QUANTITATIVE ASSESSMENT OF SUSTAINABILITY USING LINKAGE-BASED FRAMEWORKS: A CASE STUDY OF UNIVERSITIES

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by

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Abstract

A sustainability assessment tool can help decision and policy-makers to take appropriate actions for making society more equitable. Sustainability assessment involves various tiers of information such as performance objectives, assessment criteria, indices, indicators and variables. Quantitative measurement and assessment of sustainability have always been a challenge. Several approaches or conceptual frameworks have been proposed in various disciplines ranging from engineering to business and policy-making. A critical literature review of sustainability assessment frameworks revealed that existing frameworks have limited capability to deal comprehensively with different issues of sustainability. These also lack flexibility to be adapted in various disciplines with a unified interpretation. However, linkage-based frameworks can integrate information at all levels and guide long-term actions directed at reducing environmental health threats using causality relationships. Comparison of various linkage-based frameworks shows that the driving force-state-exposure-effect-action (DPSEEA) framework can be used to achieve sustained health benefits and environmental protection in accordance with the principles of sustainable development. Further, its similarity with ecological and human health risk assessment and risk management paradigms sets it apart from the other linkage-based frameworks.

A quantitative model based on the DPSEEA framework is developed for sustainability assessment of higher education institutions (HEIs) based on environmental, socio-economic, and educational performance as viable dimensions of sustainability. A comprehensive list of sustainability indicators under each dimension is selected to assess sustainability using a surrogate measure called *sustainability index* (SI). This causality based model is called **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM). As public institutions and particularly HEIs are facing the challenges of bringing sustainability in their strategic planning and development, a quantitative assessment of sustainability can be very helpful. The D-SiM can be applied to any institution provided the indicators are selected based on the performance of that institution. In D-SiM, SI is an outcome of a multitude of nonlinear effects of sustainability indicators in various stages of

DPSEEA. An empirical model based on 2^k full factorial analysis indicates that economic development, social equity, and education are the major drivers for achieving sustainability in HEIs.

As sustainability is generally regarded as a qualitative and elusive concept, it is proposed to use fuzzy multi-criteria decision-making in D-SiM for the quantitative assessment of sustainability. This uncertainly based D-SiM is referred as **u**ncertainty-based **D**PSEEA-**S**ustainability **i**ndex **M**odel (uD-SiM), where each factor is defined using fuzzy numbers. Sensitivity analysis shows that the education in sustainability and global and local research trends are the major driving forces for achieving sustainability in HEIs. These are followed by financial and economic growth rate, social equity, energy requirements rate, and institutional enhancement. The results of uD-SiM are found to be more realistic than its deterministic counterpart D-SiM.

After the development of uD-SiM, the model is used for ranking selected Canadian universities. A comparison of universities based on sustainability indicators related to environmental, economic, social and educational aspects is also carried out. The five Canadian Universities considered and evaluated using uD-SiM are the University of British Columbia (UBC), University of Toronto (UoT), University of Alberta (UoA), McGill, and Memorial University (MUN). The final ranking results are compared with the green report card ranking for 2010 through SI. It is found that the overall rankings of the UBC, UoA, and McGill by uD-SiM were quite similar to the Green report card's ranking. The difference between uD-SiM ranking and Green report card could be attributed to the difference in selection of indicators for the two approaches. In Green report card, water use and education in sustainability are not considered whereas these two indicators play a significant role in the uD-SiM model. The application of various control actions and strategies for improving sustainability in HEIs at different stages of the framework are also discussed.

DEDICATION

To my father

For his strong support and encouragement and for sharing my efforts and happiness

Acknowledgements

Important milestones in life can only be achieved through help of family, friends and mentors. During the course of completing this work, I have received enormous support from many individuals and groups, for which I am deeply grateful.

When I took this daunting task, I was working full-time with two little kids and was located in Ottawa, Ontario. Our move from Ontario to Kelowna, BC during this period added to the complexity of challenges. Many weekends and week nights I sat before my computer and children went without many outings. My husband Rehan, and children, Hibah and Hani, always provided moral support to me, their patience and understanding during my pursuit of this degree played a significant role during this process. With their help and my parents' support and prayers, I was able to keep a balance between work, family and study.

I would like to acknowledge the continuous and timely help provided by my supervisor Dr. Faisal Khan, co-supervisor Dr. Brian Veitch, and supervisor committee member Dr. Kelly Hawbodlt. Without their support and encouragement, I would not have achieved this honor. From the conception of the first idea to the final detail of the thesis, whether it was dealing with a complicated analysis or administrative tasks, preparing for the comprehensive exam and final defence or presenting a paper in a conference, I received prompt response from them. I would also like to express my gratitude to my fellow graduate student, Refaul Ferdous, for his help and support.

I have found this work to be sometimes exhausting, occasionally frustrating, but mostly satisfying. In short, the endeavor has been a pleasure, and this has been largely because of the support I have received from those around me, especially my husband Rehan, whose constant untiring help, advice and perseverance made this dream come true.

Thank you all!

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List of Abbreviations and Acronyms

AHP	Analytic hierarchy process
ANOVA	Analysis of variance
DoE	Design of Experiment
DPSEEA	Driving force-state-exposure-effect-action
DPSIR	Driving force-pressure-state-impact-response
D-SiM	**D**PSEEA **S**ustainability **i**ndex **M**odel
HEI	Higher education institution
HEIs	Higher education institutions
IC	Index change
LCA	Life cycle assessment
MADM	Multiple attribute decision making
MCDM	Multi-criteria decision-making
MLV	Most likely value
MODM	Multiple objective decision making
MUN	Memorial University
OWA	Ordered weighted averaging
PC	Percent contribution
PSR	Pressure-state-response
SA	Sensitivity analysis
SAW	Simple weighted average
SI	Sustainability index
TBL.	Triple bottom line
TFN	Triangular fuzzy number
UBC	The University of British Columbia
uD-SiM	Uncertainty-based **D**PSEEA **S**ustainability **i**ndex **M**odel
UoA	University of Alberta
UoT	University of Toronto

List of Symbols

A_j	Estimated activation level of a dependent indicator j
A_{env}	An activation level of environmental *effects*
A_{econ}	Activation level of economic *effects*
A_{soc}	Activation level of social *effects*
A_{edu}	Activation level of education *effects*
$\bar{A}_j$	Estimated fuzzy activation level of a dependent indicator j
$\bar{A}_{env}$	Fuzzy activation level of environmental *effects*
$\bar{A}_{econ}$	Fuzzy activation level of economic *effects*
$\bar{A}_{soc}$	Fuzzy activation level of social *effects*
$\bar{A}_{edu}$	Fuzzy activation level of education *effects*
$\overline{SI}$	Fuzzy sustainability index
SI_N	Normalized Sustainability index
SI_o	Centroid index is a geometric center of the fuzzy number $\overline{SI}$
SI'	Un-normalized Sustainability index
T_1 and T_2	Normalization factors
w_i	Weight assigned to the indicator i
w_{env}	Causal weight for environmental *effects*
w_{eco}	Causal weight for economic *effects*
w_{soc}	Causal weight for social *effects*
w_{edu}	Causal weight for education *effects*
X	Predefined (or predetermined) activation values of contributing indicators
$\bar{X}$	Predefined fuzzy activation values

Chapter 1: Introduction

1.1. SUSTAINABILITY

Sustainability aims to meet human needs while preserving the natural environment so that these needs can be met in the present and also in the future. In the aftermath of the Brundtland Report in 1987, sustainable development has offered the world a new perspective on intra- and inter-generations parity. The Brundtland Commission, named after former Norwegian Prime Minister Harlem Brundtland, originally proposed the most oft-used definition of sustainability that states *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987).

The above definition provides the basis for the *sustainability* paradigm in various economies and implicitly argues for the rights of future generations to raw materials (natural resources) and to vital ecosystem services. This widely accepted concept has permeated into various disciplines and is now widely adopted and encouraged by many organizations (e.g., Kenway *et al.*, 2007). Jabareen (2008) has identified seven key concepts to synthesize and assemble the theoretical framework for sustainable development. These seven key concepts include equity, natural capital stock, utopia, eco-form, integrative management, global agenda, and ethical paradoxes.

Sahely *et al.* (2005) and Becker (1997) argued that sustainable development is about achieving a balance among three objectives or dimensions — environmental, economic and social — over time and in spatial horizons. Sustainable development deals with enviro-socio-economic issues of inter- and intra-generations in a holistic way and should not be considered as an add-on to existing management systems of organizations (Kenway *et al.*, 2007). Therefore, if we focus on any single objective or dimension alone in minimizing impacts; other effects not considered can grow unchecked. As a result, burdens can merely shift from one area to another instead of decreasing overall.

Sustainability paradigm requires multidisciplinary actions and involvement of all stakeholders in the decision making process (Loucks *et al*., 2000; Maragerum, 1999). Sustainability implies capturing an overall comprehensive picture of events and actions as far as they can be envisioned. This is also referred to as *environmental accounting*. This kind of accounting assumes that all aspects of a system can be measured and audited. Environmental accounting can be a limited biological interpretation as in the case of *ecological footprint analysis*, or may include social factors as in the case of triple bottom line (TBL) analysis. The TBL analysis is about identifying improvement in the environment, social, and economic performance due to short- and long-term policy decisions. In TBL analysis, environment relates to the impacts of policy decisions on the natural environment (e.g. natural resources, flora, and fauna); economy relates to the impacts on financial sustainability, and society relates to impact on the community as a whole (e.g. public health and safety, social equity, culture).

Sustainability is a vague concept, therefore its quantitative measurement and assessment has always been a challenge. Sustainability assessment requires various tiers of information that may include performance objectives, assessment criteria, indices, indicators and variables. The objectives describe the broad goals set by the decision-makers and by the public or by the user of the service. Major sustainability objectives can be expressed as TBL, that is, as environment, social, and economic performance. Assessment criteria (indices or indicators) provide yardsticks against which sustainability objectives are measured (McLaren and Simonovic, 1999). Various assessment criteria can be identified depending on the context and the level of study. For example, in any engineering project, health and safety, economic development, social equity, environmental quality, ecology, and technical feasibility can be major assessment criteria.

Performance indicators or indices are derived from *variables* as they measure the effectiveness of a decision in satisfying the objectives. They can refer to the context, conditions, means, activities, or performance. Indicators are useful for monitoring and measuring the state of environment by considering a manageable number of variables or characteristics. Performance indicators can be single valued (i.e., derived from one variable) or composite (i.e., obtained by the aggregation of two or more variables). Indicators can also be based on quantitative or qualitative performance data. Aggregation is required to combine performance variables and derive indicators using multi-criteria decision-making techniques, such as weighted averaging, analytic hierarchy process (AHP), and ordered weighted averaging (OWA) (Sadiq and Tesfamariam, 2007). The intent of aggregation is to simplify the presentation and provide realistic interpretation of a large number of performance variables in an effective manner.

Assessment criteria (or performance indices or indicators) provide yardsticks against which sustainability objectives are measured, and these can be single valued or composite (McLaren and Simonovic, 1999). Selection of relevant indicators is essential for an effective sustainability assessment and efficient performance monitoring for a system.

1.2. PROBLEM STATEMENT

Since sustainable development became a catchphrase in the international arena, several approaches and conceptual frameworks have been proposed and developed in various disciplines ranging from engineering to business and policy making. Sustainability assessment frameworks help to focus and clarify what to measure, what to expect from the measurement, and what kind of indicators to use. These frameworks lack the capability and flexibility to comprehensively deal with multiple issues for assessing sustainability in various disciplines and to provide a unified interpretation. The main differences among frameworks are the way in which they conceptualize the main dimensions or categories (such as environment, social, and economic) of sustainable development, the inter-linkages between these dimensions, the way they group the issues to be measured, and the concepts by which they justify the selection and aggregation of indicators.

A growing number of communities, businesses, and other organizations are publicly pledging their commitment to sustainability. Public institutions and particularly higher education institutions (HEIs) like universities all over the world are also committing and taking initiatives to make their campuses sustainable. The terms HEIs and universities are used interchangeably in this thesis. The main general objectives of all HEIs are to educate students based on certain general educational goals; to preserve and refine existing knowledge while producing, disseminating, and applying new knowledge; and to define and find solutions to the problems facing society. The challenge now is that these objectives have to be achieved in a sustainable manner. Sustainability for universities can be seen as a necessity not only to avoid the costs of deteriorating social, environmental and economic indicators but also to create new opportunities to improve the rate and extent of human development. These institutions are facing serious challenges in integrating sustainability in their strategic planning and developing qualitative and quantitative assessment models for measuring sustainability.

Assessing and quantifying sustainability is a challenge. Several approaches and conceptual frameworks have been proposed in various disciplines, but their applicability is limited because of the lack of a quantitative assessment framework. This research aims to overcome these limitations.

1.3. Research Objectives and Scope

The main goal of this research is to develop a quantitative sustainability assessment framework that can be applied to any institution. In this research, it is applied to higher education institutions.

The specific objectives of the proposed research are listed below:

- Conduct a comprehensive review of existing sustainability assessment frameworks in various disciplines, and identify a suitable framework for quantitative assessment of sustainability,
- Develop a model for quantitative assessment of sustainability initiatives in universities and propose an overall *index* of sustainability to monitor and improve their performance,
- Investigate uncertainties among sustainability indicators and their impact on sustainability index (SI), and
- Apply the developed model for studying the impacts of various decision actions (risk management strategies) on the improvement of sustainability index for selected Canadian universities.

In order to achieve the objectives of the research to be carried out, the following models and approaches are developed:

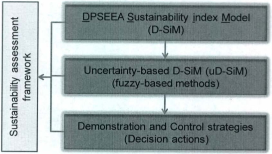
- Development of **D**PSEEA **S**ustainability **i**ndex **M**odel (D-SiM) for the sustainability assessment of higher education institutions,
- Development of uncertainty-based (probability or fuzzy-based) D-SiM (uD-SiM) that can incorporate uncertainties in the sustainability indicators and propagate them throughout the model, and
- Application of uD-SiM to identify and develop risk management and decision-making strategies for selected Canadian universities.

1.4. STRUCTURE OF THESIS

The remainder of this thesis has been structured in line with the general progression of the work from literature review to model development and demonstration, which is described in the following paragraphs. The major deliverables of this research are graphically represented by Figure 1.1.

Chapter 2 provides a detailed review of the literature to understand the frameworks and approaches taken by other researchers, to provide a basis for the choice of the most appropriate set of frameworks influencing factors, and to discuss the selection of HEIs for possible inclusion in the subsequently developed model. A journal paper (Waheed *et al.*, 2009) has been published in *Sustainability*.

Figure 1.1: Major research deliverables



Chapter 3 describes the selected framework DPSEEA, various multi-criteria making tools and challenges faced by higher education institutions. This chapter proposes a deterministic model D-SiM for sustainability assessment of HEIs. A conference paper (Waheed *et al.*, 2010) has been published in *CSCE Annual Conference Proceedings*. Another journal article (Waheed *et al.*, 2011*a*) is accepted and will be published in Issue 12 volume 4 of the *International Journal of Sustainability in Higher Education*.

Chapter 4 improves earlier proposed deterministic D-SiM model by introducing fuzzy-based concepts and presents an uncertainty-based model, called, uD-SiM. A journal paper (Waheed *et al*., 2011*b*) has been published in the *Journal of Cleaner Production*.

Chapter 5 validates the uD-SiM and demonstrates its application for selected Canadian universities. Moreover, the impacts of decision actions and risk management strategies on sustainability index are also discussed. A journal paper (Waheed *et al*., 2011*c*) is under review for possible publication in the *Stochastic Environmental Research & Risk Assessment*.

Chapter 6 summarizes the conclusions and also describes the contribution of this research. Recommendations for the future research direction are also provided.

1.5. STATEMENT OF ORIGINALITY

The novelty of the present research can be viewed from the following perspectives:

- In this research an innovative use of linkage-based framework, DPSEEA, has been explored for developing a cause-effect model for quantitative sustainability assessment, which has not been done in the past. The proposed framework is capable of incorporating inter-linkages, cause-effect relationships and feedback (actions) at any stage of DPSEEA framework and re-evaluates sustainability.
- The developed models (D-SiM and uD-SiM) have been applied to HEI in this study, however, the conceptual framework can be applied to any public institution (e.g., hospitals, schools, libraries, etc.) provided that the continuum (as cause-effects) of relevant performance indicators are available.
- The developed models provide an effective quantitative approach for ranking universities based on sustainability index instead of a point scoring system and are comparable to the existing ranking systems, such as Green Report Card.

Chapter 2: Literature Review[1]

ABSTRACT:

The main objective of this chapter is to discuss different approaches, identify challenges, and to select a framework for delivering effective sustainability assessments. Sustainable development is an idealized concept and its assessment has always been a challenge. Several approaches, methodologies and conceptual frameworks have been developed in various disciplines, ranging from engineering to business and to policy making. The chapter focuses mainly on various linkage-based frameworks and demonstrates that the driving force-state-exposure-effect-action (DPSEEA) framework can be used to achieve sustained health benefits and environmental protection in accordance with the principles of sustainable development, especially because of its resemblance to the environmental risk assessment and management paradigms. The comparison of linkage-based frameworks is demonstrated through an example of sustainability in a higher educational institution.

[1]A part of this chapter is published and cited as

- Waheed, B., Khan, F., Veitch, B. 2009. Linkage-based Frameworks for Sustainability Assessment: Making a Case for Driving Force-pressure-state-exposure-effect-action (DPSEEA) Frameworks. *Sustainability*, 1(3), 441-463; doi:10.3390/su1030441

2.1. Introduction

2.1.1. Definition

The main objective of this chapter is to provide an overview of different approaches, identify challenges, and to select a framework for delivering effective sustainability assessments. Sustainable development aims to meet human needs while preserving the natural environment so that these needs can be met not only in the present but also indefinitely in the future. Since the aftermath of the Brundtland report in 1987, sustainable development has offered the world a new perspective on how to protect environmental systems for the present as well as for the future generations. The Brundtland Commission, named after former Norwegian Prime Minister Harlem Brundtland, originally proposed the most oft-used definition of sustainability that states development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

The above definition provides the basis for the "sustainable development" paradigm in various economies at various levels, and implicitly argues for the rights of future generations to raw materials (natural resources) and to vital ecosystem services. This universally accepted concept has permeated into various disciplines and is widely adopted and (or) encouraged by many organizations (e.g., Kenway *et al*., 2007). Much has been written about principles or concepts of sustainability (Kenway *et al*., 2007; Becker, 1997; Gibson, 2000), however, the seven key concepts identified by Jabareen (2008) to synthesize and assemble the theoretical framework for sustainable development are presented here. These seven concepts include equity, natural capital stock, utopia, eco-form, integrative management, global agenda, and ethical paradoxes. Each concept represents distinctive meanings that provide the theoretical foundations of sustainability as follows:

Equity represents the social aspect of sustainable development. The most common types of equity are inter- and intra-generational. Intra-generational equity refers to fairness in allocation of resources between competing interests at the present time. Inter-generational equity refers to the fairness in allocation of resources between current and future generations.

Natural capital stock represents the sustaining of natural material assets development where natural capital stock consists of three categories: non-renewable resources, such as mineral resources; the finite capacity of the natural system to produce 'renewable resources' such as food crops and water supplies; and the capacity of natural systems to absorb the emissions and pollutants that arise from human actions without suffering from side effects which imply heavy costs to be passed onto future generations. The condition of constant natural capital is normally termed 'strong sustainability'. This concept is discussed later.

The concept of *Utopianism* represents a perfect society, where there is harmony between humans and nature, justice prevails, people are perfectly happy and content, life moves along smoothly without shortages.

The concept of *Eco-form* is one of the major contributors in bringing the global discourse on sustainability, and it deals with ecological design and form of human habitats such as the ecologically desired spatial form of cities, villages, and neighborhoods.

Integrative and holistic management represents a holistic view of social development, economic growth, and environmental protection. To preserve the natural capital stock for ecological and sustainable integrity, integrative and holistic management is essential.

Global political discourse means that political agenda has become one of the main drivers of sustainability as all major policies and programs around the globe are inspired by sustainability since 1990s.

Ethical paradoxes in sustainable development mean 1) characteristics of a state that can be maintained forever and 2) development or environmental modifications that intervene with nature and natural resources. The concept aims to mitigate and moderate the paradox between the two.

The central focus of sustainability is to provide a long-term performance. All above concepts aim to increase the quality of life for humans and other ecological entities, enhance economic activities, and reduce the impacts on ecological systems with special emphasis on major global problems like climate change, depletion of fossil fuels, emerging technologies, genetically modified food, and spread of diseases (Becker, 1997; Sahely *et al*., 2005; CEC, 2006). These concepts ensure that all developments must be undertaken with great sensitivity to minimize environmental impacts; therefore all possible alternatives must be considered comprehensively.

2.1.2. Sustainable Development

It has been argued by Becker (1997) and Sahely *et al*. (2005) that "sustainable development" is about achieving a balance among three objectives or dimensions — environmental, economic, and social — over time and spatial horizons. However, it is emphasized by Kenway *et al*. (2007) and Gibson (2000) that sustainable development deals with enviro-socio-economic issues of inter- and intra-generations in a holistic way and should not be considered as an add-on to the existing management systems of organizations as it requires stewardship of all resources. The reason is if we focus on any single objective or dimension alone while deciding on least burdening practices, it will allow all other effects to grow unchecked. As a result burdens can merely shift from one effect to another effect, instead of an overall desirable decrease of burdens. Sustainability paradigm requires multidisciplinary actions and involvements of all stakeholders in the decision making process (Loucks *et al*. 2000). Sustainability implies paying attention to comprehensive outcomes of events and actions as far as they can be anticipated at present. This is known as "environmental accounting". This kind of accounting assumes that all aspects of a system can be measured and audited. Environmental accounting can be a limited biological interpretation as the case for "ecological footprint analysis", or may include social factors as in the case of Triple Bottom Line (TBL) analysis. TBL is about identifying improvement in the environment, social, and economic performance as a result of short- and long-term policy decisions.

The concept of sustainability can be defined as "weak" or "strong". In case of weak sustainability, it is assumed that we can replace (or duplicate) natural materials and services with manufactured goods and services. This is also known as substitutability paradigm, whereas in case of strong sustainability it is assumed that the natural materials and services cannot be duplicated or natural capital stays constant over time (Pearce and Turner, 1990) as mentioned earlier in the natural capital stock concept in the previous section. Strong sustainability is also known as non-substitutability paradigm. The problem with the concept of weak sustainability is that one can easily assign a monetary value to the manufactured goods; however, assigning a monetary value to the natural materials and services can be very difficult or impossible. Similarly, ozone layer, wetland, ocean fishery, and a river full of salmon are irreplaceable. To further elaborate consider a case where one has to determine the worth of a forest full of trees. One way is to assign a monetary value to all trees by assuming that they are turned into furniture or paper. However, the forest provides a home for wildlife that provides food for hunters. It also provides a place for hikers to enjoy the natural environment. These intangible benefits are not possible to be duplicated by any monetary value. Contrarily, the concept of strong sustainability emphasizes on functions that only nature (environment) can perform and cannot be duplicated by humans. The ozone layer is one example of an ecosystem service that is difficult for humans to duplicate.

Sustainability assessment is an emerging concept and one of the typical questions raised by sustainable assessment is that how do we measure sustainability? The following section explains these questions in more detail.

2.2. Sustainability Metrics

Quantitative measurement and assessment of sustainability has always been a challenge. Sustainability assessments may require various tiers of information that may include objectives, assessment criteria, indices, indicators, and performance data/variables/parameters (Table 2.1). The objectives describe the broad goals set by the decision-makers and by the public or by the user of the service. Major sustainability objectives are generally set by TBL i.e., environment, social, and economic performance. Assessment criteria, sometimes also referred to as "indices" or "indicators" provide principles to establish that specified objectives have been met. Assessment criteria provide yardsticks against which sustainability objectives are measured. Various assessment criteria can be identified, depending on the context and the level of the study. For example, in any engineering project, health, safety, economic development, social equity, environmental quality, ecology, and technical feasibility can be major assessment criteria.

