A GREEN HOME DECISION-MAKING TOOL:

SUSTAINABILITY WEIGHTING ASSESSMENT FOR HOMEOWNERS (SWAHO)

by

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Abstract

Homeowners, the largest group of stakeholder in the building sector, are often under-served and suffer from difficulty in pursuing a green home. Few sustainability assessments and decision-making tools were created for nonprofessionals. This research adopted the Design Science method to create an integrated path for green renovation to make it easy for homeowners to make sustainable renovation decisions.

The author proposes a new path of green renovation, where a tool named SWAHO (Sustainability Weighting Assessment for Homeowners) plays a central role. SWAHO is supposed to enable tradeoffs among renovation actions and renovation products based on the homeowner's perception of sustainability. In the conceptual model, SWAHO could integrate all the tasks in green renovations, from decision-making on renovation actions to ordering products on e-commerce websites. In addition, the author developed a prototype tool that enables decision-making on renovation actions to demonstrate the concept of SWAHO. A list of 48 renovation actions and a list of 12 sustainability criteria were incorporated into the prototype tool after a thorough literature review and practice review. The knapsack problem was used as the mathematical model for SWAHO. Weighting scheme and 5-star rating were used for scoring.

A user evaluation consisting of surveys and meetings reported very positive feedback on the concept of SWAHO. Testers also provided many suggestions on the user interface design. A self-evaluation on 144 scenarios showed that all the results of SWAHO were reasonable, meaning that the mathematical model of SWAHO was effective. The two evaluations reveal that the proof-of-concept SWAHO is a good approach for green renovation.

Preface

The user evaluation in Chapter 5 was approved by the Behavioral Research Ethics Board of the University of British Columbia, Certificate Number H16-00555 and Project Title "A Green Home Decision-Making Tool: Sustainability Weighting Assessment for Homeowners (SWAHO)".

I initiated this project, conducted the research, and wrote the whole thesis by myself, under the supervision of Dr. Thomas M. Froese.

This research was not previously published in whole or in part.

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List of Abbreviations

AHP	Analytic Hierarchy Process
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BEES	Building for Environmental and Economic Sustainability
BIM	Building Information Model
BREEAM	Building Research Establishment Environmental Assessment Methodology
DGNB	German Green Building Council
DM	Decision-making
EIA	Environmental Impact Assessment
EPD	Environmental Product Declaration
HVAC	Heating, Ventilation and Air Conditioning
IMPACT	Integrated Material Profile and Costing Tool
ISO	The International Organization for Standardization
LCA	Life-Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
MADM	Multi-Attribute Decision-Making
MCDM	Multi-Criteria Decision-Making
MODM	Multi-Objective Decision-Making
SWAHO	Sustainability Weighting Assessment for Homeowners
UBC	The University Of British Columbia
VBA	Visual Basic for Applications
VOC	Volatile Organic Compounds

Acknowledgements

This thesis is the culmination of a fulfilling journey. I could never express enough thanks to those who helped me through this exciting project.

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Special thanks are owed to my parents for their love, support, and inspirations, throughout my years of education, both morally and financially. I am also grateful to my boyfriend for his consideration and support in the long-distance relationship.

To Jun and Caiting

Chapter 1: Introduction

1.1 Problem Background

The desire for green homes is increasing as sustainable development becomes a "basic" requirement nowadays. The efforts of pursuing green homes involve two main groups of people, the professionals (developers, designers, house builders, and so on) and nonprofessionals (homeowners and occupants, with homeowners referring to both in this dissertation). However, both professionals and homeowners are facing challenges when pursuing green housing.

Below is an example of the challenge faced by developers. An innovative development company was trying to provide low-cost energy-efficient houses. They built a single-family house on the campus of the University of British Columbia (UBC) in late 2015. The envelope, lighting, and heating, ventilation and air conditioning (HVAC) system design were off-the-shelf choices. A life-cycle environmental assessment of the house shows that the envelope and HVAC system are not the most environmentally friendly choices among the alternatives [1]. This indicates that without environmental assessment, one can hardly make the most sustainable decisions. The problem becomes even more complex when "sustainable" means not only environmental but also social and economic. Developers usually have multiple goals in mind, such as low cost, energy-efficiency, and occupants' satisfaction. Tradeoffs between the goals are difficult without a sustainability assessment.

The challenges faced by homeowners are easier to understand. Imagine you live in an older home. Windows are leaky, the furnace sometimes shuts down, and wall coverings are peeling off. The house needs a renovation. Besides the must-dos, such as sealing doors and windows and

painting the walls, you want to take advantage of this renovation chance to create a greener home. For example, you are interested in purchasing energy-efficient appliances, installing advanced heating, cooling and ventilation system, and others things. Moreover, your family would like to have a more comfortable indoor environment, but they do not value much to other aspects such as aesthetics. With a limited budget in your pocket and all the ideas floating around, you are standing in a fog of uncertainty and have no idea where to start.

It is obvious that without professional concepts and ideas, homeowners are facing more difficulties than professionals are. Homeowners have limited knowledge of available green practices and techniques and limited knowledge of the important aspects of a green home. There does not exist a systematical scientific sustainability assessment tool that can help them to conduct a sustainability-cost trade-off, especially when they have a limited budget but a number of interests in mind. Most of the time, people make off-the-shelf decisions that might not provide the sustainability advantages that they had hoped.

To conclude, a problem exists both in practice and in knowledge. The practical problem is the gap between the homeowner's goal and their knowledge in pursuing a green renovation. The knowledge question is the lack of knowledge about the relation between sustainable actions or products and sustainability objectives—that is, the lack of a mathematical model to specify the vague concept of home sustainability and to promote optimization given a number of conflicting sustainability objectives and a large number of alternative solutions.

Up to now, most of the sustainability assessments and decision-making tools have been created for professionals. Few efforts have been made for nonprofessionals who live in the homes.

This dissertation will focus on solving the difficulty of sustainable decision-making in pursuing a green renovation for homeowners.

1.2 Objectives

The ultimate goal is to increase the performance of buildings by encouraging sustainable decision-making by homeowners when selecting renovation actions and products. In this thesis, "actions" are home improvement activities that may range from purchasing a major appliance (e.g., purchasing a washing machine) to carrying out a major home repair or renovation (e.g., replacing windows), whereas "products" are the specific make and model of the major equipment or components used. Research has shown that one of the significant contributors to the energy performance gap of buildings is occupant behavior [2], [3]. Homeowners are the occupants and they are the ones with motivations to reduce the performance gap. It is also suggested that enhancing energy performance by renovation is an environmentally sound action for houses [4]. Therefore, this research focuses on renovation conducted by homeowners.

The specific goal of this research is to reduce the difficulty of decision-making on green renovations. This is based on the assumption that the increase of convenience will encourage homeowners to pursue a green home. Specific objectives include:

1. To investigate current resources for sustainable decision-making for green homes;
2. To design a conceptual framework to simplify the process of green renovations;
3. To demonstrate the framework by developing a prototype tool for homeowners to support their decision-making on green renovations;
4. To evaluate the framework and the tool.

1.3 Proposed Solution – SWAHO

Figure 1-1 illustrates the three paths to pursue green renovation. Path 1 and 2 are current paths, while Path 3 is the proposed new path to make green renovation more convenient.

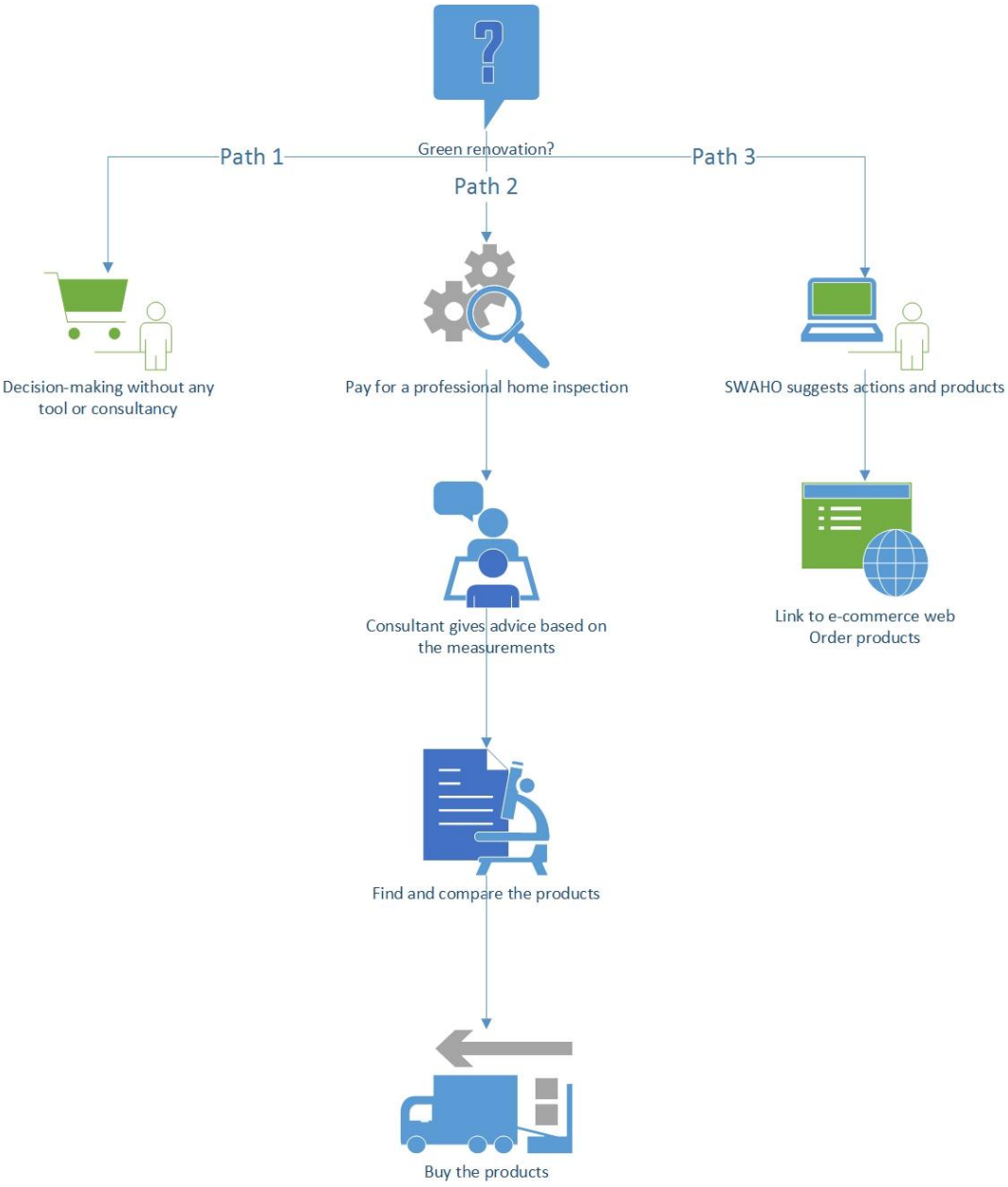


Figure 1-1 Three paths of green renovation

Path 1: Unaided Decision-making

Homeowners may decide renovation actions and products without any professional decision-making tool or consultancy.

