated impacts. An overview of the phases involved in the sequential screening process is detailed in Table 2.3.

2.4 Application of the framework - green roofs

To demonstrate the framework introduced herein, the evaluation of an intensive green roof is presented. An introduction to the technology follows and the framework is applied to illustrate the multitude of impacts a green roof has on a project. The judgements made in the technology evaluation are bounded by the context of the decision including the geographical location, climatic condition, and political environment amongst others. No attempt has been made to provide quantitative estimates of either tier 1 or tier 2 performance measures. Rather, attention has been focused on the breadth of the impacts of the technology, and hence the extensive amount of information and analysis required.

2.4.1 Overview

A green roof has been defined as a “contained green space on top of a human made structure” (GRHCC 2003a). Roof gardens or green roofs are not a new concept in the construction industry. Although what can been classified as green roofs have been installed abundantly throughout urban areas, the objectives have been for aesthetics or human use rather than environmental benefit. Today, green roof technology is more than just the placement of soil and plant material over a roof membrane; it is a system with
multiple components. The basic components of a green roof system that are placed over the traditional roof membrane include an optional layer of insulation or protective layer, drainage layer, filter layer, growing medium and plant material. Green roof classifications are generally separated into two categories in the literature: extensive and intensive systems. The categories are defined based on the soil depth, plant selection and method of irrigation. Intensive roofs are typically designed such that they are accessible to the public for recreational enjoyment, have high maintenance requirements and require modification to the structural capacity of the design due to the required soil depth. The intensive green roof technology is chosen as an example for demonstrating the framework because the introduction of growing medium and plant material to the roofing system results in numerous interactions with building systems, components and materials. For example, a particular concern with this technology is the affect on the integrity of the building envelope.

The success or failure of a green roof is not only dependent on how the system interacts with other building systems, components and materials but also the appropriate selection of system components and their design details and properties, giving due consideration to climatic conditions of the region and building type. For example, selection of plant material is integral in reducing the risk of root penetration and in the performance of a green roof. Appropriate selection requires consideration of the functional purpose of the roof, the method of irrigation, the waterproof membrane, depth of growing medium and a review of climatic conditions including wind, annual rainfall and its distribution, average temperature and its extremes (Rowe 2003). Other issues to consider include the potential
for the proliferation of invasive species, weeds and disease and its impact on the green roof. Although the landscape architect typically performs the selection of the plant material, the architect, civil and structural engineer determine variables on which it is dependant. The involvement of multiple disciplines in the design, performance and selection of green roof system components illustrates the complexity of the system. The utilisation of a systematic framework to evaluate the costs, implications and interaction of system components and facilitate communication between the professions involved can reduce the risk of improper design, construction and maintenance of green roofs.

2.4.2 Application of the evaluation framework

In order to perform the evaluation, the following decision context is assumed. The intensive green roof is to be constructed on a 35-story multi-unit residential high-rise building with a typical floor plate of 8500ft² located in Vancouver, British Columbia urban centre. As noted previously, our interest herein is limited to identifying the breadth of the physical components, life cycle phases and performance measures involved. A more complete analysis would involve quantifying relevant tier 1 and tier 2 measures and associated uncertainties (which would require the specification of much more detail about our example project), and eliciting weights for these measures, which reflect the decision makers, or client's value system.

A comprehensive understanding of the technical issues and performance of green roofs can aid in the optimization of investment and evaluation of the site and cumulative benefits. Shown in Figure 2.3 is the x-y plane of our three-dimensional evaluation framework. Systems directly related to the technology are shown black, and the
consequences of adopting the technology for other life cycle phases and components is shown as shaded. Note that as we are looking at Phase 2 and beyond in Table 2.3, we advance to a more detailed analysis of individual building components. The roofing and soft landscaping building systems or components are identified as being directly impacted by the adoption of a green roof while systems within the substructure and mechanical categories are identified as being impacted indirectly in Figure 2.3. A description of the interaction of the technology with other building systems and life cycle phases follows and illustrates both the complexity of the technology and both the tangible and intangible impacts that may be difficult to quantify.

Enclosure

A green roof will impact the building enclosure at all phases of the life cycle and impose additional demands with respect to the waterproofing of the roof structure. The roof membrane is covered by the green roof components therefore perceived building risks include the potential for leakage caused by root penetration or ponding on the waterproof membrane, the difficulty in tracing the location of a leak and fire protection of dry plant material; issues related to the operations and maintenance phase. These risks are bounded however, because as a last resort, if the risks are realized, the green roof (i.e. the soil, landscaping and drainage components) can be removed. A green roof as a system involves multiple components placed over the roof membrane and is an incremental cost relative to the baseline scenario and requires the commitment of time for its’ installation in the construction phase and review in the commissioning phase. When it is required to remove the components for membrane replacement, in the removal or renewal phases, incremental costs relative to the baseline scenario are expected based on additional
resources and design considerations such as the structural loading imposed where material is stockpiled. In terms of benefits, it has been found that a green roof can help to preserve the membrane and prolong its service life by reducing heat aging and thermal stress (Liu 2003). The plant material and growing medium protect the roof membrane from exposure to environmental elements such as ultraviolet light and temperature fluctuations. Improved membrane integrity results in a reduction of the renewal rate of the roof membrane resulting in direct financial benefits, decreased wastage resulting in reduced material disposal costs, load on public waste disposal facilities. It has also been found that green roof infrastructures when cumulated over large areas can mitigate the urban heat island effect, a social benefit, by way of the evapotranspiration process (Peck et al. 1999). It is noted that a significant amount of research on green roof system components has been performed in Europe since the 1970’s; however, uncertainties remain that relate to the benefits and durability of the technology in a Canadian context (Bass et al. 2003). Research and development opportunities of green roof installations for the assessment of technical and sustainable development considerations would enhance the understanding of the technology and could be conducted at all phases of the project. Technology uncertainties may result in difficulties acquiring warranty or insurance of the green roof system or installation, which is a risk incurred by the building owner or occupant. A green roof is considered a relatively new technology in Canada; therefore, there may be a lack of availability of contractors and consultants familiar with its design and construction and impact the amount and predictability of time factors in the tendering and design phases.

Substructure and superstructure
The impact on the superstructure and substructure are a result of the increase of the overall design forces because the weight of an intensive green roof typically adds an additional load up to 400psf fully saturated on the roof system. For the building configuration being considered, this impact could be considerable. The roof slab required would be thicker and less porous therefore impacting the structural loading, and seismic requirements of the building. Structural upgrading requirements for the design and construction of the footings, verticals and horizontals in the structure would be necessary in the conceptual and detailed design phase, and the approval phase could take longer.

With respect to underground services, a green roof offers the opportunity for reduced storm water runoff and therefore wastewater volume, which could result in an opportunity, in the design phases, to change the size of the underground storm sewers for financial savings.

**Mechanical**

A green roof directly impacts mechanical systems with respect to space conditioning, water supply and wastewater disposal measurable as cost, environmental and public infrastructure benefits in the operations and maintenance phase. Installation of green roof infrastructure can reduce a building's demand on space heating and cooling and resultant energy savings through direct shading, evaporative cooling from the plants and the soil, and additional insulation values from both the plants and the growing medium (Wark and Wark 2003; Bass et al. 2003). Energy conservation provides an economic benefit to a building owner or occupant, and the associated reduction in green house gas emissions is a social environmental benefit. Also, the reduction in peak energy demand reduces the impact on public infrastructure. The growing medium and plant material can absorb rain
and therefore decrease the volume of wastewater as a storm water runoff source control mechanism. Green roofs improve quality, delay peak flow and reduce the rate and volume of stormwater runoff before it enters the sewage system and thereby decrease the demand on municipal infrastructure. Sites that pay for wastewater disposal incur a benefit for the decreased volume. For our example building configuration, the incremental benefits in terms of energy savings and decrease in wastewater volume would be modest at best.

An intensive green roof system is typically designed to allow for public access; therefore, vertical transportation would be required at an incremental cost in the construction phase relative to baseline conditions. Water supply requirements may be increased or decreased in the operations and maintenance phase depending on water reuse opportunities, plant selection and the associated irrigation requirements. A green roof can have either a positive or negative impact on fire safety depending on component selection. For example, tall grasses are often considered a fire hazard while selection of succulent plants can be fire resistant. Additional time to review regional conditions with respect to the design, specification of green roof components and review of regulatory requirements may be required in the consideration of building fire protection, water supply, wastewater disposal and space conditioning in the conceptual and detailed design phases to obtain necessary approvals.

**Finishing**

A green roof impacts the finishing requirements related to both the hard and soft landscaping. The maintenance of a green roof helps ensure vegetation coverage and the
prevention of damage to the existing building such as the puncturing of the waterproof membrane with gardening tools. An intensive green roof can require substantial maintenance including weed control, fertilization, and irrigation resulting in increased costs in the operations and maintenance phase relative to the baseline scenario. Specialized training of maintenance staff to prevent the failure of establishment of the plants and roof upkeep is also recommended in the operations and maintenance phase. The use of a green roof as a recreational amenity and its' aesthetics are benefits evaluated at the feasibility phase of the project and could result in improved marketability, reduction in the absorption period, incremental sell price and publicity of the project.

2.5 Revenue and incentives
A number of public and private entities offer direct and indirect incentives for the installation of green roofs to compensate for the additional cost of the system that helps meet local public needs. Indirect incentives, at the feasibility phase, that may be offered by a city that influence the amount or flexibility of functional space in a project include a density bonus, flexibility in zoning or satisfaction of parkland criteria and hence would impact almost all physical components, especially if it meant added floors. An accelerated approval process, grants, improved relations with city officials, acceptance of project and company reputation are other potential benefits. For our example project, it is likely that a density bonus would be required to offset the incremental costs associated with adopting an intensive green roof, as our benefits internal to the project would be difficult to quantify in financial terms. Whether or not a premium on unit prices could be extracted given the presence of a green roof has not been addressed.
The interest in construction of green buildings and perceived benefits of green roofs has resulted in numerous programs to promote the implementation of green roofs. Currently 43% of German cities have some sort of program in place to promote roof greening, through a financial support program and regulatory measures requiring roof greening (GRHCC 2003b). Despite the lack of North American standards and comprehensive understanding of the performance of green roof technology and the site specific and cumulative benefits, various North American public and private entities are adopting incentive mechanisms. For example, Portland, Oregon has initiated the Clean River Incentive and Discount Program that provides a discount on the stormwater management portion of the sewer bill for those people who manage stormwater on their property therefore reducing the stormwater runoff load on the municipal infrastructure and in Quebec, Canada the Quebec Energy Board established the Green Roof Financial Incentive Program, a $1Cdn per square foot incentive for green roof implementation directed toward advancing energy conservation (GRHCC 2003b).

Shown in Figure 2.4 is the y-z plane of our three dimensional evaluation framework to highlight the performance measures related to the roofing building system and the Phase 3 screening process in the evaluation framework. Performance measures directly related to the roofing system are shown black. For each building component or system that is impacted a table highlighting the associated performance measures and life cycle phases would be created such that these measures could be quantified.
What we have shown is how one can systematically conduct the process of identifying how a technology interacts with the physical design of a project, the project’s time phases, and the multitude of performance measures affected which bear on the final decision dealing with the adoption or rejection of the technology being considered. For our example project, which is reflective of many projects currently under development in Vancouver, it is unlikely that adoption of intensive green roof technology can be justified by tradeoffs between increased capital costs and savings in operation and maintenance costs. On the other hand, for a project of the same scale but in the form of a low rise as opposed to a high rise structure (albeit with different lot sizes), significant benefits in terms of energy savings and stormwater retention might provide a better trade-off with the incremental costs, and the environmental benefits would also be higher.

2.6 Conclusions

This paper sets forth a technology evaluation framework to address the needs of policy makers and multi-residential developers based on our understanding of the literature, interaction with individuals in development, architectural, construction and government and our own experiences. The current movement in the construction industry to more sustainable design has resulted in the consideration or requirement to install environmental technologies based on their perceived performance. The impacts of such technologies may be both complex and difficult to quantify therefore our vision of a systematic evaluation framework has been presented as a tool to justify and communicate technology selection and stakeholder objectives. As a next step to refine this framework, we will continue to consult with design professionals, policy makers and other researchers in order to ensure comprehensiveness of the approach in terms of measures to
be treated and how best to express tangible and intangible impacts. A limited number of
case studies will be undertaken with industry personnel as well as with policy makers to
illustrate application of the framework and to determine how best to incorporate the value
systems of various decision makers into the decision making process.
2.7 Bibliography


Table 2.1 Technical attributes of three classification systems.

<table>
<thead>
<tr>
<th>Becker 2002</th>
<th>Lutz et al. 1990</th>
<th>Foliente et al. 1998</th>
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### Table 2.2 Partial list of performance categories and measures.