There are two approaches to define performance assessment criteria, i.e., a bottom-up approach and a top-down approach (Gibson, 2000). In the bottom-up approach, the objectives are defined in relation to the baseline conditions. In other words, criteria are generated by assuming that the state of sustainability can be defined by environmental, social, and economic objectives and proposed criteria are developed under these categories. For example, environment is a category and resource utilization is a proposed criteria. Triple bottom line is considered a bottom-up approach. On the other hand, a top-down approach assumes sustainability as a state to which society aspires, and then moves on to define this state in terms of sustainability criteria. Top-down approach is also called principles-based approach in which assessment criteria are derived from sustainability principles (Pearce and Turner, 1990). For instance, under sustainability principle of biodiversity and ecological integrity criteria, it should improve biodiversity and ecological integrity and builds life support. It is argued by Gibson (2000) and Pope *et al.* (2004) that the top-down or principles-based approach outweighs the bottom-up or TBL approach as it emphasizes interconnections and interdependencies between the sustainability dimensions rather than promoting conflicts and trade-offs, besides avoiding some of the inherent limitations of the TBL approach to sustainability. However, literature review shows that extensive research has been done using both approaches (e.g., urban infrastructure systems (Sahely *et al.*, 2005) and river basin management (Barrera-Roldan and Saldivar-Valdes, 2002).

Table 2.1: Sustainability matrices – an example in terms of TBL objectives

Data/ Variables	Indicators	Indices	Performance assessment criteria (C)	Objectives (O)		
				Environment (O1)	Economics (O2)	Society (O3)
Basic data that can be directly measured or monitored.	Each performance indicator derived from aggregation of various basic parameters	Each performance criteria derived from aggregation of various indicators	Health (C1)	*		*
			Safety (C2)	*		*
			Economic development (C3)	*	*	*
			Social equity (C4)		*	*
			Environmental quality (C5)	*	*	*
			Ecology (C6)	*		
			Technical feasibility (C7)		*	*

* indicates the possible relationship between a given criterion and objective

Performance indicators or indices are derived from variables as they measure the effectiveness of a decision in satisfying the assessment criteria. They can refer to the context, conditions, means, activities or performance. Indicators are useful for monitoring and measuring the state of environment by considering a manageable number of variables or characteristics. Performance indicators can be single valued (i.e., derived from one variable) or composite (i.e., obtained by the aggregation of two or more variables). Indicators can also be based on quantitative or qualitative performance data. Indicators, especially environmental, could be (i) use-based (early warning), subject- or issue-based (water quality, noise pollution), and position-based as in linkage-based frameworks described later in this chapter (Niemeijer and de Groot, 2008). Aggregation is required to combine performance variables and derive indicators using multi-criteria decision-making techniques such as weighted averaging, AHP (analytic hierarchy process), and ordered weighted averaging (OWA) to obtain an index. The intention of aggregation is to simplify the presentation and provide realistic interpretation of a large number of performance variables in an effective manner.

Alegre (1999) listed the basic characteristics of performance indicators as:

- encompassing all relevant aspects of sustainability performance
- non-overlapping (i.e., mutually exclusive)
- easy to understand and interpret
- as few in numbers as possible
- verifiable
- defined for a given time period, and
- universal enough to be measured in diverse conditions.

If the chosen indicators are not relevant and hard to measure or monitor, it leads to erroneous analyses and conclusions. Extensive lists of indicators for sustainability measurement have been provided in several studies related to the planning and management at urban, regional, and national levels (e.g., (Foxon *et al*, 2002; Maclaren, 1996; Alberti, 1996; WHO, 1996). Edwin (2002) explored the challenge of choosing appropriate indicators to measure environmental progress in the automotive industry. The author proposed two main challenges: 1) developing and evaluating appropriate normalized and functionally related indicators, and (2) integrating indicators into the design and decision process (using multi-objective approaches). The author found that the use of multi-objective decision-making could be problematic in sustainability assessment, if the indicators are not comparable or not fully applicable.

In the last decade, several attempts have been made to create aggregate measures for various aspects of sustainability by using indices to convey better information on countries and corporate performance in fields such as environment, economy, society, or for technological improvement. Some of the most prominent attempts include: Human Development Index (HDI) of the United Nations Development Programme (UNDP); Environmental Sustainability Index (ESI) and the Environmental Performance Index (EPI) of the World Economic Forum (WEF). Singh *et al.* (2009) have provided a detailed overview of various sustainability indices applied in policy practice. A summarized version of their work indicating broad classification of indices and categories is presented in Table 2.2. However, many special categories of environmental indices like air quality index and water quality index are not discussed here.

Table 2.2: Summary of sustainability indices (modified after Singh *et al.*, 2009)

Areas	Name of Index Approach	Categories
Innovative, knowledge and technology indices	Summary innovation index	• Human resources • Knowledge creation • Transmission and application of new knowledge • Innovation finance
Development indices	Human development index (HDI)	• Health • Knowledge • GDP per capita
	Index of sustainable and economic welfare	• Economics • Human Welfare
Market and economy-based indices	Green Net National Product (EDP) and System of integrated Environmental and Economic Accounting (SEEA)	• Natural resources • Economics • Environment state, pressure and destruction
Eco-system based indices	Sustainability performance index (SPI)	• Technical • Ecological • Human resources
	Eco-index methodology	• Economics • Life cycle impact data
	Living Planet index	• Biodiversity • Ecosystem
	Ecological Footprint (EF)	• Natural resources • National consumption
Composite sustainability performance indices for industries	Composite Sustainable Development Index	• Economics • Environment • Social performance
	Composite Sustainability Performance index	• Corporate citizenship • Environment • Economics
	G score method	• Voluntary environment • Health • Safety
	ITT Flgyt Sustainability Index	• Corporate contribution • Sustainable policies and commitment
Product-based sustainability indices	Life Cycle Index (LInx)	• Environment • Cost • Technology

Areas	Name of Index Approach	Categories
		• Socio-political
Environmental indices for policies, nations and regions	Environmental Sustainability Index	• Environmental systems • Stresses • Human vulnerability • Societal and institutional capacity • Global steward ship
	Environmental Quality Index	• Environmental factors
	Environmental Performance Index	• 6 policy categories
	Environmental Vulnerability Index	• Hazards • Resistance • Damage measurement
Environmental indices for industries	Eco-indicator 99	• Human health • Ecosystem quality • Resources, minerals and fossil fuels
	Green Pro-1 (Sadiq *et al.*, 2005; Khan *et al.*, 2002)	• Environmental • Technological • Economical

2.3. Sustainability Assessment Frameworks

Since sustainable development became a catchphrase in the international arena, several approaches and conceptual frameworks have been proposed and developed in various disciplines, ranging from engineering to business and to policy making. Each of these frameworks has limited capability to deal with different issues of sustainability comprehensively and lack flexibility to be used in various disciplines with a unified interpretation. The schemes to classify various sustainability frameworks may also vary, e.g., based on application discipline, methodology, mathematical techniques and tools, and the level of study. In engineering literature (Sahely *et al.*, 2005; Loucks *et al.*, 2000; Jeon and Amekudzi, 2005), sustainability assessment is generally viewed as a multi-objective optimization or multi-criteria decision-making problem. Based on detailed literature search (e.g., Kenway *et al.*, 2007; Jeon and Amekudzi, 2005; Guio-

Torres, 2006), we have classified the sustainability assessment frameworks into following six categories:

- Objective-based (e.g., strategic environmental assessment (SEA))
- Impact-based (e.g., environmental impact assessment (EIA), sustainability impact assessment (SIA), TBL assessment)
- Influence-based (e.g., Transport Canada framework (Transport Canada, 2001))
- Process-based or stakeholder-based (e.g., USDOE "Ten Steps to Sustainability" (Environmental Defense, 1999))
- Material flow accounting and Life cycle assessment (e.g., LInX (Khan *et al.*, 2004))
- Linkages-based (e.g., pressure-state-response (PSR), driving force-pressure-state-impact-response (DPSIR))

A majority of the above frameworks were developed in the last 10 to 20 years and did not evolve beyond the experimental stage (Pintér *et al.*, 2005). The main features of these frameworks include 1) setting objectives and assessment criteria based on the principles of sustainability, and 2) defining a set of measurable indicators under each assessment criterion. Various multi-criteria decision-making methods have been used for aggregating, ranking alternatives, and carrying out assessment process with a group of stakeholders (Kenway *et al.*, 2007).

Sustainability assessment frameworks help to focus and clarify what to measure, what to expect from measurement and what kind of indicators to use. A framework serves, at a high-level, direct reference to the basic concepts of sustainable development. Underlying any sustainable development framework is usually a conceptual model that helps identify and organize the issues that will define what should be measured. The main differences among frameworks are the way in which they conceptualize the main dimensions of sustainable development, the inter-linkages between these dimensions, the way they group the issues to be measured, and the concepts by which they justify the selection and aggregation of indicators. Table 2.3 provides a brief overview and main features of the above frameworks.

2.3.1. Objective-Based Frameworks

Objective-based frameworks have a proactive approach, and aim to ensure that a particular initiative contributes to a defined state of sustainability. Defining a sustainable state is a challenge. This approach can assess the extent to which an initiative contributes to a defined goal. The majority of the current frameworks, such as strategic environmental assessment (SEA) and life cycle assessment, are objective based and proactive in nature.

2.3.2 Impact-Based Frameworks

As the name suggests, the impact-based frameworks focus on the impacts of various actions on the sustainability of a particular system. It is a win-lose scenario. A typical example is environmental impact assessment (EIA) driven sustainability assessment, often referred to as sustainability impact assessment (SIA). It means that an initiative may have positive outcomes in one dimension of sustainability, such as economic performance, but negative results in social or environmental dimensions. Defining permissible or threshold limits can minimize the adverse situations. This framework has been used in various engineering disciplines such as transportation (Khan *et al.*, 2002; Litman, 2008); water and sewer systems (Ashley and Hopkinson, 2002); and building infrastructure (Pearce and Vanegas, 2002). Hacking and Guthrie (2008) have reported that both EIA and SEA are established frameworks for sustainability assessment. A matrix has been developed by Pope *et al.* (2004) that compares objective-based and impact-based frameworks against aim, focus, and contribution to sustainability and target limitations.

A common impact-based framework is three-dimensional framework of indicators based on environment, economics, and social impacts. It is known as triple-bottom line (TBL) framework. Pope *et al*. (2004) considered that TBL employs a reductionist approach to sustainability, which divides the holistic concept of sustainability into three pillars and invariably runs the risk of the sum of the parts being less than the whole. This is particularly true if the interrelations between the three pillars are not adequately understood and described. Some analysts also tried to add technical and/or institutional dimensions in sustainability (e.g., Khan *et al*., 2004). Many initiatives undertaken by various institutions using this framework are provided in Guio-Torres, (2006). It has been observed that when sustainability problems are divided into dimensions, it is much easier to use multi-criteria decision-making methods for sustainability assessment (e.g., Sahely *et al*., 2005).

2.3.3. Influence-Based Frameworks

Influence-based frameworks categorize indicators based on their level of influence on sustainability. This framework is used by Transport Canada (2001). These frameworks identify three levels of basic indicators, namely, state, behavioral, and operational (Jeon and Amekudzi, 2005). "State" indicators define the overall vision for obtaining sustainable system and measure the performance of the system against goals or vision.

"Behavioral" indicators relate to the activities of the actors or stakeholders whose actions influence the state of the system. "Operational" indicators correspond to the actions of the organization itself.

Table 2.3: Main features of sustainability frameworks

Frameworks	Main Features
Objective-based	• Proactive framework • Ensures that a particular initiative contributes to a defined state of sustainability • Form a part of majority of present frameworks (for example, strategic environmental assessment (SEA))
Impact-based	• Reactive in nature • Reductionist approach to sustainability • Focuses on the impacts of various actions on sustainability of particular system • Typical example is triple-bottom line (TBL) analysis (e.g., Global reporting initiative with five dimensions, UN-CSD with four dimensions. Also used in various engineering discipline, e.g., Transportation (Khan *et al.*, 2002; Litman, 2008; water and sewer system (Ashley and Hopkinson, 2002); building infrastructure (Pearce and Vanegas, 2002)
Influence-based	• Indicators categorized by their level of influence on sustainability of an organization or institution • Used by Transport Canada (Transport Canada, 2001)
Process/ stakeholder-based	• Involves extensive planning process that engages stakeholders • Used for developing consensus (Environmental Defense, 1999) • Extensively used for planning involving community projects
Material flow assessment/ Life cycle assessment	• Material exchanges between economy and natural environment • Cradle to grave (or gate) assessment of environmental impacts • Commonly used in chemical industry (Khan *et al.*, 2004)
Linkage-based	• Uses concept of causality (cause-effect) (Jeon and Amekudzi, 2005) • Different forms include pressure-state-response (PSR), driving force-pressure-state-impact-response (DPSIR), driving force-pressure-state-exposure-effect-action (DPSEEA) • Can be tied to sustainability through certain assumptions

2.3.4. Process- or Stakeholder-based Frameworks

A process-based framework involves a planning process that effectively engages stakeholders in creating their vision for sustainability. Environmental sustainability kit proposed by Environmental Defense (1999) explains that process-based frameworks are based on a decision aiding process for developing consensus, involving all the representatives from various constituencies within a community. Jeon and Amekudzi (2005) suggested that the involvement of stakeholders is essential when the planning for communities is being undertaken or when incorporating sustainability into local policy (e.g., Environmental Sustainability kit (Environmental Defense, 1999). This is indeed an important and critical component to achieve sustainability objectives.

Sustainable development initiatives at various university campuses around the world also use this framework, as the involvement of various stakeholders is a major component of these sustainability initiatives, such as the Talloires Declaration (ULSF, 1990). Velazquez *et al.* (2006) have proposed models that offer a clear perspective about how people responsible for sustainability initiatives affect collective behavioral change by educating stakeholders and promoting consensus-based sustainability goals for sustainable institutions such as universities.

2.3.5. Material Flow / Accounting and Life Cycle Assessment Framework

Material flow analysis is a framework to analyze the flows of a material in a well-defined system. It is referred to as Material Flow Accounting (MFA) when performed on a national or regional scale. In this framework the material exchanges between an economy and natural environment are analyzed. Indicators and indices are calculated to assess the level of resource intensity of the system and processes are optimized in such a way that materials and energy are used in the most efficient manner (Wernick and Irwin, 2005). The basic mantra is to focus on producing more with less.

The Life Cycle Assessment (LCA) framework is one step further to MFA as it uses the same principles but also tries to account for the environmental impacts of a technology, product, process, project or a service throughout their life cycles from raw materials extraction through end of life. Therefore, it is also referred to as cradle to grave (sometimes cradle to gate) approach (Wernick and Irwin, 2005; SETAC, 1991). It comprises four steps (Khan *et al.*, 2002, 2004):

- Define goal and scope helps to understand the purpose and the scope of the study and requires using system boundaries.
- Inventory analysis accounts for energy and raw material and discharges from all activities, products, and processes.
- Impact analysis determines the environmental impacts due to activities, products, and processes.
- Improvement assessment identifies the possibilities for improving the performance of the system.

Khan *et al.* (2004) developed a new indexing system - LInX, which aims to facilitate the LCA application in process and product evaluation and decision-making. The LInX consists of four dimensions, namely, environment, health and safety, cost, technical feasibility, and socio-political factors.

Another nuance of LCA, called Life Cycle Costing (LCC) is a method used in multi-criteria decision-making, when the monetary values are assigned to various activities in LCA. The discussion on this topic is beyond the scope of this chapter.

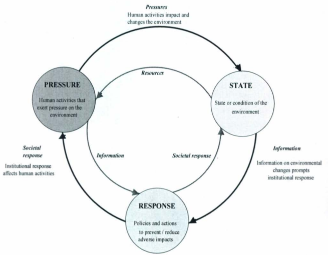
2.3.6. Linkage-Based Frameworks

The linkage-based frameworks use the concept of "causality" or cause-effect relationships. These frameworks provide linkages between each component of the framework by defining indicators for each component and recognizing effective actions to control and prevent the impacts. Three types of linkage-based frameworks are discussed in detail in the next section.

2.4. Types of Linkage-Based Frameworks

A widely known example of a linkage-based framework is the Pressure-State-Response (PSR) framework. This framework can facilitate better understanding of actions and activities that are affecting the state of the system, and appropriate response for addressing them both for the agency and stakeholders (Jeon and Amekudzi, 2005). In addition to PSR, other common linkage-based frameworks are DPSIR and DPSEEA.

Figure 2.1: Pressure-state-response (PSR) framework (adapted from OECD (1999))



2.4.1. Pressure-State-Response

The Pressure-State-Response (PSR) framework was conceived by Statistics Canada (Friend and Rapport, 1979), then further developed and adopted internationally in many countries (e.g., UN, 1991). The Organization for Economic Cooperation and Development (OECD, 1991) later adopted this framework for environmental reporting. A typical example of a PSR framework is shown in Figure 2.1.

A PSR framework states that human activities exert pressure (such as pollution emissions or land use changes) on the environment, which can induce changes in the state of the quality and quantity of the environment (such as changes in ambient pollutant levels, habitat diversity, water flows). Society then responds to the changes in the pressures or the state with environmental and economic policies / programs intended to prevent, reduce or mitigate pressures and/or environmental damage. The PSR framework highlights these (causal) linkages, and helps decision-makers and the public to see environmental and other interconnected issues (OECD, 1999). Based on its wide usage, the PSR framework can be identified as a commonly agreed upon framework by many organizations and agencies for environmental reporting (e.g., EEA, 1999, 2001; EPA, 2003; WRI, 2005).

2.4.2. Driver-Pressure-State-Impact-Response

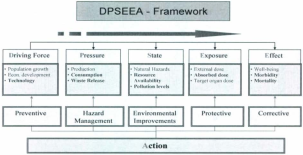
The United Nations Commission on Sustainable Development (UNCSD) modified the PSR framework and called it Driving force-State-Response (DSR) and it was used in the categorization of a first set of 134 Sustainable Development Indicators (SDIs) (UN, 1996). The OECD further modified the DSR framework and called it the Driver-Pressure-State-Impact-Response (DPSIR) framework. The DPSIR framework has been used to structure environmental information by most member states of the European Union (EU) and by many international organizations including the European Environmental Agency and EUROSTAT, the statistical office for the European Communities (Gilbert and Tanguay, 2000). A more recent example is the Environmental Sustainability Index (ESI) developed in collaborative work of the World Economic Forum (WEF), Yale and Columbia Universities (http://sedac.ciesin.columbia.edu/es/ESI/).

2.4.3. Driving Force-Pressure-State-Exposure-Effects-Action (DPSEEA)

The World Health Organization (WHO) took a broader approach to include the impacts of macro driving forces and pressures on both health and the environment (WHO, 1996). The framework was called the Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA). The DPSEEA framework (Figure 2.2) is useful as it covers the full spectrum of cause and effect relationships starting from potential forces and required actions and brings together professionals, practitioners, and managers from both environmental and public health fields to help orient them in the larger scheme of the problem. Corvalán *et al.* (1999) discussed the links among health, environment, and sustainable development. They presented DPSEEA framework to extend epidemiological domain to the policy domain.

The DPSEEA framework has been widely used in the environmental health sector (CEC, 2006). This framework is very useful in understanding the continuum starting from drivers of environmental change (such as technology and population) to pressures (such as production, consumption and waste releases) to changes in environmental state (such as pollution levels) to exposure (such as external, internal and target organ doses) to effects on health, environment and overall sustainability.

Figure 2.2: Driving Force-Pressure-State-Exposure-Effect-Action (DPSEEA) Framework



All sectors including government, private sector and individuals can take action to the outcomes at all levels, and this information can be used to provide feedback at all levels (Figure 2.2). In combination with multi-criteria decision-making, this framework has a great potential to contribute significantly to sustainability analysis.

The main advantage of DPSEEA is its flexibility and applicability. Its usefulness depends on the context in which it is used, e.g., health in sustainable development planning. The WHO and Europe and New Zealand Ministries of Health (WHO, 2004; ESR, 2005) have used the framework to develop environmental health indicators. In February 2001, the first meeting on the guidelines to assess the health impacts of climate change was attended by the representatives of WHO, Health Canada, and UNEP in Victoria (Canada); and they endorsed the DPSEEA as a viable conceptual framework for this purpose (http://www.euro.who.int/document/e74639.pdf).

Seven sustainability concepts proposed by Jabareen (2008), as discussed earlier in Section 2.1, are the main theme of DPSEEA (and other linkage-based frameworks). These concepts ensure that the resources (e.g., materials and energy) are used efficiently and effectively at the cost of minimal triple bottom line impacts. These concepts lead to improved system performance (i.e., minimizing "effect") without compromising socio-economic development (driving force) through optimal remedial "actions".

2.5. Proposed Integrated Framework for Sustainability Assessment

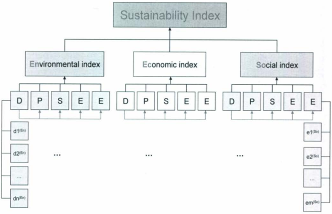
Various frameworks presented earlier (Sections 2.3 and 2.4) have some advantages and disadvantages (discussed later in Section 2.7). There is no single ideal framework for sustainability assessment. For example, impact-based methods are largely useful for assessing impacts of an activity on the economy, environment and on general social well-being. These impacts are measured on the natural environment through system effectiveness and efficiency. Process-based frameworks involve community representatives and other stakeholders in planning, and present opportunities to educate the public and influence collective behaviours. The MFA and LCA are also very popular and have extensively been used for sustainability assessment. Finally, the linkage-based frameworks use causal indicators that present a complete range of metrics to identify and measure a cause that create particular conditions affecting sustainability, the impacts of these causes, and the corrective actions that can be taken to address them. Jeon and Amekudzi (2005) suggested that an integrated causal framework helps to refine visions through developing policies, planning procedures and measurement, and monitoring systems for achieving sustainable systems for any corporation or an institution.

An integrated linkage-based framework is proposed here to emphasize the need to evaluate specific monitoring programs where goals and objectives are clearly defined. The health/environmental monitoring programs driven by the goals and objectives consider the factors involved in greater detail leading to the pressures on a system (Corvalán *et al.* (1999) and von Schirnding (2002) called them "driving forces"), at the states or responses within the system (e.g. external dose, internal dose and effects at the organism, cellular or molecular level), or at actions taken to combat adverse impacts (e.g., government emission control legislations). Therefore, for example, depending upon the differences in the focus of two frameworks, what one framework defines as a "hazard", may be referred to as an "external dose" in the other framework or what one framework terms as "pressure", may be defined as a "state" in the others.

The causality frameworks have significant benefits in sustainability assessment. These frameworks, through a clearly structured organization of the indicators, enable clear and concise communication to decision-makers. They help expose how the information provided by the indicators is related to various processes and how specific policy or management actions can address human-induced environmental problems. Additionally, a uniform approach for reporting indicators helps to link up different but related assessment areas (e.g., transport and environment, agriculture and environment). Figure 2.3 proposes DPSEEA framework to evaluate sustainability index using TBL. It can be noticed that at different levels of causality (in each dimension of sustainability) indicators are defined that can be combined using multi-criteria decision-making tools.

Linkages-based frameworks – PSR, DPSIR, and DPSEEA – emphasize the importance of causality. Driving force-Pressure-State-Exposure-Effect-Action (DPSEEA) framework is the broadest approach as it includes the impacts of macro driving forces and pressures on both health and the environment. However, the reliance on simple unidirectional linkages (chains) at the same time is not very conducive to understand and describe the complexity of the processes behind sustainability assessment. This limits the usefulness of these frameworks for environmental (and health risk) assessments. Like all other linkage-based frameworks, the DPSEEA has the following limitations:

Figure 2.3: Integrated DPSEEA and TBL framework



- It cannot work effectively if the evidence for causal linkages is missing or vague
- It leads to oversimplification of spatial and temporal interactions that results in poorly informed management decisions
- It oversimplifies inter-linkages among issues and factors. Often, it is ambiguous as to whether the issue measured by an indicator represents a driving force or a pressure. Sometimes there are multiple pressures for most states, and multiple states arising from most pressures, creating difficulties in identifying indicators.