Path 2: Professional Consultancy

In some situations, homeowners may first pay for a home inspection, which will identify the problems of the home, and then bring the report to a professional green home consultant, take their advice, and then compare and buy products themselves.

Path 3: Use SWAHO

This thesis proposes a new path to pursue green renovations that uses a decision-support tool called "Sustainability Weighting Assessment for Homeowners" or SWAHO. This sustainability assessment tool provides suggestions on renovation actions and products according to the homeowner's budget and priorities on sustainability criteria. Homeowners can use SWAHO on their computer or laptop to assess and select green renovation actions and products.

Figure 1-2 illustrates the comparison between the three paths. SWAHO, is designed to require less time and effort than the other two paths, while providing better technical decision-making than an unaided approach (though not as much as a professional consultant). The proposed path will be introduced with more details in Chapter 3.

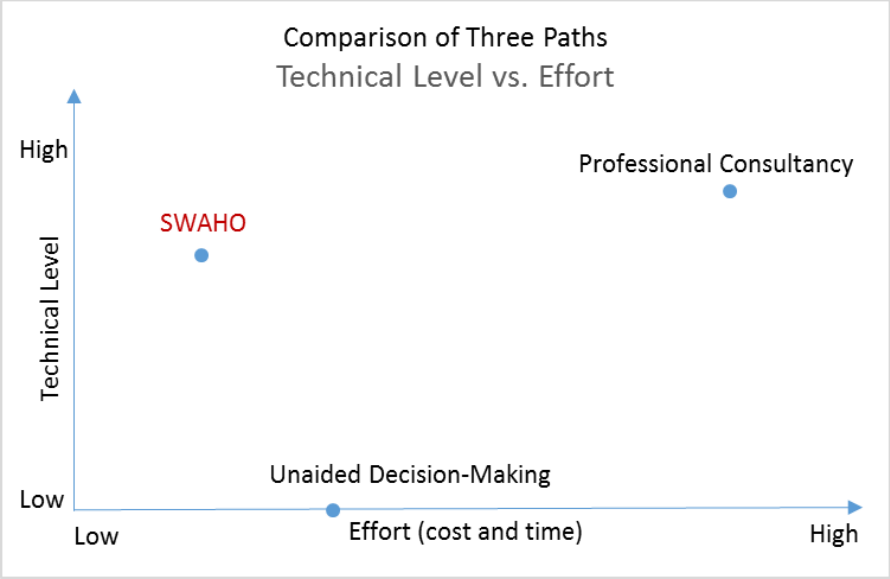


Figure 1-2 Comparison of three paths

1.4 Research Scope

The SWAHO tool plays a central role in the proposed path. Theoretically, SWAHO is able to link to e-commerce systems. For instance, SWAHO could, in principle, search relevant products online and extract the products' information; homeowners could then select the renovation solutions within SWAHO and order the required products and services directly through linked e-commerce services. This link is important because the e-commerce potential creates a business case to provide revenue to develop and support the SWAHO tool. However, to limit the scope of this study, the dissertation will not focus on the link from SWAHO to the e-commerce system.

A conceptual model of SWAHO was fully designed, including two decision-making phases. "Decision-making 1" phase suggests renovation actions, while "Decision-making 2" phase suggests renovation products. Only "Decision-making 1" phase was developed into a prototype tool since "Decision-making 2" phase requires the link to e-commerce systems. However, a mock-

up of "Decision-making 2" was included in the prototype tool to demonstrate the functions. Figure 1-3 shows the research scope and tool development scope.

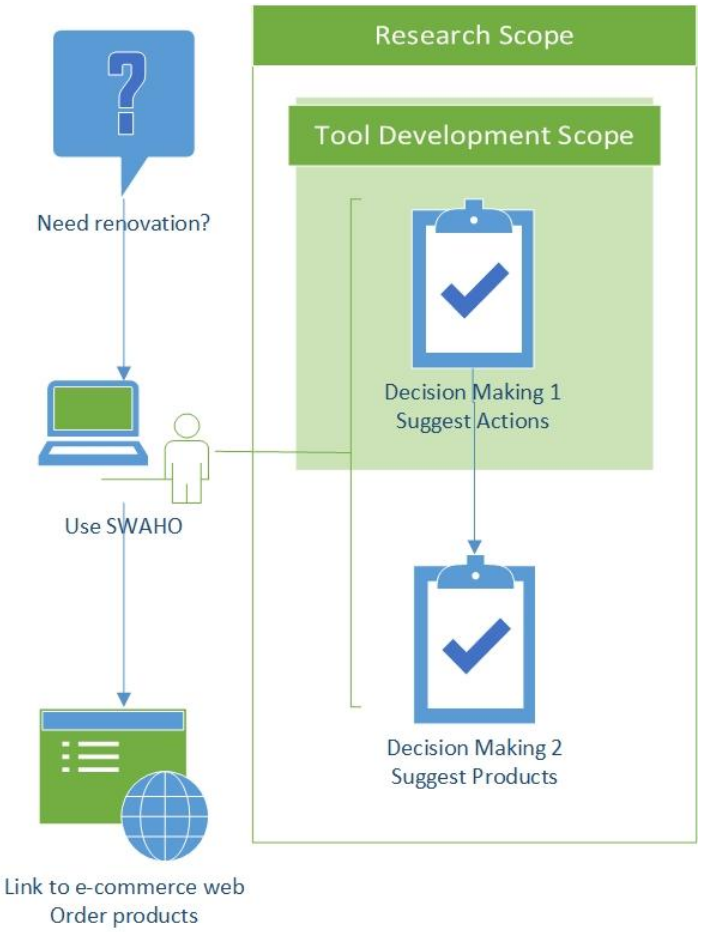


Figure 1-3 Research scope

Application Scope of the Prototype Tool

The idea of an integrated tool for green renovations is applicable anywhere in the world. However, as the context of homes varies, the alternative renovation actions, products, their costs and their influences on sustainability criteria vary significantly. Therefore, although the intent is

to span a broad domain across the building industry, the prototype tool of SWAHO was developed for a particular type of house in Vancouver, Canada, as an example for the concept (see Table 1-1).

Table 1-1 Application scope of SWAHO

	Ideal application	**Application in this thesis**
City, Country	Anywhere	Vancouver, Canada
Type of home	Any	House
Location	Anywhere	Quiet Residential Area
Stage of home	Newly purchased or Old	Old
Climate type	Any	Maritime climate
House Size	Adjustable	2000 square feet, 2-storey

1.5 Research Questions

There are two research questions. The first research question is

How to develop SWAHO?

This relates to what problem SWAHO is trying to solve. People use SWAHO to figure out

What are the greenest renovation choices?

To enable answering this question, several sub-questions should first be solved:

1. What are renovation choices?
    a. What are green renovation actions?
    b. What are green renovation products?

2. What does it mean by “greenest”?
    a. What are the proper sustainability criteria for home renovation?
    b. What indicators can assess the sustainability criteria?
    c. How to reflect different individual goals for renovation?
3. How to relate sustainable choices to renovation goals? What is the mathematical model behind the decision-making?

A literature review has been done to answer the sub-questions. Then, a conceptual model and a prototype tool of SWAHO were developed.

The second research question is

Is SWAHO a good path to support green renovation decision-making?

The word “good” could mean

1. SWAHO has some benefits over existing paths.
2. The renovation solutions suggested by SWAHO are reasonable.

To investigate the second research question, a series of evaluations were conducted.

1.6 Methodology

This research uses a Design Science method.

As opposed to behavioral science, which investigates the reality and makes no change to reality, design science tries to extend the boundary of human and organization capability by creating new artifacts. Design science was introduced in 1963 by Richard Buckminster Fuller who

defined it as a systematic form of designing [5]. Afterwards, the meaning of the term evolved to a scientific study of design.

Hevner et al. provided seven guidelines for design science in Information Systems research [6]. These guidelines also apply to other research domains. Some important guidelines that this research follows are:

1. Design as an artifact: Produce a viable artifact in the form of a construct, a model, a method, or an instantiation;
2. Problem relevance: Develop technology-based solutions to important and relevant business problems;
3. Design evaluation: The utility, quality, and efficacy of the artifact should be demonstrated by evaluation methods;
4. Communication of research: Must be presented effectively to both technology-oriented and management-oriented audiences.

Generally, there are six processes in design science research: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication [7]. This research follows the six steps (Figure 1-4).

1&2. The problem and objectives of the solution were discussed previously.

3. A framework was designed after analyzing the problem and UML (Unified Modeling Language) diagrams were used to illustrate the framework. Microsoft Excel with Macros (Visual Basic for Applications (VBA) code) was used to create a prototype tool because Excel is good at data storage and calculation, and is widely used and

understood. The prototype tool includes a list of renovation actions, a weighting scheme, a sustainability score database for the actions, and an embedded mathematical optimization model.

4. The concept of SWAHO is demonstrated through the prototype tool and the discussions given in this dissertation.
5. Both the concept and the prototype of SWAHO were evaluated by surveys and tests reported in Chapter 5 of this thesis.
6. Communication of the results is through this dissertation and related presentations and planned future publications.

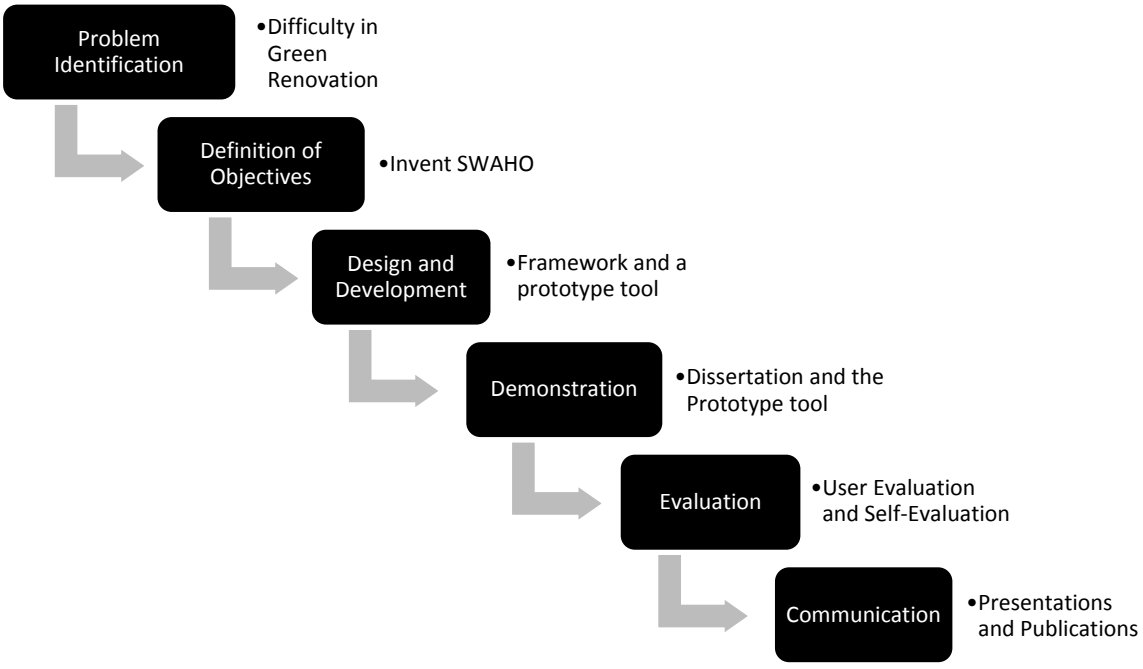


Figure 1-4 Research steps

1.7 Overview of the Dissertation – Reader's Guide

This dissertation has the following organization:

- Chapter 2 provides a thorough review of the main bodies of knowledge that contribute to the development of SWAHO, including the definition of sustainability, available green renovation actions and products, sustainability criteria and indicators, and mathematical mechanisms for decision-making. Discussion is provided along with the review relating to how these resources and theories could help the development of SWAHO.
- Chapter 3 introduces the conceptual model of SWAHO. It first states the problem that SWAHO is intended to solve and explains some important terms in this dissertation. Then it breaks the issue into two decision-making problems and examines the mechanism behind the problems. Last, diagrams are presented to show how SWAHO would solve the two problems.
- Chapter 4 introduces the working prototype of SWAHO developed for the "Decision-making 1" problem. First, screenshots of the prototype are displayed to demonstrate the functions of the tool. Then, the major components of the prototype are further introduced in terms of how they were developed, including the list of actions, the list of criteria, the scoring scheme, and the mathematical model. Last, screenshots of a mock-up sheet of "Decision-making 2" are presented for illustration purpose.
- Chapter 5 describes the evaluation of SWAHO, both for the concept and for the prototype. It consists of a user evaluation, where testers had meetings with the

author to test the prototype and give feedback, and a self-evaluation conducted by the author to investigate the results proposed by the prototype tool. Conclusions and findings of the evaluations are discussed in this chapter.

- Chapter 6 completes the dissertation by summarizing the whole research and discussing the contributions and future work.
- Appendix A contains some screenshots of a video that was used in the user evaluation to introduce SWAHO.
- Appendix B contains the full questionnaire that testers were asked to fill out in the user evaluation.

Chapter 2: Points of Departure

2.1 Sustainability Concept and Assessment Approach

To assess and achieve sustainability, we must first define it. This section reviews the definition of sustainably and provides a specific definition for "green homes". Then, sustainability assessment approaches are discussed to provide a knowledge base for developing a decision-support tool.

People became aware of the environmental cost that they paid for industrial development in last century, and gradually, the concept of "sustainability" arose. From the Merriam-Webster Dictionary, one of the definitions of sustainability is "of or relating to a lifestyle involving the use of sustainable methods". A sustainable method is "able to be used without being completely used up or destroyed, …that do not completely use up or destroy natural resource…" [8]. The most well-known concept of sustainable development is from the *Brundtland report*: "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [9]. The *Brundtland report* presented a two-pillar model for sustainable development – environmental and development concerns. Later, development concerns were separated into social and economic factors, leading to a currently dominant three-pillar model – triple bottom line [10].

Sustainability is a vague concept unless it applies to a specific area. What does "sustainability" mean for a home and for homeowners? As there is no widely accepted definition, the author defines a green home as follows from the triple bottom line—environmental, social, and economic—aspects:

1. Environmental: Minimize the life-cycle environmental impacts of the home;
2. Social: Improve people's health, happiness, and comfort;
3. Economic: Reduce costs and operational expenses.

There are two kinds of approaches for sustainability assessment.

Objectives-led integrated assessment measures the extent to which the implementation of a proposal contributes to this vision. Objectives-led integrated assessment implies that minimization of negative effects is not enough; assessment must encourage positive contributions towards greater sustainability [11]. Strategic environmental assessment is a typical example of objectives-led assessment.

In contrast, Environmental Impact Assessment (EIA)-driven integrated assessment aims to ensure that the triple bottom line impacts of a proposal are acceptable compared to baseline conditions. EIA-driven integrated assessment is, to some extent, to ensure a proposal is not harmful to the environment by measuring triple bottom line indicators. Most of the sustainability rating systems like LEED belong to this EIA-driven assessment.

Since the objective of SWAHO is to help homeowners achieve sustainability as much as possible, SWAHO is an objectives-led integrated assessment.

In terms of the approach to assessing sustainability, there are some criticisms about triple bottom line; for example, the separation of the three pillars reduces sustainability as a whole due to inadequate understanding of interrelations between the three pillars. Gibson (2001) promotes the use of a principles-based approach to sustainability assessment as an alternative to the triple bottom line [11].

However, SWAHO still uses the three triple bottom line areas as the sustainability categories because they are clear, straightforward, well received, and thus easy for homeowners to understand. Moreover, the interrelations and interdependence between pillars can be addressed in SWAHO by assessing each action and each product for their impacts on all the three pillars.

2.2 Sustainable Actions and Products

There have been many previous studies on green homes. For example, a research on a pilot house in Australia [12] concluded several common features of the smart homes, including skylight, non-split tiles, and so on. In addition, many books and websites provide extensive sources of actions and products for green renovations. The following sections describes a few of these resources that were found to be helpful in generating lists of sustainable actions and products. The final list of actions and products incorporated into SWAHO is shown in Section 4.2.

RSMeans Reference Books

RSMeans is North America's leading supplier of construction cost information. It provides cost reference books on green buildings.

- *Green Home Improvement* [13]

  This book introduces a wide range of green home renovation actions and products, including efficient flooring, roofing, insulation, windows, and doors, etc., along with their costs. This proved to be the most valuable reference to generate the list of actions and products in SWAHO, which is shown in Table 4-1 in Chapter 4.

- *Green Building: Project Planning & Cost Estimating*, 2002 [14]

  This book contains cost data for green materials, components, and systems. Some of the cost data was adjusted and used as the cost estimates for some renovation actions.

- *Green Building: Project Planning & Cost Estimating*, third edition, 2011 [15]

  This book has a thorough introduction to the latest green building technologies, design concepts, standards and practices during the lifespan of a green building. However, it does not include cost information and the technologies in the book are for general buildings, not for homes.

Energy Star

Energy Star is a U.S. Environmental Protection Agency voluntary program that helps businesses and individuals save money and protect our climate through superior energy efficiency. The website of Energy Star provides a number of ways to save energy at home [16]. The actions that have an influence on cost are included in SWAHO. Most of the actions are associated with Energy Star certification; for example, using Energy Star certified TVs, refrigerators, dishwashers, and so on.

Canadian Green Building Council

The Canadian Green Building Council has a webpage to provide general suggestions on renovation in kitchen, bathroom, and other areas [17]. The suggestions include low-flow toilets, efficient showerheads, replacing appliances, greener flooring, windows, and others.

Canada Mortgage and Housing Corporation

Canada Mortgage and Housing Corporation is Canada's authority on housing, intended to help Canadians meet their housing needs. Their “Green Housing” webpage provides information to help understand green building and renovation practices, including ways to save energy, save water, and make indoor environments healthy [18].

Sustainability BC Toolkit for Home

This document is intended to provide homeowners with practical help on sustainable homes. For example, it provides a list of sustainability labels for household products, and it offers checklists of green actions about utilities, transportation, shopping, health, participation, and waste. This is not a renovation decision-making tool, but rather an advice document.

Governments, organizations, and associations

Numerous governments, organizations, and associations provide “sustainable home” information on their websites. One example is an organization called “Sustainable Stamford”, a website that teaches people sustainability at home, at school, and at work. There are not only general suggestions such as energy audit and recycling, but also small things that can be done at home such as printing both-sided paper and purchasing Energy Star rated appliances [19].

2.3 Sustainability Criteria and Indicators

Although sustainability consists of three aspects—environmental, social, and economic concerns—most current “sustainability assessments” are, in fact, “environmental assessments”, since environment is generally seen as the most important pillar in sustainability. The assessments

that address at least one pillar of triple bottom line are reviewed in this section, to help select the most suitable sustainability criteria and indicators for SWAHO. They are introduced by category as Figure 2-1 shows. The final lists of sustainability criteria and indicators are in Section 4.3.

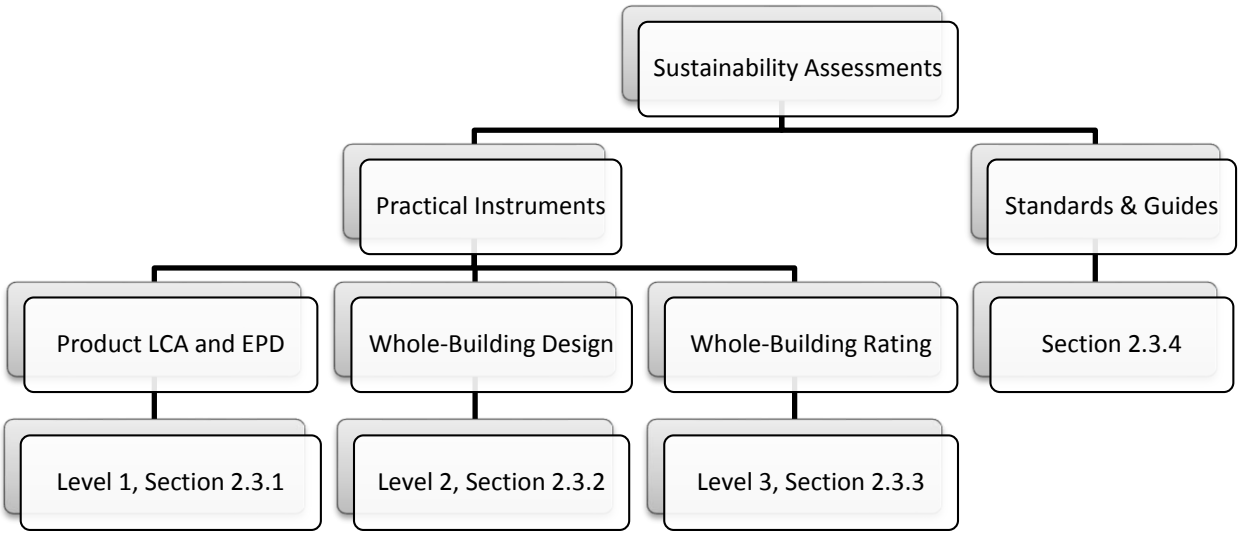


Figure 2-1 Sustainability assessment hierarchy

Practical Instruments

To better understand different tools, the ATHENA Institute classified sustainability assessment tools into three levels [20]. Below are some examples:

- Level 1: Product comparison tools and information sources (Section 2.3.1):
  GaBi, Quantis SUITE 2.0, BEES, the Environmental Resource Guide, LCExplorer, SimaPro, and TEAM.
- Level 2: Whole-building design or decision support tools (Section 0):
  ATHENA, BEAT 2002, BeCost, Eco-Quantum, IMPACT, Envest, DOE2, E10, Radiance, EQUER, LEGEP, and PAPOOSE.

