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# Education Master Plan
## *Information Submission Form*

The GCCCD is starting a year-long process to develop an Educational Master Plan that will serve as the blueprint for our future. The Educational Master Plan is a long-range, comprehensive document intended to guide institutional and program development at both the college and district levels. The priorities established in the Educational Master Plan will serve to guide College and District decisions about growth, development and resource allocation.

As the first step in this planning process, everyone in the GCCCD community (faculty, staff, students and community members) are invited to identify and submit information sources to be reviewed for the trend analysis in one of six taxonomy areas - society, technology, economy, environment, politics, and education. We are not asking you to do new research - only to identify information you already have or that you encounter during the search period (March 21 - April 25) and bring it to the attention of the Scan Teams for review.

Please feel free to submit as many of these forms as you would like. Please answer the following questions for each submission:

1) What is the document we should review? : Water Treatment Technologies and Trends in San Diego, California

2) Author: Julia Guerrero and Kit Haggard

3) Source: internet - U. S. Commercial Service - San Diego

4) Which of the following taxonomy areas does it fit into? (Please select only one):

☐ Society

☐ Technology

☐ Economy

☒ Environment

☐ Politics and Legal Issues

☐ Education

☐ Other:

5) Relevance: Water issues and solutions

6) Page / Section:

7) **Add Attachment/Hyperlink Here**: www.buyusa.gov/sandiego/sandiegowatertreatmentreport.pdf - Similar

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Questions: lynne.davidson@gcccd.edu *Research, Planning and Institutional Effectiveness*

# Educational Master Plan

## *Information Submission Form*

1) Title: Uncertainty-based quantitative assessment of sustainability for higher education institutions

2) Author: Bushra Waheed, Faisal I. Khan*, Brian Veitch, Kelly Hawboldt

3) Source: Journal of Cleaner Production vol.19 (2011)

4) Taxonomy Area:

- ☐ Society
- ☐ Technology
- ☐ Economy
- ☑ Environment
- ☐ Politics and Legal Issues
- ☐ Education
- ☐ Other: __________

5) Relevance: sustainability

6) Page / Section: 720-732

7) Link to document: __________

or

8) Attach Document Here: ☐

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# Uncertainty-based quantitative assessment of sustainability for higher education institutions

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A B S T R A C T

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 paper 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 HEI 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 HEI, 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 approach, D-SiM.

## 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 (2006a), and Cole (2003), the key characteristics of a *sustainable university* are to

(i) promote transformative rather than transmissive education by preparing students to address complex sustainability challenges
(ii) emphasize inter- and trans-disciplinary research and science
(iii) enhance problem-solving skills in education that are pertinent to the societal goals
(iv) establish networks that can tap into varied expertise around the campus to share resources efficiently and meaningfully, and
(v) 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 toward 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) and Kyoto Declaration (UNESCO, 1990), 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.

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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 1). Table 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.

## 2. D-SiM – sustainability assessment model

Waheed et al. (in review) have earlier proposed a **D**PSEEA-**S**ustainability **i**ndex **M**odel (D-SiM), which was applied to higher education institutions (universities). 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

**Table 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 | × | × | × | × | × | × | × | × | | × | |
| Halifax declaration | | | × | | | | | | | | |
| Tallories declaration | | × | × | | | | | | | | |
| **Water conservation** | | | | | | | | | | | |
| Water related building retrofit | × | × | × | × | | × | × | × | × | × | × |
| Drinking and bottled water | × | | | | | | | | | | |
| **Climate change and energy** | | | | | | | | | | | |
| Construction changes | × | × | × | | × | × | × | × | × | | × |
| Building retrofit for energy | × | × | × | × | × | × | × | × | × | | × |
| **Transportation** | | | | | | | | | | | |
| Carpool | × | × | × | × | × | × | × | × | × | × | × |
| Reduced transit fair/u-pass | × | × | × | × | × | × | × | × | × | | |
| Pedestrian friendly campus | | | | | × | | | | | × | |
| Guaranteed ride home | | | | × | | | | | | | |
| Hybrid fleet | | × | | × | × | × | × | × | × | | |
| Bike ride or repair | × | × | × | | | × | × | × | × | × | × |
| **Food and recycling** | | | | | | | | | | | |
| Trayless cafeteria or biodegradable containers | × | | × | | | | | | | | |
| Paperless theses | × | | | | | | | × | | | |
| Computer reuse and recycling | × | × | × | × | × | × | × | × | × | | × |
| Farm to table program | | × | × | × | | × | × | | × | | × |
| Organic waste collection | | | × | × | | | × | | × | | |
| Procurement and waste programs | | × | × | | | | | × | × | × | × |
| Invessel composter/composting | × | × | × | × | × | × | × | × | × | | × |
| **Curriculum initiatives** | × | × | | × | × | × | × | × | × | | |
| **Green building** | | | | | | | | | | | |
| Many Leeds silver and gold certified buildings | | × | | × | × | × | × | × | | | |
| Leeds certification for future buildings | × | × | × | × | × | × | × | × | | | × |
| **Student involvement** | × | × | × | × | × | × | × | × | × | × | × |
| **Investment priorities** | | × | | × | × | × | | | × | × | × |
| **Annual Report** | | × | | | | | | | | | |