2.6. Linkage-Based Frameworks: An Example of Universities

The use and application of linkage based frameworks is not new as mentioned earlier, what we want to do here is to briefly compare the three linkage based frameworks using the original causal frameworks not only for environmental categories but also for social, economic, and educational categories. It is our intention to explore the uni-directional links for PSR, DPSIR, and DPSEEA as a first step to identify the factors that may affect the case (universities) in hand. What is novel in the approach taken here is the integration of the concept of causal frameworks and triple bottom line approach and development of indicators for each category.

Universities, like other public institutions, are also facing the challenges of integrating sustainability in their strategic planning and development. Since the Talloires Declaration in 1990 (ULSF, 1990), International Association of Universities (IAU) is very active in promoting sustainability in universities and creating proactive leadership towards lessening the demise of the global environment. IAU continues to exert pressure through other declarations such as the Halifax and Swansea Declarations (UNESCO 1993*a*,*b*) and Kyoto Declaration (UNESCO 1991), and as a result of this pressure, signed commitments and voluntary decisions, several universities have embarked on projects and initiatives to incorporate sustainability into their systems. However, sustainable development is a still a relatively new and innovative idea for many universities. As universities are considered as institutions that promote and inculcate change through interactions of thousands of individuals on campus and outreach, in an ideal world, the concept of sustainable development should be integrated into the policies, approaches, and learning of all stakeholders. But in practice there are many hindrances in the adoption of sustainable development in a university system, such as (i) environmental protection is required for not only from lecture halls and laboratories but also from administration areas to bring financial and social gains; (ii) lack of legal bindings/ regulations or even incentives to integrate sustainable development in university policies; and (iii) many universities have initiated measures to improve environmental friendliness but a comprehensive resource-saving (sustainability) concept is still lacking.

There is no single best way of organizing and viewing the relationships between socio-economic development, environmental impacts, and human health indicators that captures all important interactions. Assessment of sustainability for universities is a complex and challenging process. Literature suggests that several frameworks and methodologies have been proposed and implemented, Lozano (2006) recommends that to apply or design any sustainability framework one must consider not only the environmental, social, and economic dimensions (categories) but also the educational performance with following indictors: (i) Education (courses and curricula), (ii) Research (basic and applied), (iii) Campus operations, and (iv) Community outreach. Table 2.4 presents comparison matrix of categories (i) environment, (ii) social, (iii) economics and (iv) educational performance along with their indicators for the conceptual frameworks of PSR, DPSIR and DPSEEA. For causal or linkage based frameworks, a combination of subject-based indicators in terms of position along the linkage-based framework is by far the most widely used indicator reporting method (Niemeijer and de Groot, 2008). The indicators are developed by using frameworks for linkages between health, environment, and development (WHO, 1996).

The list of these indicators at various causal stages (elements) of the frameworks is not exhaustive or even not comprehensive. The purpose here is to demonstrate that how various causal frameworks assign the same indicators to various causal stages. It can be noticed that indicators belong to various categories of sustainability in each causal element. It should be noted from Table 2.4 that in PSR one cannot benefit from the information about drivers or exposures or effects and in DPSIR one cannot benefit from indicators of exposure (represented in dark gray color in Table 2.4), where effects are termed as impact. The advantage of DPSEEA is that it provides better continuum from drivers to the effects in whether it's environmental, socio-economic, or educational aspect. One cannot deny that linkage-based frameworks and in particular DPSEEA framework provides clear and concise communication to decision-makers through a clearly structured organization of the indicators. They help expose how the information provided by the indicators is related to various processes and how specific policy or management actions can address human-induced environmental, social, economic and educational problems (Niemeijer and de Groot, 2008).

2.7. Discussion and Conclusions

Various sustainability frameworks presented in the previous section have many advantages and disadvantages. They can be used alone or in combination with other frameworks. Comparison of impact and objective-based frameworks by Pope *et al.* (2004) reveals that impact-based framework focus on minimizing the impacts, while objective-based frameworks maximize TBL outcomes. TBL or other dimensions of sustainability approaches even though criticized as reductionist approaches, make decision-making easier through multi-criteria decision-making techniques. Process-based frameworks by involving stakeholders in the decision-making process are usually crucial for articulating the right vision for a community at the local, state, national, or international levels (Jeon and Amekudzi, 2005). Life cycle assessment is the most widely used framework in various disciplines for sustainability assessment. Major limitations of LCA are that it focuses mainly on environmental impacts while reporting on social and economic aspects of sustainability is not easy. Moreover, LCA analysis is complex and time-consuming and also requires large data and boundary definitions (Sahely *et al.*, 2005), but its cradle to grave approach encompasses all phases of a product or a system and hence makes it the most desirable framework used.

Of all the frameworks discussed in this chapter, the introduction of the causal-chain frameworks within environmental, social, economic and other specific industry relevant indicators has been extremely useful. Niemeijer and de Groot (2008) stated that PSR and DPSIR can capture causality in overall management and policy-making. However, DPSEEA is even one step ahead as it breaks impact into exposure and effect, which enhances decision making with regards to environmental as well as economic and social aspects. Another important observation in DPSEEA framework is its similarity with ecological and human health risk assessment and risk management paradigms as demonstrated by the University example discussed earlier.

Despite the drawbacks, the linkage-based frameworks (including DPSEEA) have been successfully applied for sustainability assessment in various disciplines such as health sector, agriculture, and mining. It has been shown (CEC, 2006 ; Corvalán *et al.*, 1999; WHO, 2004; ESR, 2005) that the linkage-based frameworks either alone or in combination with other analytical methods such as life cycle analysis, multi-criteria decision-making methods and risk analysis techniques are successful for sustainability assessment. Linkage-based frameworks with other frameworks like Triple Bottom Line and integrative impact assessment can be useful for planning and decision-making for sustainable development (Sadler, 1999; Wilkinson *et al.*, 2004). Integrated DPSEEA framework provided earlier in Figure 2.3 can help better to understand complexities and overcome some of the earlier-mentioned limitations.

Niemeijer and de Groot (2008) suggest that a causal network, rather than a causal unidirectional link is a more appropriate concept to effectively deal with the complexity of real world interactions and they have developed a causal network for environmental assessment using DPSIR. But the application of DPSEEA framework for universities (for educational performance) is explored in detail not only for developing the cause-effect model for broad and (or) overall sustainability assessment but also for detailed analysis, where these have not been employed before.

Table 2.4: Comparison of linkage-based frameworks – An example of sustainability in a HEI (university)

DPSEEA	DPSIR	PSR	Factors
Driving force	Driver	N/A	• Global/local research and development trends • Institutional enhancement rate • Annual energy requirements rate • Financial and economic growth rate • Health & safety index • Social equity index • Education in Sustainability trends
Pressure	Pressure	Pressure	• Production of greenhouse gases • Production and consumption of ozone depleting substances • Production of emission, effluents, and waste • Requirement for procurement of product and services • Amount of energy used • Amount of water supplied and distributed/collected for purification • Increasing transport density • Increasing education cost • Increasing operational and maintenance cost • Requirements for labour practices and decent work • Requirements for quality of management • Increasing demands on human health and safety regulations • Requirement for changes in curriculum and courses • New research (basic and applied)
State	State	State	• Concentration of greenhouse gases • Concentration of emissions, effluents and waste • State of responsible procurement • Rate of depletion of energy resources • Rate of water consumption and quality • Percentage daily commute by motor vehicle and transport conflicts • Exceedance of noise level • Percentage of expenditure • Facilities and infrastructure costs • Labour practices and decent work (work environment / culture) • Existing state of quality of management • Existing human health and safety procedures • Number of courses on sustainability and administrative support • Grants, publications/products, and programs and centres • Community activity and learning service

DPSEEA	DPSIR	PSR	Factors
Exposure	N/A	N/A	• Changes in environmental conditions • Proportion of people exposed to poor air conditions • Proportion of people exposed to poor water quality • Proportion of people exposed to various hazards • Proportion of people exposed to high noise levels • Impact on energy resources • Financial impacts • Impacts on facilities planning • Social impacts • Proportion of research support for sustainability • Proportion of multi/inter/intra disciplinary programs & curriculum • Proportion of programs involving community and university
Effect	Impact		• Effects on human health • Effects on environment • Effects on biodiversity • Effects on revenues through educational cost and investments • Effects on maintenance costs • Effects on social aspects • Effects on educational performance
Action	Response	Response	• Sustainability strategy and plans • Economic policies and plans • Policies and plans to make a sustainable community and ensure social equity and justice

This research continues on how DPSEEA framework can be used to evaluate quantitatively *sustainability index* for a higher education institution and enhance informed decision-making (Waheed *et al.*, 2011*a*,*b*,*c*).

Chapter 3: A Quantitative Assessment of Sustainability for Higher Education Institutions: An Application of DPSEEA Framework[2]

ABSTRACT:

Implementation of a sustainability paradigm demands new choices and innovative ways of thinking. Since sustainability has become an integral part of strategies, several conceptual frameworks have been developed in various disciplines ranging from engineering to business. Most of these frameworks lack flexibility to be used across disciplines with a unified interpretation. The main objective of this chpater is to develop a quantitative assessment framework of sustainability using a driving force-pressure-state-exposure-effect-action (DPSEEA) framework for a higher education institution (HEI). This framework considers environmental, social, economic, and educational performance as categories of sustainability. A comprehensive list of performance indicators and an indicator aggregation method is proposed to assess sustainability using a measure called *sustainability index* (SI). The proposed quantitative framework is called **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM). The D-SiM is a causality-based model in which the SI is an outcome of nonlinear effects of sustainability indicators in various stages of DPSEEA. To have an improved understanding of input factors (driving forces) and their impact on sustainability, a simplified empirical model is developed. This empirical model is based on a 2^k full factorial methodology that also evaluates the percent contribution of driving forces on HEI sustainability. The study reveals that economic development, social equity, and education in sustainability are the major drivers for achieving sustainability in HEIs, while health and safety issues, energy requirements, institutional enhancement, and international research and development trends are less significant drivers.

[2] A part of this chapter is published and under review as

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- Waheed, B., Khan, F., Veitch, B. 2011. Developing a Quantitative Tool for Sustainability Assessment of HEIs. *International Journal of Sustainability in Higher Education*. 12 (4): In Press.

3.1. Introduction

The concept of *sustainability* has permeated into different disciplines since it was tossed about two decades ago. In recent years, the focus has been on solving the issues of an ever growing economy while protecting the environmental systems and enriching the quality of life for the existing as well as future generations.

One of the key challenges in the sustainability paradigm is that it demands new and innovative choices and ways of thinking. While the new developments in knowledge and technology are contributing to economic growth, they also have the potential to reduce the risks and threats to our socio-political and environmental systems. New knowledge and innovations in technology, management, and policies are challenging public organizations to make new choices in the way their operations, products, services, and activities impact the earth, people, and economies.

Many tiers of information — objectives, assessment criteria, indices, and performance indicators and variables — are required for the sustainability assessment of any system. Major sustainability objectives (or broad goals) are generally set by the triple bottom line (TBL), which includes environment, social, and economic performance. Selection of relevant performance indicators is essential for an effective assessment of sustainability and efficient performance monitoring of a system. Public institutions and particularly higher education institutions or universities (HEIs) are also facing the challenges of integrating sustainability in their strategic planning and development and developing qualitative and quantitative models for measuring sustainability of their facilities and operations.

Sustainability assessment frameworks are as diverse as the range of disciplines where sustainability is applied. Underlying any sustainable assessment framework is usually a conceptual model that helps to identify and organize the issues that will define what should be measured. The main differences among frameworks are the way in which they conceptualize the main dimensions or categories of sustainable development (TBL i.e., environment, social, and economic), the inter-linkages between these categories, the way they group the issues to be measured, and the concepts by which they justify the selection and aggregation of indicators. Sustainability assessment frameworks help to focus and clarify what to measure, what to expect from measurement, and how to relate measurement with assessment. These frameworks lack the capability to deal effectively with different issues of sustainability and the flexibility to be used in various disciplines with a unified interpretation.

Since sustainable development became an integral part of decision-making and planning in the international arena, several approaches and conceptual frameworks have been proposed in various disciplines such as engineering, business, and policy making. The schemes to classify various sustainability frameworks also vary, e.g., based on application discipline, methodology, mathematical techniques or tools, and the level of study. In engineering literature, sustainability assessment is generally viewed as a multi-objective optimization or multi-criteria decision-making problem (Raval and Donnelly, 2002; Balkema *et al*., 2002; Hellstrom *et al*., 2000; Haimes, 1992). Based on a detailed literature search (e.g., Jeon and Amekudzi, 2005; Kenway *et al*., 2007; Guio-Torres, 2007), we have classified the sustainability assessment frameworks into six major categories (Table 2.3).

The main focus of this research is the development of a quantitative sustainability assessment framework for higher education institutions. A quantitative framework called **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM) is proposed in this study, which is based on the linkage-based framework, DPSEEA. In the proposed framework, the sustainability indicators are identified and a multi-criteria decision-making (MCDM) tool is employed for the quantitative assessment. The first section of this chapter provides an introduction to various sustainability assessment frameworks. The second section elucidates DPSEEA and MCDM techniques. The third section discusses state-of-the-art sustainability assessment initiatives adopted by higher education institutions. The fourth section proposes D-SiM. The fifth section develops a simplified empirical model for sustainability assessment based on design of experiment methodology. Finally, conclusions and recommendations for future research are provided in section six.

3.2. Linkage-based Frameworks

The linkage-based frameworks use the concept of "causality" or cause–effect relationships. These frameworks provide linkages between each component of the framework by defining indicators for each component and recognizing effective actions to control and prevent the impacts. The most common linkage-based framework is pressure-state-response (PSR), which was initially proposed by Statistics Canada (Friend and Rapport, 1979). Other variations of this framework include driving force-pressure-state-impact-response (DPSIR), and driving force-pressure-state-exposure-effect-action (DPSEEA). In this study, we have explored the DPSEEA framework in detail.

3.2.1. DPSEEA framework

United Nation Agenda 21 highlights that human health is the main focus of any sustainability initiative (UN, 1993). In 1996, the World Health Organization (WHO) took a broader approach to include the impacts of macro *driving forces* and *pressures* on both health and environment (WHO, 1996) by developing the DPSEEA framework to guide decision actions for reducing the burden of disease.

Corvalán *et al*. (1999) discussed the links among health, environment, and sustainable development. They presented DPSEEA framework to extend the epidemiological domain to the policy domain. The DPSEEA can deal with environmental health problems from basic root-causes to the health effects level by identifying and implementing specific interventions (WHO, 1996). In the context of children's environmental health, the DPSEEA framework has been further developed as MEME (multiple-exposure-multiple-effects) model, which identified multiple links between exposures and the health effects (WHO, 2004). Some examples of the extensive application of the DPSEEA framework in the field of environmental health for the development of a core set of environmental health indicators are WHO (1999), Environment Canada (2001), European health indicators (WHO, 2004), Ministries of Health of Australia and New Zealand (ESR, 2005) and enHealth Council (2002). The DPSEEA framework has also been used for monitoring health impacts of climate change.

The DPSEEA is a hierarchical causal model that can link measurable sustainability indicators to human health *effects* through multiple layers of information. The DPSEEA continuum starts (Figure 2.2) with *drivers* of environmental change (anthropogenic) to *pressures* (on the environment such as production, consumption, and waste releases) to changes in the *state* (of the environment such as pollution levels) to *exposure* (of humans, i.e., interactions between the environment and humans) to the *effects* (on health, environment, and overall sustainability) (CEC, 2006). The environmental health indicators provide a link between health and environment to measure the impacts of a specific policy or management action and facilitate effective decision-making (WHO, 2001). These indicators should be scientifically valid, politically relevant, and acceptable to all stakeholders.

The DPSEEA framework is useful as it covers the full spectrum of cause and effect relationships starting from potential forces to required actions. It brings together professionals, practitioners, and managers from both environmental and public health fields to help orient them in the larger scheme of the problem for better decision making and problem solving.

Like any other sustainability assessment framework, DPSEEA has some disadvantages as well. As per WHO (1999): *"The DPSEEA framework works well for risks associated with environmental pollution, where the chain from driving force to source activity and thence to* *health effect via emissions and exposure is evident. [. . .] It is less appropriate, however, in the case of physical risks, as presented by natural hazards (e.g. flooding) or technology (e.g. traffic accidents), where the concept of 'pressure' is less meaningful. Nor can it easily be applied in full to those environmental hazards, such as famine, which affect health more by omission than commission. Like other aspects of environmental health indicators, therefore, the DPSEEA framework should be seen as an aid, not a straight-jacket; it needs to be adapted and modified according to circumstance."*

Füssel and Klein (2004) identified that DPSEEA is less suited to represent the complex and diverse causal web that links environmental, economic, and social factors to human health and must be adapted or modified. The DPSEEA framework can be made more useful by adapting it to the requirements of a specific application and introducing quantitative assessment through numerical functions ascribed to the linkages combined with multiple-criteria decision-making tools (Füssel and Klein, 2004). A description and comparison of some multi-criteria decision making tools and techniques, which could be integrated with DPSEEA, are presented in the following section.

3.2.2. Multi-criteria decision-making (MCDM) methods

For environmental management projects, generally decision makers receive four types of technical inputs: modelling and monitoring results, risk analysis, cost-benefit analysis, and preferences of stakeholders. Multi-criteria decision-making (MCDM) methods are used for decision making in the presence of two or more conflicting objectives under constraints and (or) deal with decision-analysis processes involving two or more attributes. The general objective of MCDM is to assist a decision maker or a group of decision makers in choosing the best alternative. In recent years, several MCDM methods have been proposed (Belton and Stewart, 2002) (Table 3.1).

However, the MCDM methods differ in many aspects, such as in the way the idea of multiple criteria is considered, the application and computation of weights, the mathematical algorithm used, the model to describe the system of preferences of the individual facing decision-making, the level of uncertainty embedded in the data set, and the participation of stakeholders in the process. The MCDM technique selected will typically need to:

- Deal with complex situations (criteria), consider different scales and aspects (geographical scales, micro-macro-link), social and technical issues and type of data (uncertainties)
- Involve more than one decision maker (stakeholder participation, actors, communication, and transparency)
- Inform stakeholders in order to increase their knowledge and change their opinion and behaviour (problem structuring, tool for learning, transparency)

In some categories of decision-making problems, one seeks an optimal choice based on a single evaluation attribute such as cost, revenue, and risk. But in most of the real world problems, the concentration is on decision-making with several criteria. Using a decision aid methodology could help decision-makers to manage the complexities arising from the involvement of multiple evaluation criteria. The area of MCDM has grown significantly in the recent past (Hwang and Lin, 1987; Munda, 1995; Asgharpour, 1998). Generally, this area consists of two major fields:

- Multiple-Objective Decision-Making (MODM) (Michnik and Trzaskalik, 2002) works on continuous decision spaces, primarily on mathematical programming with several objective functions.
- Multiple-Attribute Decision-Making (MADM) (Yoon and Hwang, 1981) focuses on problems with discrete decision spaces. MADM methods choose an optimal alternative from a set of alternatives with respect to several evaluation attributes with different weights.

Table 3.1: Comparison of common multi-criteria decision making methods

Methods	Logic	Advantage	Disadvantage
Max-Min	Overall performance of an alternative is determined by its poorest attribute	Simple and easy to understand	Only one attribute is used to represent an alternative
Max-Max	An alternative is evaluated by its best attribute value	Simple and easy to understand	Only one attribute is used to represent an alternative
Conjunctive	An alternative is rejected if it does not meet the minimum acceptable level for all attributes	Simple and easy to understand	An alternative with even one unacceptable attribute is discarded even if it has better values of other attributes
Disjunctive	An alternative with at least one of its attribute values better than the desirable level will be acceptable	Simple and easy to understand	An alternative that is good in all attributes but not with values better than desirable levels is rejected; conversely an alternative with just one exceptional value and other poor values is accepted
Lexicographic	In some decision-making problems, a single attribute predominates	Simple and easy to understand	The tradeoff among attributes (overall evaluation based on confluence of attainments and weights) is not considered
Linear-assignment	An alternative, which has many high ranked attributes, is ranked high	It requires less effort in data collection as it uses ordinal data	The actual cardinal difference between attainments of alternatives on each attribute is not considered
Simple additive weighting (SAW)	The overall score of an alternative is the weighted sum of its attribute values. This method becomes *weighted average method* if the weights are normalized.	Due to simplicity, it is the most widely used method	Does not consider interactions among attributes
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	Alternatives are ranked based on their distance from an ideal solution and a negative-ideal solution	It considers the tradeoff among attributes (overall evaluation based on confluence of attainments and weights)	-
Weighted product	To penalize alternatives with poor attribute attainments more heavily, a product instead of a sum of values is proposed with the attribute importance weights as the exponents	It considers the tradeoff among attributes	-
Distance from target	The attribute value is compared with a target value. The alternative with a shorter distance from the target alternative, is ranked higher	It considers the tradeoff among attributes	-
Analytic hierarchy process (AHP)	AHP method is classified under utility theory. It uses objective mathematics to process the subjective and personal preferences of an individual or a group in decision-making.	The AHP provides an ideal platform for complex decision-making problems	-

Common MCDM methods are described and compared in Table 3.1. Any decision aid model for multiple-attribute analysis is required to (*i*) clearly identify decision attributes and alternatives; (*ii*) assign an importance degree (if applicable) to these attributes; (*iii*) define the attainments of alternatives for each attribute; (*iv*) aggregate the attainments of each alternative with respect to attribute weights, which provides a utility degree for each alternative; and (*v*) compare and rank the alternatives based on their utility degrees.

3.3. SUSTAINABILITY ASSESSMENT FOR PUBLIC INSTITUTIONS

The progress in achieving goals of sustainable development has been slower than expected (UN, 2001) for various industries and institutions. A growing number of communities, businesses and other organizations are publicly pledging their commitment to sustainability. Public institutions and particularly higher education institutions (HEIs) all over the world are also committing to make their campuses sustainable (Prugh *et al*., 2000), however the real application is yet to be seen.

3.3.1. Higher education institutions

The Stockholm Declaration (UNESCO, 1972) was the first reference to *sustainability* in higher education institutions (HEIs) that recognized the interdependency between humanity and the environment, and suggested several ways of achieving environmental sustainability (UNESCO, 1972). The main turning point came in 1990 at the Tufts University campus (Talloires, France) (ULSF, 1990), where over 300 administrators from different colleges and universities world-wide gathered to discuss the collective need to address the challenges of environmental stewardship. The Talloires Declaration, a 10-point action plan, was formulated to take these sustainability challenges seriously and to take leadership toward lessening the demise of the global environment. This declaration was further strengthened by later events such as the Halifax and Swansea Declarations (UNESCO, 1993*b*) and Kyoto declaration (UNESCO, 1993*a*).

Consequently, sustainability of HEIs has become an important issue for policy makers and planners because of the realization of the impacts of the activities and operations of universities on the environment. As a result of this pressure, several universities have embarked on projects and initiatives to incorporate sustainability into their systems.

A sustainable university is defined by Cole (2003) as ''*the one that acts upon its local and global responsibilities to protect and enhance the health and well-being of humans and ecosystems. It actively engages the knowledge of the university community to address the ecological and social challenges that we face now and in the future*''. Another definition provided by Velazquez *et al*. (2006) states ''*A higher educational institution, as a whole or as a part, that addresses, involves and promotes, on a regional or a global level, the minimization of negative environmental, economic, societal, and health effects generated in the use of their resources in order to fulfill its functions of teaching, research, outreach and partnership, and stewardship in ways to help society make the transition to sustainable lifestyles*''. Universities are considered as institutions that promote and inculcate change through interactions of thousands of individuals on campus and outreach. Barnes and Jerman (2002), Cole (2003), Newman (2006), Alshuwaikhat and Abubakar (2008), Velazquez *et al*. (2006), and Lozano (2006*a*) have emphasized that a sustainable university campus must create a better balance between economic, social, and environmental goals in policy formulation as well as a long-term perspective about the consequences of campus activities. Challenges related to incorporating sustainable development into all facets of the system, structure, and activities of a university are discussed in the following section.