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<td>(See Becker 2002 for a complete list)</td>
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<td>Air Quality</td>
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<td>Water Efficiency</td>
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<td><strong>Economic Impact</strong></td>
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<td>Capital cost or savings</td>
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<td>Cost in use</td>
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<td>Life cycle cost</td>
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<td>Interest cover</td>
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<td>Incentives available</td>
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<td>Zoning changes</td>
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<td>Accelerated approvals</td>
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<td>Increased density</td>
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<td>Direct subsidy</td>
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<td>Income tax treatment</td>
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<td>Reliability issues during use</td>
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<td>Reliability issues after warranty</td>
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<td>Vendor availability and support</td>
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<td>Simplicity of technology use</td>
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<td>Consequences of technology failure bounded?</td>
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<td><strong>Knowledge Management</strong></td>
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<td>Improved public awareness</td>
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<td>Learning, research and development opportunities</td>
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<td><strong>Time</strong></td>
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<td>Overlap of phases</td>
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<td>Metric</td>
<td>Impact on project</td>
<td>Impact on environment or infrastructure</td>
<td>Criticality</td>
<td>Degree of uncertainty</td>
<td>Variable type (tier 1, tier 2)</td>
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<td>Business Performance</td>
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<td>Impact on corporate image</td>
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<td>Impact on public acceptance</td>
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<td>Support of company mandate</td>
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<td>Entry into a new market</td>
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<td>Repeat business</td>
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Table 2.3 Overview of sequential screening process for technology.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Filter</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Phase 1 Preliminary Screening: Technical and Regulatory Analysis (facts) of the technology determining building systems and life cycle phases affected and critical evaluation criteria &amp; performance measures for (see Becker, 2002 for detailed list of technical performance measures) and estimate of order of magnitude estimate of balance between costs and benefits (including incentives/subsidies)</td>
<td>Filter 1</td>
<td>This preliminary analysis of the technology of interest involves a combination of order of magnitude estimates and pass/fail judgements. If the technology successfully passes through this screening process, (passage does not ensure workability), then a more detailed analysis is undertaken.</td>
</tr>
<tr>
<td>Phase 2 Screening: Technical Analysis (facts) of technology determining what physical components within each system of the building and life cycle phases are impacted. Conduct sufficient design to determine scope parameters of the technology itself (e.g. quantities, mass, etc.). Evaluate more comprehensive range of performance measures.</td>
<td>Filter 2</td>
<td>Review each of the building systems and components relative to the project life cycle phases to determine technology impacts both positive or negative. Technology may not be considered workable or eliminated based on dominance analysis relative to the baseline comparator. This phase may require more than one iteration because it is found that other systems and/or life cycle phases may be affected, or conversely, the impact may be less than initially envisaged.</td>
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<tr>
<td>Phase 3 Screening: Technical Analysis (facts) of technology identifying the performance measures impacted for the various phases in the project life cycle. Generate estimates of the performance measures and associated uncertainty. Check that required technical and regulatory thresholds on performance are met.</td>
<td>Filter 3</td>
<td>Generate estimates of performance measures including technical measures (i.e. physical measures in terms of input quantities - materials, labour, etc and output measures such as energy consumption, volume of waste water, thermal comfort, acoustics, durability, etc), time performance (e.g. design, approval, construction, ability to overlap phases), and incremental revenue sources. Flag all measures that are marked by considerable uncertainty, and quantify the uncertainty. Phase 3 Screening may require iteration back to Phase 2 as the full spectrum of performance measures involved is assessed.</td>
</tr>
<tr>
<td>Phase 4 Screening: Economic Analysis (facts) of technology to price out associated performance measures using a variety of economic performance measures.</td>
<td>Filter 4</td>
<td>Economic performance measures including capital cost, life cycle cost, net present value, etc. can be utilized as appropriate. Risk adjusted values of key performance measures is determined.</td>
</tr>
<tr>
<td>Phase 5 Screening: Value Analysis (values) of technology using technical scores multiplied by value weights.</td>
<td>Filter 5</td>
<td>Value weights are elicited from decision makers and applied to performance measures. The use of weighted performance measures helps determine where further detailed analysis is required.</td>
</tr>
<tr>
<td>Phase 6 Final Screening:</td>
<td>Filter 6</td>
<td>Final decision is made on whether or not to implement the technology by comparing with the default design approach.</td>
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</table>
Figure 2.1 Representation in 3-dimensional space for assessing new technology.
Figure 2.2 Abstracted incremental cash flow diagram.
Figure 2.3 Technology evaluation matrix: two-dimensional view of the impact of intensive green roof technology on building systems. Systems directly related to the technology are shown in black, and the consequences of adopting the technology for other life cycle phases and components are shown as shaded.

<table>
<thead>
<tr>
<th>Project Life cycle</th>
<th>Removal</th>
<th>Renewal</th>
<th>Operations &amp; Maintenance</th>
<th>Absorption</th>
<th>Commissioning</th>
<th>Construction</th>
<th>Tendering</th>
<th>Approvals</th>
<th>Detailed Design</th>
<th>Conceptual Design</th>
<th>Feasibility Analysis</th>
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</table>
Figure 2.4 Technology evaluation matrix: two-dimensional view of intensive green roof technology performance measures related to roofing building system. Performance measures directly related to the roofing system are shown in black.

<table>
<thead>
<tr>
<th>Project Life cycle</th>
<th>Performance Measures</th>
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<tbody>
<tr>
<td>Removal</td>
<td>Technical</td>
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<tr>
<td>Renewal</td>
<td>Structural Stability</td>
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<tr>
<td>Operations &amp; Maintenance</td>
<td>Economic Impact</td>
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<td>Absorption</td>
<td>Capital Cost or Savings</td>
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<td>Commissioning</td>
<td>Incentives Available</td>
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<td>Construction</td>
<td>Environmental Impact</td>
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<td>Tendering</td>
<td>Materials Efficiency</td>
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<td>Approvals</td>
<td>Impact on Public Infrastructure</td>
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<td>Detailed Design</td>
<td>Impact on Local Environment</td>
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<td>Conceptual Design</td>
<td>Quality</td>
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<td>Feasibility Analysis</td>
<td>Warranty Availability</td>
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<td>Corporate Image</td>
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<td>Impact on Publicity</td>
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CHAPTER 3  Assessing sustainable technologies: a framework and its application

3.1 Introduction

It is widely accepted that the construction, operation and maintenance of traditional buildings consume a significant percentage of the world’s primary resources and a large percentage of its solid waste. In response to these impacts, there is growing interest among organizations committed to environmental performance targets in recommending or regulating sustainable construction practices and in encouraging the construction of “green” buildings. These buildings incorporate sustainable technologies and techniques that reduce the ecological, human health and environmental life cycle impacts of the project. Although methods exist for assessing what constitutes a “green” building, there is a dearth of comprehensive broadly applicable evaluation processes that can be used to assess a priori the advantages and disadvantages of various technologies. As a result, expensive mistakes may be made and expected benefits may be overestimated. For example, the results of a performance evaluation of six high performance or “green” buildings that incorporate sustainable building technologies to help meet ambitious design targets indicated that none of the buildings performed as well as predicted (Torcellini et al., 2004). The integration of new technology resulted in failure or difficulties in each of the case study projects. Difficulty in defining metrics and the optimistic assumptions of designers were among the other reasons attributed to building

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2 A version of this chapter is ready for submission for publication in the ASCE Journal of Architecture and Engineering.

3 Sustainable or environmental technologies are defined as available and potentially available technologies that may help decrease the human pressures on the environment or natural resources while providing a desired standard of living (Kraines and Wallace, 2003).
underperformance. Such experiences confirm the need for a framework to evaluate the technical feasibility and social, environmental, and economic implications at the project level of a sustainable technology (See, for example, Nelms et al. 2005).

The comprehensive framework, introduced in Nelms et al. 2005, is described, verified and applied in this paper. The framework is designed to assist project stakeholders (i.e., builders, designers, and owner/investors) and policy makers in systematically identifying and evaluating the implications and relative merits of a sustainable technology. A desired outcome of the application of this framework is to provide a holistic rational process for thinking about multiple decision criteria and to encourage the selection of appropriate sustainable technologies with respect to the stakeholders' values and objectives. From a communication perspective, the framework is intended to provide a forum in which stakeholders may share their concerns and findings. It therefore promotes dialogue and may facilitate the appropriate allocation of risk inherent in new technologies, and the identification of suitable incentive schema.

The application of the framework is demonstrated for the evaluation of green roof technology in a multi-unit residential building. Building professionals (i.e. a public authority, designer and developer) were interviewed to test the completeness and applicability of the framework using green roof technology as the example sustainable technology. Simple models are used to illustrate how selected performance measures may be quantified to assist project stakeholders in assessing the merits of technology implementation and policy makers in identifying economic incentives. The performance
of green roof technology in each of a high-rise and low-rise multi-unit residential building of identical capacity is compared for the purpose of showing how technology performance metrics differ as a function of building context. The application of the framework illustrates that technology selection decisions should be based on a clear understanding and proper evaluation of the full range of implications of the technology.

Section 3.2 introduces the current state of the art in technology and building evaluation in addition to the interests of stakeholders involved in project delivery. This is followed by an explanation of the principles and methodology of the framework in Section 3.3. Section 3.4 presents a description of green roof technology and the perceived benefits and adverse impacts of this technology from the perspective of three project stakeholders using the evaluation framework. The application of the framework and comparison of performance estimates for two different multi-unit residential building configurations are also presented in this section. Section 3.5 provides a general discussion of the performance of green roof technology in different building contexts and how the green roof technology evaluation results can vary depending on the stakeholder and the decision context. Finally, we recommend future work to refine the framework.

3.2 Background

The growing awareness of how the building stock and its features contribute to environmental degradation has resulted in the creation of a number of building environmental assessment methods. These assessment methods have been developed in many countries to define a “green building” such as CASBEE in Japan, LEED® in the United States, LEED™ Canada in Canada, NABERS in Australia, and BREEAM in the
United Kingdom. Each method awards points for meeting performance criteria in a range of categories, typically environment-focused, such as resource use reduction and improved indoor air quality. A comprehensive list of building assessment methods and a relative comparison of each of their attributes is available at www.auspebbu.org. While the building assessment methods listed deal with the assessment of a building, there are few studies in North America that quantify the actual life cycle benefits and costs of a building technology at the project level and consider the different value systems of stakeholders involved in the building project. We have therefore identified the need for a framework to evaluate sustainable technologies because we believe that the successful implementation of the technology on a demonstration project does not guarantee its performance and success in all project contexts or with respect to differing project objectives.

3.2.1 Current state of the art in technology evaluation

The literature on technology evaluation schema is scarce although various authors have used multiple criteria approaches for evaluating technical, environmental, social and economic aspects. Few of these approaches recognize the importance of building system interaction and the integration of intangible environmental or social criteria with technical and financial measures. Nelms et al. (2005) present a synthesis of classification schema that focus on the use of technical attributes of building systems (see also Becker, 2002, Lutz et al., 1990, and Foliente et al., 1998) and develop a comprehensive framework that incorporates a set of evaluation criteria that builds on the work of various authors. Foliente et al. (1998) introduce the performance concept in a performance matrix of building systems versus attributes and include sustainability life cycle
performance measures in their approach. Becker (2002) proposes a unified method for establishing minimum performance criteria and performance grading tools for buildings. A method for evaluating the performance of a technology considering both building systems and components is presented in Lutz et al. (1990). The use of traditional financial models to optimize technology selection is found in Russell and Arlani (1981). An approach for comparing alternative technologies or methods using only sustainability criteria is introduced in Baetz and Korol (1995). The framework verified and demonstrated herein represents an integration and extension of these works and is developed to evaluate building technologies from multiple perspectives to broaden the approach beyond technical and financial evaluation to include the social and environmental measures. The framework is intended to be holistic and to include the subjective qualities inherent in sustainable technologies and reflect various stakeholder viewpoints.

3.2.2 Project stakeholder interests

Stakeholders who are impacted by technology selection have a variety of interests in traditional construction project delivery. In general, the responsible developer is interested in maximizing profits in the shortest time while building a quality product that enhances the developer’s reputation. The design professional is interested in improving his reputation and profile in industry and maximizing profit while minimizing time, input and liabilities. The public authority is interested in maximizing community socio-economic and environmental benefit. Advocates of sustainable technologies generally speak of the performance of a specific sustainable technology from a generalist perspective. For example, the advocate may state that green roof technology can reduce
stormwater runoff by ‘X’ percent, sound reflection and transmission by ‘X’ decibels, reduce the urban heat island effect by ‘X’ degree Celsius and improve outdoor air quality among other benefits. These statements may be true in whole or in part, although performance measurement and monitoring of new sustainable technologies at both the cumulative building stock and individual project levels is in its infancy in North America. And, the advocate may be stating optimistic values without consideration of important design factors that influence performance such as building context or local climatic conditions. This creates an environment where the end user expects a level of technology performance that may be unrealistic and he may be neither aware nor willing to accept the potential of technology failure. This conflict arises where environmental objectives, common in public sector construction projects, often lie outside the traditional economic objectives of a private sector development firm that aims for profit maximization and minimizing liabilities.

Each of the stakeholders views the benefits and costs of a sustainable technology differently. In Section 3.4 we describe the results of the interviews with an architect, developer, and city planner and identify the different value systems of each of these stakeholders in the context of green roof technology and the project objectives that are of common interest to all individuals interviewed. Understanding that stakeholders have conflicting objectives is an important foundation of the framework. Furthermore, application of the framework may help to address communication difficulties among the participants involved in a typical project.
3.3 Framework for evaluating technologies

The framework, introduced previously in Nelms et al. 2005, was designed to accommodate diverse stakeholder performance criteria. Thus, in order to verify the framework we solicited information from project stakeholders regarding potential risks in the technology, design, workmanship, climatic conditions, value systems, interaction with building systems and project context. The use of multiple criteria in the framework follows the principles of sustainability commonly referenced by the construction industry and defined to support sustainable construction efforts at http://www.sustainable.doe.gov/overview/principles.shtml. The use of multiple criteria should improve communication amongst stakeholders in situations where financial and technical performances are not the only project objectives. The framework can be applied to all building types and technologies.