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). Fig. 1 illustrates DPSEEA for higher education institutions.

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) (Fig. 2). 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 2 are connected hierarchically through causal relationships that finally lead to the quantitative assessment of sustainability.

### 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 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. Some include UBC (2007a,b), Rodriguez et al. (2002), Lozano (2006b), Cole (2003), Shriberg (2002), Viebahn (2002), Clarke and Kouri (2009), Lukman et al. (2010), Goognough et al. (2009), and Evangelinos et al. (2009).

The indicators were validated by comparing them with Global Reporting Indicators (GRI 2006) for universities and its modification provided by Lozano (2006b). 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. 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 2).

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

(i) positive causality refers to the connection between quality and sustainability, i.e., when quality improves sustainability and vice versa, and

(ii) negative causality refers to the connection between pollution and sustainability, therefore an increase in pollution reduces the sustainability and vice versa.

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 an increase in $D_1$ (global and local research and development trends) and $D_7$ (education in sustainability trends, which is combination of courses and curricula, research (basic and applied), and community outreach) decreases the

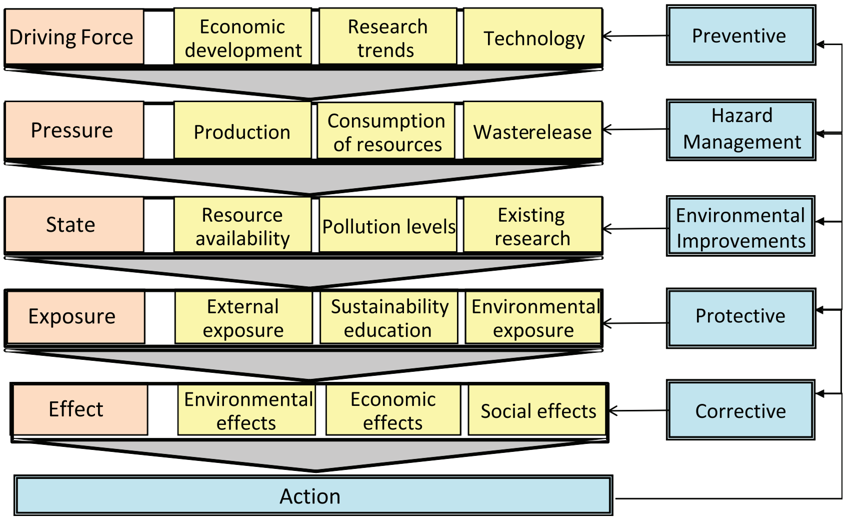


**Fig. 1.** Driving force–pressure–state–exposure–effect (DPSEEA) framework.

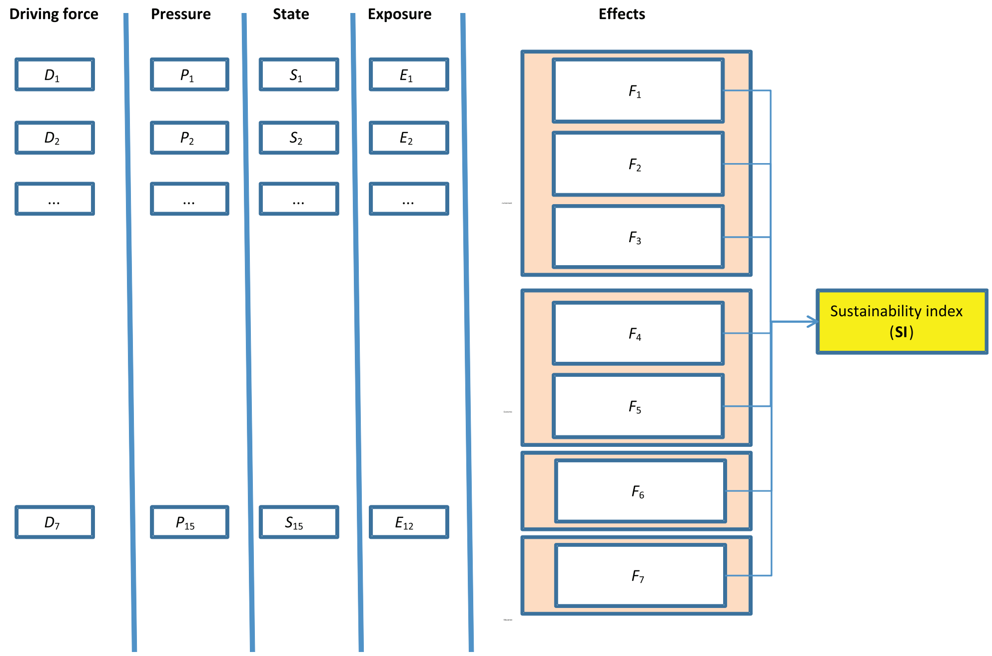


**Fig. 2.** D-SiM model.

production of greenhouse gases. Similarly, the driving forces institutional enhancement rate ($D_2$), annual energy consumption rate ($D_3$), and financial and economic growth rate ($D_4$) increase the production of greenhouse gases ($P_1$).

**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.

**Step 4** defines the input values for driving force indicators. The linguistic scale for activation levels of sustainability indicators at all stages is 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.

$$A_j = \frac{[w_1X_1 + w_2X_2 \ldots + w_nX_n]}{(w_1 + w_2 \ldots + w_n)} \tag{1}$$

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

$$\mathrm{SI} = T_1\frac{[A_{\mathrm{env}}w_{\mathrm{env}} + A_{\mathrm{econ}}w_{\mathrm{eco}} + A_{\mathrm{soc}}w_{\mathrm{soc}} + A_{\mathrm{edu}}w_{\mathrm{edu}}]}{(w_{\mathrm{env}} + w_{\mathrm{eco}} + w_{\mathrm{soc}} + w_{\mathrm{edu}})} + T_2 \tag{2}$$

where

$A_{\mathrm{env}}$ is the estimated activation level of environmental *effects*;
$A_{\mathrm{econ}}$ is the estimated activation level of economic *effects*;
$A_{\mathrm{soc}}$ is the estimated activation level of social *effects*;
$A_{\mathrm{edu}}$ 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];
$w_{\mathrm{env}}$ is the causal weight for environmental *effects*;
$w_{\mathrm{eco}}$ is the causal weight for economic *effects*;
$w_{\mathrm{soc}}$ is the causal weight for social *effects*;
$w_{\mathrm{edu}}$ 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

**Table 2**
Proposed indicators for sustainability assessment of higher education institutions.

| 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 labor 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 | | ▨ | | |
| | $S_{10}$ | Labor 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 centers | | | | ▨ |
| | $S_{15}$ | 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 | | | | ▨ |