3.3.2 Major sustainability related issues for HEIs

The main general objectives of all HEIs are to educate students; to preserve and refine existing knowledge while producing, disseminating, and applying new knowledge; and to define and assist in finding solutions for problems in society. The challenge is that these objectives have to be achieved in a sustainable manner. Sustainability for universities can be seen as a necessity not only to avoid the costs of deteriorating social, environmental, and economic systems but also to create new opportunities to improve the rate and extent of human development. These institutions are facing serious challenges in integrating sustainability in their strategic planning and developing qualitative and quantitative assessment models for measuring sustainability. Sustainable development is a relatively new and innovative idea for many HEIs. Innovation is usually divided into three categories: (*i*) product, (*ii*) process, and (*iii*) idea. The sustainable development for universities falls into an "idea" category, even though it usually carries with it new products, processes, policies, and values (Lozano, 2006*b*). Ideally, the concept of sustainable development should be integrated into the policies, approaches, and learning of all stakeholders. In practice, this is not possible in the early stages of implementation of sustainable development in a university system. Viebahn (2002) and Clarke and Kouri (2009) have identified the main challenges of integrating sustainable development in a university system:

i) **Environmental protection**: Generally energy and material consumption and pollution generation (not only from lecture halls and laboratories but also from administration areas) in universities are at par with commercial organizations. Promoting and using energy saving measures will not only bring financial gains but also provide significant social gains.

ii) **Control instruments (regulations)**: There are no legal bindings or regulations or even incentives to integrate sustainable development in university policies. The focus has been on safety measures, whereas the measures related to ecological use of resources are carried out on voluntary bases. Moreover, the university system is heterarchic (network-based) instead of hierarchic, which means that feeling of responsibility is lacking, especially on the academic side. Also incentives for staff for careful use of resources are lacking as compared with a commercial organization because Universities have a nonconductive financial system and non-productive orientation.

iii) **Resource-saving**: Many universities have initiated measures to improve environmental friendliness but a comprehensive resource-saving concept is still lacking.

Koester *et al*. (2006) suggested that for a university to evolve successfully in a sustainable manner, all functioning components and linkages within the whole system must be considered. Ball State University USA (one of the leaders in sustainability) has applied the concept of "whole systems approach", which explicitly recognizes that the entity of a university or other institution of higher learning is composed of interdependent components that can mimic a complex ecosystem. Velazquez *et al*. (2006), Lozano (2006*b*), Cole (2003), Lidgren *et al*. (2006), Koester *et al*. (2006) and Alshuwaikhat and Abubakar (2008) proposed models that offer a clear perspective about how people responsible for sustainability initiatives affect collective behavioral change by educating stakeholders and promoting consensus-based sustainability goals in universities. According to Lozano (2006*b*), a large percentage of university leaders and faculty members worldwide are unaware of sustainable development goals and its principles, and even if they are aware of them, they have done little to incorporate them into their courses, curricula, research, and outreach. Therefore, the main problems faced by the universities can be summarized as (1) finding ways and means for effective and efficient incorporation of sustainability concepts into the policies, education, research, outreach, and campus operations of a university, and (2) establishing a system that makes sustainable development an integral part of the university culture and creates a multiplying effect within the institution and in the society as a whole.

3.4. Application of DPSEEA

3.4.1. Problem identification and formulation

There is no single best way of organizing and viewing the relationships between socio-economic development, environmental impacts, and human health indicators, which are important ingredients of sustainability measurement. The literature indicates that major decision categories for HEIs are (i) increasing the focus of research and curriculum on sustainability, (ii) selection of environment-friendly construction and procurement, (iii) community outreach, and (iv) assessment measures for environmental, economic, social, and educational efficiency and benefits. As higher education systems and academic environments are fundamentally similar in all universities, therefore, a framework for a given university will require similar types of indicators for sustainability assessment and decision-making. Lozano (2006*b*) recommends that to apply or design any sustainability framework one must consider not only the environmental, social, and economic categories but also the educational performance with the following indicators: (i) education (courses and curricula), (ii) research (basic and applied), (iii) campus operations, and (iv) community outreach. Extending these categories and recognizing the hierarchical causal links among driving forces-pressures-state-exposure-effects (criteria or indices), a comprehensive list of indicators for a modelling framework is proposed to assess sustainability using a measure called *sustainability index* (Table 3.2). Seven indicators have been identified for *driving force*. These seven indicators belong to the four major categories of sustainability identified above. Similarly, 15, 15, 12, and 7 indicators have been identified for *pressure*, *state*, *exposure* and *effects*, respectively. For each stage in the DPSEEA framework, these indicators can still be categorized as either environment, economic, social, or education.

3.4.2. Model development

A deterministic modelling framework for sustainability assessment is proposed in this chapter. The primary objective of this framework is to develop a meaningful sustainability assessment tool for higher education institutions to make informed decisions. The proposed framework can help identify and evaluate single and multiple effects of a *driving force* or policy on *sustainability index* (SI). The *pressures* are associated with various phases in the life cycle of an institution's development, related to raw materials, use, processing, distribution, transportation, final consumption and disposal. Both *pressure* and *driving force* are the most effective points of hazard control. The DPSEEA framework (Figure 2.2) shows that the preventive actions and controls are the best actions for risk management and achieve sustainability in a cost effective manner.

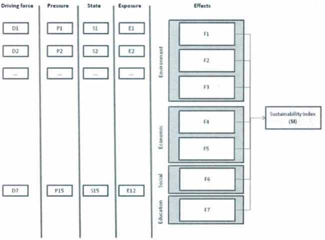
The indicators identified in Table 3.2 are connected hierarchically through causal relationships that finally lead to the quantitative assessment of sustainability. Finally, the indicators of *effects* are used to estimate *sustainability index* (Figure 3.1). The proposed quantitative framework is called **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM) and consists of seven procedural steps, the details of which are illustrated in Figure 3.2.

Step 1 - Selecting sustainability indicators: The first step involves selection of suitable sustainability indicators in each stage of DPSEEA. Each indicator should represent a unique aspect of sustainability; therefore, selecting a relevant measurable indicator is a key for successful assessment of sustainability. The identification process is a subjective and qualitative process because the objectives of sustainability can be interpreted differently by different stakeholders.

Table 3.2: Proposed list of indicators for sustainability assessment in universities using DPSEEA corresponding to environment (Env.), economics (Eco.), social (Soc.), and education (Edu.)

Stages	No.	Indicators	Env.	Eco.	Soc.	Edu.
Driving force	D_1	Global/local research and development trends	■			
	D_2	Institutional enhancement rate	■			
	D_3	Annual energy consumption rate	■			
	D_4	Financial and Economic growth rate		■		
	D_5	Health and safety index			■	
	D_6	Society equity index			■	
	D_7	Education in sustainability trends				■
Pressure	P_1	Production of greenhouse gases	■			
	P_2	Production and consumption of ozone depleting substances	■			
	P_3	Production of emission, effluents, and waste	■			
	P_4	Requirement for procurement of product and services	■			
	P_5	Amount of energy used	■			
	P_6	Amount of water supplied and distributed/collected for purification	■			
	P_7	Increasing transport density	■			
	P_8	Increasing education cost		■		
	P_9	Increasing operational and maintenance cost		■		
	P_{10}	Requirements for labour practices and decent work			■	
	P_{11}	Requirements for quality of management			■	
	P_{12}	Increasing demands on human health and safety regulations			■	
	P_{13}	Requirement for changes in curriculum and courses				■
	P_{14}	New research (basic and applied)				■
	P_{15}	Provision of service				■
State	S_1	Concentration of greenhouse gases	■			
	S_2	Concentration of emissions, effluents and waste	■			
	S_3	State of responsible procurement	■			
	S_4	Rate of depletion of energy resources	■			
	S_5	Rate of water consumption and quality	■			
	S_6	Percentage daily commute by motor vehicle and transport conflicts	■			
	S_7	Exceedance of noise level	■			
	S_8	Percentage of expenditure		■		
	S_9	Facilities and infrastructure costs		■		
	S_{10}	Labour practices and decent work (work environment / culture)			■	
	S_{11}	Existing state of quality of management			■	
	S_{12}	Existing human health and safety procedures			■	
	S_{13}	Number of courses on sustainability and administrative support				■
	S_{14}	Grants, publications/products, and programs and centres				■
	S_{15}	Community activity and learning service				■
Exposure	E_1	Changes in environmental conditions	■			
	E_2	Proportion of people exposed to poor air conditions	■			
	E_3	Proportion of people exposed to poor water quality	■			
	E_4	Proportion of people exposed to various hazards	■			
	E_5	Proportion of people exposed to high noise levels	■			
	E_6	Impact on energy resources	■			
	E_7	Financial impacts		■		
	E_8	Impacts on facilities planning		■		
	E_9	Social impacts			■	
	E_{10}	Proportion of research support for sustainability				■
	E_{11}	Proportion of multi/inter/intra disciplinary programs & curriculum				■
	E_{12}	Proportion of programs involving community and university				■
Effects	F_1	Effects on human health	■			
	F_2	Effects on environment	■			
	F_3	Effects on biodiversity	■			
	F_4	Effects on revenues through educational cost and investments		■		
	F_5	Effects on maintenance costs		■		
	F_6	Effects on social aspects			■	
	F_7	Effects on educational performance				■

Figure 3.1: Proposed D-SiM for sustainability assessment of universities



The sustainability indicators identified and included in D-SiM are based on a comprehensive study of institutions that have employed sustainability initiatives. Some include UBC (2007*a*), UBC (2007*b*), Rodriguez *et al*. (2002), Lozano (2006*a*), Cole (2003), Shriberg (2002), Viebahn (2002), Clarke and Kouri (2009), Lukman *et al*. (2010), Goognough *et al*. (2009), and Evangelinos *et al*. (2009).

The validity of indicators has been assessed by comparing them with Global Reporting Indicators (GRI, 2006) for universities and its modification provided by Lozano (2006*a*). A major challenge in the selection of indicators is to consider various stages of DPSEEA – *driving force*, *pressures*, changes in *state*, *exposures*, and *effects* not only for the environment but also for the society, economics, and educational performance. As *action* is an exogenous and decision variable, no indicators are required for it. A total of fifty–six sustainability indicators are identified for a typical educational institution, where each indicator is classified under environment, economics, social, or educational categories (Table 3.2). Indicator selection is also explained in Sections 4.4.1, 5.2.1 and 5.4.1.

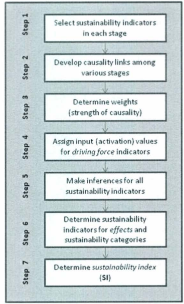
Driving forces are usually based on policies that determine trends in economic development, technology development, consumption patterns, and population growth. In the present case, the relevant indicators for driving forces are international research and development trends, institutional enhancement, energy requirement, economic development, health and safety issues, social equity, and education sustainability. These *driving forces* generate different kinds of *pressures* in various categories, which are indicated as

- Environment: production of waste and consumption of resources, emissions, effluents, wastes, transport, and products and services;
- Economy: education cost, operation and maintenance cost;
- Society: labor practices and decent work environment, human rights, and quality of management; and
- Education: curriculum, research, and service.

The indicator "products and services" under environment refers to responsible purchasing of paper and furniture for the university. Service represents challenges faced by the universities to respond to local, regional, and global environmental and societal challenges in the sustainable development (Lukman *et al.*, 2010).

Generally, *pressures* lead to changes in the *state* of the environment, as seen when land use is changed (deforestation or drainage problems) or when concentration of emissions and effluents and waste increases, energy resources are depleted, air quality, transport, noise level, and water demand are exceeded, and the state of responsible procurement.

Figure 3.2: Procedural steps for D-SiM implementation



The *pressure* on the economy of a university is indicated by change in facilities and infrastructure costs and the proportion of expenditures in different areas. The existing health, safety, and security situation, the *state* of quality management, and social equity represent the *state* of social aspects of a university. The number and percentage of courses on sustainability and administration support, grants, publications / products and programs and centers, and community activity and learning services indicate the *state* of educational performance of a university. Orr (1991) and Lidgren *et al*. (2006) argued that the state of our world today is not the work of "ignorant" people, but is rather the result of work by the people with "university" degrees. Therefore, the inclusion of sustainability education in university curriculum is very important.

Exposure requires that people are present both at the place and time when the *state* of the environment changes and becomes hazardous. *Exposure* thus refers to the intersection between people and environmental hazards. Levels of exposure may range from "harmless and acceptable" to "dangerous and unacceptable", depending on the potential for physical harm. Given known exposures and the knowledge of dose–response relations, estimates can be made of the health risk of specific hazards to the extent that current knowledge allows. Although "hazard" describes the potential for causing harm to human health, it says nothing about the statistical probability that such harm will occur. In contrast, "risk" is a quantitative estimate of the probability of damage associated with exposure to a hazard. This framework does not focus on whether a resultant altered state of the environment creates a hazard to human health depending on the degree to which humans may actually be exposed. It focuses on *exposure* and impacts caused by the changes in state with respect to environment, economic, social, and educational performance of a university by the following indicators: changes in environmental conditions, proportion exposed to poor environmental conditions, hazardous waste, poor water quality, high noise levels, impacts on energy resources, existing state and cost, facilities planning, social impacts, proportion of research support for sustainability, proportion of multi-/inter-/intra-disciplinary programs and curriculum, and proportion of programs involving community and university.

The indicators representing the *effects* for a university due to defined *exposures* consist of human health, ecological and social risks, effects on biodiversity, reduced maintenance costs, revenues through education cost and investments, and educational performance.

Step 2 – Establishing causality: To define relationships between cause and effect, a sign convention of causal relationships is established between connections: (*i*) For example, positive causality refers to the connection between sustainability and *quality*, i.e., when quality improves sustainability increases and vice versa, and similarly (*ii*) negative causality refers to the connection between sustainability and *pollution*, i.e., an increase in pollution reduces sustainability and vice versa.

A list of connections (causal relationships) among various sustainability indicators is presented in Table 3.3. For example, a *pressure* indicator P_1 (production of greenhouse gases) is affected by a set of *driving forces* $\{D_1-, D_2+, D_3+, D_4+, D_7-\}$, where increases in D_1 (global/local research and development trends) and D_7 (education in sustainability trends) decrease the production of greenhouse gases. Similarly, the *driving forces* D_2, D_3, and D_4 positively impact P_1, i.e., increases in these indicators increase P_1, and vice versa. Using the same principles, connections are established between *pressures* and *states*, *states* and *exposures*, and *exposures* and *effects*.

Step 3 – Assigning weights (strength) of causality: Assigning weights (i.e., defining causal strength) is an important step in D-SiM. The weights (w_i) are assigned to input indicators based on their relative importance for a response sustainability indicator. For example, a *pressure* indicator P_1 is affected by a set of indicators $\{D_1, D_2, D_3, D_4, D_7\}$, therefore the relative weights are assigned to these five input indicators. The values of these weights vary in an interval [0 1]. Table 3.3 provides the weight matrix for each dependent sustainability indicator. Assignment of weights is also discussed in Sections 4.4.3 and 5.2.3. The type of causality (negative or positive) determines the value of the strength, as given in Table 3.4.

Step 4 – Activating driving force (defining input values): As DPSEEA is a causal model, the input values are defined for *driving force* indicators. Once the sustainability indicators for *driving force* are activated, the D-SiM estimates the intermediate indicators at various stages of the DPSEEA framework. These input indicators are "measured" values or are defined by a decision maker. A simple approach is proposed here, in which the current level of *driving force* indicators are defined linguistically. Table 3.5 provides a linguistic meaning of activation levels for sustainability indicators.

Step 5 – Making inference: After selection of indicators, an appropriate multi-criteria decision making (MCDM) method is used for aggregating and evaluating the activation level of dependent indicators. We propose the *simple weighted average method*, because it is intuitive and most widely used because of its simplicity. It considers the tradeoffs among attributes. After assigning weights and activating input indicators, an inference to estimate activation for any dependent indicator can be made using the following equation:

$$[3.1] \quad A_j = \frac{[w_1 X_1 + w_2 X_2 \ldots + w_n X_n]}{(w_1 + w_2 \ldots + w_n)}$$

where A_j is the estimated activation level of a dependent indicator j, w_i is the weight assigned to the indicator i, and X represents predefined (or predetermined) activation values of contributing indicators. This formulation is valid for any dependent indicator in pressure (P), state (S), exposure (E), and effect (F) stages.

Step 6 – Estimating *effects*: The step five is repeated in succession until we estimate activation values for seven sustainability indicators of *effects*. The effects indicators are then grouped into environment, economics, social and education categories using the same formulation as described in Equation (3.1).

Step 7 – Determining sustainability index (SI): To measure the sustainability of a higher education institution quantitatively, the sustainability index (SI) is calculated using the following formulation:

[3.2] $$\mathrm{SI} = \frac{[A_{env}w_{env} + A_{econ}w_{econ} + A_{soc}w_{soc} + A_{edu}w_{edu}]}{(w_{env} + w_{econ} + w_{soc} + w_{edu})}$$

where A_{env} is an activation level of environmental *effects*, A_{econ} is an activation level of economic *effects*, A_{soc} an activation level of social *effects*, and A_{edu} is an activation level of education *effects*. Higher values of SI represent that an institution is "sustainable" and vice versa. The estimated values of SI can be used to determine ranking of various universities with respect to sustainability. Equation (2) is modified to assure that SI $\in$ [0, 1], therefore normalized SI can be calculated as follows:

[3.3] $$\mathrm{SI}_N = \frac{(\mathrm{SI} - 0.10)}{(0.34)}$$

3.4.3 Demonstration of D-SiM

Table 3.6 demonstrates the use of D-SiM. For example, for a particular set of input values of driving forces $\{D_1, D_2, \ldots, D_7\}$, sustainability index is determined. In this example, "international research and development trends / advancement" (D_1) is assigned a value of 0.9, "institutional enhancement" (D_2) and "sustainability education" (D_7) are assigned 0.4 and 1.0, respectively. Similarly, "energy requirements" (D_3), "economic development" (D_4), "health and safety issues" (D_5) and "social equity" (D_6) are assigned values of 0.5, 0.5, 0.5, and 0.65, respectively (the linguistic meaning of these values is given in Table 3.5).

Table 3.3: Causal relationships among sustainability indicators

Driving force (D)	Pressure (P)	State (S)	Exposure (E)	Effects (F)	Sustainability categories	Sustainability Index (SI)
D_1	P1 = {D1-, D2+, D3+, D4+, D7-} wp1 = {0.4, 0.4, 1, 0.6, 0.4}	S1 = {P1+, P2+, P5+, P15-} ws1={1, 0.8, 0.4, 0.6}	E1 = {= {S1+,S2+, S3+, S4+, S5+, S15-} we1 = {0.6, 0.2, 0.2, 1, 0.8, 0.2}	F1 = {E1+, E2+, E3+, E4+, E5+, E12-} wf1= {0.4, 0.8, 0.6, 0.4, 0.2. 0.2}	Env = {F1, F2, F3} wenv = {0.8, 0.2, 0.4}	SI = {Env, Eco, Soc, Edu} Wsus ={0.6, 0.4, 0.2, 0.8}
D_2	P3 = {D1-, D2+, D4+, D7-} wp2 = {0.2, 0.2, 1, 0.4}	S2 = {P3+, P15-} ws2 = {1, 0.4}	E2 = {S3+, S15-} we2= { 0.4, 0.2}	F2 = {E3+, E4+, Ex6+, E12-} wf2= {0.8, 0.6, 0.6, 0.2}	Eco = {F4, F5, F6} weco = {0.4, 0.6, 0.2}	
D_3	P3 = {D1-, D2, D3+, D4+, D6-, D7-} wp3={0.2, 0.4, 1, 0.6, 0.2, 0.6}	S3 = {P4+, P14, P15+} ws3 = {1, 0.4, 0.4}	E3 ={S5+, S15+} we3= {0.8, 0.4}	F3 = {E1+, E12-} wf3= {0.6, 0.4}	Soc = {F6} wsoc = {0.2}	
D_4	P4 = {D1+, D2-, D3-, D4-, D7+} wp4 = {0.8, 0.2, 0.4, 0.2, 1.0}	S4 = {P5+, P15-} ws4={1, 0.2}	E4 = {S5+,S6+, S15-} we4= {0.2, 0.2, 0.2}	F4 = { E7} wf4= {1}	Edu = {F7} wedu = {1}	
D_5	P5 = {D1-, D2+, D4+, D3+, D7-} wp5= {0.6, 0.2, 1, 0.4, 0.6}	S5 = {P6+} ws5 = {1}	E5= {S7+} we5={1}	F5= {E8} wf5= {1}		
D_6	P6 = {D1-, D2+, D3+, D5+, D7-} wp6= {0.6, 1,0.2, 0.8, 0.8}	S6= {P7+} ws6= {1}	E6 = {S4+, S7+, S14-, S15-} we6={1, 1, 0.2, 0.2}	F6 = {E9+} wf6= {1}		
D_7	P7 = {D2+, D3+, D4+, D7-} wp7= {1,0.6,0.8, 0.6}	S7 = {P7+} ws7= {0.6}	E7 = {S8+} we7={1}	F7 = {E10+, E11+, E12+} wf7= {0.6, 1.0, 0.8}		
	P8 = {D1+, D2+, D4+, D7+} wp8= {0.4, 0.2, 1, 0.2}	S8 = {P8+, P9+} ws8 = {0.8, 0.6}	E8 = {S9+} we8={1, 0.4}			
	P9 = {D1+, D2+, D3+, D4+,D5+, D7-} wp9 = {0.8, 0.4, 0.6, 1, 0.2, 0.4}	S9 = {P9+} ws9 = {1}	E9 = {S10+, S11+, S12+} we9={0.4, 0.8, 0.6}			
	P10 = {D5+,D6+} wp10 = {1, 0.8}	S10 = {P10-} Ws10={1}	E10= {S13+, S14+} we10={1, 0.4}			
	P11 = {D6+} wp11 = {1}	S11 = {P11+} ws11= {1}	E11 = {S13+, S14+} we11={0.6, 0.8}			
	P12 = {D5+,D6+, D7-} wp12 = {0.2, 0.8, 1}	S12 = {P12+} ws12 = {1}	E12 = {S15+} we12={1}			
	P13 = {D7+} wp13 = {1}	S13 = {P13+} ws13 = {1}				
	P14 = {D1+, D2+, D7+} wp14={0.8, 0.4, 1}	S14 = {P14+} ws14= {1}				
	P15 = {D1+, D7+} wp15= {0.8, 1}	S15 = { P15} ws15={ 1}				

Table 3.4: Linguistic meaning of causality weights

Linguistic descriptor	Strength of positive causality	Strength of negative causality
Very small	0.0	1.0
Small	0.2	0.8
Fair	0.4	0.6
Moderate	0.6	0.4
Significant	0.8	0.2
Very high	1.0	0.0

Table 3.5: Linguistic meaning of activation of input indicators

Linguistic descriptor	Activation level (A)
No	0.0
Extremely low	0.10
Very low	0.25
Low	0.45
Medium	0.50
High	0.65
Very high	0.75
Extremely high	0.90
Absolute	1.00

These driving forces cause pressures on the four categories. Each pressure is caused by one or more driving forces. For example, the resulting activation level for P_1 is 0.36. The D-SiM calculates the activation for each dependent indicator based on defined weights and values of activation of input indicators. After estimating the *effects* indicators, *sustainability index* is calculated (Eqs. 2 and 3) from the sustainability categories — environmental, economic, social, and education by assuming the weights of these categories as 0.6, 0.4, 0.2 and 0.8. This results in a normalized value of sustainability SI_N of 0.97. Now if the driving force D_1 is reduced to 0.4, the SI_N reduces to 0.94. The effect of changing D_7 is even more profound, e.g., if it is reduced to 0.4, the SI_N reduces to 0.74. It is noticed that increases in input values from D_2 to D_6 result in higher values of SI_N.