In section 3.4, the framework is applied to the evaluation of green roof technology in multi-unit residential buildings, which currently comprise a large portion of the new residential building stock in Canadian urban centres. Green roof technology, specifically an intensive green roof, is selected because of the multiple interactions with building systems that it exhibits, the range of disciplines required for its design, construction, operation and maintenance and the range of benefits and implications for stakeholders.

3.3.1 Principles and structure of the framework

The framework is founded on four guiding principles: (a) A building system or component is not an isolated entity but a part of, and has implications on, other systems within the building as a whole, (b) The framework must reflect the diverse set of values held by project stakeholders, (c) The majority of project costs occur after the construction
and during the operation and maintenance of the building, hence performance over the
total life cycle of the project must be considered, and (d) All new and established
technologies are subject to risks and uncertainties that must be considered explicitly
relative to project objectives and individual stakeholder perspectives.

The conceptual basis of the framework is illustrated by a representation of the building
systems or components, life cycle phases and performance measures in a three
dimensional structure (see Figure 3.1). The x-axis represents the primary classes of
building systems or components of the project, the y-axis shows a universal breakdown
of the life cycle phases of the project and the z-axis shows the spectrum of quantitative
and qualitative performance measures that describe the impacts on the building
component or system and life stage of the project. Each applicable ‘cell’ in the figure
represents the performance measure evaluated for indirect and direct impacts on the
corresponding building system or component and the respective time phase. For example,
consider a cell as a representation of the performance measure ‘design forces’ under the
‘Technical’ class that is directly or indirectly impacting the superstructure at the
feasibility analysis time phase. The fineness of the cell becomes more defined as the user
moves from a preliminary to a detailed evaluation of the technology. In a preliminary
evaluation the user may identify the impacted performance measure as ‘structural
stability’ under the ‘Technical’ class and if a more detailed analysis is performed the
more specific measure ‘seismic forces’ is selected.
Application of the framework involves a multi-phase process, which is summarized in Table 3.1. The user follows a series of filters, described in Phases 1-6, in this tiered approach. This minimizes the time and cost spent on the evaluation and helps determine the degree to which the technology should be evaluated. Where stakeholders such as public authorities or developers do not have the knowledge or information to perform this analysis, the framework serves as a guide for their consultants to follow. In the preliminary evaluation, Phase 1, regulatory feasibility and pass/fail judgements on whether or not the technology may be suitable for further scrutiny is assessed. Each performance measure can be characterized as to the nature of its impact on the physical component/life cycle phase being considered (+/-) and on the surrounding environment/infrastructure (+/-), its significance in terms of decision making (critical, non-critical), how it is measured (e.g., pass/fail), degree of uncertainty, and whether it is a tier 1 or tier 2 measure. A tier 1 measure is a basic performance measure derived as a function of the physical properties of the technology or component affected by the technology, and overall project context; a tier 2 measure is derived from tier 1 measures and other design parameters, and relates mostly to economic measures such as capital cost, life cycle cost, etc. Tier 2 measures provide a means of synthesizing a number of metrics across one or more life cycle phases and building systems into a single measure. Thus, the measures cannot be considered to be independent of one another when making the final decision. If the technical, regulatory and incremental costs and benefits are considered suitable a more detailed analysis of the technology can proceed. A more detailed analysis, described in Phases 2-6, is best performed during the conceptual and detailed design phases where the project conceptual design, and project context have
been clarified. Phase 2 of the framework involves an initial assessment estimates for the impacts of the technology based on user judgements. The user indicates which performance impacts and measures are of interest with respect to his project objectives and identifies whether building systems or components are impacted directly or indirectly. A comprehensive listing of performance measures is outlined in Table 3.2 based on an extensive review of the literature, the experience of the authors and some preliminary consultation with industry. Table 3.2 also lists the views of industry with respect to the application of green roofs described later in Section 3.4. Technical (e.g., design and seismic forces), economic (e.g., initial, operations and maintenance costs), environmental (e.g., wastewater quality and energy use), and social (e.g., public infrastructure) performance measures that are considered to be an impact of interest are evaluated. An example of the performance measures, the corresponding building systems or components that are impacted for green roof technology evaluation is presented in a summary format in Table 3.3. For example, the user considers the performance measure, air quality, an impact of interest and no building systems or components are impacted with respect to this measure. A comprehensive listing of systems, subsystems and components is developed based on GSA Uniformat and AIA MASTERCOST. Risk adjusted estimates of all performance measures that impact building systems or components is generated in Phase 2 and the overall project in Phase 3. Since the design and development of a building and its program is an evolving process, several iterations may be required between Phases 1, 2 and 3 as the full spectrum of performance measures are assessed. The final steps, described in Phases 4-6, involve the integration of the
estimates and development of value weights for each performance measure to determine the final performance, expressed in terms of an economic measure, of the technology.

In order to predict technical performance, order of magnitude estimates of physical economic, environmental, and social outcomes are required. For example, in the context of applying the framework to green roof technology, one needs to be able to determine the impact on stormwater runoff, energy consumption, and additional design requirements for the superstructure, substructure and foundations. Once the user identifies the performance metrics that are impacts of interest (Table 3.2) and a summary table is developed (Table 3.3) the supporting infrastructure required in the evaluation framework, estimation approaches for impacts such as energy consumption or stormwater runoff, can be identified.

3.4 Application of the framework

The following application of the framework demonstrates its use for evaluating green roof technologies in a hypothetical multi-unit residential building. We first define green roof technology and some of the benefits and implications of its implementation. The results of interviews with industry professionals are presented to illustrate their value systems and thought processes in the context of green roof technology and are an indirect validation of the framework because it was found to replicate various industry practices, albeit in a more formalized way. Finally, order of magnitude approaches for estimating two performance measures are explained, the framework is applied to evaluate green roof technology and the performance of green roof technology in a wood frame low-rise and concrete high-rise building is compared. The analysis undertaken and the values of the
performance measures generated are based on our experience, interviews with design professionals in the construction industry and order of magnitude estimates. Due to time and monetary constraints in the early design stages of a project, it is difficult for design professionals to allocate the time required to analyse in depth the performance of a new technology. Therefore, we present examples of simplified relationships for selected performance measures to calculate order of magnitude estimates of benefits and costs quickly to assist in the decision making process.

3.4.1 Green roof technology

We define an intensive green roof as layers of soil, plants and drainage that form a garden over the traditional roof structure and are accessible to the public. A detailed drawing of this technology is shown in Figure 3.2 and illustrates the multiple layers over the traditional roof structure. The construction industry has become interested in the implementation of green roof technology due to the potential economic, environmental and social benefits shown by researchers and advocated by individuals. Proposed benefits include: (1) Improved service life and protection of roof membrane from environmental exposure and ultraviolet radiation, (2) Reduction in space conditioning requirements of building due to improved insulating capacity, (3) Improved stormwater quality, delayed peak flow and reduction of the rate and volume of stormwater runoff, and (4) Improved building marketability due to the amenity space.

Designers are typically hesitant to implement this technology because of its initial cost, operation and maintenance requirements, and interaction with other building systems.

The Landscape Research, Development and Construction Society (FLL) in Germany
have developed industry standard tests for green roof technology components including tests for growing medium, moisture content, and grain size distribution among others, available at www.f-l-l.de/, however, a North American equivalent of these guidelines is not yet available. The American Society for Testing and Materials (ASTM) Subcommittee E06.71 on sustainability is in the process of developing a set of guidelines and standard of practice. The lack of guidelines in North America is a significant barrier to green roof technology adoption.

3.4.2 Consultation with Industry Professionals

Three construction industry professionals were interviewed in order to identify the multiple viewpoints of stakeholders involved in the evaluation of a sustainable technology, specifically green roof technology, so as to enhance the framework and to verify its relevance. These professionals include an experienced architect in residential high and low-rise buildings, one of the largest Canadian developers of multi-unit residential and commercial mid and high-rise projects, and a green buildings planner for the City of Vancouver, B.C. which is moving towards a city wide green building policy. Interviewees all hold senior or middle management positions in their respective organization and each interview was conducted in person and was approximately two-hours in length. Follow up interviews were carried out to ensure consistent stakeholder responses to allow for feedback regarding the interviews conducted with the other interviewees. The perspective of each stakeholder was consistent and did not change after being shown the performance measures of interest selected by the other interviewees. Although this is a small sample size, we believe the quality of the interviews and the level of authority of each individual result in generalizable information that illustrates the
conflicting objectives and similarities of each of these types of stakeholders. The one-on-one interviews allowed for the clarification of the decision context and performance measures, equal allocation of time to discuss the framework and therefore consistency among interviews.

The interviewees were asked to identify their priorities in determining whether to employ green roof technology in a typical multi-unit residential high-rise point tower including street oriented townhouses. Many of these buildings are currently under construction in Vancouver, B.C. The performance measures identified by applying the framework to green roof technology were defined and listed in Table 3.2 and the stakeholders were asked to identify the performance measures they considered important, from the perspective of their organization, if green roof technology were to be implemented. Table 3.3 contains a partial list of the performance measures indicated as important in the interviews. The performance measures are organized first by class (e.g., technical, economic, and environmental), then by individual measure within a class. The results, in Table 3.2, illustrate the varied viewpoints, motivations and conflicting objectives of the potential users of the framework and stakeholders involved in the building construction process. The interviewees were also asked whether the measures of interest for the high-rise concrete building would change if they were evaluating a green roof application on a low-rise four-story wood frame building which had the same capacity as the high rise building in terms of the number of units; the difference being the much greater green roof area for the low-rise scenario.
Primary impacts of interest to the developer are accelerated approvals, vendor availability and support and the simplicity of technology implementation. The quality issues are raised due to concern regarding the availability of a vendor to fix problems that may arise quickly and the impact on building materials and systems not addressed in design and construction due to the lack of standards. The developer considers the ‘Incentives Available’ category to be comprised solely of accelerated approval because it is perceived as the only reward the City might be willing to give developers for the cost of implementing green roof technology. The developer also indicates in the ‘Time’ class that the timing of the commitment and project resources in the construction stage of the project, and the time to rectify defects are of interest as they could impact both the schedule and costing of the project. In the case of evaluating the technology in the low-rise building the performance measures of interest are the same as those for a high-rise structure with the exception of ‘Design Forces’ under the ‘Structural Stability’ class, which is of interest to the developer particularly in the case of wood frame construction because of the potential for moisture infiltration.

The primary impacts of interest for the public authority are environmental (e.g., stormwater management and efficient energy use) and public acceptance of the technology. In Vancouver, many residents may have considerable reservations concerning green roof technology after years of condominium owners being plagued with moisture infiltration and the resultant costs and health issues of building envelope failures. Residents may be concerned that the green roof technology interaction with the traditional roof structure results in building envelope failures. The concerns include the
pooling of water at the interface between the roof membrane and system components resulting in the waterproofing leaking, the relative newness of the components of the technology and performance over the long term. The difficulty in reviewing the roof membrane for maintenance where it is covered by the green roof components is also a concern. The acceptance of the technology by the public as well as the development community, who must sell the built product to its client the public, is therefore a particular concern to the public authority. The costing of the technology is not considered a major factor of interest to the public authority except in small developments with low densities because of the inability to share costs over a large number of units. The impact on the opportunity to maximize daylighting is a measure of interest in the low-rise building scenario but not for a high-rise building. Green roofs are typically placed on the podium of a high-rise building under which is the amenity space, such as the fitness or meeting rooms, which is not considered regularly occupied and does not require daylighting. However, in a low-rise building the green roof will typically be placed over occupied units and may therefore impact the opportunity to install skylights to provide interior daylighting. (It is noted that a green roof on top of a high-rise building is not practical in most cases because of wind conditions.)

Strata restrictions and privacy issues in relation to the accessibility of the green roof are the primary impacts of interest to the architect. The architect indicated that the operations and maintenance of the green roof in relation to both the availability of funds over the lifecycle of the project and the accessibility to perform the necessary upkeep in addition to initial cost of the technology are important issues of interest. The liability of
technology non-performance is considered a responsibility of the building envelope specialist who is commonly responsible for the roof design details, and so is not considered relevant to the architect. The architect indicated that the performance measures of interest for the high-rise scenario are the same as those for the low-rise.

Among the general comments worth noting from these interviews, the developer expressed that the reason a green roof may be implemented in a project is because "everybody is doing it". He discussed that there is an expectation on the part of the City of Vancouver, and an opportunity to capture LEED® points and assist in the approval process with the City, but that values for its positive economic benefits are unknown. In contrast, design panels, the professional advisers to the Director of Planning in the City of Vancouver, review a developer's submission and have in the past recommended the inclusion of green roof technology in developments as an amenity to the occupants and a selling feature (City of Vancouver, 2004). This difference in viewpoints is illustrated in Table 3.2 where the developer and architect share a strong interest in financial impact in terms of initial, operation, and maintenance costs and the public representative is only concerned with initial costs in the case of small scale, low density development where it would be difficult to distribute the cost of the technology per square foot.

The architect and public authority share an interest in environmental stewardship measures (e.g., water quality, stormwater management) that is beneficial to the community at large while the developer does not. The developer and the public authority share interest in public safety and business performance measures. Impacts of interest
shared by each of the stakeholders include durability and architectural function measures in addition to water use and accelerated approvals.