- Level 3: Whole-building assessment and rating systems (Section 2.3.3):

  SBTool (international), BREEAM (UK), EcoEffect (Sweden), EcoProfile (Norway), ESCALE (France), LEED (US), Passive House (German), Living Building Challenge (international), WELL Building Standard (international), BNB (German), DGNB (German) and Energy Star (US).

Standards and Guides

The International Organization for Standardization (ISO) and European Committee for Standardization (CEN) are both well-known international standards creators. They have published many standards regarding the sustainability in the building industry. Examples are:

- ISO 15392, Sustainability in building construction — General principles;
- ISO 21929-1, Sustainability in building construction — Sustainability indicators — Part 1: Framework for the development of indicators and a core set of indicators for buildings;
- ISO 21930, Sustainability in building construction — Environmental declaration of building products;
- ISO 14025, Environmental labels and declarations — Type III environmental declarations — Principles and procedures;
- ISO 21931-1, Sustainability in building construction — Framework for methods of assessment of the environmental performance of construction works — Part 1: Buildings.

ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, has also published many standards for the built environment to standardize some quantified indicators. In addition, there are standards and guides from commercial companies, for either one sustainability pillar or overall sustainability. The standards and guides that are helpful for SWAHO are reviewed in Section 2.3.4.

2.3.1 Product LCA and EPD

Life-Cycle Assessment (LCA) has an approximately 30-year history so far. LCA addresses the potential environmental impacts of products and services, both embodied and consumed, from extraction to disposal [21]. It can help product design and decision-making, provide opportunities to increase the environmental performance of a product, and increase marketing value by Environmental Product Declarations (EPD). As one of the three environmental labels [22], EPD is a self-declared product document with quantified environmental impacts from LCA, such as global warming potential (kg CO_2 equivalent) and acidification potential (kg SO_2 equivalent). The concept of LCA can be also applied to social and economic aspects, leading to social life-cycle assessment and life-cycle costing. However, the term "LCA" still refers to environmental assessment only.

There are four phases in LCA: define goal and scope, develop life-cycle inventory (LCI), life-cycle impact assessment (LCIA), and life-cycle interpretation. LCA database discloses the materials that flow in and flow out of a certain process. The data is then used to create the LCI of a product. Then, the LCI is categorized into potential environmental impacts through environmental impact assessment (EIA) methods, which define environmental impact indicators

and calculation rules. This process is called an LCIA. Life-cycle interpretation includes identifying lessons learned from the results, checking the completeness of the LCA, etc.

To foster LCA calculations, a variety of LCA software has been created with embedded LCA databases (Table 2-1) and EIA methods (Table 2-2). Moreover, LCA software can generate EPD directly using the LCA results. In the future, ideally, each product will be equipped with an EPD, thus the LCA indicators can provide perfect inputs to SWAHO since the LCA indicators address a wide range of environmental issues quantitatively. Figure 2-2 concludes the steps and the important elements of LCA and illustrates the relation between SWAHO and LCA in an ideal case. All the indicators from LCA and EPD are summarized in Table 2-3. Although these indicators are considered in the current design of SWAHO since only a small number of products in the market provide EPD, the indicators reviewed can be used for future development.

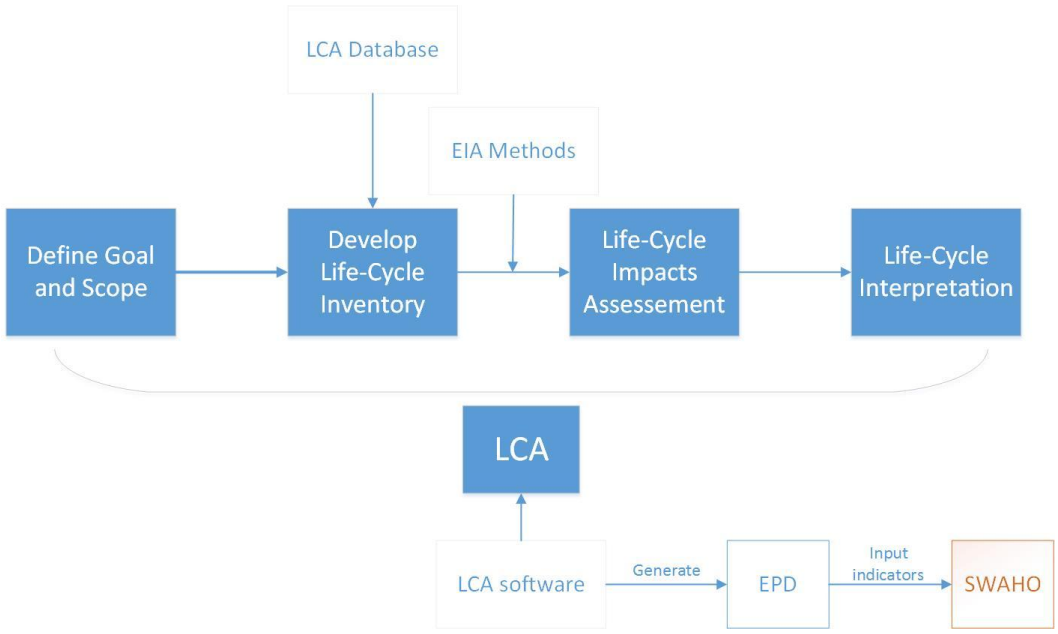


Figure 2-2 The relation between LCA, EPD and SWAHO in the ideal case

Table 2-1 LCA databases

Database	Description
ecoinvent	Developed by the Swiss Centre for Life Cycle Inventories. It is the most widely used database.
ELCD (European reference Life Cycle Database)	Since its first release in 2006, the ELCD comprises Life Cycle Inventory (LCI) data from EU-level business associations and other sources for key materials, energy carriers, transport, and waste management.
U.S. LCI Database	It was created by National Renewable Energy Laboratory (NREL) in the U.S. This database provides a cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing common material, component, or assembly.
GaBi Databases	GaBi Databases are created by thinkstep. The databases contain over 10,000 ready-to-use Life Cycle Inventory profiles and they are used in GaBi software.
SPINE@CPM	The Swedish Life Cycle center (formerly CPM) created the Swedish national LCA database. It continuously provides transparent and quality reviewed LCA data. This database contains detailed information on all types of freight transports, energyware production, production of selected materials and waste management alternatives.
IVAM LCA Data 4.0	IVAM is a research and consultancy agency in Netherland. It consists of about 1000 processes, leading to more than 300 materials. The data can be used for LCA applications in various sectors.
GEMIS (Global Emissions Model for Integrated Systems)	GEMIS is a public free life-cycle and material flow analysis model and database provided by International Institute of Sustainability Analysis and Strategy in Germany.

Table 2-2 Environmental Impact Assessment (EIA) Methods

EIA methods	Created by	Description
CML 2001	Leiden University, the Netherlands	It provides characterization factors for more than 1700 different flows. The results are grouped in midpoint categories according to common mechanisms (e.g., climate change) or commonly accepted groupings (e.g., ecotoxicity).
Eco-indicator 99	PR é Consultants	It provides a single score for human health, ecosystem quality, and resources. The standard unit is point (Pt) or millipoint (mPt). The aim of this method is to compare products or components. The characterization factors for Eco-indicator 99 are also included in the CML 2001 documentation.
Ecological Scarcity Method 2013	ESU-services GmbH	The more the level of pollutant emissions or consumption of resources exceeds the environmental protection target set, the greater the eco-factor becomes, expressed in eco-points (EP). Just like Eco-indicator 99, the main aim of this method is to compare products and improve processes and/or products.
EDIP 2003	Institute for Product Development at the Technical University of Denmark	Environmental Development of Industrial Products is a method that enables the possibility of exposure in the characterization modeling of non-global impact categories.
ILCD 2011	Joint Research Centre of the European Commission	International Reference Life Cycle Data System (ILCD) recommends a method for each environmental theme, at both midpoint and endpoint.
ReCiPe 8	RIVM, CML, PR é Consultants, and Radboud Universiteit Nijmegen.	The main objective of ReCiPe is to provide a method that combines Eco-Indicator 99 and CML. ReCiPe distinguishes midpoint indicators and endpoint indicators (damage to human health, damage to ecosystems and damage to resource availability).
TRACI 2.1	Environmental Protection Agency of the U.S.	TRACI stands for Tool for the Reduction and Assessment of Chemical and other environmental Impacts. The methodology were developed specifically for the U.S. locations.
US EPA-default LCIA methods	Environmental Protection Agency of the U.S.	The impact categories recommended by the US Environmental Protection Agency are obtained from the methods TRACI 2.0, RECIPE, Water Footprint and Cumulative Energy Demand.
USEtox 2.0	UNEP/SETAC Life Cycle Initiative	USEtox is a scientific consensus model endorsed by the UNEP/SETAC Life Cycle Initiative for characterizing human and ecotoxicological impacts of chemicals. The main output is a database of recommended and interim characterization factors including fate, exposure, and effect parameters.

Table 2-3 LCA indicators (a)

Category	LCA Indicator	Unit	From which EIA method
Acidification	Acidification Potential	kg SO_2 eq.	CML 2001, ReCiPe 8
	Acidification Potential	m^2 UES per functional unit	EDIP 2003
	Acidification Air	kg H+ moles eq.	TRACI 2.1, ILCD
Climate change	Global Warming Potential 100	kg CO_2 eq.	CML 2001, ReCiPe 8, TRACI 2.1, ILCD
	Global Warming Potential 20, 50, 100	g CO_2 eq.	EDIP 2003
Depletion of abiotic resources	Abiotic Depletion elements	kg Sb eq.	CML 2001, ILCD
	Abiotic Depletion fossil	MJ	CML 2001
	Fossil Depletion	kg oil eq.	ReCiPe 8
	Metal Depletion	kg Fe eq.	ReCiPe 8
	Water Depletion	m^3	ReCiPe 8
	Water Depletion	kg	ILCD
Ecotoxicity	Freshwater Aquatic Ecotoxicity Potential	kg DCB eq.	CML 2001
	Marine Aquatic Ecotoxicity Potential	kg DCB eq.	CML 2001
	Terrestrial Ecotoxicity Potential	kg DCB eq.	CML 2001
	Ecotoxicity in continental water, marine and soil	m^3/g	EDIP 2003
	Freshwater Ecotoxicity	CTUe	ILCD
	Freshwater Ecotoxicity	kg 1,4-DB eq.	ReCiPe 8
	Marine Ecotoxicity	kg 1,4-DB eq.	ReCiPe 8
	Terrestrial Ecotoxicity	kg 1,4-DB eq.	ReCiPe 8
	Ecotoxicity Air, Soil, Water	PAF m^3 day/kg	TRACI 2.1

Table 2-3 LCA indicators (b)