Table 3.6: Activation levels of sustainability indicators – an example

j	A_D	A_P	A_S	A_E	A_F	A_{Sus}	SI_N
1	**0.9**	0.34	0.28	0.25	0.34	0.27	0.97
2	**0.4**	0.33	0.26	0.61	0.22	0.57	
3	**0.5**	0.35	0.01	0.26	0.17	0.12	
4	**0.5**	0.82	0.26	0.23	0.59	0.88	
5	**0.5**	0.30	0.28	0.20	0.56		
6	**0.65**	0.28	0.20	0.21	0.59		
7	**1**	0.20	0.20	0.59	0.88		
8		0.63	0.59	0.56			
9		0.52	0.56	0.59			
10		0.57	0.57	0.78			
11		0.65	0.65	0.88			
12		0.31	0.69	0.96			
13		1.00	1.00				
14		0.78	0.78				
15		0.96	0.96				

Note: A_D: Defined activation level of driving force; A_P: estimated activation level of pressure; A_S: estimated activation level of state; A_E: estimated activation level of exposure; A_F: estimated activation level of effect; A_{Sus}: estimated activation level of sustainability including estimated activation level of environmental effects (env), estimated activation level of economic effects (econ), estimated activation level of social effects (soc), estimated activation level of education effects (edu); SI_N: estimated normalized sustainability index.

3.5. Discussion and Results

3.5.1. Empirical model

The D-SiM is a causality-based model in which the final value of a sustainability index (SI) is an outcome of a multitude of non-linear effects of sustainability indicators in various stages of DPSEEA. To better comprehend the contributions of various input factors (D_k, *driving forces*) and their effects on SI, a 2^k full factorial Design of Experiment (DoE) methodology is used. Seven input factors (D_k), each defined at two levels, were used in D-SiM simulation experiments. The values of each of these input factors were in an interval [0, 1], where 0 refers to "low" and 1 refers to "high" level. Therefore, a total of 128 simulation experiments (k = 7) were performed using the D-SiM model for various combinations of input factors, as defined in Table 3.7. The response (SI_N) value is estimated for each experiment and used to build a simplified empirical model, as described below.

The estimated effects of each input factor and their possible interactions and percent contributions are provided in Table 3.8. The normal probability plot of effects shows that all the *main factors* are significant, and all interactions are not important (Figure 3.3*a*). Thus, the regression model in terms of actual input factor values (i.e., $\in [0, 1]$) will be

[3.4] $$\widehat{SI}_N = 0.007 + 0.029D_1 + 0.045D_2 + 0.074D_3 + 0.160D_4 + 0.086D_5 + 0.169D_6 + 0.420D_7$$

where the input factors are D_k $(k = 1, 2, \ldots, 7)$; and $D_k \in [0, 1]$.

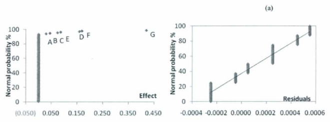
Table 3.7: Seven input factors for full factorial experimentation

Driving force (input factors for *full factorial* experiments)	D_k
International research and development trends or advancement	D_1
Institutional enhancement	D_2
Energy requirements	D_3
Economic development	D_4
Health and safety issues	D_5
Social equity	D_6
Sustainability education	D_7

Table 3.8: Percent contribution of main factors on sustainability index (SI_N)

D_k	Coded name	% contribution
D_1	A	0.35
D_2	B	0.81
D_3	C	2.21
D_4	**D**	**10.34**
D_5	E	3.01
D_6	**F**	**11.61**
D_7	**G**	**71.69**

Figure 3.3: Normal probability plots



(a) Normal probability plots for effects (b) Normal probability plots for residuals

To check the model adequacy, the analysis of variance (ANOVA) is performed (Table 3.9). The results of ANOVA are similar to the effects estimation. All the major factors have the *p*-value less than 0.0001, which indicates they are significant factors. Figure 3.3*b* shows the normal probability plot of residuals. It can be observed that the residuals are not aligned into a straight line. They fall into three separate zones. At each zone, residuals are very close to each other, which make them look like non-normality.

From Table 3.8, we can see that the total contribution of coded factors D, F and G amount to 93.63% of total sums of squares. Thus, to refine this empirical model, the full 2^7 factor design is projected into full 2^3 factor design with 16 replicates for each experiment. The projected model results show that all the major factors are significant while the interactions between them are non-significant. The results of ANOVA presented in Table 3.9 concur with the effect analysis. Thus the refined regression model in terms of actual input factor values (i.e., $\in [0, 1]$) will be:

[3.5] $\widehat{SI_N} = 0.124 + 0.156D_4 + 0.169D_6 + 0.420D_7$

where the input factors D_k $(k = 1, 2, \ldots, 7)$; and $D_k \in [0, 1]$.

Table 3.9: Analysis of variance (ANOVA) for a 2^7full factor design

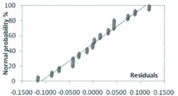
Factors	Sums of squares	Degree of freedom	Mean Squares	F_o	p-Value
A	0.0274	1	0.0274	3.2854E+05	<0.0001
B	0.0634	1	0.0634	7.6042E+05	<0.0001
C	0.1741	1	0.1741	2.0886E+06	<0.0001
D	0.8141	1	0.8141	9.7691E+06	<0.0001
E	0.2367	1	0.2367	2.8401E+06	<0.0001
F	0.9140	1	0.9140	1.0967E+07	<0.0001
G	5.6448	1	5.6448	6.7738E+07	<0.0001
Error	1.0000E-05	120	8.3333E-08		
Total	7.8743	127			

To check the model adequacy, the lack-of-fit analysis is used. The results are listed in Table 3.10. The *p*-value of 1 for *lack-of-fit* indicates that the model can predict the responses very well. To further check the adequacy, the analysis of residuals is done. Figure 3.4 shows the normal probability plot of residuals. The residuals are aligned with a straight line, which indicates there are no severe non-normality issues. Comparing this model with the full factor model, it is noted that the refined model is more adequate than the full factor model in terms of the residuals' normal distribution.

Table 3.10: Analysis of variance (ANOVA) for a projected 2^3 factor design (with 16 replicates)

Factors	Sums of squares	Degree of freedom	% Contribution	Mean Squares	F_o	p-Value
D	0.8141	1	10.339	0.8141	201.3	<0.0001
F	0.9140	1	11.607	0.9140	226	<0.0001
G	5.6448	1	71.686	5.6448	1395.8	<0.0001
Residual	0.5015	124	6.369	0.0040	1.0000	
Lack-of-fit	0.0000	4		0.0000	0.0000	1.0000
Pure error	0.5015	120		0.0040	1.0000	
Total	7.8743	127				

Figure 3.4: Residual Normal probability plots for projected model



3.5.2. Sensitivity analysis

It can be seen from the ANOVA presented in Section 5.1 (Table 3.10) that more than 70% contribution to the sustainability index (SI_N) values is from "Education sustainability (D_7)". To understand further the impacts of a factor D_7, the following four scenarios are generated by fixing:

Scenario 1: $D_4 = D_6 = 0$

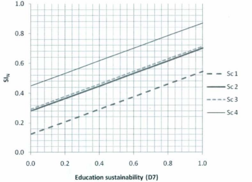
Scenario 2: $D_4 = 1$ and $D_6 = 0$

Scenario 3: $D_4 = 0$ and $D_6 = 1$; and

Scenario 4: $D_4 = 1$ and $D_6 = 1$.

In each scenario, the value of D_7 is varied over an interval [0, 1], while the change in the value of SI is recorded. Figure 3.5 provides the linear characteristic curves for these four scenarios. It can be seen that D_7 plays a very significant role in achieving the sustainability goals for a university. Another interpretation of this plot is that a unit change in "education sustainability" brings approximately 0.42 unit change in SI for the given values of D_4 and D_6 (see the coefficient of D_7 in Equation (5)).

Figure 3.5: Characteristic curves for four scenarios of D_7 — sensitivity analysis



3.5.3. Potential of DPSEEA

The DPSEEA framework is similar to ecological and human health risk management paradigms. To be useful for the identification and monitoring of sustainability of an institution and for the development of response strategies, the DPSEEA framework should be extended in a flexible way to include indicators relevant to an institution and combined with multi-criteria decision tools for better interpretation of causal links. **D**PSEEA **S**ustainability **i**ndex **M**odel (D-SiM) presents a deterministic quantitative framework for assessing the sustainability of an institution.

There are two major challenges of employing the DPSEEA framework for the assessment of sustainability in educational institutions. First, a conceptual framework for an educational institution should ideally be able to consider all factors that affect the causation of an effect on humans, biodiversity, and ecology. However, the causal pathways along which activities of an institution may affect humans, biodiversity, ecology, economic performance, and social well-being are very diverse and complex. Some effects occur as a direct consequence of a person being exposed to pollutant (e.g., wastewater), whereas others are the consequence of a complex interaction of environmental, ecological, and social factors (e.g., educational performance, economic development). As a result, the choice of suitable indicators for monitoring sustainability of an institution is difficult and crucial. Second, the causation of increase in social risks often involves complex interactions between social and non-social risk factors. Therefore, the original DPSEEA framework is extended by adding educational performance indicators for sustainability assessment of a higher education institution.

3.6. Conclusions and Recommendations

Several approaches and conceptual frameworks have been proposed and developed in various disciplines ranging from engineering to business and policy making for sustainability. These frameworks lack flexibility to be used in various disciplines with a unified interpretation and have their own limitations and capabilities to deal with different issues of sustainability effectively. An integrated quantitative framework is developed for sustainability assessment for a higher education institution (HEI) using the linkage-based approach driving force-pressure-state-exposure-effect-action (DPSEEA) by using a simple weighted average (an MCDM) method.

Application of sustainable development for HEIs (universities) is a relatively new phenomenon and is very challenging because of the complex set-up of universities. A large percentage of university leaders and faculty members worldwide are unaware of sustainable development goals and principles, or if they are aware of them, they have made little effort to incorporate them into their courses, curricula, research, and outreach. Therefore, the main problems faced by the universities can be summarized as (1) finding ways and means for effective incorporation of sustainability concepts into the policies, education, research, outreach, and campus operations of a university, and (2) establishing a system that makes sustainable development an integral part of the university culture and creates a multiplying effect within the institution and in the society as a whole.

The proposed modelling framework provides a meaningful sustainability assessment tool for HEIs to make informed decisions. This framework considers not only the environmental, social, and economic categories but also the educational performance. Extending these categories and recognizing the hierarchical causal links among driving forces-pressures-state-exposure-effects, a comprehensive list of indicators for the modelling framework is proposed to assess sustainability using a measure called *sustainability index.* The proposed quantitative framework is called **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM). The D-SiM is a causality-based model in which the final value of a sustainability index (SI) is an outcome of nonlinear effects of sustainability indicators in various stages of DPSEEA. To develop a simplified empirical model and determine the contribution of various driving forces on sustainability of HEI, a 2^k full factorial methodology is adopted. This study revealed that financial and economic growth rate, social equity index, and education in sustainability trends are the major drivers for achieving sustainability in HEI. Less significant drivers in descending order are health and safety index, annual energy requirements rate, institutional enhancement rate, and global/local research and development trends.

In the present form, the D-SiM is a complex interaction model that describes cause-effect interactions from driving force to pressure, pressure to state, state to exposure, and exposure to effect. Notwithstanding the somewhat subjective nature of the analysis, D-SiM can contribute to more rational decision-making by analyzing decisive indicators, tradeoffs, and weighting sensitivities, establishing complex interactions between stages, and incorporating uncertainty-based analysis. These concepts will be explored in the following chapters.

Chapter 4: Uncertainty-based Quantitative Assessment of Sustainability for Higher Education Institutions[3]

ABSTRACT:

Evaluation of sustainability in various facets of life is gaining increasing importance. Traditionally, different multi-criteria decision-making methods have been used for sustainability assessment. "Sustainability" can be a qualitative concept, and as such several researchers have attempted fuzzy logic for the quantitative assessment of sustainability. This chapter outlines a new evaluation model based on fuzzy multi-criteria decision-making. The model is tested for sustainability assessment of higher education institutions (HEIs). It is based on a driving force-pressure-state-exposure-effect-action (DPSEEA) framework and is called **u**ncertainty-based **D**PSEEA-**S**ustainability **i**ndex **M**odel (uD-SiM). The uD-SiM is a causality-based model in which the sustainability index is an outcome of nonlinear impacts of sustainability indicators in different stages of DPSEEA. The percent contribution of driving forces on the sustainability index of HEIs is investigated using sensitivity analysis. The study reveals that education in sustainability and global and local research trends are the major driving forces for achieving sustainability in HEIs, followed by financial and economic growth rate, social equity, energy requirements rate, and institutional enhancement, in descending order. The results of uD-SiM were found to be more realistic and rational than our earlier proposed model, D-SiM.

[3] A part of this chapter is published as

- Waheed, B., Khan, F., Veitch, B., Hawboldt, K. 2011. Uncertainty-based Quantitative Assessment of Sustainability for Higher Education Institutions. *Journal of Cleaner Production*. 19 (7): 720-732.

4.1. INTRODUCTION

Given the environmental, economical, and social pressures on sustainability, opportunities are emerging for different societal stakeholders and institutions to engage in innovative ways for advancing more sustainable practices. Higher education institutions (HEIs), particularly universities, hold a unique position in society, as they have the potential to promote and encourage societal response to sustainability challenges facing communities around the world through interactions of thousands of individuals on campus and outreach to millions (Stephens *et al*. 2008). Therefore, universities promote sustainability on campus by rethinking their missions and restructuring their research programs, curriculum, and life style on campus, and enhancing their trans-disciplinary activities with other societal institutions. According to Viebahn (2002), Clarke and Kouri (2009), Velazquez *et al*. (2006), Lozano (2006*b*), and Cole (2003), the key characteristics of a *sustainable university* are to

- promote transformative rather than transmissive education by preparing students to address complex sustainability challenges
- emphasize inter- and trans-disciplinary research and science
- enhance problem-solving skills in education that are pertinent to the societal goals
- establish networks that can tap into varied expertise around the campus to share resources efficiently and meaningfully, and
- provide leadership and vision that promotes the needed change and guides to a long-term transformation of the university that is responsive to the changing needs of a society.

Since the Talloires Declaration in 1990 (ULSF, 1990), International Association of Universities (IAU) is very active in promoting sustainability in universities and creating proactive leadership towards lessening the demise of the global environment. IAU continues to exert pressure through other declarations such as the Halifax and the Swansea Declarations (UNESCO, 1991, 1993*b*) and Kyoto Declaration (UNESCO, 1993*a*), and as a result of this pressure, signed commitments and voluntary decisions, several universities have embarked on projects and initiatives to incorporate sustainability into their systems.

The application of sustainable development for universities is a relatively new phenomenon and is very challenging because of the complex set-up of universities. A large percentage of university leaders and faculty members worldwide are unaware of sustainable development goals and principles, or if they are aware of them, they have made little effort to incorporate them into their courses, curricula, research, and outreach.

As the primary objectives of universities include not only to educate students, preserve and advance knowledge but also to find sustainable solutions for societal problems through research, therefore the policy- and decision-makers are facing challenges to integrate sustainability in their strategic planning and development and to assess quantitatively the impact of sustainability programs in their institutions (Barth *et al*., 2007; Clarke and Kouri, 2009). A decision support tool is required that can guide what actions should (or not) be taken to achieve sustainable development. Therefore, the main problems faced by universities can be summarized as (1) finding ways and means for effective incorporation of sustainability concepts into the policies, education, research, outreach, and campus operations of a university, and (2) establishing a system that makes sustainable development an integral part of the university culture and creates a multiplying effect within the institution and in the society as a whole.

Universities all over the world are committing to provide sustainable campuses; likewise Canadian universities are also at the forefront of sustainability initiatives. According to Lukman *et al*. (2010) various ranking tables for universities are available to access the quality of universities and these rankings are based on different methodologies and indicators. In 2007, Sustainable Endowments institute started issuing a college sustainability report card for the universities in the United States. The report card includes Canadian universities since 2008. The primary motive behind this Report Card was that universities should be ranked not only on their education and research quality but also on their potential to demonstrate sustainable principles in their campus operations. Sustainable Endowments Institute's College Sustainability Report Card for 2010 (SEI, 2009) was used to provide a systematic comparison of sustainability initiatives in various universities across Canada (Table 4.1). Table 4.1 also includes additional information related to water use and disposal, curriculum initiatives, waste management, and annual sustainability reports. The information presented here is obtained by researching various web-sites of universities and informally contacting their sustainability offices. It can be seen that all major universities are spearheading their efforts on energy conservation, building retrofit (green buildings), and recycling of waste.

4.2. D-SIM – SUSTAINABILITY ASSESSMENT MODEL

Waheed *et al.* (2011*a*) have earlier proposed a **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM), which was applied to higher education institutions (universities) (refer to Chapter 3). The D-SiM is a linkage-based framework in which the final value of sustainability index (SI) is an outcome of nonlinear effects of sustainability indicators. Linkage-based sustainability frameworks use the concept of *causality* or *cause-effect* relationships. These are the most popular form of indicator reporting (World Resource Institute (WRI, 2005); Organization for Economic Corporation and Development (OECD, 1999); European Environment agency (EEA, 2001); (UN, 1996)). These causality frameworks share roots in the stress-response framework originated by Stats Canada (Friend and Rapport, 1979).

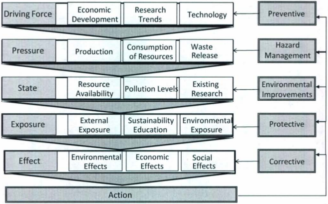
In each framework, a causal chain is defined where a distinction is made between (1) forces that act on the environment, (2) changes as a consequence of those forces in the environment, and (3) societal reaction to those changes. The most common types of linkage-based framework are pressure-state-response (PSR), driving force-pressure-state-impact-response (DPSIR), and driving force-pressure-state-exposure-effect-action (DPSEEA). These frameworks mainly differ in the degree to which they subdivide the steps in the causal chain.

The DPSEEA theoretically provides a better insight into causality because it subdivides into more steps (continuums) and also brings out the important distinction between state and impact. At a macro level, changes in society, such as population growth or income increase, may exert different and variable pressures on the environment as driving forces, depending on the constellation of driving forces and on the way a society deals with such changes. Also, it leads to the fact that driving forces do not necessarily lead to an increase in certain pressures but may lead to reductions in particular pressures. The DPSEEA framework illustrates the cause–effect relationships for various driving forces, pressures, and states of sustainability, the impacts in the form of exposure, and the effects of these causes in a hierarchical fashion. The actions to mitigate the adverse effects could be taken at various stages of DPSEEA — driving forces (preventive action), pressures, states, exposures, or effects. Driving forces are the socio-economic and socio-cultural forces driving anthropogenic activities, which increase or mitigate pressures on the environment. This provides a secondary level of analysis mainly for policy- or decision-makers. This is described in detail in various reports by the UN Commission on Sustainable Development (CSD, 1995). Figure 4.1 illustrates DPSEEA for higher education institutions.

Table 4.1: Overview of sustainability initiatives in Canadian universities

Sustainability Initiatives	Universities										
	MUN	UBC	Dalhousie	McGill	UoM	UoS	UoA	UoT	Queen's	UPEI	UNB
Policy / declaration											
Sustainability policy	x	x	x	x	x	x	x	x		x	
Halifax declaration			x								
Tallories declaration		x	x								
Water conservation											
Water related building retrofit	x	x	x	x		x	x	x	x	x	x
Drinking and bottled water	x										
Climate change and energy											
Construction changes	x	x	x		x	x	x	x	x		x
Building retrofit for energy	x	x	x	x	x	x	x	x	x		x
Transportation											
Carpool	x	x	x	x	x	x	x	x	x	x	x
Reduced transit fair/u-pass	x	x	x	x	x	x	x	x	x		
Pedestrian friendly campus					x					x	
Guaranteed ride home				x							
Hybrid fleet		x		x	x	x	x	x	x		
Bike ride or repair	x	x	x			x	x	x	x	x	x
Food and Recycling											
Trayless cafeteria or biodgradable containers	x		x								
Paperless theses	x							x			
Computer reuse and recycling	x	x	x	x	x	x	x	x	x		x
Farm to table program		x	x	x		x	x		x		x
Organic waste collection		x	x				x		x		
Procurement and waste programs		x	x					x	x	x	x
Invessel composter/composting	x	x	x	x	x	x	x	x	x		x
Curriculum initiatives	x	x		x	x	x	x	x	x		
Green Building											
Many Leeds silver and gold certified buildings		x		x	x	x	x	x			
Leeds certification for future buildings	x	x	x	x	x	x	x	x			x
Student involvement	x	x	x	x	x	x	x	x	x	x	x
Investment priorities		x		x	x	x			x	x	x
Annual Report		x									

Figure 4.1: Driving force-pressure-state-exposure-effect (DPSEEA) framework



The **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM) can help to identify and evaluate single and multiple effects of a *driving force* or policy on *sustainability index* (SI) (Figure 3.1). In the present form, D-SiM is a deterministic model that employs multi-criteria decision-making (MCDM) techniques to make inferences throughout the model, and finally estimates a point estimate of *sustainability index* (SI) — a surrogate measure of sustainability.

The indicators identified in Table 3.2 are connected hierarchically through causal relationships that finally lead to the quantitative assessment of sustainability.

4.2.1. D-SiM procedure

The following seven steps constitute D-SiM:

Step 1 identifies core indicators for "*D*" driving force, "*P*" pressure, "*S*" state, "*E*" exposure, and "*E*" effect, under each performance category of sustainability (environment, economic, social, and education), as shown in Table 3.2. The identification process is a subjective and qualitative process because the objectives of sustainability can be interpreted differently by different stakeholders. The sustainability indicators identified and included in D-SiM are based on a comprehensive study of institutions that have employed sustainability initiatives, such as UBC (2007*a*,*b*); Rodriguez *et al*. (2002); Lozano (2006*b*); and Cole (2003).

A total of fifty–six sustainability indicators are identified for a typical educational institution, where each indicator is classified under environment, economics, social, or educational categories (Table 3.2).

Step 2 establishes causality relationships between cause and effect using a positive and negative sign convention, where

- positive causality refers to the connection between quality and sustainability, i.e., when quality improves sustainability and vice versa, and
- negative causality refers to the connection between pollution and sustainability, therefore an increase in pollution reduces the sustainability and vice versa.

Step 3 uses the same principles and establishes connections in subsequent stages, between pressures and states, states and exposures, and exposures and effects. The weights or strengths of causality (w_i) are assigned to input indicators based on their relative importance to a response sustainability indicator. The values of these weights may vary in an interval [0, 1]. The type of causality (negative or positive) determines the value of the strength. Expert opinion was used to rank the connections and once the ranks were established weights were assigned at various stages, as shown in Table 3.3.

Step 4 defines the input values for driving force indicators. The linguistic scale for activation levels of sustainability indicators at all stages are defined as *no* (0.0), *extremely low* (0.10), *very* *low* (0.25), *low* (0.45), *medium* (0.50), *high* (0.65), *very high* (0.75), *extremely high* (0.90), and *absolute* (1.0). The input values can be "measured" values or heuristically defined by a decision-maker. Once the sustainability indicators for driving force are activated, the D-SiM estimates the values for intermediate indicators in various stages of the DPSEEA framework.

Step 5 uses a simple weighted average method for aggregating and evaluating the activation level of dependent indicators in each stage of the DPSEEA framework. In D-SiM, the inference to estimate activation for any dependent indicator is the normalized value of summation of the product of weight and activation value.

$$[4.1] \quad A_j = \frac{[w_1 X_1 + w_2 X_2 \ldots + w_n X_n]}{(w_1 + w_2 \ldots + w_n)}$$

where A_j is the estimated activation level of a dependent indicator j, w_i is the weight assigned to the indicator i, and X represents predefined (or predetermined) activation values of contributing indicators. This formulation is valid for any dependent indicator in pressure (P), state (S), exposure (E), and effect (F) stages

Step 6 provides an estimation of effects under environment, economics, social, and education categories. A *simple weighted average* method is used for aggregation.