### 3.4.3 Evaluating Technical Performance

In this section we look at two performance measures and introduce simple approaches for their estimation. We note that in practice, prescreening is conducted by industry based on back-of-the-envelope calculations, which is similar to the early phases of the framework, and partial validation of the framework approach. In practice and as noted previously, it is highly unlikely that clients or their consultants will commit the resources required to conduct sophisticated analyses of new technologies in the early design phases and therefore, our focus is on first order effects only. Here, we introduce two simple order of magnitude estimation approaches that support the framework, and which provide an estimate of the impact of using the technology of interest, in this case green roof technology.

We use the simplified Rational Method (ASCE, 1960) to develop an order of magnitude performance estimate for stormwater mitigation. The Rational Method determines the predicted peak water discharge, \( Q (L^3/T) \), from a small watershed as follows:

\[
Q = CiA \quad (1)
\]

where \( C \) is the runoff coefficient that varies as a function of land use, \( i \) represents rainfall intensity \((L/T)\), and \( A \) is the drainage area \((L^2)\). Other methods developed to estimate green roof performance more accurately than the Rational Method take into account factors such as moisture content, field capacity and depth of growing medium and evaluate the quantity of percolated water versus surface runoff (Miller, 2002). We have
selected the Rational Method to calculate an order of magnitude estimate because it is familiar to design professionals and not data intensive. If we assume the rainfall intensity and surface area variables remain constant and we compare the impact of a green roof with an optimistic runoff coefficient (C) of 0.1 versus that of a traditional asphalt roof with a C value of 0.9 the quantity of runoff will be reduced by a factor of nine. The quantification of runoff reduction helps the user determine whether the green roof contributes to effective reduction in stormwater runoff discharge, improvements in stormwater quality discharged into the municipal storm sewer system, and the potential reduction in costs for drainage basins or other stormwater management infrastructure. Quantification of technology performance metrics assists the user in identifying who incurs incremental costs or receives benefits and how.

Green roofs can contribute to energy savings in buildings by reducing the energy demand and lowering roof surface temperatures, although exact energy savings are difficult to predict. The contribution to passive cooling in the summer period still cannot be part of a building energy simulation study despite the research conducted to date and the green roof technology is proposed therefore primarily for its qualitative rather than quantitative value (Theodosiou, 2003). The thermal behaviour of green roofs is influenced by a multitude of factors including the attributes of the components such as the plant type, depth, density, field capacity and moisture content of the growing medium. In addition, the climatic conditions such as solar radiation, winds, relative humidity and rainfall impact energy performance. Efforts to simplify complex models have been made to assist in and optimize the design process (Palomo, 1999); however, this approach requires
in-depth understanding of the technology. Green roofs have been shown to be most
effective in the summer months for reducing heat gain and less effective in the winter
months for reducing heat loss (Liu, 2004). In the heating period, thermal losses in the
roof can be calculated using the heat transfer equation:

\[ q = \sum (U_i A_i / A) A \Delta T \]  

(2)

The factor U represents the thermal transmittance of the green roof components, and is
important for the thermal protection of the green roof during the winter. One needs to
calculate a modified U value depending on the treatment applied at each floor level and
depending on the configuration of the building. For example, a green roof on the top floor
of a 19 story high-rise building is a treatment for only one of the nineteen floors,
therefore, its contribution to total building energy savings may be very small. Thermal
transmittance is dependant on the thermal conductivity (\( \lambda \)) of the soil. A green roof loses
a significant amount of its insulation capacity when the soil is wet, which occurs
particularly in the heating season, therefore the soil has a higher thermal conductivity
value (and lower U value). The factor A represents the surface area and the factor \( \Delta T \) is
the difference between the internal temperature (\( t_i \)) and the average external temperature
(\( t_a \)). Of course, one must recognize that the energy demand of the building is influenced
by other factors including vertical building elements, orientation of the building and
contribution of plants to shading and absorption of solar radiation. Discussions with
design professionals and building energy simulation experts indicate that in some
circumstances a traditional black roof, with a higher capacity to absorb sunlight, may be
the preferable choice from an energy savings perspective in cities such as Vancouver
with year-round mild climates and minimal air conditioning loads.
A full spectrum of simplified or first order estimation approaches can be developed in future research work to assist design professionals evaluate technology performance for selected measures and building systems and to improve the usefulness of the framework. The simplified relationships presented here and the information from design professionals are applied to green roof technology to develop order of magnitude performance estimates, which are discussed further in Section 3.5.

3.5 Application results

Assuming the technology has passed the judgements of Phase 1, a more detailed analysis can be conducted. Under the first Phase of the detailed analysis, Phase 2, the user systematically identifies the building systems or components which are impacted with respect to selected performance measures. The remaining performance measures, that do not impact building systems or components are not evaluated until Phase 3. For example, the incremental increase in structural load imposed on the structure by the weight of the green roof technology results in impacts, measured by the additional cost of concrete to sustain the load, on both the foundation and superstructure systems for the 'Design Forces' performance measure, in the construction phase. This is illustrated in the sample portion of an input table shown in Table 3.4. Building systems or components are impacted in only three performance measures (design forces, seismic resistance and wastewater quality) in the green roof technology evaluation. The user is required to complete forms, similar to Table 3.4, for each performance measure in which systems are impacted to identify which subsystems and components are impacted, the change in cost relative to baseline conditions, a surrogate for uncertainty expressed numerically, and the
respective life cycle phase where the majority of impact occurs. Green roof technology may generate enough energy savings that the sizing of mechanical equipment can be reduced resulting in lower capital, operations and maintenance costs. However, in multi-unit residential buildings energy systems are typically decentralized into individual units and metered separately. Only the units in the top floor under the green roof may benefit from its insulative contribution, therefore creating an unequal distribution of the technology benefits between units. Thus, a conflict may arise between the goal of sustainability and the structure of the industry in terms of delivering services. In this example, the contribution to improved thermal performance is considered minimal and therefore building systems or components under operations and maintenance are not impacted and this measure is not estimated until Phase 3. Table 3.5 illustrates how performance measures that do not impact systems or components, but impact the overall project, are evaluated. The order of magnitude estimates in Table 3.5 illustrate the net impact on the overall project for these measures. In this analysis, we take the viewpoint of a stakeholder with profit maximization goals, hence environmental measures such as improved air quality, wastewater quality, stormwater treatment, and positive benefits to public infrastructure are considered to have no economic value, while sellable or marketable features such as increasing the useable floor area, are valued positively. End users are typically not willing to pay for public environmental benefits and so the matter becomes one of regulating and passing the cost of compliance on to the end users. In Canada, although green roofs can contribute to these public benefits, no public policies recognize or support their implementation (Liu, 2004). Order of magnitude estimates of these benefits are calculated using relationships, such as Equations 1 and 2, or through
discussions with design professionals. What is particularly important is that considerable uncertainty can surround the forecast value of a performance measure, and risk should be formally treated in the evaluation process. These risk-adjusted estimates, from Phase 2 and Phase 3, form the foundation for the economic analysis that is performed in the following phases. Uncertainty is measured to indicate the user's degree of confidence in these estimates. For example, users who consider the performance measure 'Personal Safety' as an impact of interest may require insurance to cover potential liabilities and if the cost for such insurance is unknown they may indicate that the degree of uncertainty associated with their estimate is 100% which can translate to potentially a 100% error in cost estimate. Users may also be uncertain of long-term technology performance of metrics such as energy savings or detention of stormwater water runoff when the technology performance for these metrics is a function of factors that are difficult to control. Such factors may include, for example, proper installation, operation and maintenance policies and budgets. On the other hand, the degree of uncertainty for measures such as 'Initial Cost' may be low because the user is confident in the estimate based on a supplier’s fixed quote. In the application of Phases 2 and 3, we assume that the user has access to information and values of a baseline building for comparison. The final steps, Phase 4-6, involve the development of a cash flow model that integrates the benefits and costs over the relevant time phases such that value weights can be assigned, a final net present value (NPV) determined and a preferred technology selected. Nelms et al. (2005) illustrate how indirect and direct costs and benefits can be assessed in an abstract cash flow diagram that spans all phases of the project life cycle. NPV is selected
as the parameter most suitable to reflect the motivations of a stakeholder with profit maximization goals.

Output from application of the framework is a report describing the project details, parameters used, characterization of the user value system, performance criteria impacted, expressions of uncertainty (either numerical or linguistic) and cash flow model that details both indirect and direct costs and benefits to the project, and corresponding change in NPV.

3.6 Technical performance for different building types
An important consideration in the development of the framework is the emphasis on understanding the impact of the project context (e.g., building type, climatic condition, program) on technology performance and its evaluation. We believe it is necessary that technology selection decisions be based on a clear understanding and proper evaluation of the full range of implications and context with which it is associated. Technology performance in a region, program or building type may differ from performance in another context. A comparison of the primary decision-making performance measures in intensive green roof technology is performed on a four-story low-rise wood frame building and a nineteen-story concrete high-rise building with equal interior square footage. Figure 3.3 illustrates the dimensions of the buildings. The fundamental differences in the evaluation of green roof technology in these buildings are the available roof area assuming no mechanical equipment on the roof (576 m² versus 2704 m²) and the structure type (concrete versus wood).
A comparison of the differences between performance measure estimates in a high-rise and low-rise building scenario expressed numerically and linguistically, are illustrated in Table 3.6. The initial costs, annual operations and maintenance and replacement costs for the implementation of a green roof technology, based on estimates from local design professionals, is considerably higher for the low-rise building based on the area coverage.

The costs for the performance measures ‘Design forces’ and ‘Seismic resistance’ are valued together based on a percentage of the structural costs. Assuming a construction cost of the low-rise building as $8.2 million and the high-rise as $10.6 million, structural upgrading for the low-rise is based on an increase of 6% in structural costs while the high-rise requires a 15% increase in structural costs primarily to cover seismic loads. To calculate the reduction in the quantity of runoff from the replacement of a traditional asphalt roof with a green roof we assume a uniform rainfall intensity of 10 mm in 15 minutes for the Vancouver, British Columbia area (NBC, 1998) which is a storm with a 10 year return period. Using Equation 1, we find that the installation of a green roof may reduce the quantity of runoff from the high-rise from 0.00576 m$^3$/s to 0.00064 m$^3$/s and the peak discharge from the low-rise from 0.02706 m$^3$/s to 0.00300 m$^3$/s in a 15 minute storm. This is assuming the green roof runoff coefficient, $C$, is 0.1 and the traditional roof runoff coefficient is 0.9. Of course, the value selected for the green roof runoff coefficient will depend on the water holding capacity of the soil and its depth and therefore the efficacy of the green roof in reducing stormwater runoff. For long duration rainfall events, once the soil is saturated, one may expect that the reductions are less. The reduction in stormwater runoff may result in an opportunity to reduce the sizing of storm leaders i.e., diameter differences. However, discussions with design professionals
indicate designers would be reluctant to reduce the drainage capacity because the
potential for plugging may increase with a green roof and a larger diameter leader is
easier to maintain and access.

Energy savings are calculated only during the heating period. Equation 2 is used to
calculate energy savings. Based on an exterior temperature of \(-4.7^\circ C\) and interior
temperature of \(18^\circ C\), and assuming the thermal conductivity of the green roof soil
component as \(1.16 \text{ W/mK}\) (Eumorfopoulou, 1998), the potential reduction in heat loss in
the high-rise scenario is \(15,167\text{ W}\) while for the low-rise scenario it is \(71,201\text{ W}\). This
indicates that the implementation of green roof technology results in different energy
savings depending on building configuration. This also indicates that the potential energy
savings calculated from one project cannot be assumed to be equal to that of another
project where the building and technology design differ.

The relative amount of usable area, initial cost, annual operation and maintenance and
replacement costs for the implementation of the green roof technology are approximately
five times greater for the low-rise building versus the high-rise building. The potential
benefits in a trade-off analysis, both environmental and economic, are also greater for the
low-rise building but are difficult to measure. These include incentives available from the
City, capital appreciation potential and environmental measures such as improved air
quality among others.
3.7 Discussion and conclusions

Although a number of buildings have implemented green roof technology across North America, site specific and cumulative benefits from its adoption have not been verified through comprehensive performance monitoring of heat transfer, stormwater runoff and durability (Bass et al. 2003). In addition, policies to provide incentives or regulate the implementation of this technology are in their infancy in North America. It is therefore difficult to both quantify and justify the implementation of this technology by developers with profit maximization goals motivated by the bottom line of their cost model and concerns about competitiveness.

The difference in performance illustrates the potential benefits and costs to stakeholders involved in the project in addition to the tradeoffs that must be assessed. The problem rests with the allocation of payment for the various benefits, costs and risks. The developer will either bear the costs and risks of the technology or pass these onto the occupants for these both public and occupant benefits. Disregarding demographic accessibility issues, all occupants benefit from the green roof as an amenity space; however, policy makers should consider whether all users should bear the totality of risks of technology non-performance and the operations and maintenance costs for such community benefits as reduction in stormwater runoff. One may argue that it is the responsibility of the public authority to provide regional stormwater management strategies and consider encouraging the use of green roof technology through incentives or direct regulations imposed on all buildings. The fundamental differences in value systems as discussed in Section 3.2 indicate the need for the formal treatment of performance measures to lessen conflicts between parties, to identify mutually agreed
upon tradeoffs and to provide benchmarks for establishing rational policies regarding the adoption of such technologies.