Category	LCA Indicator	Unit	From which EIA method
Eutrophication	Eutrophication Potential	kg Phosphate eq.	CML 2001
	Eutrophication Potential	kg N eq.	TRACI 2.1
	Terrestrial Eutrophication	m^2 UES per functional unit	EDIP 2003
	Terrestrial Eutrophication	Mole of N eq.	ILCD
	Aquatic Eutrophication	kg NO_3 Eq.	EDIP 2003
	Freshwater Eutrophication	kg P eq.	ReCiPe 8, ILCD
	Marine Eutrophication	kg N eq.	ReCiPe 8
Human toxicity	Human Toxicity Potential	kg DCB eq.	CML 2001
	Human Toxicity via air, soil, water	m^3/g	EDIP 2003
	Human Toxicity	kg 1,4-DB eq.	ReCiPe 8
	Human Health Cancer Air, Soil, Water	cases	TRACI 2.1
	Human Health Non Cancer Air, Soil, Water	cases	TRACI 2.1
	Cancer Effects	CTUh	ILCD
	Non-cancer Effects	CTUh	ILCD
Human health	Ionizing Radiation	U235 eq.	ReCiPe 8, ILCD
	Particulate Matter Formation	kg PM10 eq.	ReCiPe 8
	Human Health Criteria Air	kg PM10 eq.	TRACI 2.1
	Particulate Matter/Respiratory Inorganics	PM 2.5 eq.	ILCD

Table 2-3 LCA indicators (c)

Category	LCA Indicator	Unit	From which EIA method
Land use	Natural Land Transformation	m^2	ReCiPe 8
Ozone layer depletion	Ozone Layer Depletion Potential	kg R11 eq.	CML 2001, ILCD
	Stratospheric Ozone Depletion	g CFC-11 eq.	EDIP 2003, ReCiPe 8, TRACI
Photochemical oxidation	Photochemical Oxidation Creation Potential	Kg Ethane eq.	CML 2001
	Photochemical ozone formation – impact on vegetation	m^2 UES*ppm*hours	EDIP 2003
	Photochemical ozone formation – human health	pers*ppm*hours	EDIP 2003
	Photochemical Oxidant Formation	kg NMVOC	ReCiPe 8, ILCD
	Smog Air	kg O_3 eq.	TRACI 2.1

LCA can be applied to any industry and to different degrees. Four popular LCA software that can be used for building products are reviewed in Table 2-4. GaBi 6, Quantis SUITE 2.0, and SimaPro are thriving commercial product LCA software that can be used to generate EPD for products in any industry. The differences between SWAHO and LCA are concluded in Table 6-1 in Chapter 6. BEES is for selecting cost-effective and environmentally preferable building products. Compared to the other typical LCA software, BEES is more similar to—but still not exactly the same as—SWAHO. Thus, BEES is introduced with more details and then compared to SWAHO in Table 2-5 later in this section.

Table 2-4 Product LCA software

	GaBi 6	Quantis SUITE 2.0	SimaPro	BEES
Inventor	PE Europe GmbH and IBP University of Stuttgart	Quantis	PR é Sustainability	NIST (National Institute of Standards and Technology) in the U.S.
Latest update	2015	2015	2015	2011
Access	Desktop software	Web-based	Desktop software	Web-based
Databases	ecoinvent and GaBi database	ecoinvent, and Quantis water footprint database	ecoinvent, U.S. LCI Database, ELCD, etc.	BEES
Pros	Sketching interface; International LCA Database formatting; Generate report aligned with ISO and EPD.	Easy-to-use interface for non-LCA expert; Simplicity in product labeling and reporting; Robust results analysis.	Transparent database, allow tracking to smallest detail; Various databases; Support EPD; Support multi-users.	Weights among 12 environmental indicators; Weights between environmental and economic performance.
LCA Type(s)	Environmental, cost and social profiles	Environmental	Environmental	Environmental and Economic
Applied Area	Products, company	Products, company	Products	Building Products
Reference	[23]	[24]	[25]	[26]

BEES stands for Building for Environmental and Economic Sustainability. BEES is aimed at designers, builders, and product manufacturers. The online tool includes actual environmental and economic performance data for 230 building products. It measures the environmental performance of building products by LCA and measures economic performance using the ASTM standard life-cycle cost method (further introduced in Section 2.3.4). Environmental performance and economic performance are combined into an overall performance using the ASTM standard

for Multi-Attribute Decision Analysis. Building products are defined and classified according to the ASTM standard classification for building elements known as UNIFORMAT II [27].

On BEES online, users first assign weights between environmental indicators and between environmental performance and economic performance. Then users select one building element for comparison, e.g., Bath and Tile Cleaners, Water Pipes, etc. After choosing product alternatives and defining transportation distance from manufacturer to site for each product alternative, environmental and economic performance calculations will be conducted. Results include graph comparisons for environmental performance and for economic performance, respectively, as well as an overall score combining two performances based on the weights assigned aforehand. Table 2-5 compares BEES and SWAHO in further details.

Table 2-5 Differences between BEES and SWAHO

	BEES	**SWAHO**
Trade-off	Environmental-Economic	Social-Environmental-Economic
Product list	Limited. Users may choose products from the existing alternatives, which are usually 3 to 4 for each element.	Flexible. Users can search and add product alternatives from e-commerce websites.
Results	One product for one element	For many renovation actions, suggest one product for each action.
Product type	Construction products such as foundation, shell, pipes, etc.	Renovation products such as windows, insulation materials, etc.

2.3.2 Whole-Building Design Tools

Whole-building design tools contain environmental indicators as well. However, those tools usually do not provide calculations for the indicators. Instead, the data is from product LCA software, whole-building rating systems, or other energy simulation tools. The indicators in whole-building design tools are mostly the same as reviewed in other sections. Therefore, only a few whole-building design tools are reviewed in this section.

ATHENA™

ATHENA™ created Athena Impact Estimator for buildings (IE4B), which is the only free software for whole-building LCA in North America. The Athena database was developed through the research conducted by Athena experts. Athena software provides environmental indicators categorized into four groups [28]:

- Environmental Impacts: TRACI v2.1 indicators (see Section 2.3.1);
- Resource Use: Renewable/non-renewable primary energy, secondary material, fresh water, and renewable/non-renewable fuels;
- Waste categories: Hazardous/non-hazardous waste (kg) and radioactive waste (kg);
- Output flows: Components for reuse (kg), materials for recycling (kg), materials for energy recovery (kg), and exported energy (MJ).

Eco Quantum

Eco Quantum is software developed in Netherland to compute LCA for houses, only available in Dutch. Four environmental indicators are supported: resource depletion, emissions,

energy, and waste. Scores for the indicators are calculated based on pre-conducted LCA by SimaPro and Dutch Energy Performance Standard [29].

IMPACT

IMPACT (Integrated Material Profile and Costing Tool) is a specification and database for software developers to incorporate into their tools to enable integration of Life Cycle Assessment, Life-Cycle Costing and Building Information Model (BIM) [30]. IMPACT compliant tools allow the users to attribute environmental and cost information to drawn or scheduled items in the BIM. Put simply, IMPACT takes quantity information from the BIM and multiplies this by environmental impact and cost 'rates' to produce an overall impact and cost for the whole (or a selected part) of the design. The results generated by IMPACT can be used in whole-building assessment schemes like BREEAM. IMPACT provides numerous indicators covering issues such as toxicity, water and resource efficiency in addition to carbon and climate change.

EQUER

EQUER is a French tool for yearly simulations of a building life cycle, providing mechanical, energy and architectural engineers or architects with environmental indicators (e.g., global warming, acidification and eutrophication potentials, and exhaust of natural resources). EQUER is linked to the energy simulation tool COMFIE for thermal and lighting analysis. Replacement of components at the end of their life is automatically accounted for in the tool. Impacts due to the activities of occupants (e.g., home-work transportation, domestic waste production, water consumption) may be taken into account according to the purpose of the study [31].

2.3.3 Whole-Building Rating Systems

Whole-building rating systems offer certifications based on score evaluation. They are great sources of sustainability criteria and indicators for green homes. Some prominent rating systems are: BREEAM (UK), SBTool (international), LEED (US), Passive House (German), Living Building Challenge (international), WELL Building Standard (international), BNB (German), DGNB (German), and Energy Star (US).

Home Quality Mark, BREEAM

BREEAM (Building Research Establishment Environmental Assessment Methodology) was developed by the Building Research Establishment (BRE) in the UK and is the first building assessment tool [32]. Previously, BREEAM did not provide certifications for home, but a Home Quality Mark (HQM) is available since 2015. HQM is a UK national standard created by BRE [33]. Independent professionals assess and score wide-ranging aspects of a new home to give an overall 5-star quality rating, as well as specific 5-star ratings for the cost (economic), wellbeing (social), and footprint (environmental). HQM assesses 35 issues from construction phase to post-occupancy phase.

SBTool (Formerly GBTool)

The SB Method is a generic framework for rating the sustainable performance of buildings and projects. Authorized third parties can use SB Method to establish adapted SBTool versions of rating systems to suit their own regions and building types. SBTool is managed by the International Initiative for a Sustainable Built Environment. It is a flexible framework operating on Excel. The latest version is SBTool 2015. There are seven categories, each of which involves a number of

"sustainability issues" (indicators) [34]. Weightings are applied to all the categories and issues. Some indicators that are suitable for home furnishing are incorporated into SWAHO.

LEED

LEED (Leadership in Energy and Environmental Design), which was developed by the U.S. Green Building Council, is a rating system that is recognized as an international mark of excellence for green building in 150 countries. It provides certifications for almost all types of buildings, including homes. The LEED v4 checklist for Homes assesses nine categories: Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority [35]. Relevant indicators are taken into account in SWAHO.

Passive House

The Passive House Standard goes beyond LEED. It was firstly proposed by Passivhaus Institut (PHI) in Germany and now has been used in North America as well, i.e., CanPHI, PHIUS. Passive House is a rigorous design and building standard that focuses on the building envelope and results in cost-effective, low-energy homes with less complex heating and cooling systems. The standard mainly regulates space heating and cooling demand (kWh/m^2a), renewable primary energy demand and generation (kWh/m^2a), and airtightness (1/h). Passive House Planning Package (PHPP) is the tool provided for passive house design and certification. PHPP supports 3D design through a Sketchup plugin "designPH". The fundamental strategies for passive house are efficient building shape, solar exposure, superinsulation, advanced windows (i.e., triple glazing, insulated

window frames), high airtightness, ventilation heat recovery, ventilation air preheating, and thermal-bridge-free construction [36].

Living Building Challenge

The Living Building Challenge, a program of the International Living Future Institute, is a building certification program, advocacy tool, and philosophy that addresses sustainable development at all scales, which is more stringent than LEED. The Living Building Challenge is comprised of seven performance categories called "Petals": Place, Water, Energy, Health & Happiness, Materials, Equity, and Beauty. Petals are subdivided into a total of twenty "Imperatives", each of which focuses on a specific sphere [37]. The imperatives may be qualitative description or involve quantitative requirement.