**Table 3**
Causality weights in D-SiM.

| Pressure ($P$) | State ($S$) | Exposure ($E$) | Effect ($F$) | Categories | Sustainability index |
|---|---|---|---|---|---|
| $P_1 = \{D_1-, D_2+, D_3+, D_4+, D_7-\}$ | $S_1 = \{P_1+, P_2+, P_5+, P_{15}-\}$ | $E_1 = \{S_1+, S_2+, S_3+, S_4+, S_5+, S_{15}-\}$ | $F_1 = \{E_1+, E_2+, E_3+, E_4+, E_5+, E_{12}-\}$ | Env = $\{F_1, F_2, F_3\}$<br>wenv = {0.8, 0.2, 0.4} | SI = {Env+, Eco+, Soc+, Edu+}<br>$w_{\mathrm{SI}}$ = {0.6, 0.4,0.2, 0.8} |
| $wp1 = \{0.4, 0.4, 1, 0.6, 0.4\}$ | $ws1 = \{1, 0.8, 0.4, 0.6\}$ | $we1 = \{0.6, 0.2, 0.2, 1, 0.8, 0.2\}$ | $wf1 = \{0.4, 0.8, 0.6, 0.4, 0.2, 0.2\}$ | Eco = $\{F_4, F_5\}$<br>weco = {0.4, 0.6} | |
| $P_2 = \{\mathrm{D}_1-, \mathrm{D}_2+, \mathrm{D}_4, \mathrm{D}_7-\}$ | $S_2 = \{P_3+, P_{15}-\}$ | $E_2 = \{S_3+, S_{15}-\}$ | $F_2 = \{E_3+, E_4+, E_6+, E_{12}-\}$ | Soc = $\{F_6\}$<br>wsoc = {0.2} | |
| $wp2 = \{0.2, 0.2, 1, 0.4\}$ | $ws2 = \{1, 0.4\}$ | $we2 = \{0.4, 0.2\}$ | $wf2 = \{0.8, 0.6, 0.8, 0.2\}$ | Edu = $\{F_7\}$ | |
| $P_3 = \{D_1-, D_2, D_3+, D_4+, D_6-, D^7-\}$ | $S_3 = \{P_4+, P_{14}, P_{15}+\}$ | $E_3 = \{S_5+, S_{15}+\}$ | $F_3 = \{E_1+, E_{12}-\}$ | wedu = {1} | |
| $wp3 = \{0.2, 0.4, 1, 0.6, 0.2, 0.6\}$ | $ws3 = \{1, 0.4, 0.4\}$ | $we3 = \{0.8, 0.4\}$ | $wf3 = \{0.6, 0.4\}$ | | |
| $P_4 = \{D_1+, D_2-, D_3-, D_4-, D_7+\}$ | $S_4 = \{P_5+, P_{15}-\}$ | $E_4 = \{S_5+, S_6+, S_{15}-\}$ | $F_4 = \{E_7\}$ | | |
| $wp4 = \{0.8, 0.2, 0.4, 0.2, 1.0\}$ | $ws4 = \{1, 0.2\}$ | $we4 = \{0.2, 0.2, 0.2\}$ | $wf4 = \{1\}$ | | |
| $P_5 = \{D_1-, D_2+, D_4+, D_3+, D_7-\}$ | $S_5 = \{P_6+\}$ | $E_5 = \{S_4+\}$ | $F_5 = \{E_8\}$ | | |
| $wp5 = \{0.6, 0.2, 1, 0.4, 0.6\}$ | $ws5 = \{1\}$ | $we5 = \{1\}$ | $wf5 = \{1\}$ | | |