This paper sets forth a holistic technology evaluation framework that includes environmental, technical, economic and social performance measures to address the needs of policy makers and stakeholders involved in the evaluation of the benefits and costs of sustainable technologies. The increasing popularity of sustainable construction and therefore implementation of sustainable technologies in “green” buildings based primarily on their environmental performance presents challenges to project stakeholders whose objectives may conflict. The popularity of sustainable technologies, given the insufficient understanding of the technology risks, actual benefits accrued, and their beneficiaries, and the willingness to pay for these benefits, is a particular concern where the consequence of failure can be significant. The evaluation of sustainable technologies can be conducted using this framework, and the benefits and costs of its implementation may be quantified to assess who bears the positive and negative consequences of technology implementation. The framework focuses on the consequences and motivations for technology implementation in a given decision context and the identification of where stakeholders’ objectives align and conflict. It may also be used to assist policy makers in identifying the best choice of economic incentive or direct regulation approach for encouraging sustainable technologies.

The framework was applied to a selected sustainable technology, green roofs, in order to illustrate its features and demonstrate the differences in technology evaluation objectives.
of various industry participants. This technology was selected because of its popularity, proposed community benefits that are difficult to quantify and high interaction with other building systems over the project life cycle. The framework was applied to green roof technology for a multi unit residential building type and the technology performance in a wood frame low-rise and concrete high-rise building was compared. It was shown that under different contexts, such as building configuration, the technology performance differs. It should be noted that the application of the framework to evaluate green roof technology is performed using hypothetical building examples and order of magnitude estimates. The framework assists in making a distinction between the benefits that accrue to the project and those that accrue to the community. Green roof technology has the potential for contributing to larger positive community impacts outside of the building although it may adversely impact overall building performance. From a policy perspective, where the technology impacts public infrastructure, we suggest that public authorities review the cumulative requirement to make measurements meaningful. On the regional scale, we suggest a distinction be made between the impacts and benefits of individual projects and the cumulative impact of regulating the technology for a building type. Green roof technology is not the complete solution for improving the environmental performance of buildings. There is still a significant amount of research required to validate its proposed impacts both positive and negative, the performance of the components themselves, as well as the cumulative impact of proposed benefits.

The framework could be further improved by incorporating lessons learned from its application to case study projects of other sustainable technologies and other building
types including commercial or industrial buildings to verify comprehensiveness of the
approach in terms of the measures to be treated and the best expressions of tangible and
intangible impacts. Industry practitioners found that the framework was helpful in
identifying the pros and cons of a technology. One practitioner noted that the process was
so comprehensive that it may become a checklist for due diligence that is transferred
from one project to another without consideration of the decision context. Such an
application could defeat the underlying intent of the framework. Further work is required
to refine the framework and develop related tools, such as simple models, that are easy to
use and provide insight into technology performance which is useful to project
stakeholders and necessary for policy makers. The underlying goal of the framework is to
provide an objective assessment of the benefits and risks associated with different
technologies and the building contexts for which they are best suited.
3.8 Bibliography


Table 3.1 Overview of the multi-phase screening framework for evaluation of sustainable technology.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Filter</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Phase 1 Preliminary Screening:  
*Technical and Regulatory Analysis* (facts) of the technology determining building systems and life cycle phases affected and critical evaluation criteria & performance measures for (see Becker, 2002 for detailed list of technical performance measures) and estimate of order of magnitude estimate of balance between costs and benefits (including incentives/subsidies) | Filter 1 | This preliminary analysis of the technology of interest involves a combination of order of magnitude estimates and pass/fail judgements. If the technology successfully passes through this screening process, (passage does not ensure workability), then a more detailed analysis is undertaken. |
| Phase 2 Screening:  
*Technical Analysis* (facts) of technology determining what physical components within each system of the building and life cycle phases are impacted. Conduct sufficient design to determine scope parameters of the technology itself (e.g. quantities, mass). Evaluate more comprehensive range of performance measures. | Filter 2 | Review each of the building systems and components relative to the project life cycle phases to determine technology impacts both positive or negative. Technology may not be considered workable or eliminated based on dominance analysis relative to the baseline comparator. |
| Phase 3 Screening:  
*Technical Analysis* (facts) of technology identifying the performance measures impacted for the various phases in the project life cycle. Generate estimates of the performance measures and quantify associated uncertainty. Check that required technical and regulatory thresholds on performance are met. | Filter 3 | Generate estimates of performance measures including technical measures. Physical measures can be estimated in terms of input quantities (e.g. materials, labour) and output measures (energy consumption, volume of waste water). Other measures may include time performance (e.g. design, construction, ability to overlap phases), and incremental revenue sources. |
| Phase 4 Screening:  
*Economic Analysis* (facts) of technology to price out associated performance measures using a variety of economic performance measures. | Filter 4 | Economic performance measures including capital cost, life cycle cost, net present value, can be utilized as appropriate. Risk adjusted values of key performance measures is determined. |
| Phase 5 Screening:  
*Value Analysis* (values) of technology using technical scores multiplied by value weights. | Filter 5 | Value weights are elicited from decision makers and applied to performance measures. The use of weighted performance measures helps determine where further detailed analysis is required. |
| Phase 6 Final Screening:  
*Final Filter* | Filter 6 | Final decision is made on whether or not to implement the technology by comparing with the default design approach. |
Table 3.2: List of framework performance measures indicating the similarities and differences of three stakeholders involved in a typical building project evaluating the implementation of green roof technology in a multi unit residential building.

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Architect</th>
<th>Developer</th>
<th>Public Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TECHNICAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural Stability</td>
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<td>X</td>
<td></td>
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<td>Design Forces</td>
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<td></td>
<td></td>
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<tr>
<td>Wind Resistance</td>
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<td></td>
<td></td>
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<tr>
<td>Seismic Resistance</td>
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<td></td>
<td></td>
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<tr>
<td>Fire Safety</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Detection &amp; Suppression</td>
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<td></td>
<td></td>
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<tr>
<td>Egress Provision</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Smoke Control</td>
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<tr>
<td>Fire Spread Control</td>
<td></td>
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<td></td>
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<tr>
<td>Toxicity</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Human Health, Comfort &amp; Safety</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Air Quality</td>
<td>X</td>
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<td>Daylighting</td>
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<td>Moisture Protection</td>
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<td>X</td>
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</tr>
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<td></td>
<td></td>
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<tr>
<td>Compatibility With Materials</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Wear or Abuse Resistance</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Deterioration Resistance</td>
<td>X</td>
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<tr>
<td><strong>Architectural Function</strong></td>
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<td>Aesthetics</td>
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<td>Acoustics</td>
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<tr>
<td><strong>Flexibility</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adapt for multiple uses</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Useable Floor Area</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scalability</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ECONOMIC IMPACT</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Financial Impact</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Initial Costs or Savings</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Operations &amp; Maintenance Cost</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Replacement Costs</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salavage Value</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Appreciation Potential</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Incentives Available</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zoning Changes</td>
<td>X</td>
<td></td>
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</tr>
<tr>
<td>Accelerated Approvals</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Increased Density</td>
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<td>Direct Subsidy</td>
<td>X</td>
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</tr>
<tr>
<td>Income Tax Treatment</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Property Tax Treatment</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENVIRONMENTAL IMPACT</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Water Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Use</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Wastewater Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wastewater Disposal</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Wastewater Quality</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stormwater Treatment</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Energy Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Use</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Source</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Materials Efficiency</strong></td>
<td></td>
<td></td>
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<td>Recycled Material</td>
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<td></td>
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<tr>
<td>Salvaged Materials</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficient Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impact on Public Infrastructure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact public infrastructure</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impact on Local Environment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact local environment</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Impact of Interest? (X = Yes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Architect</td>
</tr>
<tr>
<td>QUALITY CONTROL</td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td></td>
</tr>
<tr>
<td>Warranty Availability</td>
<td>X</td>
</tr>
<tr>
<td>Liability</td>
<td></td>
</tr>
<tr>
<td>Reliability Issues</td>
<td></td>
</tr>
<tr>
<td>Vendor Availability and Support</td>
<td>X</td>
</tr>
<tr>
<td>Simplicity of Technology Use</td>
<td>X</td>
</tr>
<tr>
<td>Failure bounded</td>
<td></td>
</tr>
<tr>
<td>KNOWLEDGE MANAGEMENT</td>
<td></td>
</tr>
<tr>
<td>Impact on Knowledge Management</td>
<td></td>
</tr>
<tr>
<td>Improved public awareness</td>
<td></td>
</tr>
<tr>
<td>Learning, R&amp;D</td>
<td></td>
</tr>
<tr>
<td>TIME</td>
<td></td>
</tr>
<tr>
<td>Impact on Time</td>
<td></td>
</tr>
<tr>
<td>Timing of commitment</td>
<td></td>
</tr>
<tr>
<td>Project Resources - Design</td>
<td></td>
</tr>
<tr>
<td>Project Resources - Construction</td>
<td></td>
</tr>
<tr>
<td>Project Resources - O&amp;M</td>
<td></td>
</tr>
<tr>
<td>Duration of Phases</td>
<td></td>
</tr>
<tr>
<td>Time to Rectify Defects</td>
<td></td>
</tr>
<tr>
<td>BUSINESS PERFORMANCE</td>
<td></td>
</tr>
<tr>
<td>Impact on corporate image</td>
<td></td>
</tr>
<tr>
<td>Impact on publicity</td>
<td></td>
</tr>
<tr>
<td>Impact on public acceptance</td>
<td></td>
</tr>
<tr>
<td>Support of company mandate</td>
<td></td>
</tr>
<tr>
<td>Entry into a new market</td>
<td></td>
</tr>
<tr>
<td>Opportunity for repeat business</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3 Partial list of performance measures indicated by interviewees as important in Phase 2 of green roof technology evaluation.

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>Impact of interest? (Yes/No)</th>
<th>Systems or components impacted? (Yes/No)</th>
<th>Performance indicator in net present value (NPV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Forces</td>
<td>Yes</td>
<td>Yes</td>
<td>NPV for the change in design and construction requirements to accommodate horizontal or vertical design forces</td>
</tr>
<tr>
<td>Seismic Resistance</td>
<td>Yes</td>
<td>Yes</td>
<td>NPV for the change in design and construction to achieve the seismic design requirements relative to baseline conditions</td>
</tr>
<tr>
<td>Air Quality</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in design and construction requirements to meet specified criteria for energy efficiency of the ventilation system and indoor air quality and climate</td>
</tr>
<tr>
<td>Personal Safety from Physical Injury</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in design and construction requirements to meet or improve specified criteria to provide personal safety to individuals to prevent physical injury relative to baseline conditions</td>
</tr>
<tr>
<td>Useable Floor Area</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in design and construction requirements to meet or improve specified criteria for the amount of marketable space relative to baseline conditions</td>
</tr>
<tr>
<td>Initial Costs or Savings</td>
<td>Yes</td>
<td>No</td>
<td>NPV for direct initial costs or savings of technology adoption relative to baseline conditions</td>
</tr>
<tr>
<td>Operations &amp; Maintenance Cost</td>
<td>Yes</td>
<td>No</td>
<td>NPV for direct costs or savings incurred by the implementation of the technology under evaluation over the life cycle of the project relative to baseline conditions</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td>Yes</td>
<td>No</td>
<td>NPV for technology replacement relative to baseline conditions</td>
</tr>
<tr>
<td>Capital Appreciation Potential</td>
<td>Yes</td>
<td>No</td>
<td>NPV for capital appreciation of the investment relative to the baseline conditions</td>
</tr>
<tr>
<td>Incentives Available</td>
<td>Yes</td>
<td>No</td>
<td>NPV for incentives available</td>
</tr>
<tr>
<td>Wastewater Quality</td>
<td>Yes</td>
<td>Yes</td>
<td>NPV for the change in quality of water effluent leaving the site relative to baseline conditions</td>
</tr>
<tr>
<td>Stormwater Treatment</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in percentage of stormwater infiltration relative to baseline conditions</td>
</tr>
<tr>
<td>Energy Use</td>
<td>Yes</td>
<td>No</td>
<td>NPV for change in the annual source operating energy used in the building relative to baseline conditions</td>
</tr>
<tr>
<td>Impact public infrastructure</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in impact on public infrastructure relative to baseline conditions</td>
</tr>
<tr>
<td>Project Resources (Design)</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in time incurred to design and specify the technology relative to baseline conditions</td>
</tr>
<tr>
<td>Project Resources (Construction)</td>
<td>Yes</td>
<td>No</td>
<td>NPV for the change in time incurred to install the technology relative to baseline conditions</td>
</tr>
</tbody>
</table>
Table 3.4 Portion of performance measure input table where systems are evaluated.

<table>
<thead>
<tr>
<th>Analysis for DESIGN FORCES performance metric</th>
<th>Parameter</th>
<th>Selected Environmental Technology</th>
<th>Degree of uncertainty</th>
<th>Project life cycle phase with majority of impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems, subsystems &amp; components</td>
<td>Unit</td>
<td>Cost</td>
<td>Quantity</td>
<td>Total cost</td>
</tr>
<tr>
<td><strong>Foundations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Foundations</td>
<td>m³/concrete</td>
<td>$200</td>
<td>90</td>
<td>$18,000</td>
</tr>
<tr>
<td>Special Foundation Conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Substructure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab on Grade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement Excavation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement Walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Superstructure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor Construction</td>
<td>m³/concrete</td>
<td>$200</td>
<td>30</td>
<td>$6,000</td>
</tr>
<tr>
<td>Roof Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stair Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ext Closure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Doors &amp; Windows</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Roofing</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Roofing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interior Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partitions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Finishes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specialties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.5 Portion of performance measure input table where respective systems are not impacted.