Step 7 estimates the overall sustainability of a university through a surrogate measure, *sustainability index* (SI), which is defined as a function of environmental, economic, social, and education categories. Higher values of SI represent that an institution is "sustainable" and vice versa. The estimated values of SI can be used to determine ranking of various universities with respect to sustainability. The final relationship is written as

$$[4.2] \quad \mathrm{SI} = T_1 \frac{[A_{env} w_{env} + A_{econ} w_{eco} + A_{soc} w_{soc} + A_{edu} w_{edu}]}{(w_{env} + w_{eco} + w_{soc} + w_{edu})} + T_2$$

where

A_{env} is the estimated activation level of environmental *effects*;

A_{econ} is the estimated activation level of economic *effects*;

A_{soc} is the estimated activation level of social *effects*;

A_{edu} is the estimated level of education *effects*;

T_1 and T_2 are the normalization factors (to convert the values in the full range of [0, 1];

w_{env} is the causal weight for environmental *effects*;

w_{eco} is the causal weight for economic *effects*;

w_{soc} is the causal weight for social *effects*;

w_{edu} is the causal weight for education *effects*;

SI is the sustainability index value.

The T_1 and T_2 in this equation are used to map the results in the range of [0, 1]. We ran various scenarios and estimated the minimum (worst) and the maximum (best) possible value of sustainability index before normalization. Later, these values are used to normalize the results as following:

$SI = (SI' - Min) / (Max - Min)$

$SI = T_1 * (SI') - T_2$

where

SI' = Sustainability index (un-normalized)

$T_1 = 1/(Max - Min)$

$T_2 = Min/(Max - Min)$

4.2.2. A Critique on D-SiM

In D-SiM, each pressure is caused by one or more driving forces, each state is caused by one or more pressures, and likewise exposure and effect are caused by one or more states and exposures, respectively. The D-SiM calculates the activation for each dependent indicator based on defined weights and values of activation of input indicators. After estimating the *effects* indicators, *sustainability index* is calculated using Eq. [2] from the sustainability categories – environmental, economic, social, and education by assuming the weights of these categories.

To better comprehend the contributions of various input factors (D_k, *driving forces*) and their effects on SI, a 2^k full factorial Design of Experiment (DoE) methodology is employed. Seven input factors (D_k), each defined at two levels, are used in D-SiM simulation experiments. The values of each of these input factors are in an interval [0, 1], where 0 refers to "low" and 1 refers to "high" level. Therefore, a total of 128 simulation experiments (k = 7) are performed using the D-SiM model for various combinations of input factors, which is followed by analysis of variance and sensitivity analysis (Waheed *et al.*, 2011*a*). It has been well established that sustainability assessment is a challenging task due to involved uncertainties and vagueness. The complexity is further aggravated due to inherent randomness in the processes and interdependency among various factors in the proposed framework. It was also found that assigning of point values to the basic sustainability indicators and the overall assessment through D-SiM bears subjectivity and uncertainty that may lead to less confidence in the SI estimates. Although the D-SiM in the present form can help in rational decision-making through aggregating numerous sustainability indicators and establishing causality-based interactions among these indicators, however it does not explicitly address the issue of uncertainty related to vagueness and subjectivity. To achieve enhanced understanding of the interrelations among sustainability indicators of higher education institutions, it is important to include uncertainty analysis sin the decision-making model. This chapter introduces an uncertainty-based D-SiM (uD-SiM) to counter the deficiency described in the earlier model. The newly proposed model will provide more realistic results and help improve the decision-making process. Following section provides basic information related to uncertainty modelling. Section

4.4 provides a formulation for the proposed uncertainty-based D-SiM, followed by results and discussion and comparison of D-SiM and uD-SiM in Section 4.5. Finally, conclusions are presented in Section 4.6.

4.3. UNCERTAINTY MODELLING

There are two kinds of uncertainties: the first arises as *variability* resulting from heterogeneity or stochasticity, and the second arises from partial ignorance, systematic measurement error or subjectivity (*epistemic* uncertainty) (Ang and Tang, 2007). Epistemic uncertainty (incomplete knowledge) dominates the decision analysis problems, such as the health effects by exposure to unknown contaminants and the economical risks associated with climate change. It plays an important role when the evidence base is small, such as the case of sustainability assessment of higher education institutes. These uncertainties are critical to analyze because of associated high consequence due to failures (Ferson *et al*., 2004 *a,b*).

Traditionally, probabilistic methods have been used to quantify and display uncertainties. The probabilistic methods are designed and refined over time (using Bayesian approach) to propagate uncertainties. Major probabilistic risk analysis applications have been in the fields of industrial, aeronautical, environmental, petroleum, nuclear, and chemical engineering. In civil engineering, the probabilistic methods handling risk and uncertainties were developed for the analysis of structural reliability using analytical or numerical integration, simulation, moment-based methods, or first- and second-order methods (FORM / SORM) of approximation of the limit state of a system (Ahammed and Melchers, 1994). They are now the basis for the design codes for common structures.

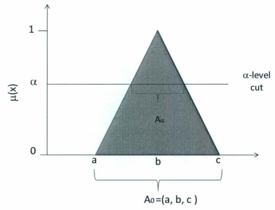
Both set theory and probability theory are the classical mathematical frameworks for characterizing uncertainty. Since 1960s, a number of generalizations of these frameworks became available for formalizing various types of uncertainties. Klir (1995) reported that well-justified measures of uncertainty of relevant types are now available not only in the *classical set theory* and *probability theory* but also in the *fuzzy set theory* (Zadeh, 1965), *possibility theory* (Dubois and Parade 1988), and the *Dempster-Shafer theory* (Dempster, 1967; Shafer, 1976). In 1965, Zadeh introduced fuzzy logic and fuzzy set theory, which is widely used in representing uncertain knowledge. The parameters of uncertainty model can be treated as fuzzy numbers that can be manipulated by specially designed operators. Later, Klir (1995) proposed a comprehensive *general information theory* to encapsulate these concepts into a single framework.

4.3.1. Fuzzy set theory

As the fuzzy set theory effectively deals with uncertainties encompassing vagueness to approximate reasoning and help in representing and propagating the uncertainties throughout the decision process, therefore the fuzzy-based techniques are used for assessing sustainability which is also known for its vagueness. Fuzzy-based techniques are a generalized form of interval analysis used to address uncertain or imprecise information. To qualify as a fuzzy number, a fuzzy set must be normal, convex, and bounded (Klir and Yuan, 1995). Any shape of a fuzzy number is possible, but generally because of simplicity triangular or trapezoidal fuzzy numbers are used (Lee, 1996). A fuzzy set is an extension of the classical set theory (x is either a member of set A or not) in which an x can be a member of set A with a certain membership function μ_x. A fuzzy number describes the relationship between an uncertain quantity x and a membership function, which ranges between 0 and 1, μ: $R \rightarrow [0, 1] \subseteq R$. Figure 4.2 shows a triangular fuzzy number (TFN). The *membership function* μ determines the imprecision through the *shape* of the fuzzy number. Values $x \in R$ for which $\mu(x) = 1$ are said to have *full membership*, values

$x \in R$ for which $0 < \mu(x) < 1$ are said to have *partial membership*, and values $x \in R$ for which $\mu(x) = 0$ are said to have *no membership* to the fuzzy number. Triangular fuzzy number (TFN) is represented by three points (a, b, c) on the universe of discourse, representing the minimum, most likely and maximum value, respectively. The wider the support of the membership function, the higher the uncertainty. In this work, to simplify the implementation, a TFN is selected. Although any fuzzy number shape is possible, the selected shapes are justified by available information (Guyonnet *et al*., 1999).

Figure 4.2: Triangular fuzzy number (TFN)



4.3.2 Fuzzy Arithmetic

One important feature of fuzzy numbers (sets) is the concept of α-cut (Figure 4.2). The α-cut of a fuzzy set is a crisp set A_α that contains all the elements of the universal set X whose membership grades in A are greater than or equal to the specified value of an α-cut, i.e., $A_\alpha = \{x \mid \mu_x \geq \alpha\}$ (Klir and Yuan 1995). Fuzzy operations are carried out on fuzzy numbers using fuzzy arithmetic. Fuzzy arithmetic is based on two properties:

1) each fuzzy number can fully and uniquely be represented by its α-cut, and

2) α-cuts of each fuzzy number are closed intervals of real numbers for all $\alpha \in (0,1)$.

Fuzzy arithmetic operations require that specific rules and applicable procedures (Klir and Yuan, 1995) be followed to ensure reliable outcomes, such as the simplification of equations prior to establishing their fuzzy form. Hence, once the interval numbers are obtained, a well-established operation of interval analysis can be used (Ferson *et al*., 2004*b*) in fuzzy arithmetic.

Fuzzy numbers can represent vagueness or imprecision in the parameter(s). Phillis and Andriantiatsaholiniaina (2001) demonstrated using Fuzzy logic for sustainability. The linguistic input values (driving forces) in D-SiM can be easily described using triangular fuzzy numbers (TFNs). The uncertainties can be propagated through the D-SiM using fuzzy arithmetic operations.

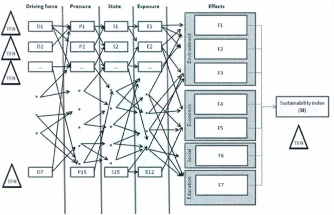
4.4. UNCERTAINTY-BASED D-SIM

In D-SiM, the sustainability indicators were assigned "crisp" or point values; however, such values are often hard to come by because of insufficient statistical data and lack of knowledge. Consequently, such crisp values may lead to "precise" but unrealistic results. The proposed uncertainty based D-SiM is illustrated in Figure 4.3. The following procedural steps are taken to develop uD-SiM.

4.4.1. Identification of indicators

Table 3.2 provides a comprehensive list of indicators for education, environment, social, and economic dimensions for driving forces, pressures, state, exposure, and effect. A number of key factors that broadly affect the environmental, economic, social and educational processes for a typical higher education institution are selected. For example, the indicators, such as global and local research and development trends, institutional enhancement rate, annual energy consumption rate, economic growth rate, help decision makers at this level in setting policies and for examination of the root cause problems.

Figure 4.3: Structure of proposed model



The selected driving forces result in pressures on the environment, education, social, and economic aspects. The various driving forces considered result in pressures on the environment, economic activity, social, and educational aspects of a university, such as production of greenhouse gases, increasing costs of education, increasing requirements for health and safety, and requirements for changes in curriculum and courses. The state of environment, economic, social, educations aspects are affected by the various pressures exerted, such as, pollutant concentration, exceedance of drinking water quality standards, percentage of expenditure, existing health and safety procedures, number of courses on sustainability, and administrative support. The direct or indirect impacts or exposure are indicated as a proportion exposed to poor environmental conditions, economic and social impacts, and proportion of research support for sustainability. The effects on various dimensions are manifested as effects on human health, ecology, biodiversity, social aspects, economic aspects, and education on sustainability.

4.4.2. Establishing causality

The concepts for defining positive and negative causality were based on the connection between sustainability and *quality* or *pollution* parameters, respectively. For example, a *pressure* indicator P_1 (production of greenhouse gases) is affected by a set of *driving forces* {D_1-, D_2+, D_3+, D_4+, D_7-}, where increases in D_1 (international research and development trends or advancement), and D_7 (sustainability education) decrease the production of greenhouse gases. Similarly, the *driving forces* D_2, D_3, and D_4 positively impact P_1, therefore the increase in these indicators increases P_1, and vice versa. Similarly, a state indicator S_1 (concentration of greenhouse gases) is affected positively by a set of pressures {P_1+, P_2+, P_5+, P_{15}-}, where production of greenhouse gases (P_1), production and consumption of ozone-depleting substances (P_2), amount of energy used (P_5), while provision of services (P_{15}) has negative impact on S_1. Using the same principles, connections are established between *pressures* and *states*, *states* and *exposures*, and *exposures* and *effects*.

4.4.3. Assigning weights (strength) of causality

The determination of weights is always an important issue in multi-criteria decision-making (MCDM). Several approaches (e.g., Hwang and Lin, 1987; Tsamboulas and Mikaroudis, 2000) have been developed, including direct assignment, Delphi survey, pair-wise comparison, eigenvector method, and linear programming. In this chapter, direct assignment method is used to assign crisp causality weights (w_i) to input indicators based on their relative contribution to a receiving (dependent or effect) sustainability indicator in the next phase. For example, a *pressure* indicator P_1 is impacted by a set of driving force indicators $\{D_1, D_2, D_3, D_4, D_7\}$, therefore causality weights are assigned to these five input indicators. The values of these weights may vary in an interval [0 1]. Table 3.4 lists the scale of causality weights used in this study. The causality weights are assigned in each phase of the DPSEEA framework, from driving force to the final effects (i.e., environment, economics, social, and education categories) and finally sustainability index. The sequence and weights assigned at each stage are the same as for D-SiM, as shown in Table 3.3.

4.4.4. Activating driving force based on fuzzy input values

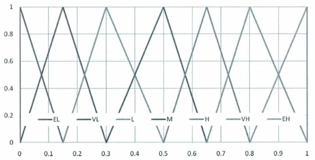
The main difference between the D-SiM and uD-SiM is that in uD-SiM the input values defined for *driving force* indicators are triangular fuzzy numbers (TFNs). Figure 4.4 provides a linguistic interpretation of activation levels for sustainability indicators. These input indicators can be "measured" or heuristically defined values by a decision-maker. In this analysis, the driving forces are defined linguistically. The activation level of driving forces can be based on numerous factors identified by a specific university. In this study, we have tried to define driving forces in a very general context. For example, "Global/local research and development trends" is a broad term that can be a function of numerous factors that are measurable or observable, such as zero carbon policy, LEED certified buildings, sustainability curriculum, etc. These factors can be aggregated through some scoring methods to obtain activation levels for driving forces. For simplicity, in this analysis, we assume that these activation levels are available. Once the input values are activated, the uD-SiM estimates the intermediate indicators at various stages of the

DPSEEA framework using fuzzy arithmetic operations (Figure 4.4). These fuzzy numbers will be able to propagate uncertainties throughout the structure of the uD-SiM.

4.4.5. Aggregation (Inferencing)

Aggregation is the process by which fuzzy sets that represent the input indicators are combined or inferred as a single fuzzy set. It is achieved by using an appropriate MCDM method for aggregating and evaluating the activation level of dependent indicators.

Figure 4.4: Triangular fuzzy numbers



Linguistic descriptor	Fuzzy activation level ($\bar{A}$)
Extremely low	(0, 0, 0.15)
Very low	(0, 0.15, 0.3)
Low	(0.15, 0.3, 0.5)
Medium	(0.3, 0.5, 0.65)
High	(0.5, 0.65, 0.8)
Very high	(0.65, 0.8, 1)
Extremely high	(0.8, 1, 1)

The *simple weighted average method* is proposed here because it is intuitive, simple, and most widely used (Yager, 2004). It considers the tradeoffs among attributes. After assigning weights and activating input indicators, an inference to estimate activation for any dependent indicator can be made using the following equation:

$$[4.3] \quad \bar{A}_j = \frac{[w_1\bar{X}_1 + w_2\bar{X}_2 ... + w_n\bar{X}_n]}{(w_1 + w_2 ... + w_n)}$$

where $\bar{A}_j$ is the estimated fuzzy activation level of a dependent indicator *j*, and $\bar{X}$ represents predefined (or predetermined) fuzzy activation values of contributing sustainability indicators, w_i is the weight assigned to the indicator *i*. This formulation is valid for any dependent indicator in pressure (*P*), state (*S*), exposure (*E*), and effect (*F*) stages. To measure the sustainability of a higher education institution quantitatively, the fuzzy sustainability index ($\overline{\text{SI}}$) can be calculated using following formulation:

$$[4.4] \quad \overline{\text{SI}} = \frac{[\bar{A}_{env}w_{env} + \bar{A}_{econ}w_{econ} + \bar{A}_{soc}w_{soc} + \bar{A}_{edu}w_{edu}]}{(w_{env} + w_{econ} + w_{soc} + w_{edu})}$$

where $\bar{A}_{env}$ is a fuzzy activation level of environmental *effects*, $\overline{\text{A}}_{econ}$ is a fuzzy activation level of economic *effects*, $\bar{A}_{soc}$ a fuzzy activation level of social *effects*, and $\bar{A}_{edu}$ is a fuzzy activation level of education *effects*. Fuzzy sustainability index ($\overline{\text{SI}}$) will require a special interpretation based on possibility theory.

4.4.6. Defuzzification

Fuzzy defuzzification methods can be used for ranking or obtaining crisp values of fuzzy numbers. The *defuzzification* entails converting the final fuzzy $\overline{\text{SI}}$ value into a crisp value (SI). Various techniques are used for defuzzification however each technique extracts different levels of information from the fuzzy numbers (Tesfamariam and Sadiq, 2006). In this analysis, Yager's centroid index method (Yager, 1980) is used. The centroid index is a geometric center (SI_o)

of the fuzzy number $\overline{\text{SI}}$, where the geometric center corresponds to a crisp (representative) value of SI on its universe of discourse. For a given TFN (*a*, *b*, *c*), Yager (1980) proposed a centroid index as follows:

$$[4.5]\quad \text{SI}_o = \frac{\int_0^1 \text{SI}_i\ \mu_{SI_i}}{\int_0^1 \mu_{SI_i}} = \frac{(b-a)\left[\left(a+\frac{2}{3}(b-a)\right)\right]+(c-b)\left[\left(b+\frac{1}{3}(c-b)\right)\right]}{(b-a)+(c-b)}$$

where SI_i is treated as a moment arm (weight function). The denominator serves as a normalizing factor whose value is equal to the area under the membership function μ_{SI_i} for a given scenario. The value of SI_o may be seen as the weighted mean value of the TFN of the sustainability index ($\overline{\text{SI}}$).

4.5. Results and Discussion

4.5.1. Estimation of sustainability index

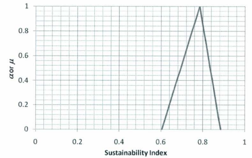
On the basis of the proposed evaluation-framework of sustainability index (uD-SiM), the fuzzy-based input values (driving force) are selected for the base trial or scenario (Table 4.3). The authors assumed the role of decision-maker and assigned these input values to demonstrate the proof-of-concept. Assuming that the global research and development trends and education in sustainability play the most significant role in making a campus sustainable, we chose extremely *high* and *very high* values for D_7 and D_1, respectively. It can be seen from university initiatives in Canada (Table 4.1) that measures to reduce energy consumption by building retrofits and green buildings are common among the universities. The direct positive relation between reduction in energy costs and increase in financial and economic growth rate could explain this commonality. Therefore, the input value for D_3 and D_5 is considered *medium*. Health and safety index (D_5) is also assigned the same value, as this aspect has been at the core of all environmental initiatives.

More emphasis is placed on the social equity index (D_6), therefore it is given a higher value. The importance of institutional enhancement rate (D_2) is assumed as low in the trial base.

After the base trial of uD-SiM using predefined fuzzy inputs and weights, the outcome was a TFN of a sustainability index [0.63, 0.78, 0.86], representing an uncertainty measure (max.-min) of 0.23 (Table 4.3 and Figure 4.5). To analyze the impact of weights assigned to various categories (i.e., environment, economics, education, and social) on overall sustainability and uncertainty, 13 trials or scenarios were investigated. The weight vectors are [1 0.2 0.2 0.2], [1 0.6 0.6 0.6], and [1 0 0 0]. It is observed that the most likely value (MLV) of sustainability index reaches its highest value of 0.91 when education is set at 1 and the remaining categories are set to 0. The percent change in this trial is 14.21%. From trial 13, [0 1 0 0], one can notice that MLV of $\overline{\text{SI}}$ is at its lowest when economics and social are set as 1 while keeping the rest at 0 and the percent change from the base value is 30%. Moreover, the trial with [Env(0.2) Eco(0.2) Soc(1) Edu(0.2)] gives a second highest MLV of 0.83 with a percent change of 6%, whereas for the remaining trials, the percent change from the base value is less than 10%. In other words, the $\overline{\text{SI}}$ value is not significantly affected in other trials.

Another important aspect is the uncertainty measure, which is based on the fact that the wider the support of the membership function, the higher the uncertainty. Table 4.3 shows that uncertainty is the lowest (0.23) for the base trial. The percent change in uncertainty for the trial 10 is 0.25, which is about 9% more than the base case. For the remaining trials, uncertainty increases from 12% to 45% from the base value.

Figure 4.5: Triangular fuzzy numbers (TFN) for sustainability index (base trial)



α	$(\bar{SI})$min	$(\bar{SI})$max
0	0.60	0.89
0.1	0.62	0.88
0.2	0.64	0.87
0.3	0.66	0.86
0.4	0.68	0.85
0.5	0.69	0.84
0.6	0.71	0.82
0.7	0.73	0.81
0.8	0.75	0.80
0.9	0.77	0.79
1	0.78	0.78

4.5.2. Sensitivity Analysis

Sensitivity analysis (SA) is the process of estimating the degree to which output of an uD-SiM model changes as values of input parameters are changed. The American Standard for Testing and Materials (ASTM, 1998) has recognized the role of SA in the fate modeling as follows:

- SA can identify the input parameters that have the most influence on model output;
- SA can identify the processes that have greatest influence on model output; and
- SA can quantify the change in output caused by uncertainty and variability in the values of input parameters.

Table 4.3: Comparison of various trials

	Sustainability categories				TFN for SI				Uncertainty
Trials	Env.	Eco.	Soc.	Edu.	Min. (*a*)	MLV (*b*)	Max. (*c*)	%Δ**	(*c*-*a*)***
1	0.6	0.2	0.4	0.8	0.63	0.78	0.86	0*	0.23
2	1	0.2	0.2	0.2	0.61	0.79	0.89	1.27	0.28
3	0.2	0.2	0.2	1	0.58	0.76	0.87	2.63	0.29
4	0.2	0.2	1	0.2	0.64	0.83	0.91	6.02	0.27
5	0.2	1	0.2	0.2	0.49	0.67	0.80	16.42	0.31
6	0.6	0.6	0.6	1	0.59	0.77	0.87	1.30	0.28
7	0.6	0.6	1	0.6	0.56	0.73	0.85	6.85	0.29
8	0.6	1	0.6	0.6	0.54	0.72	0.84	8.33	0.30
9	1	0.6	0.6	0.6	0.57	0.75	0.86	4.00	0.29
10	0	0.0	0.0	1.0	0.72	0.91	0.97	14.29	0.25
11	0	0.0	1.0	0.0	0.52	0.68	0.81	14.71	0.29
12	0	1.0	0.0	0.0	0.42	0.60	0.75	30.00	0.33
13	1	0.0	0.0	0.0	0.59	0.77	0.88	1.30	0.29

* Base value

** Uncertainty = Max. – Min. = $(c - a)$

*** $\%\Delta = \frac{|Base\ value - Trial\ value|}{(Base\ value)} \times 100$

Sensitivity of the uD-SiM is linked to input parameters (driving force) through inferencing equations described earlier. There are several reasons for identifying key model inputs, which contribute to uncertainty in model outputs. An identification of significant contributors to output variance gives the analyst an awareness of which input variable is controlling the output results. The basic exploration of the models, inputs and results, promotes improved understanding and interpretation of the analysis (Cullen and Frey, 1999).

In an uncertainty analysis, the majority of the variance in the output is attributable to variability or uncertainty in a small subset of the inputs. There are varieties of methods of identifying key input variables from model outputs. These methods include the scatter plot, partial and rank correlation coefficients, multivariate regression, and contribution to variance and probabilistic sensitivity analysis. These methods are discussed in detail in Iman and Helton (1988) and Cullen and Frey (1999).