| $P_6 = \{D_1-, D_2+, D_3+, D_5+, D_7-\}$ | $S_6 = \{P_7+\}$ | $E_6 = \{S_4+, S_7+, S_{14}-, S_{15}-\}$ | $F6 = \{E_9+\}$ | | |
| $wp6 = \{0.6, 1,0.2, 0.8, 0.8\}$ | $ws6 = \{1\}$ | $we6 = \{1, 1, 0.2, 0.2\}$ | $wf6 = \{1\}$ | | |
| $P_7 = \{D_2+, D_3+, D_4+, D_7-\}$ | $S_7 = \{P_7+\}$ | $E_7 = \{S_8+\}$ | $F_7 = \{E_{10}+, E_{11}+, E_{12}+\}$ | | |
| $wp7 = \{1,0.6,0.8, 0.6\}$ | $ws7 = \{0.6\}$ | $we7 = \{1\}$ | $wf7 = \{0.6, 1.0, 0.8\}$ | | |
| $P_8 = \{D_1+, D_2+, D_4+, D_7+\}$ | $S_8 = \{P_8+, P_9+\}$ | $E_8 = \{\mathrm{S9}+\}$ | | | |
| $wp8 = \{0.4, 0.2, 1, 0.2\}$ | $ws8 = \{0.8, 0.6\}$ | $we8 = \{1\}$ | | | |
| $P_9 = \{D_1+, D_2+, D_3+, D_4+, D_5+, D_7-\}$ | $S_9 = \{P_9+\}$ | $E_9 = \{S_{10}+, S_{11}+, S_{12}+\}$ | | | |
| $wp9 = \{0.8, 0.4, 0.6, 1, 0.2, 0.4\}$ | $ws9 = \{1\}$ | $we9 = \{0.4, 0.8, 0.6\}$ | | | |
| $P_{10} = \{D_5+, D_6+\}$ | $S_{10} = \{P_{10}-\}$ | $E_{10} = \{S_{13}+, S_{14}+\}$ | | | |
| $wp10 = \{1, 0.8\}$ | $ws10 = \{1\}$ | $we10 = \{1, 0.4\}$ | | | |
| $P_{11} = \{D_6+\}$ | $S_{11} = \{P_{11}+\}$ | $E_{11} = \{S_{13}+, S_{14}+\}$ | | | |
| $wp11 = \{1\}$ | $ws11 = \{1\}$ | $we11 = \{0.6, 0.8\}$ | | | |
| $P_{12} = \{D_5+, D_6+, D_7-\}$ | $S_{12} = \{P_{12}+\}$ | $E_{12} = \{S_{15}+\}$ | | | |
| $wp12 = \{0.2, 0.8, 1\}$ | $ws12 = \{1\}$ | $we12 = \{1\}$ | | | |
| $P_{13} = \{D_7+\}$ | $S_{13} = \{P_{13}+\}$ | | | | |
| $wp13 = \{1\}$ | $ws13 = \{1\}$ | | | | |
| $P_{14} = \{D_1+, D_2+, D_7+\}$ | $S_{14} = \{P_{14}+\}$ | | | | |
| $wp14 = \{0.8, 0.4, 1\}$ | $ws14 = \{1\}$ | | | | |
| $P_{15} = \{\mathrm{D}_1+, \mathrm{D}_7+\}$ | $S_{15} = \{P_{15}+\}$ | | | | |
| $wp_{15} = \{0.8, 1\}$ | $ws15 = \{1\}$ | | | | |