<table>
<thead>
<tr>
<th>Analysis for performance indicators</th>
<th>Impact on Project (+/-)</th>
<th>Value of Impact ($) where base case is $0</th>
<th>Degree of uncertainty (%)</th>
<th>Project life cycle phase with majority of impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Quality</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Personal Safety from Physical Injury</td>
<td>-</td>
<td>5,000</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Useable Floor Area</td>
<td>+</td>
<td>0</td>
<td>100</td>
<td>Absorption</td>
</tr>
<tr>
<td>Initial Costs or Savings</td>
<td>-</td>
<td>104,000</td>
<td>0</td>
<td>Construction</td>
</tr>
<tr>
<td>Operations &amp; Maintenance Cost (annual)</td>
<td>-</td>
<td>12,000</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td>-</td>
<td>57,600</td>
<td>50</td>
<td>Renewal</td>
</tr>
<tr>
<td>Capital Appreciation Potential</td>
<td>+</td>
<td>0</td>
<td>100</td>
<td>Absorption</td>
</tr>
<tr>
<td>Incentives Available</td>
<td>+</td>
<td>100,000</td>
<td>0</td>
<td>Conceptual Design</td>
</tr>
<tr>
<td>Wastewater Quality</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Stormwater Treatment</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Energy Use</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Impact public infrastructure</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Project Resources (Design)</td>
<td>-</td>
<td>11,500</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
<tr>
<td>Project Resources (Construction)</td>
<td>-</td>
<td>62,000</td>
<td>0</td>
<td>Operations/Maintenance</td>
</tr>
</tbody>
</table>
Table 3.6 Difference between performance measures for high-rise and low-rise building types.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>High Rise</th>
<th>Low Rise</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Forces</td>
<td>$400,000</td>
<td>$120,000</td>
<td>Additional weight of technology may require high rise structure to be upgraded (includes estimate for seismic resistance measure)</td>
</tr>
<tr>
<td>Seismic Resistance</td>
<td>Included in above</td>
<td>Included in above</td>
<td>Additional weight of technology may require high rise structure to be upgraded to meet seismic design requirements</td>
</tr>
<tr>
<td>Moisture Protection</td>
<td>Low</td>
<td>High</td>
<td>Low rise wood structure more susceptible to deterioration in comparison to concrete structure in the event of moisture infiltration</td>
</tr>
<tr>
<td>Air Quality</td>
<td>Low</td>
<td>High</td>
<td>Relative estimate based on comparison of useable “green” area</td>
</tr>
<tr>
<td>Personal Safety from Physical Injury</td>
<td>Equal</td>
<td>Equal</td>
<td>Same value assumed for both structures assuming same usage of space</td>
</tr>
<tr>
<td>Useable Floor Area</td>
<td>576m$^2$</td>
<td>2704m$^2$</td>
<td>Based on relative comparison of area for alternative uses</td>
</tr>
<tr>
<td>Initial Costs or Savings</td>
<td>$104,000</td>
<td>$486,700</td>
<td>Based on $180/m$^2</td>
</tr>
<tr>
<td>Operations &amp; Maintenance Cost (annual)</td>
<td>$12,000</td>
<td>$56,500</td>
<td>Based on $21/m$^2</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td>$57,600</td>
<td>$270,400</td>
<td>Based on $100/m$^2</td>
</tr>
<tr>
<td>Capital Appreciation Potential</td>
<td>Low</td>
<td>High</td>
<td>Based on relative comparison of available amenity space to building occupants</td>
</tr>
<tr>
<td>Incentives Available</td>
<td>Low</td>
<td>High</td>
<td>Relative estimate based on comparison of useable area of green roof</td>
</tr>
<tr>
<td>Wastewater Quality</td>
<td>Low</td>
<td>High</td>
<td>Relative estimate based on comparison of area of green roof</td>
</tr>
<tr>
<td>Stormwater Treatment</td>
<td>0.00512m$^3$/s</td>
<td>0.02406m$^3$/s</td>
<td>Relative estimate based on comparison of area of green roof</td>
</tr>
<tr>
<td>Energy Use</td>
<td>15,167W</td>
<td>71,201W</td>
<td>Relative estimate based on comparison of area of green roof</td>
</tr>
<tr>
<td>Impact public infrastructure</td>
<td>Low</td>
<td>High</td>
<td>Relative estimate based on comparison of area of green roof</td>
</tr>
<tr>
<td>Project Resources (Design)</td>
<td>$12,000</td>
<td>$54,000</td>
<td>Design, specification and project admin based on 7.5% of roofing costs (including traditional roof membrane cost of $86/m$^2</td>
</tr>
<tr>
<td>Project Resources (Construction)</td>
<td>$62,000</td>
<td>$289,000</td>
<td>Installation and labour costs of technology based on $107/m$^2. Costing varies depending on the on-site moving equipment available</td>
</tr>
</tbody>
</table>

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Figure 3.1 3-Dimensional structure that illustrates a framework to assess sustainable building technology in multi-unit residential buildings.

Figure 3.2 Detail of intensive green roof technology.

LEGEND:
1 = Vegetation
2 = Growing Medium
3 = Filter Layer
4 = Drainage Course
5 = Protection Layer
6 = Waterproof Membrane
7 = Reinf. Conc. Roof Deck
8 = Interior Space
Figure 3.3 Difference in roof area for different building types with equal interior square footage.
CHAPTER 4  Conclusions and Recommendations

4.1 Conclusions

As sustainable construction practices and the implementation of sustainable technologies become more common in the building sector, many questions remain regarding the performance of such technologies due to the lack of performance data and difficulty in assessing subjective performance attributes. Stakeholders involved in a building project are in need of a tool to assist them in evaluating the risks, adverse impacts and subjective and objective benefits associated with a sustainable technology.

Traditionally, stakeholders involved in selection of a new building technology have performed the evaluation from primarily a single-issue perspective, e.g., only financially or only environmentally. The primary focus of this thesis is to develop a technology evaluation framework that considers a holistic set of performance criteria with respect to the totality of influences on all building systems and life cycle phases. The objectives of this thesis, as stated in Chapter 1, are to provide project stakeholders and policy makers with a way of thinking about and assessing technology using a systematic framework and to verify this framework by applying it to a selected sustainable technology.

A comprehensive literature search was conducted regarding evaluation approaches and includes a summary of the building industry's motivation and the perceived benefits and barriers for the implementation of sustainable construction practices. A review of the current state of the art in terms of technology assessment methods and frameworks
available in the building sector is performed and the framework developed builds upon these works. Literature that attempts to quantify the benefits of sustainable construction practices is not abundant but growing, particularly in terms of reports published by not-for-profit and public sector government organizations. This lack of information can be attributed to the unique characteristics of the building sector including the long life cycle of the building, its components and systems and to a distinction between constructors, owners and users.

A list of performance measures, including a compilation of technology attributes identified by other authors, is developed that should be considered in describing sustainable technology characteristics (presented in Chapter 2). The risks and benefits of a selected sustainable technology, the green roof technology, are described and estimated using both simple order of magnitude functions and discussions with design professionals (presented in Chapter 2 and 3). This technology was selected because of the multiple interactions between building systems and the social and environmental benefits to the community.

The framework is applied to green roof technology in order to illustrate its features and provide insights into the attitude and perceptions of the technology from the point of view of three project stakeholders; a developer, public authority and architect. The results reveal that conflicting objectives exist among the project stakeholders and help to explain the challenges and risks involved in the technology adoption (presented in Chapter 3). The framework is applied to green roof technology for a multi-unit residential building.
type and its performance is evaluated for a low-rise and high-rise building. It was shown that the performance of the technology differs depending on the context, in this case building configuration. The popularity of sustainable technologies, given the insufficient understanding of the technology risks, actual benefits accrued, the beneficiaries, and the willingness to pay for these benefits, is a particular concern where the consequence of failure can be significant and is an indication of the industry need for a technology evaluation framework.

A holistic framework for assessing the performance of sustainable technologies for building projects is developed and presented as a systematic approach to assist users in evaluating sustainable technologies. The process provides insight into the evaluation of the technical, social, environmental and financial performance of selected sustainable technologies including the subjective benefits associated with these technologies and identifying the benefits that accrue to the project and those that accrue to the community. Indicators that could be used to guide multiple decision makers in testing a new technology in terms of its compatibility with project objectives are developed. Government policies are expected to play a significant role in reducing the environmental impact of buildings and the information gathered using the framework could provide input to determining the cumulative impact of the technology as well as assisting in the development of policy legislation, incentives or regulations.
4.2 Recommendations

There are a number of recommendations as extensions of the work presented in this thesis that are directed to improving policy development and the selection of sustainable technologies.

Future research may include the validation of this framework in case study projects, and reviewing its usefulness in different decision contexts. In order to gather the most useful data, committed building industry partners willing to allocate time to the process and provide access to key project decision makers are required. Undertaking case study projects with industry personnel as well as with policy makers will help illustrate the application of the framework and determine how best to incorporate the value systems of various decision makers into the decision making process. Case study projects could include reviewing technology performance in multiple building types, selecting sustainable technologies both familiar and unfamiliar to key decision makers and comparing technology performance in different climatic conditions and regional contexts.

Although a broad literature search was conducted to assess the current state of the art in technology evaluation, a comprehensive literature search in disciplines other than those connected to the building sector should be carried out. Since multiple decision makers are involved in a building project, methods of including their weighted values in the evaluation process could be assessed and included as part of the framework. Further work could be performed in developing a set of order of magnitude indicators to assist decision makers in testing the performance of a sustainable technology with respect to their project objectives.
More importantly, research could be conducted to evaluate technology performance in a more detailed fashion across all stages of the project including a post occupancy evaluation. The focus could be on determining the extent to which technology performance follows or deviates from the perceived risks, adverse impacts and benefits elicited through the use of the framework. In addition, further consultation with design professionals, policy makers and other researchers could be carried out in order to ensure comprehensiveness of the approach in terms of the measures to be treated and how best to express tangible and intangible impacts.

Future researchers may wish to develop an electronically based format of the framework with a user friendly interface accessible for both the input and sharing of information between multiple decision makers at all stages of the project. An examination of decision makers perception of a sustainable technology through the project life cycle could provide insight into their motivations and ability to rationalize their estimates of technology performance in particular if one reviewed their reaction to success or failure with respect to their project objectives.
Appendix A  Sustainable construction websites

The following websites are considered to be informative and useful to researchers looking at technology evaluation and sustainable construction practices.

**Sustainable Building Toolkit**

This toolkit was developed by the California Sustainable Building Task Force to assist design professionals in the specification, design and construction of green buildings. The Governor of the State of California signed an Executive Order S-20-04 to design, construct and operate all new and renovated state-owned facilities as “LEED Silver” or of a higher certification level. The toolkit includes links to case studies, performance standards, financing programs and costing reports.

http://www.ciwmb.ca.gov/GreenBuilding/Toolkit.htm

**Guide to Green Buildings Resources**

This guide was developed as one part of an initiative to improve the performance of the British Columbia, Canada education and health agencies new and retrofit buildings. The guide includes a comprehensive list of resources for green building design. Specifically, performance resources under the topics energy, water, landscape, materials, waste, construction practices, and indoor environmental quality are included. Links to Canadian financial funding initiatives and building programs, case studies, and economic performance resources are also referenced.

http://www.greenbuildingsbc.com/new_buildings/resources_guide/

**Advanced Building Technologies and Practices**

This website includes articles by design professionals on over ninety advanced building technologies and practices. The technologies assist in achieving improved building performance relative to a traditional building for indoor air quality, water conservation, waste management, electricity production, non-toxic materials, recycled materials, daylighting and energy efficiency. In addition, details of multiple building type case study projects across Canada are outlined.

http://www.advancedbuildings.org/

**Santa Monica Green Building Program**

The City of Santa Monica, California is one of the first North American cities to develop guidelines and requirements to promote sustainability and their commitment to protecting the environment. In order to achieve these commitments, the City has adapted a number of requirements and recommendations set out in the City ordinances and modifications to
the municipal code. Guidelines were designed to increase sustainability without putting excessive burdens on builders or developers and are relevant to multiple building types. Also included are links to useful websites and case studies in North America to assist design professionals meet sustainable construction best practices.

http://greenbuildings.santa-monica.org/

**SEEDA Sustainability Checklist**

The Sustainability Checklist for Developments in the South East (SEEDA) is an initiative to provide assistance and a framework for local authorities to create and implement sustainability in development plans. The checklist is divided into ten sections with each section containing information, a set of structured questions for each sustainability issue addressed and performance indicators to allow the user to determine the level of sustainability the development is or will achieve.

http://www.sustainability-checklist.co.uk/

**LEED (Leadership in Environmental Design)**

The LEED (Leadership in Energy and Environmental Design) Green Building Rating System® is a voluntary, consensus based standard developed by members of the United States Green Building Council (USGBC) representing a broad spectrum of individuals involved in the building industry. The standards were created to establish a common standard for measurement what is defined as a “green” building as well as to stimulate and transform the building market towards the design of integrated high performance buildings. Projects are rated depending on the number of credits achieved and meeting prerequisite requirements in six different categories. Standards have been developed for new commercial construction and major renovation projects, existing building operations, commercial interior projects and core and shell projects.

http://www.usgbc.org/leed_main.asp

**New York City Department of Design and Construction – High Performance Building Guidelines**

The Department of Design and Construction (DDC) in New York City established an Office of Sustainable Design (OSD) for the purpose of identifying and implementing cost-effective ways to promote greater environmental responsibility in building design. The document High Performance Building Guidelines were developed as a means to introduce sustainable design practices to DDC project teams and assist design professionals achieve a. This document has been a means of introducing sustainable design to DDC project teams and has been recognized internationally as a green building reference. Also available at this website are technical manuals and a complete list of specification language issued by the Office of the DCC on environmental technologies and practices to assist in processes to achieve a high performance building.
LEED Canada - Canadian Green Building Council

The Canada Green Building Council (CaGBC) is a coalition of representatives from the building industry to accelerate the design and construction of “green” buildings across Canada. The LEED Canada for New Construction and Major Renovations is an adaptation of the standards developed by the United States Green Building Council LEED® and specific to the climate, regulations and construction practices in Canada.

http://www.cagbc.ca/


The U.S. Department of Energy is committed to improve building performance measuring methods by collecting data on various factors that affect a building’s performance, such as energy, materials, and land use. The website includes a comprehensive searchable database on over seventy building projects, a range of building types, from around the world. Some of these buildings have been certified by a building certification program or have a notable environmental feature. This website also includes research reports on environmental technologies, links to websites that assist in the development or assessment of “green” buildings and whole building design guidelines.