A common method used for SA is to estimate the relative approximate percent contribution (PC) of each parameter to the variance of final outputs by squaring the rank correlation coefficients and normalizing them to 100% (Maxwell and Kastenberg, 1999). The parameters having the greatest effect are considered to be those for which additional data should reduce the amount of overall uncertainty in the results. Hammonds *et al*. (1994) and Maxwell and Kastenberg (1999) used this technique in human health risk assessment for identifying the key input variables. In this chapter, the percent contribution (PC), which is a measure of an input's influence on the output, is calculated. It can range from −100 to 100. If the output tends to increase when the input increases, the PC is positive. If the output tends to decrease when the input increases, the PC is negative. The PC is calculated based on Spearman Rank Correlation as following:

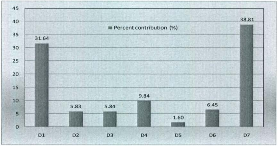
$$[4.6] \qquad PC_j = 100 \cdot \frac{\rho_j |\rho_j|}{\sum_{i=1}^{N} \rho_i^2}$$

where ρ_j is the Spearman's Rank Correlation for the j^{th} input. We use $\rho_j|\rho_j|$ rather than ρ_j^2 to preserve the sign of ρ_j. Using the absolute values of percent contribution for driving forces, (where the input factors are D_k $(k = 1, 2, \dots, 7)$ and $D_k \in [0, 1]$), we found that education in sustainability (D_7) and global and local research trends (D_1) at 38.81% and 31.64% are the major contributors toward $\overline{\mathrm{SI}}$ (shown as a base case in Table 4.4 and Figure 4.6). It can be seen that D_7 along with D_1 plays a very significant role in achieving the sustainability goals for a university, while financial and economic growth rate (D_4) and social equity (D_6) are also imperative. The input forces, institutional enhancement rate (D_2) and annual energy consumption rate (D_3), have equal contribution of 5.83% toward $\overline{\mathrm{SI}}$. It is noted that except health and safety index (D_5), the contribution of the remaining inputs are significant, where contributions of institutional enhancement (D_2), annual energy consumption rate (D_3), and health and safety index (D_5) are negligible. Furthermore, the education in sustainability (D_7) is an important factor for making a sustainable campus, which was clearly observed in both models, i.e., 72% and 39% for D-SiM and uD-SiM, respectively. In D-SiM, an ANOVA based on full factorial analysis was used to perform sensitivity analysis (Waheed *et al*., 2011*a*). However in this analysis, we have proposed a simulation-based sensitivity analysis. The difference in percent contributions is due to the type of different sensitivity methods employed in both models. The sensitivity analysis concludes that to quantify sustainability in a HEI, the decision makers must give priority to global and local research trends and education in sustainability.

Table 4.4: Comparison of uD-SiM and D-SiM based on % contribution

Driving force D_k	uD-SiM (%)	D-SiM (%)
D_1	31.64	0.35
D_2	5.83	0.81
D_3	5.84	2.21
D_4	9.84	10.34
D_5	1.60	3.01
D_6	6.45	11.6
D_7	38.81	71.69

Figure 4.6: Percent contribution of driving forces towards sustainability index (SI)



4.6. Conclusions and Recommendations

The decision-making model uD-SiM, based on DPSEEA and an integration of MCDM and fuzzy logic, is proposed as a solution to evaluate a *sustainability index* for higher education institutions. Using hierarchical causal links among driving forces-pressures-state-exposure-effects and a comprehensive list of indicators, this model recognizes the subjective nature of the analysis by using fuzzy input values to assess a *sustainability index.* The proposed model is more robust and provides more rational decision-making by analyzing decisive indicators, tradeoffs, and weighting sensitivities, establishing complex interactions between stages, and incorporating uncertainty-based analysis. The uD-SiM revealed that education in sustainability and global and local trends are the major driving forces for achieving sustainability in HEIs, followed by financial and economic growth rate, social equity, institutional enhancement, and energy consumption rate. The health and safety index was the least significant input driving force. In D-SiM, the combined contribution of education in sustainability, economic development, and social equity was ~ 93% in HEI and the less significant driving forces in descending order were health and safety issues, energy requirements, institutional enhancement, and international research and development trends.

In the present analysis, uncertainty is not considered in the weights and "action" stage of the DPSEEA framework. The incorporation of "action" stage of the DPSEEA framework in uD-SiM will be covered in the following chapter to promote more comprehensive decision-making related to HEI sustainability and to improve the understanding of complex connections among decision actions and their impacts on various sustainability indicators.

Chapter 5: Ranking Canadian Universities: A Quantitative Approach for Sustainability Assessment using uD-SiM[4]

ABSTRACT:

This chapter introduces a model that enables a comparison between universities based on sustainability indicators related to environmental, economic, social and educational aspects. The proposed model is based on a driving force-pressure-state-exposure-effect-action (DPSEEA) framework and is called **u**ncertainty-based **D**PSEEA-**S**ustainability **i**ndex **M**odel (uD-SiM). The uD-SiM is a causality-based approach in which the sustainability index is an outcome of nonlinear relationships of sustainability indicators in different stages of DPSEEA. The uD-SiM is a fuzzy based multi-criteria decision-making model and is used to evaluate sustainability of five Canadian Universities, namely, The University of British Columbia, University of Toronto, University of Alberta, McGill, and Memorial University. The final ranking results are compared with the green report card ranking for 2010 through sustainability index. The application of various actions and strategies that can be applied to different stages of the framework to improve the sustainability in higher education institutions is also discussed.

[4]A part of this chapter is under review as

- Waheed, B., Khan, F., Veitch, B., Hawboldt, K. 2011. Ranking Canadian Universities: A Quantitative Approach for Sustainability Assessment using uD-SiM. *Stochastic Environmental Research & Risk Assessment*. Under review.

5.1. Introduction

The concept of sustainability has been around for many decades now. The definition of sustainability varies depending on the context in which it is used. According to the Brundtland report (WCED 1987), sustainability refers to reducing footprint without compromising quality of life for the present and future generations. The most common framework that is used to illustrate sustainability is triple bottom line (TBL), which is about identifying improvements in the environment, social, and economic performance by adopting short- and long-term policy decisions (Lozano, 2008). In TBL, the environment relates to the impacts of policy decisions on the environment (e.g. natural resources, flora and fauna); economy relates to the impacts on financial or economical sustainability, and society relates to the impact on a community as a whole (e.g. public health and safety, social equity, culture) (Savitz and Weber, 2006; Mebratu, 1998). Efforts towards sustainable pathways have been gaining momentum in all disciplines and institutions. Ideas and new actions are being developed, tested, and disseminated by promoting discussions to define the exact nature of the concept of sustainability and its effective implementation.

Universities all over the world are promoting sustainability on campus by reflecting it in their missions and restructuring their research programs, curriculum, and life style on campus, and enhancing their trans-disciplinary activities with other societal institutions. The efforts vary from one campus to another; however the primary objectives of higher education institutions (particularly universities) are to educate students, preserve and advance knowledge, and find sustainable solutions for societal problems through research. A sustainable campus program addresses all three components of the TBL approach, i.e., 1) improving economic efficiency, 2) protecting and restoring ecological systems, and 3) enhancing the well-being of all people through (Viebahn, 2002; Clarke and Kouri, 2009; Velazquez *et al*., 2006; Lozano, 2006*a*; Stephens and Graham, 2010; Cole, 2003).

Like any other mission, the implementation of sustainability on campus has its own challenges and limitations. The sustainable development for universities is a relatively new phenomenon and is very challenging because of the complex set-up of universities. According to Lozano (2006*a*), not only is the level of awareness among university leaders and faculty members worldwide about sustainable development goals and its principles still low, but the progress of implementing sustainability into their courses, curricula, research, and outreach is also evolving slowly. Therefore, the first and foremost challenge universities are facing can be summarized as finding ways and means for effective and efficient incorporation of sustainability concepts into policies, curricula, research, outreach, and campus operations of a university (Lozano 2009). The second challenge is establishing a system that makes sustainable development an integral part of the university culture and creates a multiplying effect within the institution and in the society as a whole.

There is no perfect method of organizing and viewing the interconnected aspects of socio-economic development, environmental impacts, and human health indicators, which are important ingredients of sustainability measurement according to the TBL approach. This determines the first and foremost aim of this chapter, that is, to extend these interconnected stages through a hierarchical causal linkage framework: driving forces-pressures-state-exposure-effects (DPSEEA). This framework helps to assess sustainability using a measure called *sustainability index* by developing an uncertainty-based model uD-SiM, which stands for uncertainty-based DPSEEA Sustainability Index Model. As higher education systems and academic environments are fundamentally similar in all universities, therefore, a framework for a given university will require similar types of indicators for sustainability assessment and decision-making.

In recent years, the emphasis of ranking charts for universities has changed from just providing information about the quality and other characteristics of higher education institutions to ranking them on the basis of their environmental performance. For higher education institutions, many methods for auditing and ranking sustainability performance are available (Cole, 2003). This includes sustainability tracking, assessment and rating system (STARS) (AASHE, 2009), and an environmental ranking system proposed by Lukman *et al.*, 2010. The eleven methods analysed by Shriberg 2002 for evaluating sustainable development at student campuses can be used for strategic planning but not for comparing campuses. The most renowned sustainability ranking card for universities is the College Sustainability Report card or Green Report Card (2010). Green report card is the first website that provides an in-depth sustainability profiles for hundreds of colleges in USA and Canada. It emerged in 2007 as an initiative of the Sustainability Endowments Institute. It identifies colleges and universities that are leading by example in their commitment to sustainability and endowment practices by considering nine criteria: administration, climate change, food and recycling, green building, student involvement and transportation, endowment transparency and shareholder engagement. Its weakness is that it does not consider all university efforts toward sustainability such as education or research in sustainability and water initiatives. Therefore, the second aim of this chapter is to demonstrate that uD-SiM can be effectively used as a ranking chart for evaluating performance of universities toward sustainability.

This chapter will unfold as follows: Section 5.2 explains the uD-SiM model in detail and Section 5.3 presents an analysis on Green Report card. This is followed by data verification and application of uD-SiM in Section 5.4. The insight into the model, its use for ranking along with improvement through actions is discussed in Section 5.5. The conclusions and recommendations are presented in Section 5.6.

5.2. Uncertainty based DPSEEA Sustainability Index Model

Waheed *et al.* (2011*b*) developed a unique decision-making model called **u**ncertainty-based **D**PSEEA **S**ustainability **i**ndex **m**odel (uD-SiM) that assesses the performance of a higher education institution by calculating the sustainability index. This model is based on driving force-pressure-state-exposure-effect and action (DPSEEA), which is a causal framework (Figure 4.1). These are the most popular forms of indicator reporting (World Resource Institute (WRI), 2005; Organization for Economic Corporation and Development (OECD), 1999; European Environment Agency (EEA), 2001; UN, 1996). These causality frameworks share roots in the stress–response framework originated by Stats Canada (Friend and Rapport, 1979). Various steps or continuums of DPSEEA provide a deeper insight into causality and especially by bringing out the important distinction between state and impact (WHO, 2010; Corvalán *et al.*, 1999; Brulming, 1997; Briggs *et al.*, 1996; Dalal-Clayton *et al.*, 2002). At a macro level, changes in society, such as population growth or income increase, may exert different and variable pressures on the environment as driving forces. Driving forces do not necessarily lead to an increase in certain pressures but may lead to reductions in particular pressures. The DPSEEA framework illustrates the cause–effect relationships for various driving forces, pressures, and states of sustainability, the impacts in the form of exposure, and the effects of these causes in a hierarchical fashion. The actions to mitigate the adverse effects could be taken at various stages of DPSEEA — driving forces (preventive action), pressures (hazard management), states (environmental improvements), exposures (protective), or effects (corrective). Figure 4.1

illustrates DPSEEA for higher education institutions. Driving forces are the socio-economic and socio-cultural forces driving anthropogenic activities, which increase or mitigate pressures on the environment. This provides a secondary level of analysis mainly for policy- or decision-makers. This framework is explained in various reports by the UN Commission on Sustainable Development (CSD, 1995). The uncertainty-based **D**PSEEA-**S**ustainability **i**ndex **M**odel (uD-SiM) can help to identify and evaluate fuzzy-based effects single and multiple effects of a *driving force* or policy on *sustainability index* ($\overline{SI}$) (Figure 4.3).

The uncertainty uD-SiM is a linkage-based framework in which the final value of sustainability index ($\overline{SI}$) is an outcome of nonlinear effects of sustainability indicators. The primary objective of this model is to develop a meaningful sustainability assessment tool for higher education institutions to make informed decisions. The seven procedural steps of uD-SiM are explained in the following subsections and graphically represented in Figure 5.1.

5.2.1. Identification of indicators

The quantitative assessment of sustainability requires various tiers of information that may include objectives, assessment criteria, indices, indicators, and performance data or variables. Objectives describe the broad goals set by the decision-makers and by the public or by the user of the service. Major sustainability objectives are generally set by the triple bottom line (TBL i.e., environment, social, and economic performance) approach. Assessment criteria, sometimes also referred to as "indices" or "indicators" provide principles to establish that specified objectives have been met. Assessment criteria provide yardsticks against which sustainability objectives are measured. Indicators could be leading and lagging and measurable and could be based on various methods and frameworks. The main focus should be on the outcome of performance as required by the Global Reporting Initiative (GRI). In this chapter, the indicators are selected after thorough study and are broken down under environment, economic, social and educational categories. In addition, an informal consultation with faculty members at various universities was performed.

Figure 5.1: Procedural steps for uD-SiM

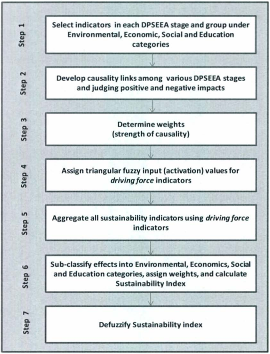


Table 3.2 provides a comprehensive list of indicators for education, environment, social, and economic dimensions for driving forces, pressures, state, exposure, and effect. For this model, seven indicators were identified as *driving forces*: D_1 - global/local and research and development trends, D_2 - institutional enhancement, D_3 - Annual energy consumption rate, D_4 - financial and economic growth rate, D_5 - health and safety index, D_6 - social equity index, and D_7 - education in sustainability trends. These seven indicators belong to four major categories of sustainability, i.e., environment, social, economic and education. Similarly, 15, 15, 12, and 7 indicators have been identified for *pressure*, *state*, *exposure* and *effects*, respectively.

The indicators identified in Table 3.2 are connected hierarchically through causal relationships that finally lead to the quantitative assessment of sustainability. Finally, the indicators of *effects* are used to estimate *sustainability index* (Figure 4.3).

5.2.2. Establishing causality

The concepts of positive and negative causality were applied to develop causality links, which are based on connection between sustainability and *quality* or sustainability and *pollution* parameters, respectively. For example, a *pressure* indicator production of greenhouse gases (P_1) is affected by a set of *driving forces* $\{D_1-, D_2+, D_3+, D_4+, D_7-\}$, where increases in international research and development trends or advancement (D_1) and sustainability education (D_7) decrease the production of greenhouse gases. Similarly, the *driving forces* D_2, D_3, and D_4 positively impact P_1; therefore, increase in these indicators increases P_1, and vice versa. Similarly, a state indicator S_1 (concentration of greenhouse gases) is affected positively by a set of pressures $\{P_1+, P_2+, P_5+, P_{15}-\}$, where production of greenhouse gases (P_1), production and consumption of ozone-depleting substances (P_2), amount of energy used (P_5), while provision of services (P_{15}) has negative impact on S_1. Using the same principles, connections are established between *pressures* and *states*, *states* and *exposures*, and *exposures* and *effects*.

5.2.3. Assigning weights (strength) of causality

Many methods are available for determining the weights in multi-criteria decision-making (MCDM), such as direct assignment, Delphi survey, pair-wise comparison, eigenvector method, and linear programming. In this chapter, the direct assignment method is used to assign crisp causality weights (w_i) to input indicators based on their relative contribution to a receiving (dependent or effect) sustainability indicator in the next phase. For example, a *pressure* indicator P_1 is impacted by a set of driving force indicators $\{D_1, D_2, D_3, D_4, D_7\}$. Therefore, causality weights are assigned to these five input indicators. The values of these weights may vary in an interval [0 1] and are assigned in each stage of the DPSEEA framework from driving force to the final effects and finally for the environment, economics, social, and education categories for the sustainability index (Table 3.3). These weights can be assigned by a team of decision makers or measured. In the present study, the weights are assigned based on relative importance of the indicators and causal link between the indicators.

5.2.4. Activating driving force based on fuzzy input values

In uD-SiM, the input values defined for *driving force* indicators are triangular fuzzy numbers (TFNs) (Cullen and Frey, 1999; Zadeh, 1965). These input indicators can be "measured" or heuristically defined values by a decision-maker. The activation level of driving forces can be based on numerous factors identified by a specific university. The seven broad driving forces are defined in this study. For example, "Global/local research and development trends" is a broad term that can be a function of numerous factors that are measurable or observable, such as zero carbon policy, LEED certified buildings, and sustainability curriculum. These factors can be aggregated through some scoring methods to obtain activation levels for driving forces. Once the input values are activated, the uD-SiM estimates the intermediate indicators at various stages of the DPSEEA framework using fuzzy arithmetic operations. These fuzzy numbers will be able to propagate uncertainties throughout the structure of the uD-SiM.

5.2.5. Aggregation (Inferencing)

After assigning weights and activating input indicators, an inference to estimate activation for any dependent indicator can be made by using equation 1:

$$[5.1] \quad \bar{A}_j = \frac{[w_1\bar{Y}_1 + w_2\bar{Y}_2 \ldots + w_n\bar{Y}_n]}{(w_1 + w_2 \ldots + w_n)}$$

where $\bar{A}_j$ is the estimated fuzzy activation level of a dependent indicator *j*, and $\bar{Y}$ represents predefined (or predetermined) fuzzy activation values of contributing sustainability indicators, w_i is the weight assigned to the indicator *i*. This formulation is valid for any dependent indicator in pressure (*P*), state (*S*), exposure (*E*), and effect (*F*) stages.

5.2.6. Sub-classification and sustainability index

At the effects stage, indicators are sub-classified under environment, economic, social and education categories. The sustainability of a higher education institution quantitatively, that is the fuzzy sustainability index ($\overline{SI}$), is calculated using the following formulation:

$$[5.2] \quad \overline{\mathrm{SI}} = \frac{[\bar{A}_{\mathrm{env}}w_{\mathrm{env}} + \bar{A}_{\mathrm{econ}}w_{\mathrm{econ}} + \bar{A}_{\mathrm{soc}}w_{\mathrm{soc}} + \bar{A}_{\mathrm{edu}}w_{\mathrm{edu}}]}{(w_{\mathrm{env}} + w_{\mathrm{econ}} + w_{\mathrm{soc}} + w_{\mathrm{edu}})}$$

where $\bar{A}_{\mathrm{env}}$ is a fuzzy activation level of environmental *effects*, $\bar{A}_{\mathrm{econ}}$ is a fuzzy activation level of economic *effects*, $\bar{A}_{\mathrm{soc}}$ is a fuzzy activation level of social *effects*, and $\bar{A}_{\mathrm{edu}}$ is a fuzzy activation level of education *effects*. Fuzzy sustainability index ($\overline{\mathrm{SI}}$) will require a special interpretation based on possibility theory.

5.2.7. Defuzzification

Fuzzy defuzzification methods can be used for ranking or obtaining crisp values of fuzzy numbers. In *defuzzification*, the final fuzzy $\widetilde{SI}$ value is converted into a crisp value (SI_o). Various techniques are used for defuzzification. Each technique extracts different levels of information from the fuzzy numbers (Tesfamariam and Sadiq, 2006). In this chapter, Yager's centroid index method (Yager, 1980) is used, where the centroid index is a geometric center (SI_o) of the fuzzy $\widetilde{SI}$, in which the geometric center corresponds to a crisp (representative) value of SI on its universe of discourse. For a given TFN (*a*, *b*, *c*), Yager (1980) proposed a centroid index as follows:

$$[5.3] \quad SI_o = \frac{\int_0^1 SI_i \, \mu_{SI_i}}{\int_0^1 \mu_{SI_i}} = \frac{(b-a)\left[\left(a+\frac{2}{3}(b-a)\right)\right]+(c-b)\left[\left(b+\frac{1}{3}(c-b)\right)\right]}{(b-a)+(c-b)}$$

where SI_i is treated as a moment arm (weight function). The denominator serves as a normalizing factor whose value is equal to the area under the membership function μ_{SI_i} for a given scenario. The value of SI_o may be seen as the weighted mean value of the TFN of the sustainability index ($\widetilde{SI}$).

5.3. Green Report Card

The Green report card is currently the most comprehensive ranking method available and applied to North American universities. As the Green report card is originated by the endowment institute, it emphasizes more on the impacts of endowment practices and operations of the university on sustainability (Green report card, 2010). It identifies the colleges and universities that are leading by example on sustainability. It focuses on nine main criteria: administration, climate change and energy, food and recycling, green building, student involvement, transportation, endowment transparency, investment priorities, and shareholders engagement. The methodology includes selection of universities, composition of four surveys (campus operations, dining services, endowment investment practices, and student activities), data collection and verification (survey conducted through students and administrators), assessment, and recognition. A school's overall grade is calculated from the grades received in nine equally-weighted criteria. A total of 48 indicators are used to evaluate performance within the criteria. The Overall College Sustainability Leaders award is given to universities that have made notable achievements in sustainability by earning an overall grade of "A-."

The major drawback of this ranking is that the main criteria do not encompass all sustainability efforts in a university, such as teaching research and other academic aspects that are recommended as core components in assessing sustainability of a campus by Lozano (2006*a*,*b*; 2010) and Lukman *et al.* (2010). Moreover, water consumption and wastewater initiatives are not considered and some of the indicators are based on qualitative definitions and are difficult to evaluate.

Therefore, in this chapter, we are proposing uD-SiM as a ranking chart by modifying the data obtained from Green report card and identifying the driving forces behind implementation of sustainability in universities. For the past two decades, the commitment of Canadian universities toward sustainability-related issues has been growing. Many universities and colleges are in various stages of implementing sustainability initiatives. A series of national and international declarations on sustainability in education have been developed, and many Canadian universities have committed themselves for implementing the declarations' objectives on their own campuses (Cole, 2003). The most common of these declarations include the Talloires Declaration (ULSF 1990), the Kyoto Declaration, the Halifax Declaration, and the Swansea Declaration (UNESCO, 1991, 1993*a*,*b*). Therefore, the application of uD-SiM will be verified by application to Canadian universities only.

5.4. APPLICATION OF UD-SIM

In uD-SiM, the driving forces inputs activate the whole model systematically. In this study, it is assumed that the cause and effect move sequentially from driving force to the effect, which means that the driving forces activate pressures, each state is activated by one or more pressures, an exposure is activated by one or more states, and likewise effects are activated by one or more exposures. The uD-SiM calculates the activation for each dependent indicator based on defined weights and fuzzy based values of activation of input indicators. It means that once the input values are activated, the uD-SiM estimates the intermediate indicators at various stages of the DPSEEA framework using fuzzy arithmetic operations. These fuzzy numbers will be able to propagate uncertainties throughout the structure of the uD-SiM.

After aggregation of *effects* indicators, *sustainability index* is calculated using Eq. [3] from the sustainability categories — environmental, economic, social, and education — by assuming the weights of these categories. To consolidate various input factors (D_k, *driving forces*) and their effects on SI, this chapter focuses on establishing the driving forces for various universities by preparing input from known data for selected Canadian universities and the Green report card for 2010. This process is used to rank these universities on the basis of SI.

5.4.1. Preparation of Data

After extensive literature review and from various auditing reports, ranking charts, and assessment frameworks (Green report card, 2010; AASHE, 2010; Lozano, 2009; Lukmen *et al.*, 2010; Barth *et al.*, 2007; Baboulet *et al.*, 2010; UoT, 2010; UoA, 2010; UBC, 2010; MUN, 2010; McGill, 2010), the following major decision categories for higher education institutions (HEIs) or universities are identified:

- increasing the focus of research and curriculum on sustainability,
- selecting environment-friendly construction and procurement,
- increasing community outreach, and
- defining assessment measures for environmental, economic, social, and educational efficiency and benefits.

Based on the literature research and keeping in view the nine criteria of Green report card (2009), the criteria $\{X_1, \ldots, X_n\}$ are grouped for seven driving forces of uD-SiM. Strengths (weights) have been assigned as per their relative importance for that driving force as [0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9] from *very low* to *extremely high*. The criterion directly related to the driving force is called the *lead* and is assigned the highest weight and the remaining criteria are referred to as *lagging*. The grouping of criteria under driving forces is shown in Table 5.1 and is explained as follow.