sustainability index before normalization. Later, these values are used to normalize the results as following:

$$\mathrm{SI} = (\mathrm{SI}' - \mathrm{Min})/(\mathrm{Max} - \mathrm{Min})$$

$$\mathrm{SI} = T_1 * (SI') - T_2$$

where

$\mathrm{SI}'$ = Sustainability index (un-normalized)
$T_1 = 1/(\mathrm{Max} - \mathrm{Min})$
$T_2 = \mathrm{Min}/(\mathrm{Max} - \mathrm{Min})$

A brief demonstration of D-SiM is provided in Appendix A.

### 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., in review). 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 paper 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 modeling. Section 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 5. Finally, conclusions are presented in Section 6. For sake of completeness and convenience of the readers, a brief discussion on an earlier developed model D-SiM is provided in Appendix A.

## 3. Uncertainty modeling

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., 2004a,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.

### 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 $\mu_x$. A fuzzy number describes the relationship between an uncertain quantity $x$ and a membership function, which ranges between 0 and 1, $\mu: R \to [0,1] \subseteq R$. Fig. 3 shows a triangular fuzzy number (TFN). The *membership function* $\mu$ 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).

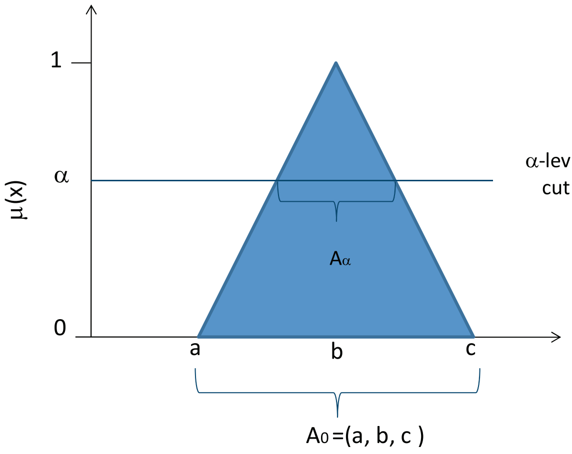


**Fig. 3.** Triangular fuzzy number (TFN).

### 3.2. Fuzzy arithmetic

One important feature of fuzzy numbers (sets) is the concept of $\alpha$-cut. The $\alpha$-cut of a fuzzy set is a crisp set $A_\alpha$ 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 $\alpha$-cut, i.e., $A_\alpha = \{x|\mu_x \geq \alpha\}$ (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 $\alpha$-cut, and
2) $\alpha$-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., 2004b) in fuzzy arithmetic.

Fuzzy numbers can represent vagueness or imprecision in the parameter(s). 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. 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 Fig. 4. The following procedural steps are taken to develop uD-SiM.

### 4.1. Identification of indicators

Table 2 provides a comprehensive list of indicators for education, environment, social, and economic dimensions for driving forces, pressures, state, exposure, and effect. Interested readers are referred to Waheed et al. (in review) for more detailed discussion on these indicators. 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 and economic growth rate help decision-makers at this level in setting policies and for examination of the root cause problems.

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.

### 4.2. 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 S1 (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 S1. Using the same principles, connections are established between *pressures* and *states*, *states* and *exposures*, and *exposures* and *effects*.