WELL Building Standard

The WELL Building Standard v1 was pioneered by Delos in 2015, as a performance-based standard focusing solely on the health and wellness of building occupants. The WELL Building Standard is designed to work harmoniously with LEED, the Living Building Challenge, and other leading global green building standards. WELL Assessors will perform or oversee on-site measurements and inspections to certify the buildings. The WELL Building Standard evaluates seven aspects: Air, Water, Nourishment, Light, Fitness, Comfort, and Mind [38]. Proper indicators for New and Existing Building Interiors are incorporated into SWAHO.

BNB

BNB (The Assessment System for Sustainable Building), promoted by The Federal Building Ministry in Germany, provides scientific, well-founded and planning based evaluation

processes. The individual criteria are assessed according to determined rules. The main groups of criteria will be assessed separately and collated, using the determined priority to form a total grade of performance and with that a final result. A building can be awarded the quality levels of bronze, silver or gold dependent on the total grade of performance. The evaluation is carried out by an auditor and will be subject to a test of conformity. The five groups of criteria are Ecological Quality, Economical Quality, Socio-Cultural and Functional Quality, Technical Quality, and Process Quality [39]. Although BNB is for offices and administration buildings, some of the criteria are applicable for home.

DGNB System

DGNB is the German Green Building Council. The DGNB System assesses the overall building performance and offers certification in bronze, silver, gold and platinum. DGNB system covers all of the key aspects of a sustainable building: Environmental, Economic, Sociocultural and Functional Aspects, Technology, Processes, and Site. The first four quality sections have equal weight in the assessment. This means that the DGNB system is the only one that gives as much importance to the economic aspect of sustainable building as it does to the ecological criteria [40]. Some sustainability indicators were taken into account in SWAHO.

Energy Star

Energy Star certifies homes that use 15-30% less energy than typical new homes while delivering better comfort, quality, and durability. To earn an Energy Star label, the new home has to be verified by a rater that it has a complete thermal enclosure system, complete heating and cooling system, complete water management system, and energy-efficient lighting and appliances.

2.3.4 Standards and Guides

Lots of standards and guides have been proposed to deal with either one pillar of sustainability or the overall sustainability of buildings. In this section, some common and well-known standards and guides are reviewed with the focus on the sustainability indicators in them. These standards and guides are grouped as below:

1. Focus on one pillar of sustainability:
    a. ASHRAE 55-2013 Thermal Environmental Conditions for Human Occupancy
    b. ASHRAE 62.2-2013 Ventilation for Acceptance Indoor Air Quality in Low-Rise Residential Buildings
    c. ASHRAE 90.2-2007 Energy Efficient Design of Low-Rise Residential Buildings
    d. ASTM E917-15 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems
2. Focus on overall sustainability:
    a. Arup SPeAR
    b. ISO 21929-1, Sustainability in building construction — Sustainability indicators — Part 1: Framework for the development of indicators and a core set of indicators for buildings

ASHRAE is the acronym of the American Society of Heating, Refrigerating and Air-Conditioning Engineers. ASHRAE publishes standards with the intent to advance human well-being through sustainable technology for the built environment.

ASHRAE 55-2013 Thermal Environmental Conditions for Human Occupancy

This standard specifies the combinations of environmental factors (temperature, thermal radiation, humidity, and air speed) and personal factors (activity and clothing) that will contribute to acceptable thermal comfort for healthy adults [41].

ASHRAE 62.2-2013 Ventilation for Acceptance Indoor Air Quality in Low-Rise Residential Buildings

The standard defines the roles and minimum requirements for mechanical and natural ventilation system to provide acceptable indoor air quality in single-family houses or multi-family structures. A whole-building ventilation can be an intermittent mechanical ventilation or equivalent ventilation. A local mechanical exhaust system can be achieved by a demand-control or a continuous mechanical exhaust system. For any kind of ventilation, it should meet the total required ventilation rate (cubic feet per minute or liter per second). Air-moving equipment should meet sound requirements. One of the indicators is sone, which is a unit of loudness [42].

ASHRAE 90.2-2007 Energy Efficient Design of Low-Rise Residential Buildings

The purpose of the standard is to provide minimum requirements for the energy-efficient design of residential buildings, applying to building envelope, heating equipment and systems, air-conditioning equipment and systems, and domestic water-heating equipment and systems. There is a requirement of capacity (Btu/h or KW) for air conditioners, heat pumps, warm air furnaces, and boilers. Ducts of air distribution system and pipes for HVAC system should meet insulation requirements (R-value). Windows and doors need to meet the maximum allowable air infiltration rate (cfm/ft or cfm/ft^2). Thermostats should be capable of being set from 55°F (13°C) to 85°F

(29°C). Ventilation system should be equipped with a control to shut off the supply or exhaust. Humidistat should be provided to maintain the relative humidity in the space above 30%. Unfired storage water heating equipment should have a heat loss less than 6.5 Btu/h·ft2 through its tank surface [43].

ASTM E917-15 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems

ASTM International (formerly The American Society for Testing and Materials formed in 1898) is a globally recognized leader that provides over 10,000 voluntary consensus standards. ASTM E917 provides the computation practices for life-cycle cost, which includes initial investment, maintenance, replacement, operating energy cost, and resale [44].

Arup SPeAR

SPeAR (Sustainable Project Appraisal Routine) is a sustainability appraisal tool for civil engineering projects. It was developed in-house by Arup, a world-leading engineering consulting company in 2000, and now has been used over 100 projects in over 10 countries. SPeAR provides quantitative and qualitative appraisal based on 23 core indicators, which were developed after a review of over 10 other sustainability indicator sets including LEED [45]. For each indicator, professional experts in this field need to answer several questions to get a score from -1 to +3. Despite a scoring scheme, SPeAR is more a communication tool for design and trade-offs than a building rating system. The SPeAR manual provides a full indicator list, including core indicators and sub-indicators in social, environmental and economic aspects. Some interesting indicators that might be relevant to this study are art, security, access to green, indoor environment, engagement,

waste in operation, use of recycled or reused materials, water monitoring, direct air emissions, energy demand, noise and vibration, and affordability.

ISO 21929-1 Sustainability in building construction — Sustainability indicators — Part 1: Framework for the development of indicators and a core set of indicators for buildings

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies. ISO 21929-1 was first released in 2006 and updated in 2011. It provides a set of core indicators for buildings, some of which are applicable to renovation and refurbishment, i.e., emissions to air, amount of non-renewable resources consumption by type, amount of fresh water consumption, amount of waste generation by type, accessibility, indoor conditions and air quality, adaptability, life cycle costs, maintainability, safety, serviceability, and aesthetic quality.

2.4 Mathematical Mechanism for Decision-Making

This section first briefly analyzes the problems that SWAHO is intended to solve, and then reviews the theories that might help to solve the problems.

SWAHO is designed to answer the question "What are the greenest renovation choices?" This question involves two specific decision-making (DM) problems.

- DM 1

Given a set of actions that are of potential interest to the homeowner, which actions should the homeowner do to achieve the maximum sustainability?

- DM 2

For each action, which product should the homeowner choose to achieve a total maximum sustainability?

Both of the two DM problems have two features: a number of sustainability criteria and a number of solution alternatives. The sustainability criteria are often conflicting. For example, a ceiling fan provides cooling air but makes noise (i.e., good for thermal comfort; bad for acoustic comfort). Moreover, each of the DM problems has a variety of solution alternatives – different combinations of renovation actions or different combinations of renovation products. The problem, since it has a number of conflicting criteria and a number of alternatives, is a Multi-Criteria Decision-Making (MCDM) problem. Theories of MCDM are reviewed first in order to find a mathematical model for SWAHO DM problems.

2.4.1 Multi-Criteria Decision-Making

A well-received classification for Multi-Criteria Decision-Making (MCDM) defines two categories: Multi-Attribute Decision-Making (MADM) and Multi-Objective Decision-Making (MODM). Criteria are the standards or rules for judgment. Attributes are the properties of an alternative, either quantitative or qualitative. Objectives are the desired states of an alternative, which usually shows the directions of improvement of one or more attributes [46].

Multi-Attribute Decision-making

MADM works for a finite (small) number of alternatives and provides one optimal solution through a variety of calculation rules regarding multiple attributes of the alternatives. In MADM, attributes are regarded as both design variables and design criteria. MADA methods can address

three types of problems: screening alternatives, ranking alternatives, or picking a "best" alternative [47].

Multi-Objective Decision-making

MODM is promoted to support an infinite (large) number of alternatives and to generate a Pareto set of optimal solutions through constraints on multiple objectives. Theoretically, any solution in the Pareto set is optimal; that is, every Pareto optimal solution is not worse than any of other solutions for every objective and is better than all the other solutions for at least one objective. A MODM problem usually has a large number of optimal solutions, but it is possible to find one ultimate optimal solution if preferences on objectives are indicated. In MODM, design variables and design criteria (objectives) are often different.

Because the objectives are conflicting and the number of alternatives is large, the number of Pareto optimal solutions might be very large. Generating the Pareto optimal solutions could be infeasible or computationally expensive. This raises two difficulties:

1. How to find the optimal solutions quickly?
2. How to decide which optimal solution to use?

To solve the first difficulty, a number of stochastic search strategies have been developed, such as Evolutionary Algorithms, Tabu Search, Simulated Annealing, Memetic Algorithm, Particle Swarm Optimization, and Ant Colony Optimization. These strategies usually do not guarantee to identify optimal trade-offs, but try to find a good approximation. On the other hand, weighting or algorithms based on preferences are usually adopted to solve the second difficulty.

Figure 2-3 concludes some common methods developed for MCDM.