Appendix B  Framework results from consultation with industry professionals on green roof technology

The following are results from the interviews with industry professionals (developer, architect and public authority) using the framework presented herein to evaluate green roof technology. The tables are provided as additional background to the discussion in Chapter 3.
Results of interview with developer

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Technology Impact of Interest</th>
<th>Performance Indicator in Net Present Value (NPV)</th>
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<td>Air Quality</td>
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<td>NPV for the change in design and construction requirements to meet specified criteria for energy efficiency of the ventilation system and indoor air quality and climate</td>
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<td>Daylighting</td>
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<td>criteria for the percentage of occupied floor area where daylighting is the primary source of light</td>
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<td>Opportunity for repeat business</td>
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NPV for the change in annual potable water usage in the building relative to baseline conditions.
NPV for the change in annual wastewater disposal relative to baseline conditions.
NPV for the change in the quality of water effluent leaving the site relative to baseline conditions.
NPV for the change in percentage of stormwater infiltration relative to baseline conditions.
NPV for change in the annual source operating energy used in the building relative to baseline conditions.
Supplied by renewable energy sources or retrofit ready for its supply relative to baseline conditions.
NPV for the change in the amount of recycled content materials used on the project relative to baseline conditions.
NPV for the change in the amount of salvaged or reclaimed materials used on the project relative to baseline conditions.
NPV for the change in the use of materials or design strategies that impact the amount of materials used on the project relative to baseline conditions.
NPV for the change in impact on public infrastructure relative to baseline conditions.
NPV for the change in impact on public infrastructure relative to baseline conditions.
NPV for the change in the impact on the global environment.
NPV for performance bond or other guarantee relative to baseline conditions.
NPV for availability of insurance to cover liability identified.
NPV for the value of short and long-term reliability testing of technology for reliability issues during use and after warranty.
NPV for the value of technology supply and support availability.
NPV for the amount of training required operating, maintaining the technology relative to baseline conditions.
NPV for the value of the impacts in the event of technology failure.
environmental issues in the design, installation or operation of the technology relative to baseline conditions.
design, installation or operation of the technology relative to baseline conditions.
requirements in the design, installation, commissioning or operation of the technology relative to baseline conditions.
NPV for the change in time required to research, design, manage, commission and receive approvals relative to baseline conditions.
NPV for the change in employee time to operate and maintain technology relative to baseline conditions.
NPV for the change in time required completing a phase in the construction process relative to the baseline scenario.
NPV for the change in time requirements to rectify technology defects relative to the baseline scenario.
NPV for the amount and type (positive or negative) of media coverage of project.
NPV for the change in public perception and acceptance of the project.
NPV for the opportunity to meet corporate policy objectives relative to baseline conditions.
NPV for the opportunity to expand or develop a new market share.
NPV for the opportunity to increase repeat business.
### Results of interview with public authority

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<th>Performance Indicator in Net Present Value (NPV)</th>
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<td>NPV for the change in design and construction requirements to accommodate detection and suppression requirements relative to baseline conditions.</td>
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<td>Egress Provision</td>
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<td>NPV for the change in design and construction requirements to accommodate egress provision relative to baseline conditions.</td>
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<td>Fire Spread Control</td>
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<td>NPV for the change in design and construction requirements to accommodate fire spread control relative to baseline conditions.</td>
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<tr>
<td>Air Quality</td>
<td>Y, Y</td>
<td>NPV for the change in design and construction requirements to meet specified criteria for energy efficiency of the ventilation system and indoor air quality and climate.</td>
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<tr>
<td>Daylighting</td>
<td>Y</td>
<td>Criteria for the percentage of occupied floor area where daylighting is the primary source of light.</td>
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<td>Moisture Protection</td>
<td>Y, Y</td>
<td>Technology retains its properties and performance abilities under exposure to moisture conditions.</td>
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<td>Personal Safety</td>
<td>Y, Y</td>
<td>Improve specified criteria to provide personal safety to individuals to prevent physical injury relative to baseline conditions.</td>
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<tr>
<td>User Control</td>
<td>Y, Y</td>
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<td><strong>Durability</strong></td>
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<tr>
<td>Compatibility With Materials</td>
<td>Y, Y</td>
<td>Technology is compatible with existing norms and procedures relative to baseline conditions.</td>
</tr>
<tr>
<td>Wear or Abuse Resistance</td>
<td>Y, Y</td>
<td>Improve specified criteria for wear and abuse resistance from physical or mechanical wear relative to baseline conditions.</td>
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<td>Deterioration Resistance</td>
<td>Y, Y</td>
<td>Improve specified criteria for deterioration resistance to chemical and electro processes relative to baseline conditions.</td>
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<td><strong>Architectural Function</strong></td>
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<td>Aesthetics</td>
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<tr>
<td>Acoustics</td>
<td>Y, Y</td>
<td>NPV for the change in design and construction requirements to meet specified criteria for the transmission of noise relative to baseline conditions.</td>
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<td><strong>Flexibility</strong></td>
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<tr>
<td>Adapt for multiple uses</td>
<td>Y, Y</td>
<td>Rule etc. due to uncertainty in future requirements relative to baseline conditions.</td>
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<td>Useable Floor Area</td>
<td>Y, Y</td>
<td>Improve specified criteria for the amount of marketable space relative to baseline conditions.</td>
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<td><strong>Economic Impact</strong></td>
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<td>Initial Costs or Savings</td>
<td>Y</td>
<td>NPV for direct initial costs or savings of technology adoption relative to baseline conditions.</td>
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<td>Operations &amp; Maintenance Cost</td>
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<td>Technology under evaluation over the life cycle of the project relative to baseline conditions.</td>
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<td>Zoning Changes</td>
<td>Y, Y</td>
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<td><strong>Property Tax Treatment</strong></td>
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<td><strong>Environmental Impact</strong></td>
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<td><strong>Water Use</strong></td>
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<td><strong>Wastewater Efficiency</strong></td>
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<td><strong>Wastewater Disposal</strong></td>
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<td><strong>Wastewater Quality</strong></td>
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<td><strong>Stormwater Treatment</strong></td>
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<td><strong>Energy Efficiency</strong></td>
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<td><strong>Energy Use</strong></td>
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<td><strong>Energy Source</strong></td>
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<td><strong>Materials Efficiency</strong></td>
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<td><strong>Recycled Material</strong></td>
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<td><strong>Savaged Materials</strong></td>
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<td><strong>Efficient Materials</strong></td>
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<td><strong>Impact on Public Infrastructure</strong></td>
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<td><strong>Impact on public infrastructure</strong></td>
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<td><strong>Impact on Local Environment</strong></td>
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Appendix C  Definition of performance measures

Technical criteria

Structural Stability

Design Forces
Each structure must be designed to resist horizontal or vertical design forces.

Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate horizontal or vertical design forces

Wind Resistance
Each structure must be designed to meet the design pressure rating according to a code approved standard with tests performed by independent parties to verify the results.

Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate applied pressures for wind uplift and wind fatigue relative to baseline conditions

Seismic Resistance
Special material requirements, design considerations and construction practices may be required for high-seismic design and construction. The cost of this can be more relative to low-seismic design and construction. The goal of this performance criterion is to minimize the cost to incorporate design provisions for the seismic system such that the level of available energy dissipation and corresponding level of ground motion can be withstood relative to baseline conditions.

Performance Indicator: Net Present Value for the change in design and construction to achieve the seismic design requirements relative to baseline conditions

Fire Safety

Detection & Suppression
The building technology should not prevent the installation of detection devices and their accessories, cables, etc or suppression systems.

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Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate detection or suppression requirements relative to baseline conditions

**Egress Provision**
Size of openings in walls should not be limited to a width smaller than necessary for main egress door and secondary openings.

Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate egress provision relative to baseline conditions

**Smoke Control**
The basic design of joints within and between separation elements (partitions, walls, floors, etc.) should prevent the propagation of smoke from one room to another, neither directly or through internal cavities or voids with respect to prescribed code requirements from the start of a standard fire.

Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate smoke control relative to baseline conditions

**Fire Spread Control**
The possible choices of materials should not enable the propagation of fire from one room to another, neither directly nor through internal cavities or voids, with respect to applicable code requirements.

Performance Indicator: Net Present Value for the change in design and construction requirements to accommodate fire spread control relative to baseline conditions

**Toxicity**
Different materials produce different combustion products in the event of the fire. The goal of this performance criterion is to select materials that limit the emission of toxic combustion products or meets applicable standards.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet threshold performance criteria from applicable codes or standards for toxicity when burning

**Architectural Function**

**Aesthetics**
The aesthetics of a building can be an integral aspect in its design and integration with the surrounding built and natural environment. Building components or systems should not be designed individually but as a part of an integrated set of systems where aesthetics is of interest.
Performance Indicator: Net Present Value for the change in design and construction requirements to meet criteria for aesthetics relative to baseline conditions

**Acoustics**
It should be possible to design the acoustic insulation of separation elements so that the combined effect of transmitted noise levels would not cause disturbing conditions for the envisaged activities in every given room.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet specified criteria for the transmission of noise relative to baseline conditions

**Human Health, Comfort & Safety**

**Air Quality**
The goal of this performance criterion is to identify the physical, chemical and biological properties that indoor air must have in order to not cause or aggravate illnesses in the building occupants and to secure a high level of comfort to the building occupants in the performance of the designated activities for which the building has been intended and designed. If toxic compounds are present in the materials, then it should be possible to limit their emission.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet specified criteria for energy efficiency of the ventilation system and indoor air quality and climate

**Daylighting**
It is preferable that the primary light source for occupied space during the day is daylight for human health and comfort.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet specified criteria for the percentage of occupied floor area where daylighting is the primary source of light

**Moisture Protection**
Technology selection should be made in consideration of location, climatic condition and exposure to moisture penetration. The prevention of moisture from entering the interior spaces and/or the building systems is the goal of this performance criterion.

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Performance Indicator: Net Present Value for the change in design and construction requirements to ensure that the technology retains its properties and performance abilities under exposure to moisture conditions

**Safety from Injury**
The technology under evaluation should not harm the occupant for example through contact or emissions.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria to provide personal safety to individuals to prevent physical injury relative to baseline conditions

**User Control**
The opportunity to control settings in the space improves occupant comfort and is the objective of this performance criterion

Performance Indicator: Net Present Value for the change in design and construction requirements such that occupants have an improved opportunity to control their surroundings relative to baseline conditions

**Glare Control**
The ability to control glare into the building improves occupant comfort

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria for glare control relative to baseline conditions

**Deterioration Resistance**
The technology evaluated should resist chemical and electro processes such as absorption-freeze-thaw or UV radiation.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria for deterioration resistance to chemical and electro processes relative to baseline conditions

**Wear/Abuse Resistance**
The technology evaluated should resist wear and abuse to minimize the generation of waste and the rate of its replacement.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria for wear and abuse resistance from physical or mechanical wear relative to baseline conditions
Compatibility
The technology evaluated should not induce risks or disturbance with respect to the function of other systems and materials in the completed building. The more the option is compatible with existing norms and procedures the easier the adaptation.

Performance Indicator: Net Present Value for the change in design and construction requirements to ensure that the technology is compatible with existing norms and procedures relative to baseline conditions.

Flexibility

Adapt for Multiple Uses
The technology under consideration should be flexible to changes in technology, demand and performance requirements. The objective relates to the fact that certain technologies are more robust than others with a change in demand requirements. The more flexible the technology to change the greater the minimization of future costs to changes in design and technology requirements.

Performance Indicator: Net Present Value for the opportunity for the technology to accommodate new technologies, fuels etc. due to uncertainty in future requirements relative to baseline conditions.

Useable Floor Area
The goal of this criterion is to maximize the amount of useable floor area.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria for the amount of marketable space relative to baseline conditions.

Scalability
Uncertainty surrounds future demand requirements of a building. The demand of a system changes with time and user requirements. Since the life span of a building typically exceeds 50 years, the changes in demand over this time period are difficult to forecast. Technologies that can scale up or down to accommodate changes in demand result in a more flexible complete building and decrease the need for whole system removal and replacement.