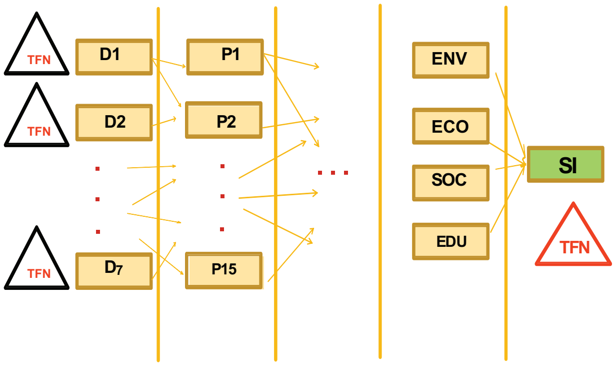


**Fig. 4.** Structure of proposed model.

### 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 Mikroudis, 2000) have been developed, including direct assignment, Delphi survey, pair-wise comparison, eigenvector method, and linear programming. In this paper, 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 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.

### 4.4. Activating driving force based on fuzzy input values

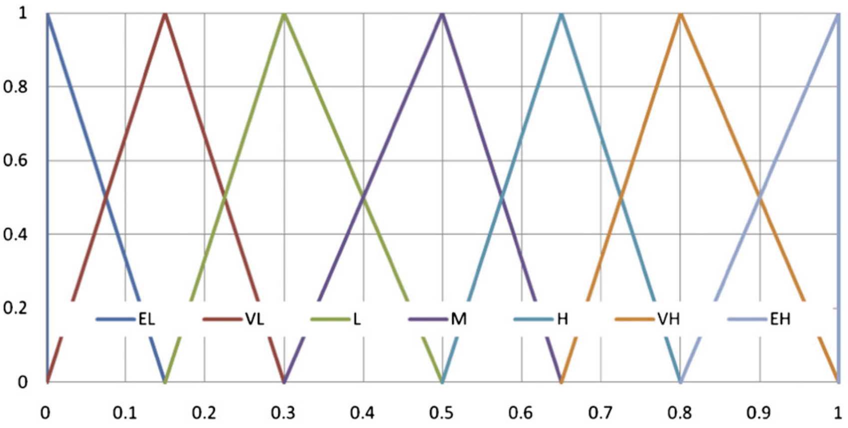
The main difference between the D-SiM and uD-SiM is that in uD-SiM the input values defined for *driving force* indicators are triangular fuzzy numbers (TFNs). Fig. 5 provides a linguistic interpretation of activation levels for sustainability indicators. These input indicators can be "measured" or heuristically 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 paper, 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 (Fig. 5). These fuzzy numbers will be able to propagate uncertainties throughout the structure of the uD-SiM.

### 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

**Table 4**
Linguistic meaning of causality weights.

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



| Linguistic descriptor | Fuzzy activation level ($\overline{A}$) |
|---|---|
| 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) |

**Fig. 5.** Triangular fuzzy numbers.

and evaluating the activation level of dependent indicators. 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:

$$\overline{A}_j = \frac{[w_1\overline{X}_1 + w_2\overline{X}_2 \ldots + w_n\overline{X}_n]}{(w_1 + w_2 \ldots + w_n)} \tag{3}$$

where $\overline{A}_j$ is the estimated fuzzy activation level of a dependent indicator $j$, and $\overline{X}$ 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 ($\overline{\mathrm{SI}}$) can be calculated using following formulation:

$$\overline{\mathrm{SI}} = \frac{[\overline{A}_{\mathrm{env}} w_{\mathrm{env}} + \overline{A}_{\mathrm{econ}} w_{\mathrm{econ}} + \overline{A}_{\mathrm{soc}} w_{\mathrm{soc}} + \overline{A}_{\mathrm{edu}} w_{\mathrm{edu}}]}{(w_{\mathrm{env}} + w_{\mathrm{econ}} + w_{\mathrm{soc}} + w_{\mathrm{edu}})} + T_2 \tag{4}$$

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

### 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 $\overline{\mathrm{SI}}$ 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 paper, Yager's centroid index method (Yager, 1980) is used. The centroid index is a geometric center ($\mathrm{SI_o}$) of the fuzzy number $\overline{\mathrm{SI}}$, 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:

$$\begin{aligned}\mathrm{SI_o} &= \frac{\int_0^1 \mathrm{SI}_i \mu_{\mathrm{SI}_i}}{\int_0^1 \mu_{\mathrm{SI}_i}} \\ &= \frac{(b-a)\left[\left(a + \frac{2}{3}(b-a)\right)\right] + (c-b)\left[\left(b + \frac{1}{3}(c-b)\right)\right]}{(b-a) + (c-b)}\end{aligned} \tag{5}$$

where $\mathrm{SI}_i$ 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 $\mu_{\mathrm{SI}_i}$ for a given scenario. The value of $\mathrm{SI}_o$ may be seen as the weighted mean value of the TFN of the sustainability index ($\overline{\mathrm{SI}}$).

## 5. Results and discussion

### 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 5). 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 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 6 and Fig. 6). 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 6 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.