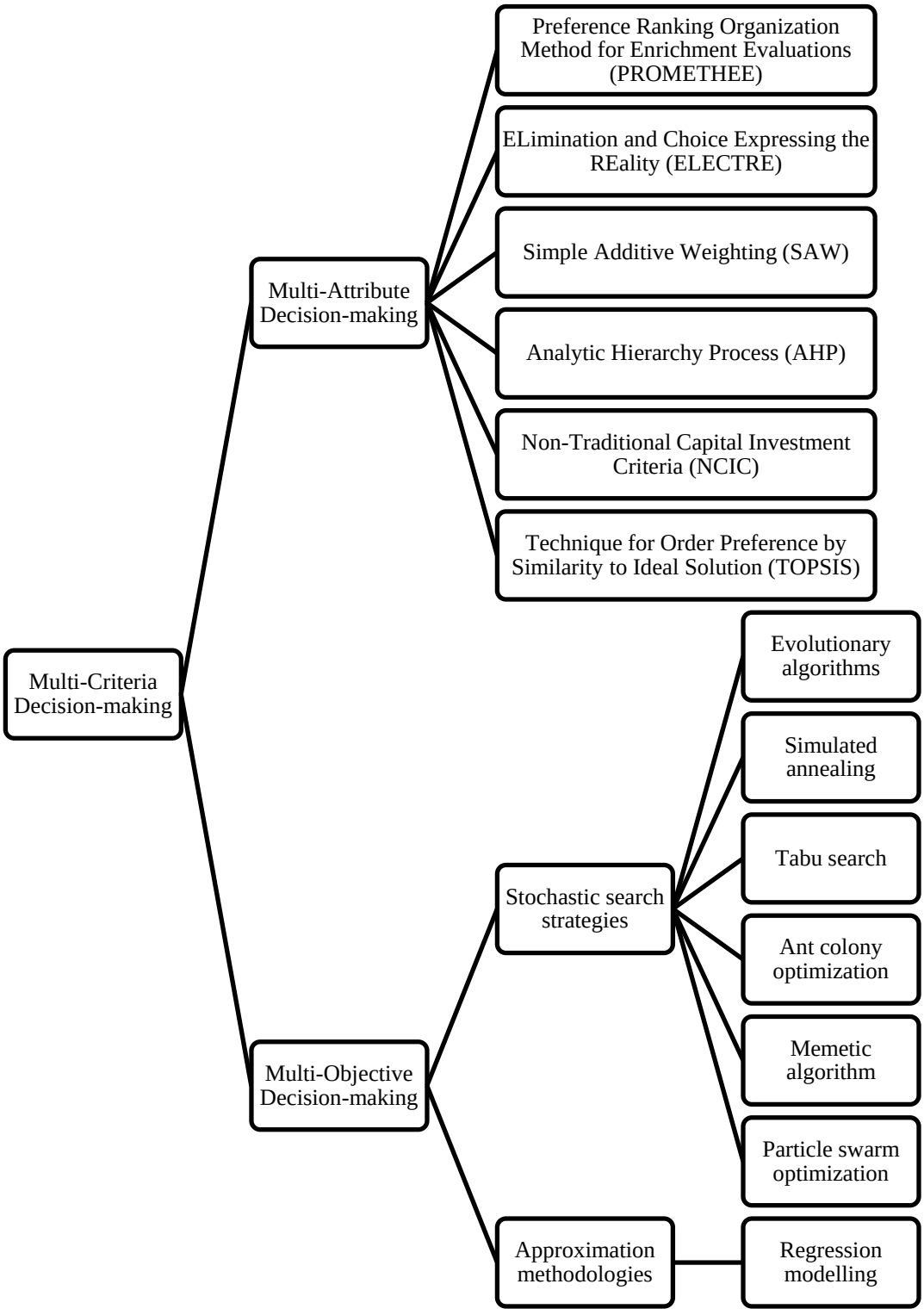


Figure 2-3. MCDM methods and classifications

To find out which MCDM category applies to the two DM problems in SWAHO, DM 1 and DM 2 are analyzed in further detail. Table 2-6 shows simplified examples of DM 1 and DM 2. Then, DM 1 and DM 2 are compared to MADM and MODM in Table 2-7.

Table 2-6 Simplified examples of DM 1 and DM 2 in SWAHO

	DM 1	**DM 2**
Problem	The homeowner is interested in four actions: • insulate the walls • paint the walls • replace windows • buy a clothes washer What actions to do?	The homeowner has decided to do 3 actions: 3. insulate the walls 4. paint the walls 5. buy a clothes washer Which insulate material to use? Choose from product A, B, C. Which paint to use? Choose from paint type D, E, F. What clothes washer to buy? Choose from model G, H, I.
Design variables	Include this action or not	Choose this product or not
Objectives	Maximize Acoustic comfort, Thermal comfort, Functionality, Energy saving… Minimize cost	Maximize Acoustic comfort, Thermal comfort, functionality, energy saving… Minimize cost
Attributes	Each action's impact on Acoustic comfort, Thermal comfort, Functionality, Energy saving… and their cost	Each product's impact on Acoustic comfort, Thermal comfort, Functionality, Energy saving… and their cost
Solution	A set of actions: Insulating; insulating + clothes washer, etc.	A set of products: A, E, I; B, D, I; C, D, G; etc.
Solution alternatives	Different combination of actions. The number of actions can be one, two, three, or four.	Different combination of products. The total number of product is three.

Table 2-7 Comparison of MADM, MODM, DM 1 and DM 2 (adapted from Table 3.1 in [46]**)**

	MADM	**MODM**	**DM 1**	**DM 2**
Objectives defined	Implicitly	Explicitly	Explicitly	Explicitly
Alternatives defined	Explicitly	Implicitly	Implicitly	Explicitly
Number of alternatives	Finite (small)	Infinite (large)	Large	Large
Attributes defined	Explicitly	Implicitly	Explicitly	Explicitly
Criteria defined by	Attributes	Objectives	Objectives	Objectives
Constraints defined	Implicitly	Explicitly	Implicitly	Implicitly
Decision-making paradigm	Outcome-oriented	Process-oriented	Outcome-oriented	Outcome-oriented
Relevant to	Evaluation/choice	Design/search	Design	Choice

As Table 2-7 shows, neither DM 1 nor DM 2 is exactly MODM or MADM. Some modifications might be available to help present SWAHO DMs as MCDM, but it will complicate the SWAHO DMs. Even if SWAHO DMs can be successfully expressed as MCDM, there are difficulties in computation as mentioned previously. Therefore, this research did not apply MCDM to SWAHO DMs, but rather investigated other mathematical models.

2.4.2 Knapsack Problem

Since cost is the only economic criterion, it is intuitive to treat the two SWAHO DMs as Cost-Benefit analysis. “Benefit” consists of social and environmental criteria. This way, the DM problems turn into a knapsack problem.

The knapsack problem is a problem in combinatorial optimization: given a set of items, each with a weight and a value, determine what items include in a collection to maximize the total

value while making the total weight less than or equal to a given limit [48]. This is the basic 0-1 Knapsack problem.

DM 1 can be expressed as the 0-1 knapsack problem: given a set of *n* actions, each action $1 \leq j \leq n$ with a cost c_j and a sustainability benefit S_j, determine the actions to do, to maximize the total sustainability benefit while making the total cost under the budget *B*.

The knapsack problem has many variations, one of which is multiple-choice knapsack problem. Multiple-choice knapsack problem was first defined in 1979 as a binary knapsack problem with the addition of disjoint multiple-choice constraints [49]. The additional constraint is that items are subdivided into a number of classes and exactly one item must be taken from each class.

DM 2 is a multiple-choice knapsack problem: given k actions denoted N_i, exactly one product must be chosen from each action class, to maximize the total sustainability benefit while making the total cost under budget *B*.

As discussed above, the knapsack problem is able to model the SWAHO DM problems. The mathematical expressions of the DM problems are presented in Section 4.5.1.

2.4.3 Scoring and Weighting

All the variables in the knapsack problem model are straightforward except S_j. This section reviews the theories about scoring and weighting to help express the sustainability benefit S_j.

Almost all the whole-building sustainability assessments provide results using a “score”, “credit”, or “rating”. Ratings and scores can be uniform quantitative or qualitative measures

regardless of the units. This is the best method to measure sustainability, a concept that covers a wide range of aspects. Therefore, this study adopted a rating score to express sustainability benefit, according to the previous experience of sustainability assessments.

The most common form for ratings and scores is a 5-star rating. People use 5-star ratings when booking hotels, choosing restaurants and purchasing cars (customer reports). People are so familiar with 5-star ratings that they can relate the stars to degrees without the definition of the star classification. In addition, there might be positive or negative impact on the criteria. Therefore, SWAHO enables positive 5-star rating and negative 5-star rating.

The value of the sustainability benefit of a certain action or product should be different for different people because of different individual comprehension of sustainability. Weighting is the strategy to express personal preferences on sustainability criteria. There are several calculation rules available for weighting.

The following symbols are used in Equation 2-1 and Equation 2-2.

- S_j – Sustainability benefit score of Action *j* or Product *j*
- w_i – Weight of sustainability criterion *i*
- e_{ij} – Rating score of Action *j* or Product *j* with respect to criterion *i*
- n – Number of sustainability criteria

A Weighted Sum Method is the simplest calculation rule [50] (see Equation (2-1)).

$$S_j = \sum_{i=1}^{n} w_i e_{ij} \qquad \textbf{Equation (2-1)}$$

The Weighted Product Method is similar to Weighted Sum Method, but the weight is the power in the multiplication function (see Equation (2-2)).

$$S_j = \prod_{i=1}^{n} \left(e_{ij}\right)^{w_i} \qquad \textbf{Equation (2-2)}$$

Both of the calculation rules are applicable for the knapsack problem since the only objective of the problem is to maximize the total sustainably benefit. The higher the S_j is, the greater the benefit is. In this research, the Weighted Sum Method was chosen to calculate S_j for each action and product because of its simplicity.

However, if a MODM model is used, the Weighted Sum Method has limitations in finding the Pareto set, despite its usefulness in an approximation of one's preferences [51]. Researchers tend to use other calculation rules for MODM, such as weighted Tchebycheff approach (compromise programming), global criterion method, and goal programming method [52]–[54].

There are two variables that constitute S_j, the weight of sustainability criteria w_i and the score of an action or product to a criterion e_{ij}. Some theories can facilitate the generation of w_i and e_{ij}, such as Analytic Hierarchy Process (AHP) and Fuzzy Set Theory. These theories are able to increase the usability of the tool, but they do not address the fundamental mechanism of SWAHO. Since the purpose of the development of SWAHO prototype is to prove the concept, these theories were not adopted in SWAHO, but they are briefly introduced below.

Analytic Hierarchy Process (AHP) was firstly proposed by Thomas L. Saaty in 1977 [55]. It makes weighting easy for users by enabling pair-wise comparison rather than comparing all the criteria together. Users assign pair-wise weights between each pair of criteria (i.e., alternative A

relative to alternative B is rated as 9; alternative B relative to alternative C is rated as 3, etc.), which then are converted into global weights w_i that add up to 100% in total (i.e., A – 12.9%, B – 6.5%, C – 8.7%, etc.). AHP is also considered one of the MADM methods [47]. After determining w_i and e_{ij}, the Weighted Sum Method is used to generate a total score for each alternative. The results will present the ranking of the alternatives. SWAHO does not need the ranking of actions or products. Instead, it needs a combination of actions or products to achieve maximum sustainability benefit. Although AHP is not the method used to model SWAHO, the mathematical mechanism that turns pair-wise weights to global weights can be utilized to provide ease of weighting.

In terms of e_{ij}, experts can set the e_{ij} of each action to each criterion, but the e_{ij} of each product to each criterion may need input from the homeowners, such as the rating score of satisfaction level of functions. In the knapsack problem model, e_{ij} is a deterministic number. However, there are uncertainties about e_{ij}, the sources of which may be incomplete information, non-obtainable information, partial ignorance, and unquantifiable information [56]. Fuzzy Set Theory was proposed by Lotfi Zadeh in 1965 [57] and was firstly applied to decision-making problems in 1970 [58]. Fuzzy Set Theory can enable uncertain inputs which are useful in DM 2.

Figure 2-4 concludes the steps to determine S_j (in the center pink box) and the methods that are currently used in SWAHO (in the left orange box) and the methods that could be used in SWAHO (in the right green box). The current methods were chosen because of their simplicity and their capacity for illustrating the concept of SWAHO. The methods in the green box may be used in future development.