Performance Indicator: Net Present Value for the change in design and construction requirements to meet or improve specified criteria to accommodate changes in demand without the requirement for whole system removal and replacement.
Economic impact criteria

**Capital Cost**

**Initial Costs or Savings**
The goal of this performance criterion is to minimize capital cost expenditures. The cost of innovative technologies can vary from no additional cost to substantial increased capital cost depending on its complexity, quality and maturity. A technology with the least cost is the most desirable. The measure is determined based on the direct cost or savings of the technology relative to the technical function the system it is intended to replace.

Performance Indicator: Net Present Value of direct initial costs or savings of technology adoption relative to baseline conditions

**Operation Maintenance**
The actions and processes involved in the upkeep of a building and control of its equipment in a proper working condition is termed operation and maintenance. Effective operation and maintenance has the potential to improve water and energy efficiency and ensure reliability and safety of the building systems. It has been estimated that operation and maintenance programs targeting energy efficiency can save 5% to 20% on energy bills without a significant investment. Preference is for technologies that result in the greatest operations and maintenance savings over the life cycle of the building.

Performance Indicator: Net Present Value of direct costs or savings incurred by the implementation of the technology under evaluation over the life cycle of the project relative to baseline conditions

**Capital Appreciation**
The goal of this performance criterion is to maximize the appreciation and profitability of the investment. The potential exists that the implementation of a new technology will add value to the project such that the investment could be sold or used as collateral at a greater value relative to its baseline condition.

Performance Indicator: Net Present Value of the capital appreciation of the investment relative to the baseline conditions

**Incentives Available**
Many utilities and government entities offer incentives for the implementation of environmental innovative technologies. Incentives range from increased floor space

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ration (FSR), accelerated approval process, special tax considerations, or direct rebates for the purchase or design requirements of the new system. In general, each program establishes qualification criteria for technology performance in order for eligibility. The value of the incentive can be translated into dollar terms in order to determine the ultimate benefit. Potential incentives available include:

- **Zoning Changes**
- **Accelerated Approvals**
- **Increased Density**
- **Direct Subsidy**
- **Income Tax Treatment**
- **Property Tax Treatment**

**Performance Indicator:** Net Present Value of incentive available relative to baseline conditions

**Replacement Costs**
The goal of this criterion is to maximize the service life of the technology and thereby minimize its replacement and the associated adverse environmental and financial impacts.

**Performance Indicator:** Net Present Value of technology replacement relative to baseline conditions

**Salvage Value**
The goal of this criterion is to maximize the salvage value when the building in the demolition or removal phase of the project life cycle.

**Performance Indicator:** Net Present Value of technology salvage in its removal relative to baseline conditions

**Quality Control**

**Warranty Availability**
A product warranty is a guarantee that performance expectations are met or exceeded as outlined by the manufacturer. A warranty is desirable, particularly for products on the market for a limited time) because it transfers an element of risk associated with technology non-performance to the manufacturer. The performance objective relates to the standard of warranty offered for the technology under evaluation relative to the baseline condition.

**Performance Indicator:** Net Present Value of performance bond or other guarantee relative to baseline conditions
Reliability Issues
Reliability in the context of building technologies is defined as the ability of the technology to function within the manufacturers performance limits. Assessing reliability beyond short-term estimates is difficult because of the level of uncertainty and quality of data required for modeling and analysis. Data is uncertain due to the difficulty in testing technologies designed to have a long life span and most testing data on new technologies is carried out on the product or technology itself and not on a full-scale application. Some technologies may be selected based on the performance efficiencies; therefore, operation at sub-optimal levels between routine maintenance checks is undesirable because it defeats original criteria that formed the basis of technology selection. Review of whether design objectives will be sustained despite disturbances during normal operations is a key consideration of this performance objective. A decision maker requires adequate short and long term performance testing and data on a new technology for proper assessment of technology reliability.

Performance Indicator: Net Present Value for the value of short and long-term reliability testing of technology for reliability issues during use and after warranty

Liability
The implications of a technology non-performance are a consideration of most design professionals. Liability may be classified as direct (the organization is held responsible for its actions or failure to act), vicarious (the organization is held responsible for harm caused by persons acting on its behalf), or strict (responsibility is automatic and a finding of negligence or misconduct is not required). Liability associated with technology non-performance can result in the adverse impacts on a decision makers finances and/or reputation. Insurance costs or savings and potential claims that may arise with the technology selection are the measure of this performance objective.

Performance Indicator: Net Present Value for availability of insurance to cover liability identified

Availability and support
Vendors can be the most familiar and qualified individuals with the operation and optimization of the new technology they supply. Design professionals very often rely upon the quality testing and performance results supplied by the vendor. The availability of technical support can aid in the maximization of performance optimization and integration of the technology with other building systems. Procurement restrictions or difficulties in accessing the technology can have implications on project schedule and are therefore undesirable.

Performance Indicator: Net Present Value for the value of technology supply and support availability

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Failure bounded?
In the event of a technology failure, the economic impact could have large financial, environmental, social or technological impacts. The goal of this performance criterion is to minimize the impact of technology failure.

Performance Indicator: Net Present Value for the value of the impacts in the event of technology failure

Simplicity of Use
The degree of aptitude required to implement a technology could influence whether or not it is adopted. Inability to locate design professionals or contractors familiar or willing to install and design for the technology would adversely affect its adoption. Simplicity can be evaluated relative to the construction processes operations and maintenance and user familiarity.

Performance Indicator: Net Present Value for the amount of training required operating, maintaining the technology relative to baseline conditions

Business performance - marketability
It is important for a government entity or corporation to develop a prominent public profile and to be represented by images, which convey success, innovation, social awareness and future focus. The implementation of innovative technologies or using the project to test new systems is one approach in developing a positive image.

Public Acceptance
Any development plan must be reviewed and approved by the appropriate local government before construction can begin. Public input or protest of project objectives can delay the development process and can result in adverse implications on project cost and schedule. It is therefore desirable to have the public favour the project objectives, which can aid in streamlining and speed up the city’s approval process of the project. A negative perception of the project by the public could be based on visual quality concerns and conflicts with heritage values. Planners, plan checkers and elected officials have the influence to change a project design and plan due to the political influence of special public interest groups, therefore positive public acceptance aids in a timely approval process.

Performance Indicator: Net Present Value for the change in public perception and acceptance of the project

Publicity
Publicity is often one component of a project budget allocated for advertisement or promotion of a project. Positive and free media publicity of a project improves a
company profile and the marketability of a project. Negative publicity is undesirable for a company's image.

Performance Indicator: Net Present Value for the amount and type (positive or negative) of media coverage of project

**Entry Into a New Market**
The interest in innovative technologies has increased in the past years in particular for technologies that have a decreased environmental impact. New markets may open for the developers who construct buildings with reduced environmental impacts such as the inclusion of low emission building materials or improved energy and water efficiencies relative to the traditional building. Becoming a market leader can result in a competitive advantage as the company becomes more familiar with the risks, design and economic implications of new technologies. Expansion in the size of market share is of direct benefit to a company.

Performance Indicator: Net Present Value for the opportunity to expand or develop a new market share

**Support Mandate**
Many large corporations and governments have a corporate mandate that outlines the current state of the company and its desired future direction. The mandate is a proactive document with indicators of success to measure progress in achieving policy goals. For example, many companies have a sustainability policy to which they must measure the degree to which objectives have been achieved and communicate performance to stakeholders. Sustainability policy objectives could be met through implementing technology alternatives with a decreased environmental impact relative to the baseline technology.

Performance Indicator: Net Present Value for the opportunity to meet corporate policy objectives relative to baseline conditions

**Repeat Business**
The maintenance of an existing client base and the enhancement of repeat business opportunities are desirable to ensure company longevity.

Performance Indicator: Net Present Value for the opportunity to increase repeat business

**Knowledge management**

**Public Awareness**
A priority of many government entities is to increase public awareness about environmental or social issues. Whether the government provides the service or whether it is through a private sector project, the priority must be addressed. The performance objective is directed at technologies that provide an opportunity to educate the public.
Performance Indicator: Net Present Value for the opportunity to educate or improve public awareness of environmental issues in the design, installation or operation of the technology relative to baseline conditions

**Learning, R& D**
Implementing new technologies creates the opportunity to collect performance data on its full-scale application that would otherwise be both difficult and expensive to obtain. Empirical studies indicate that research and development tends to create improvements in well-being that are much larger than the private returns that are captured by the organization undertaking it\(^8\). The social rate of return on the acquisition of knowledge can be the basis of measurement for this performance objective.

Performance Indicator: Net Present Value for the opportunity to contribute towards research and development in the design, installation or operation of the technology relative to baseline conditions

**Time management**

**Timing of Commitment**
The success of a project schedule depends on adherence to the dates outlined on the critical path. Interruptions or delays can have a negative impact on the overall estimated budget. The performance objective relates to the timing of when the critical events occur for technology implementation and the resultant impact on factors that would impact schedule including the number of resources required for technology implementation, the impact on slack resources and management’s responsibility in overseeing activities relative to the baseline condition.

Performance Indicator: Net Present Value for the change in timing of commitment of the design and construction requirements in the design, installation, commissioning or operation of the technology relative to baseline conditions

**Project Resources**
The amount of time spent by project resources on the implementation of a new technology can differ from the project time allocated in a baseline scenario.

A. **Construction Processes**
The amount of time required to implement a new technology depends on the degree of familiarity of technology by regulators and architectural and engineering professionals. The amount of time required in the research, design, construction, commission and receive related approvals of the technology is measured relative to the baseline condition.

Performance Indicator: Net Present Value for the change in time required to research, design, manage, commission and receive approvals relative to baseline conditions

B. Operations and Maintenance

The amount of time required to operate and maintain a technology can vary depending on the simplicity and familiarity of the technology to the operator.

Performance Indicator: Net Present Value for the change in employee time to operate and maintain technology relative to baseline conditions

Duration of Phases
The amount of time spent to complete each phase relative to the baseline conditions.

Performance Indicator: Net Present Value for the change in time required completing a phase in the construction process relative to the baseline scenario

Time to Rectify Defects
The amount of time to rectify defects that occur in the installation or operation of the technology can impact operational requirements of the tenants.

Performance Indicator: Net Present Value for the change in time requirements to rectify technology defects relative to the baseline scenario.

Environmental impact

Water Efficiency

Water Usage
The building design can incorporate a number of practices to reduce the overall water usage that can result in both financial savings and societal benefits.

Performance Indicator: Net Present Value for the change in annual potable water usage in the building relative to baseline conditions

Wastewater Efficiency

Wastewater Disposal
The building design can incorporate a number of technologies and practices to reduce the overall wastewater disposal that can result in both financial savings and societal benefits.

Performance Indicator: Net Present Value for the change in annual wastewater disposal relative to baseline conditions
**Wastewater Quality**
The quality of the water that leaves the site will impact the public infrastructure system. The goal of this criterion is for the wastewater quality to be at least as good as or better than the potable water flowing to the site.

Performance Indicator: Net Present Value for the change in the quality of water effluent leaving the site relative to baseline conditions

**Stormwater Management**
Stormwater runoff is the runoff that flows over land after a rainfall. Areas that are developed and the land is more impervious impact the amount and rate of stormwater runoff negatively which in turn impacts downstream ecosystems. The goal of this criterion is to implement stormwater management practices such as infiltration, flow attenuation, detention etc. to minimize the amount and rate of stormwater runoff.

Performance Indicator: Net Present Value for the change in percentage of stormwater infiltration relative to baseline conditions

**Energy Efficiency**

**Energy Use**
The amount of energy used in a building has both a financial and environmental impact. The goal of this criterion is to reduce the amount of the annual source operating energy used in the building to minimize these impacts.

Performance Indicator: Net Present Value for change in the annual source operating energy used in the building relative to baseline conditions

**Energy Source**
The goal of this criterion is to maximize the percentage of the source of a buildings operating energy from a renewable source. Renewable energy sources are naturally replenishing and include hydropower (from water), wind, solar (from the sun), biomass and geothermal reservoirs (from the earth) and have less environmental impacts than fossil fuel based energy sources.

Performance Indicator: Net Present Value for the change the percentage of the buildings total operating energy use supplied by renewable energy sources or retrofit ready for its supply relative to baseline conditions

**Materials Efficiency**
The goal of this performance criterion is to conserve natural resources while minimizing the generation of waste and pollution from their manufacture, distribution and use.
**Recycled Material**
Recycled material is defined as “The amount or proportion of a product that is made of recycled material. Recycled content can be described broadly by weight, volume and many other measures.”

Performance Indicator: Net Present Value for the change in the amount of recycled content materials used on the project relative to baseline conditions

**Salvaged Materials**
The goal of this criterion is to maximize the amount of materials that are reused or salvaged from other building sites because they can have both environmental and financial benefits.

Performance Indicator: Net Present Value for the change in the amount of salvaged or reclaimed materials used on the project relative to baseline conditions

**Efficient Materials**
The goal of this criterion is to maximize the use of technologies or practices that minimize the generation of waste or mater usage on the project.

Performance Indicator: Net Present Value for the change in the use of materials or design strategies that impact the amount of materials used on the project relative to baseline conditions

**Public Infrastructure**
The goal of this criterion is to increase the opportunity to decrease the demand or load on public infrastructure to minimize infrastructure costs to the public

Performance Indicator: Net Present Value for the change in impact on public infrastructure relative to baseline conditions

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