**Table 6**
Comparison of various trials.

| Trials | Sustainability categories | | | | TFN for SI | | | %Δ[b] | Uncertainty $(c-a)$[c] |
|---|---|---|---|---|---|---|---|---|---|
| | Env. | Eco. | Soc. | Edu. | Min. (***a***) | MLV (***b***) | Max. (***c***) | | |
| 1 | 0.6 | 0.2 | 0.4 | 0.8 | 0.63 | 0.78 | 0.86 | 0[a] | 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 |

[a] Base value.
[b] Uncertainty = Max. − Min. = $(c-a)$
[c] $\%\Delta = \frac{|\text{Base value}-\text{Trial value}|}{(\text{Base value})} \times 100$

**Table 5**
Basic data input in uD-SiM for trial 1.

| Driving force ($D_k$) | Linguistic descriptor | Fuzzy activation level ($\bar{A}$) |
|---|---|---|
| $D_1$ | Very high | (0.65, 0.8, 1) |
| $D_2$ | Low | (0.15, 0.3, 0.5) |
| $D_3$ | Medium | (0.3, 0.5, 0.65) |
| $D_4$ | Medium | (0.3, 0.5, 0.65) |
| $D_5$ | Medium | (0.3, 0.5, 0.65) |
| $D_6$ | High | (0.5, 0.65, 0.8) |
| $D_7$ | Extremely high | (0.8, 1, 1) |

### 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:

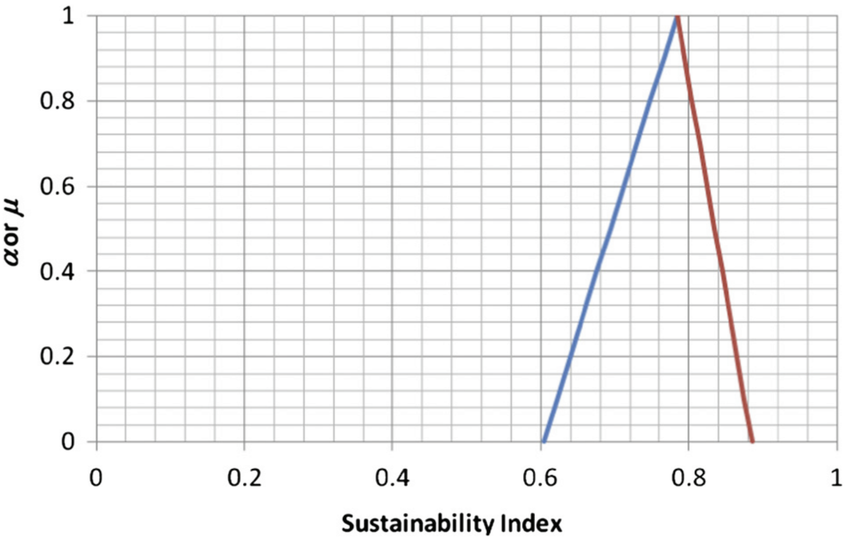
- SA can identify the input parameters that have the most influence on model output;
- SA can identify the processes that have greatest influence on model output; and
- SA can quantify the change in output caused by uncertainty and variability in the values of input parameters.

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 paper, 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:

$$\text{PC}_j = 100 \cdot \frac{\rho_j |\rho_j|}{\sum_{i=1}^{N} \rho_i^2} \tag{6}$$



| α | $(\overline{SI})$min | $(\overline{SI})$max |
|---|---|---|
| 0 | 0.603 | 0.885 |
| 0.1 | 0.622 | 0.875 |
| 0.2 | 0.640 | 0.865 |
| 0.3 | 0.658 | 0.855 |
| 0.4 | 0.676 | 0.845 |
| 0.5 | 0.694 | 0.835 |
| 0.6 | 0.712 | 0.824 |
| 0.7 | 0.730 | 0.814 |
| 0.8 | 0.748 | 0.804 |
| 0.9 | 0.766 | 0.794 |
| 1 | 0.784 | 0.784 |

**Fig. 6.** Triangular fuzzy numbers (TFNs) for sustainability index (base trial).

where $\rho_j$ is the Spearman's Rank Correlation for the $j$th input. We use $\rho_j\ |\rho_j|$ rather than $\rho_j^2$ to preserve the sign of $\rho_j$. Using the absolute values of percent contribution for driving forces, (where the input factors are $D_k$ ($k = 1, 2, \ldots, 7$) 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 $\overline{SI}$ (shown as a base case in Table 7 and Fig. 7). 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