D_1 – Global / local research and development trends

The criteria *policy declaration* (X_1) and *education and research* (X_2) are considered for deriving input values for D_1. Policy declaration, the lead criterion, entails demonstration of commitment to sustainability of a university by the president (Vice Chancellor) and senior administrators through a sustainability policy, adoption of sustainability related mission statements, strategic plans, and local, national, and international agreements such as the Talloires Declaration. It shows the commitment of the university administration toward sustainability initiatives by integrating sustainability efforts from all stakeholders into an advisory council. The education and research (X_2) factor focuses on the following key areas:

- Research: it is further divided into research, publications, and funding for sustainability. Research includes research related to sustainability, identification and involvement of faculty, departments doing research related to sustainability, research incentives, and interdisciplinary research in tenure and promotion.
- Curriculum: consists of courses or programs available for students related to sustainability.
- Co-curriculum activities: it includes student sustainability educators program, sustainability in new student orientation, sustainability material and publications, and student sustainability outreach program.

Based on the relative importance, the weights assigned to X_1 and X_2 are 1 and 0.8, respectively.

D_2 – Institutional enhancement

As institutional enhancement depends on investment priorities such as shareholder advocacy, positive sustainable investments, endowment transparency, and shareholders' engagement; green building criteria for all construction and renovations on a campus. The emphasis on LEED building standards, tracking of greenhouse gas emissions inventory, plans for reduction, and energy efficiency is also important. Therefore, the criteria that contribute significantly to D_2 are categorized as investment priorities (X_3); buildings, operations and maintenance (X_4); and climate change and energy (X_5). The weights assigned to X_3, X_4, and X_5 are [1 0.5 0.8], respectively, where X_1 is assigned a maximum value because of its direct relation with institutional enhancement.

D_3 – Annual energy consumption rate

The criteria considered for obtaining inputs for D_3 include

- *Transportation* (X_6) is defined as campus motor fleet based on clean-burning fuels or electricity, local transportation alternatives, bicycle programs, car-pooling and planning of policies to discourage single-occupancy vehicles and encourage use of alternative modes of transportation.

- *Waste reduction and recycling* (X_7) incorporates food purchase of organic, fair trade, or other sustainable food products, recycling of food, other traditional materials, electronic wastes, and source reduction.

Table 5.1: Data preparation for driving forces

Driving forces	Criteria		Weights
Global/ local research development trends (D_1)			
	Policy and declaration	X_1	1
	Education and research	X_2	0.8
Institutional enhancement (D_2)			
	Investment priorities	X_3	1
	Buildings, operations, and maintenance	X_4	0.5
	Climate change and energy	X_5	0.8
Annual energy consumption rate (D_3)			
	Buildings, operations, and maintenance	X_4	0.7
	Climate change and energy	X_5	1
	Transportation	X_6	0.5
	Waste reduction and recycling	X_7	0.8
	Water conservation	X_8	0.7
Financial/ economic growth rate (D_4)			
	Investment priorities	X_3	1
	Buildings, operations, and maintenance	X_4	0.7
	Climate change and energy	X_5	0.6
	Water conservation	X_8	0.5
Health and safety (D_5)			
	Investment priorities	X_3	0.8
	Planning, administration, and engagement	X_9	1
	Transportation	X_6	0.5
	Buildings, operations, and maintenance	X_4	0.7
Social activity index (D_6)			
	Transportation	X_6	0.7
	Waste reduction and recycling	X_7	0.9
	Planning, administration, and engagement	X_9	1
Trend in education sustainability (D_7)			
	Education and research	X_2	1
	Planning, administration, and engagement	X_9	0.6

- *Water conservation* (X_8) entails initiatives for water consumption and storm water management and efforts toward drinking water and bottled water.
- *Building, operations and maintenance* (X_4) relates to green building criteria for all construction and renovations on a campus, such as LEED building standards.

The weights assigned to X_4, X_5, X_6, X_7 and X_8 are [0.7 1, 0.5, 0.8, 0.7], respectively.

D_4 – Financial /economic growth rate

The lead criterion *investment priorities* X_3 is assigned the full weight of 1, while *building operations* X_4 is weighted as 0.7, followed by *climate change and energy* X_5 at 0.6, and *water conservation* X_8 at 0.5.

D_5 – Health and safety

The lead criterion for this driving force is *Planning, administration, and engagement* **(X_9)** because it includes coordination and planning, diversity and affordability, human resources, public engagement, and student engagement. Sustainability coordination and facilitating student participation in institutional decision-making are also related to sustainability. The weight assigned to this criterion is 1. The lagging criteria for D_5 are *investment priorities* X_3, *building operations and maintenance* X_4, and *transportation* X_6.

D_6 – Social activity index

The lead criterion for D_6 is *planning, administration, and engagement* X_9. The remaining input is received from *waste reduction and recycling* X_7, and *transportation* X_6.

D_7 – Trends of education in sustainability

The lead contributor for D_7 is *education and research* X_2 and the remaining input comes from *planning, administration and engagement* X_9.

5.4.2. Activation

After the weights are established for various factors, the next step is to develop input activation values for driving forces for five universities in Canada, namely, Memorial University (MUN), The University of British Columbia (UBC), University of Toronto (UoT), University of Alberta (UoA), and McGill. Allowing for the fact that universities do not post data on the internet every year, the latest available data was taken into consideration during the research. The input activation values defined for *driving force* indicators are triangular fuzzy numbers (TFNs) instead of deterministic values. As shown in Section 5.4.1, the TFN driving forces for the five universities are obtained from the Green report card for these universities and also through extensive web-search (UBC, 2010; UoT, 2010; UoA, 2010; McGill, 2010; MUN, 2010). It is found that the sustainability initiative at MUN is relatively new and it did not participate in the Green report card ranking for 2010, therefore, the data obtained for MUN for this research were obtained through the website and by informal discussion with the faculty. The conversion of green card report rankings into numerical triangular fuzzy numbers is shown in Table 5.2. For X_2, the information was not found in the green report card for 2010, therefore the sustainability office website of the five selected universities was thoroughly reviewed.

Table 5.2: Conversion of green report card ranking into numerical triangular fuzzy based numbers

Linguistic descriptor	Fuzzy activation level ($\bar{A}$)
1 – ranking A	(0.9, 1, 1)
0.8 – ranking B	(0.7, 0.8, 0.9)
0.6 – ranking C	(0.5, 0.6, 0.7)
0.4 – ranking D	(0.3, 0.4, 0.5)
0.2 – ranking E	(0.1, 0.2, 0.3)
0.0 – ranking F	(0, 0, 0.1)

The information related to the above three main items (research, curriculum and co-curriculum) were investigated and it was found that UBC's sustainability website provides thorough information to all stakeholders including students, faculty, staff, and social groups about the academic programs in education and research related to sustainability and also the link to all relevant courses. Therefore, it was be assigned a value of [0.9, 1, 1]. The information related to research and courses available for sustainability was not comprehensive for the remaining four universities in comparison to the UBC. Therefore, for UoA, UoF, and McGill, the values were assigned as [0.7, 0.8, 0.9]. Memorial University, on the other hand, has a comparatively recent sustainability initiative and there is not enough information available; therefore the activation value was assigned as [0.3, 0.4, 0.5]. The information available for water-related initiatives for all five universities was limited, so the activation values were assumed as [0.5, 0.6, 0.7] for all universities. Similarly, the numerical averages were taken when two or three different ranks were transferred from Green report card to a TFN used in uD-SiM.

5.4.3. Aggregation

Aggregation is the process by which fuzzy sets that represent the input indicators are combined or inferred as a single fuzzy set. Using a simple weighted average method, an input activation level for driving forces is obtained by using the following equation:

$$[5.4]\quad \bar{A}_{di} = \frac{[w_1\bar{X}_1 + w_2\bar{X}_2 \ldots + w_n\bar{X}_n]}{(w_1 + w_2 \ldots + w_n)}$$

where $\bar{A}_{di}$ is the estimated fuzzy activation level of a driving force i, and $\bar{X}$ are the fuzzy activation values of the factors contributing to driving forces, w_i is the weight assigned to the factor i. As a result of this aggregation, fuzzy-based activation inputs are obtained for the five

Canadian universities, as shown in Table 5.3. These input activation levels are considered for the application of uD-SiM to the various universities under consideration.

5.4.4. Application of uD-SiM to Canadian Universities

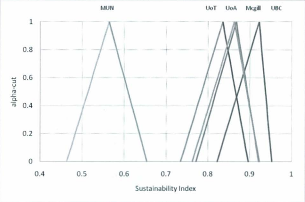
Using input activation levels obtained through data preparation, uD-SiM was simulated following the steps explained in Section 5.4 for Memorial University (MUN), The University of British Columbia (UBC), University of Alberta (UoA), University of Toronto (UoT), and McGill. The resulting sustainability index obtained is presented in Figure 5.2. It is found that the defuzzified SI_o was 0.90 for UBC and the smallest base width for UBC indicates lowest uncertainty for this university. Therefore, SI_o was highest for UBC at 0.90, followed by McGill at 0.87, UoA at 0.87, UoT at 0.84, and MUN at 0.57 (Table 5.4).

It can be seen that the overall rankings of UBC, UoA, and McGill were similar (B+) under the green report card ranking. The difference between uD-SiM ranking and Green report card could be attributed to the fact that the green report did not consider the water use and education in sustainability (Table 5.4). The uD-SiM ranking provides a quantitative evaluation of sustainability as compared to green report card ranking. Moreover, the inclusion of initiatives in education and water in this study has provided a more comprehensive sustainability based ranking.

5.5. DISCUSSION

This chapter ranks universities and demonstrates the use of uD-SiM as a decision making tool. The uD-SiM examines universities based on educational, environmental, social, and economic categories. The proposed model allows better understanding of the efforts of HEIs toward sustainability in a hierarchical causal linkage system and further provides opportunities for improvement or control strategies at any level of the model.

Figure 5.2: Sustainability index for Canadian Universities



	UBC		UFT		McGill		UOA		MUN	
α	(SI)min	(SI)max	(SI)min	(SI)max	(SI)min	(SI)max	(SI)min	(SI)max	(SI)min	(SI)max
0.00	0.82	0.95	0.73	0.90	0.77	0.92	0.76	0.92	0.46	0.65
0.10	0.83	0.95	0.74	0.89	0.78	0.92	0.77	0.92	0.47	0.65
0.20	0.84	0.95	0.75	0.88	0.79	0.91	0.78	0.91	0.48	0.64
0.30	0.85	0.94	0.76	0.88	0.80	0.91	0.79	0.91	0.49	0.63
0.40	0.86	0.94	0.77	0.87	0.81	0.90	0.80	0.90	0.50	0.62
0.50	0.87	0.94	0.78	0.87	0.82	0.89	0.81	0.89	0.51	0.61
0.60	0.88	0.93	0.79	0.86	0.83	0.89	0.82	0.89	0.52	0.60
0.70	0.89	0.93	0.80	0.85	0.84	0.88	0.83	0.88	0.53	0.59
0.80	0.90	0.93	0.81	0.85	0.85	0.88	0.84	0.87	0.54	0.58
0.90	0.91	0.93	0.82	0.84	0.86	0.87	0.85	0.87	0.55	0.57
1.00	0.92	0.92	0.83	0.83	0.87	0.87	0.86	0.86	0.56	0.56

Table 5.3: Fuzzy-based activation input

Driving forces		UBC	UoT	McGill	UoA	MUN
D1	L	0.90	0.81	0.81	0.81	0.52
	M	1.00	0.91	0.91	0.91	0.62
	H	1.00	0.96	0.96	0.96	0.72
D2	L	0.73	0.55	0.68	0.61	0.47
	M	0.83	0.65	0.78	0.71	0.57
	H	0.87	0.72	0.85	0.81	0.63
D3	L	0.82	0.68	0.71	0.73	0.71
	M	0.92	0.78	0.81	0.83	0.81
	H	0.94	0.85	0.85	0.90	0.86
D4	L	0.72	0.55	0.64	0.63	0.44
	M	0.82	0.65	0.74	0.73	0.54
	H	0.88	0.73	0.82	0.83	0.62
D5	L	0.73	0.61	0.71	0.75	0.46
	M	0.83	0.71	0.81	0.85	0.56
	H	0.89	0.80	0.86	0.90	0.64
D6	L	0.82	0.78	0.90	0.90	0.68
	M	0.92	0.88	1.00	1.00	0.78
	H	0.96	0.94	1.00	1.00	0.85
D7	L	0.83	0.78	0.79	0.78	0.38
	M	0.93	0.88	0.88	0.88	0.48
	H	0.96	0.94	0.94	0.94	0.58

Note: L- low; M-most appropriate; H-high.

Table 5.4: Comparison of Green report card rankings (2010) with UD-SiM

Universities	Green Report Card (Overall)	uD-SiM (SI_o)
The University of British Columbia	B+	0.90
University of Toronto	B	0.84
University of Alberta	B+	0.87
McGill University	B+	0.87
Memorial University	-	0.57

Note: Memorial University did not participate in the Green Report Card 2010; SI_o is the crisp or defuzzified value of Fuzzy-based Sustainability index calculated by using equation 5.3.

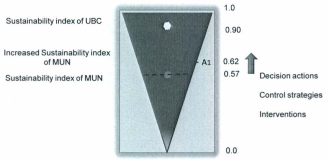
The uD-SiM is primarily a decision making tool that enables control strategies and decision actions to be taken at any stage of the DPSEEA framework to improve the overall sustainability index. If the estimated sustainability index is lower than the desired value, proper "actions" are selected (e.g., least cost, most effective) to avoid any serious adverse effect on the public and environment. As the linkages between the different levels in the DPSEEA framework are the focus of quantitative research and assessing the sustainability for an institution (University campus in this case), various actions can be implemented at different stages of the framework and may take a variety of forms, including prevention (policy development, standard setting), hazard management (reduction in emissions), improvement (technical control measures), protective (pollution monitoring), and corrective (such as treatment, rehabilitation) (Figure 4.1).

Generally, environmental research focuses on linking pressure and state levels, human health research focuses on the links between state and exposure, and environmental epidemiology deals primarily with the exposure to effect linkages (Corvalán *et al*., 1999). The traditional way of analyzing data and taking action at the immediate or end levels does not encourage a broader analysis of the consequences for policy and prevention. Meaningful interpretation of any indicator in the framework in relation to decision making about policies or actions should be based on an understanding of these linkages.

In the short-term, actions are often corrective or remedial at the "effect" stage, such as providing health care for individuals affected by poor air quality or treating waste. Actions for the long term can be various protective measures to reduce exposure, water saving strategies and waste minimization. The most effective long-term interventions aim at eliminating or reducing the effects of the driving forces or the environmental pressures that cause the hazards. Interventions at the level of driving forces often have multiple implications, because major driving forces exert influence through several causal pathways. Sometimes this can multiply benefits, but care must be taken that the overall impact is beneficial.

It can be observed from the ranking of universities through uD-SiM that sustainability index of MUN needs improvement. To increase the SI_o from 0.57 to 0.90 (Figure 5.3), various actions at different stages of the framework (Table 5.5) are required. An action such as developing a policy at the highest administration level for more sustainability related courses and initiatives will enhance the sustainability index for the university. Similarly, the commitment of university senior management, as well as energy saving initiatives, will increase sustainability index. If the financial accounting is integrated with the uD-SiM, the model will guide informed decision-making and help in selecting effective and timely interventions. Actions like reduction in energy usage can only be effective in the long-term for economic growth though they take a relatively long time to implement and even longer time to produce results.

Figure 5.3: Application of actions to improve sustainability index (SI)



The basic rule for the selection of a specific "action" A_i will be to *maximize* Index Change (IC_i)

$$[5.5]\ \text{Percent } IC_i = \left(\frac{(SI_o)_{After} - (SI_o)_{Before}}{(SI_o)_{After}} \bullet 100 \right)$$

where $(\bar{SI}_o)_{Before}$ is the defuzzified sustainability index before taking an "action" and $(SI_o)_{After}$ is the defuzzified sustainability index after taking an "action".

The uD-SiM can be first used to estimate $(SI_o)_{Before}$, i.e., the "control" value of sustainability index (status quo or baseline condition). To demonstrate the impact of selected preventive actions on sustainability index value, three driving forces D_1, D_3 and D_7 are changed and results are summarized in Table 5.6. A suitable action at one stage or combination of actions at various stages will lead to an optimal solution that guarantees an improvement in the overall sustainability of the university in a cost effective manner.

5.6. CONCLUSIONS AND RECOMMENDATIONS

The decision-making tool uD-SiM, based on DPSEEA coupled with MCDM and fuzzy logic, is proposed as a solution to establishing a *sustainability index* for higher education institutions. In this chapter, it is established that this model can provide objective perspective in ranking universities because it allows the decision makers to better understand the hierarchical perspective of various levels on the final index. Moreover, this fuzzy-based model can be effectively applied to foster improvement by promoting action at any level of DSPSEEA. Better policies can definitely lead toward longer-term, broad-spectrum interventions and long-term solutions by evaluating the driving forces operating in an institution. To implement proactive preventive approaches, development policies and planning need a long time horizon. It can be observed that those universities where sustainability is an integral part of the planning and decision making, and where initiatives related to sustainability started decades ago have higher sustainability indices.

Table 5.5: Example of actions for Memorial University at various stages of uD-SiM

Level	Descriptive indicators	Descriptive actions
Driving Force (D_7)	Education in sustainability trends	Approval of policy to increase education and research in sustainability
Pressure (P_{13})	Requirement of changes in curriculum and courses	Request for more courses in sustainability
State (S_{13})	Number of courses on sustainability	Approval of courses and increase in number of courses, programs related to sustainability changing the status from elective to compulsory
Exposure (E_{11})	Proportion of multi/inter/intra disciplinary programs and curriculum	Promoting awareness of the courses available to students by providing better information through websites.
Effect (F_7)	Effects of sustainability educational performance	Number of students taking courses and involved in programs related to sustainability
Driving Force (D_3)	Annual energy consumption rate	Approval of investment in energy reduction options and investment in green buildings and building retrofits
Pressure (P_5)	Amount of energy used	Implementation of green buildings and using alternative energy sources
State (S_4)	Rate of depletion of energy resources and institutional contribution	Improvement in existing monitoring and measuring facilities and equipment
Exposure (E_6)	Impact on energy resources	Ensure various venues for new energy resources are explored and implemented
Effect (F_2)	Effect on environment	Percentage of faulty and old technology equipment and system replaced

Table 5.6: Result of various actions on Sustainability index (SI) for Memorial University

Actions	Action Description	IC (%)
A_1	10% increase in initiatives for Education in Sustainability D_7	3.69
A_2	20% increase in initiatives for D_7	7.35
A_3	10% increase in initiative for reducing energy requirements D_3	0.69
A_4	10% increase in global/local research development trends D_7	1.29
A_5	20% increase in input for global/local research development trends D_1	5.34

Note: Index Change (IC) is calculated based on $(SI_o)_{Before} = 0.57$ for MUN from Equation 5.5

Clearly, further studies are needed to improve the uD-SiM by better and more comprehensive selection of indicators and assignment of weights. Application of uncertainty to the weights of indicators at various levels of DPSEEA and financial accounting will enhance the model and its capability to evaluate the alternatives and decision actions in terms of cost and benefits.

Chapter 6: Conclusions and Recommendations

This chapter provides conclusions drawn from the research work. Some recommendations for future research have also been provided.

6.1. Summary and Conclusions

Considering the availability of several approaches and conceptual frameworks for the assessment of sustainable development, such as life-cycle assessment, objective-based framework, impact-based framework and stakeholder-based framework, the author found that these frameworks lack flexibility to be used in various disciplines with a unified interpretation. Each has its own advantages and disadvantages to deal with different issues of sustainability effectively. The linkage-based frameworks have been found extremely useful in management and policy-making in health, agriculture, and mining sectors. The DPSEEA framework is even one step ahead because of its similarity with ecological and human health risk assessment and risk management paradigms and also its capability to split impacts into exposure and effect, thereby enhancing decision-making with regards to environmental as well as economic and social aspects. In this research, it has been shown that the DPSEEA framework in combination with other analytical methods, such as impact-based analysis (TBL), multi-criteria decision analysis and risk analysis, can be very useful for quantitative assessment of sustainability.

HEIs are selected for this research because application of sustainable development for HEIs is a relatively new phenomenon and is very challenging because of the complex administrative set-up of universities. The main challenges facing universities can be summarized as (1) finding ways and means for effective and efficient incorporation of sustainability concepts into the pragmatic policies, education, research, outreach, and day-to-day university campus operations, and (2) establishing a system that makes sustainable development an integral part of the university culture and society as a whole.

The proposed modelling framework provides a unique sustainability assessment tool that enhances the understanding of causal relationships among various sustainability indicators and the effects of decision actions on overall sustainability improvement. This model considers the environmental, social, and economic dimensions and overall educational performance. Through extending these categories and recognizing the causal links among driving forces-pressures-state-exposure-effects, a comprehensive list of indicators for the modelling framework is developed to assess sustainability using a surrogate measure - sustainability index. This study was conducted in four phases: (1) literature review and a selection of suitable quantitative framework for sustainability assessment, (2) development of the D-SiM model for quantitative assessment of sustainability of HEIs, (3) extension of the model to consider uncertainties in the analysis by developing uncertainty-based D-SiM (uD-SiM) and (4) application of uD-SiM for the selected Canadian universities and determination of decision-action impacts on sustainability improvement of HEIs. Major conclusions of this study are:

- A linkage-based framework DPSEEA can be integrated with multi-criteria decision-making tool to develop a causal model that can predict the sustainability of a HEI and its improvement based on continuum of performance indicators. The main strength of the proposed modelling approach is its flexibility and transparency that enable the inclusion of additional indicators if required.
- The proposed model provides a scheme to estimate sustainability of HEI as a snapshot, which can be re-evaluated if new information becomes available over time.

- The ANOVA-based sensitivity analysis results of the D-SiM model reveal that driving forces, such as economic development, social equity and education in sustainability, collectively contribute more than 90% to the sustainability index of HEIs. Other driving forces, including health and safety index, annual energy consumption, institutional enhancement and global and local research & development trends, constitute the remaining contribution.
- The simulation-based sensitivity analysis of uD-SiM models concludes that driving forces, such as "education in sustainability" and "global/local research and development trends" collectively contribute more than 70% to the sustainability index of HEIs. The difference in percent contributions of D-SiM and uD-SiM is due to the type of sensitivity methods employed in both models. However, "education in sustainability" is identified to be an important driving force for the sustainability of HEI regardless of the type of sensitivity method used.
- The proposed models provide unique and objective ways of ranking universities on the basis of sustainability index that can be easily compared with Green Report Card and AASHE's STAR ranking systems. The proposed ranking system highlights the opportunities for identifying key indicators of HEI sustainability and fosters their improvement. For example, the SI for Memorial University was comparatively *low* because of its relatively new sustainability initiative as compared to other leading Canadian universities. It can also be concluded that the application of decision actions and management strategies that can enhance "education in sustainability trends" and "global/local research and development trends" will substantially improve the overall sustainability of an HEI.

6.2. Recommendations

Based on this thesis, the following recommendations can be made for the future research:

- In the present form, the D-SiM and uD-SiM models consider causal relationships in series from driving force to pressure, pressure to state, state to exposure, and exposure to effect. The limitation of the model in the present form is that the interactions among various indicators at a given level are not considered, which may introduce uncertainties in the results. The proposed methodology can be improved by considering dependency relationships among indicators at a specific level.
- The causal weights used in this research are derived based on a limited number of experts. This limitation can be avoided by group decision-making using more experts from different fields and incorporating AHP approach to check the consistency of the answers.
- Uncertainties related to causal weights are not considered in this research. A fuzzy-based AHP approach can be investigated to describe uncertainties in the future research.
- Decision actions and control strategies at various stages have different effects on the improvement of sustainability of an HEI. Further research is required to integrate the cost of these decision actions on the improvement and perform a comprehensive cost-benefit analysis.
- The proposed models have been developed specifically for HEI. The conceptual framework can be adjusted to any public institution (e.g., hospitals, schools, libraries) or in the field of engineering provided that the continuum (as cause-effects) of relevant performance indicators is available.

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