**Table 7**
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 |

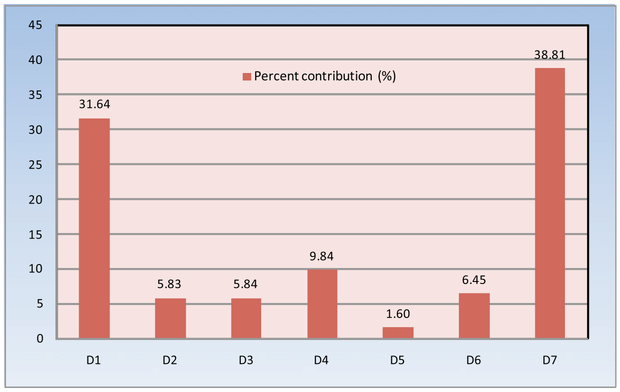


**Fig. 7.** Percent contribution of driving forces toward sustainability index (SI).

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., in review). However in this paper, 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.

## 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 paper, uncertainty is not considered in the weights and “action” stage of the DPSEEA framework. The authors of this paper are currently working on incorporating the “action” stage of the DPSEEA framework in uD-SiM. This will promote more comprehensive decision-making related to HEI sustainability and improve the understanding of complex connections among decision actions and their impacts on various sustainability indicators.

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## Appendix A

In D-SiM, the negative and positive causality weights are defined qualitatively as follows: [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−)].

### A1 Demonstration of D-SiM

Using the assigned weights (Table 3) and particular set of input values of driving forces {$D_1$, $D_2$… $D_7$} the model estimates the sustainability index (SI) value. The assumed valued of driving forces are as shown in Table A1 as $A_D$. These driving forces trigger pressures, e.g., the resulting activation level for $P_1$ is 0.357. The D-SiM calculates the activation for each dependent sustainability indicator in each stage based on assigned causality weights and values of activation of indicators in the previous stage. After estimating the *effects* indicators (last stage of DPSEEA), the *sustainability index* is calculated (Equation (2)) from sustainability categories — environmental, economic, social, and education. For the selected input of driving forces, the weights are assigned to these categories as 0.4, 0.6, 0.6 and 0.8, indicating that educational sustainability is the most important category followed by economic and social. The estimated sustainability index (SI) is 0.87. If the driving force $D_1$ reduces to 0.4, the SI reduces to 0.787. The effect of $D_7$ is even more profound, i.e., if it is reduced to 0.4, the SI reduces to 0.658. It can be observed that an increase in the input values from $D_2$ to $D_6$ results in higher value of SI.

### A2 Empirical model

To better understand 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. The response (SI) 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 A2.

**Table A1**
Activation levels ($A$) of sustainability indicators — an example.

| $j$ | $A_D$ | $A_P$ | $A_S$ | $A_E$ | $A_F$ | $A_{Sus}$ | SI |
|---|---|---|---|---|---|---|---|
| 1 | 0.9 | 0.357 | 0.232 | 0.247 | 0.248 | 0.205 | 0.87 |
| 2 | 0.4 | 0.333 | 0.263 | 0.232 | 0.269 | 0.513 | |
| 3 | 0.5 | 0.350 | 0.010 | 0.300 | 0.086 | 0.119 | |
| 4 | 0.5 | 0.823 | 0.257 | 0.251 | 0.586 | 0.711 | |
| 5 | 0.5 | 0.300 | 0.300 | 0.200 | 0.402 | | |
| 6 | 0.65 | 0.253 | 0.200 | 0.212 | 0.594 | | |
| 7 | 1 | 0.200 | 0.200 | 0.586 | 0.711 | | |
| 8 | | 0.633 | 0.586 | 0.402 | | | |
| 9 | | 0.524 | 0.563 | 0.594 | | | |
| 10 | | 0.567 | 0.567 | 0.345 | | | |
| 11 | | 0.650 | 0.650 | 0.855 | | | |
| 12 | | 0.310 | 0.690 | 0.804 | | | |
| 13 | | 1.000 | 1.000 | | | | |
| 14 | | 0.782 | 0.746 | | | | |
| 15 | | 0.956 | 0.804 | | | | |

**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: estimated sustainability index.

**Table A2**
Percent contribution of main factors on sustainability index (SI).

| $D_k$ | % Contribution |
|---|---|
| $D_1$ | 0.348 |
| $D_2$ | 0.805 |
| $D_3$ | 2.210 |
| $D_4$ | 10.339 |
| $D_5$ | 3.006 |
| $D_6$ | 11.607 |
| $D_7$ | 71.686 |

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