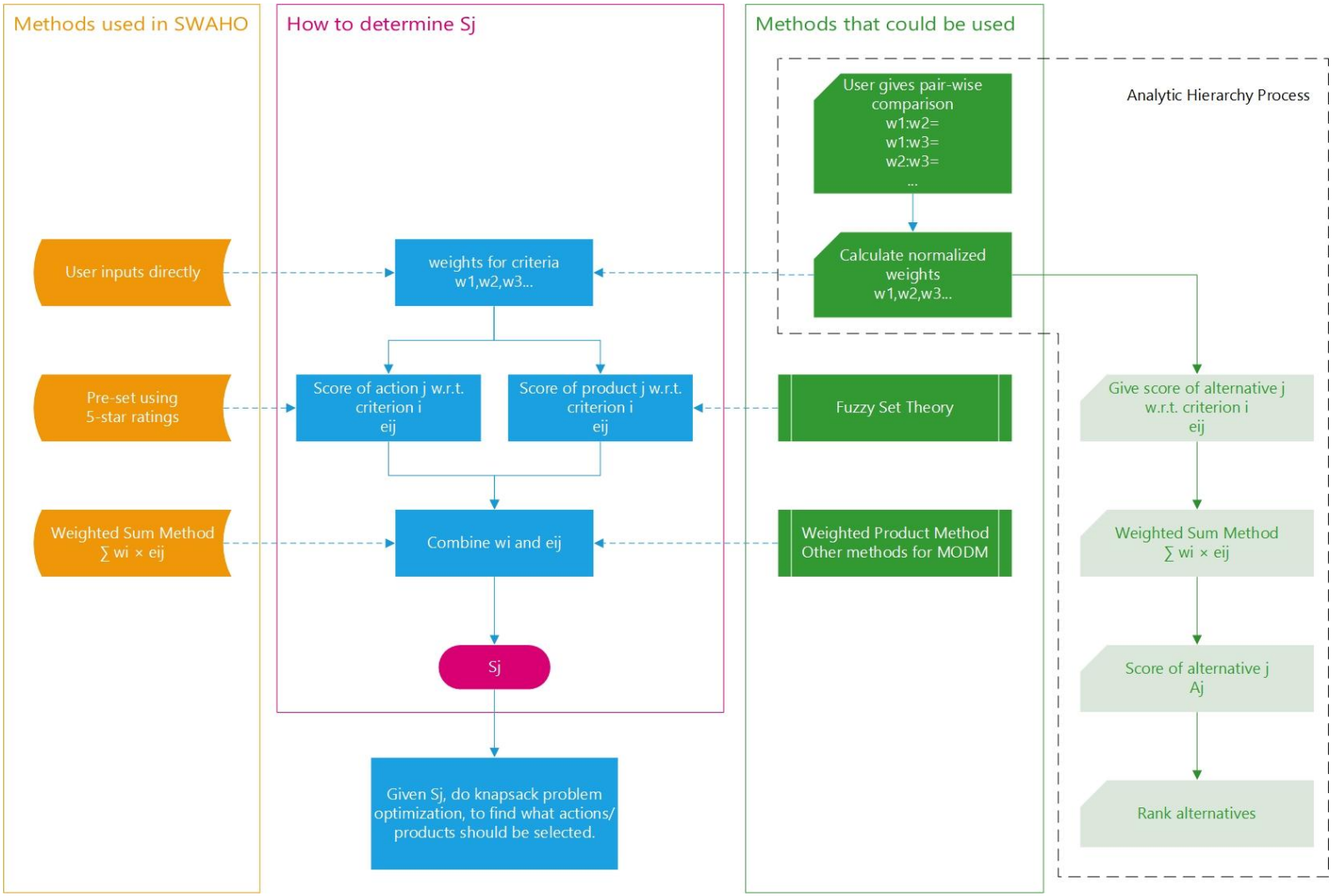


Figure 2-4 Theories behind scoring and weighting

Chapter 3: SWAHO Framework – Conceptual Model

Based on the literature review in Chapter 2, the author developed a conceptual model of SWAHO to help homeowners make green renovation decisions. This section first clarifies the problem that SWAHO will solve and defines the major pieces involved in the problem-solving process. Then, the mechanism behind the problem-solving process is analyzed in order to identify user activities. Last, a Use Case Diagram and a Sequence Diagram are presented to demonstrate the SWAHO framework.

3.1 Problem Statement and Terminology

SWAHO was developed to help the homeowners to answer the question

What are the greenest renovation choices?

Figure 3-1 was created to help the homeowners understand the main pieces involved in the question by some examples. This question involves two parts:

- What does it mean by "greenest"?
- What are renovation choices?

To be able to address "greenest", criteria are identified, such as thermal comfort and energy saving. In this context, a criterion is a sustainability objective. To reflect the personal definition of "greenest", relative weights, in the form of percentages, are assigned to the criteria.

Renovation choices are different renovation actions, such as adding insulation to walls and purchasing a new clothes washer. An action is a major renovation task. For each action, there are choices of product, such as multiple types of insulation materials and different clothes washers.

Each product is associated with several indicators. These indicators relate to the sustainability criteria. For example, the higher the power of a clothes washer is, the less energy it saves.

Moreover, to answer the question "What are the greenest renovation choices?" we need to create the relation between the renovation choices and renovation objectives; that is, the mathematical model. The five major pieces of SWAHO and the mathematical model are defined as follows:

- Criterion: A sustainability objective of the renovation project.
    - e.g., thermal comfort, indoor air quality, energy saving, etc.
- Weight: A percentage that represents the individual preferences on the sustainability criteria, with higher number means more importance.
- Indicator: A quantitative, qualitative or descriptive measure of one criterion.
    - e.g., operating energy (Watt), satisfaction of functions, aesthetic level, etc.
- Action: A major renovation or home improvement task.
    - e.g., replace heating system, add insulation to the walls, etc.
- Product: A specific object purchased to fulfill an action.
    - e.g., Heat pump, fiberglass insulation rolls, certain clothes washer, etc.
- Mathematical model: The calculation rules that enable optimization on renovation choices based on the criteria.

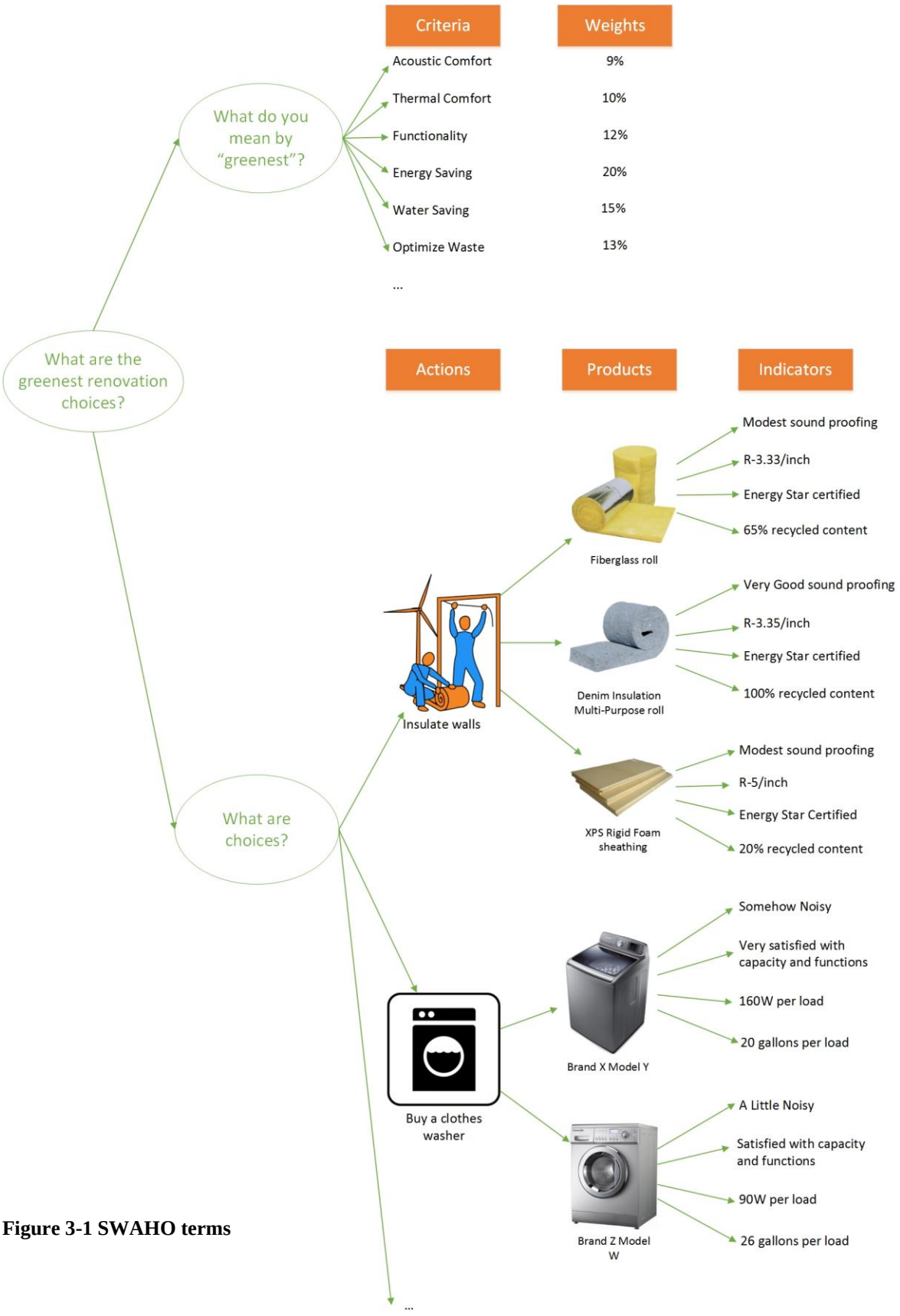


Figure 3-1 SWAHO terms

3.2 Mechanisms

The question "What are the greenest renovation choices?" involves two stages of decision-making (DM):

- DM 1

  Given a set of actions that are of potential interest to the homeowner, which actions should the homeowner do to achieve the maximum sustainability?

- DM 2

  For each action, which product should the homeowner choose to achieve a total maximum sustainability?

Figure 3-2 shows the mechanism behind DM 1; that is, how renovation actions lead to sustainability. Each renovation action has either a positive or a negative impact on one or more sustainability criteria, which then contribute to the overall sustainability represented by the sustainability benefit score. The sustainability criteria consist of social benefits and environmental benefits. In addition, each action is associated with a cost. The goal is to achieve the maximum sustainability benefit score with the constraint that the total cost is less than the budget.

For each row in the mechanism in Figure 3-2, the user activity is identified. Homeowners can assign weights to the sustainability criteria as their objectives, check renovation actions that they are interested in, estimate the cost for each action, and enter the budget for the whole renovation project.

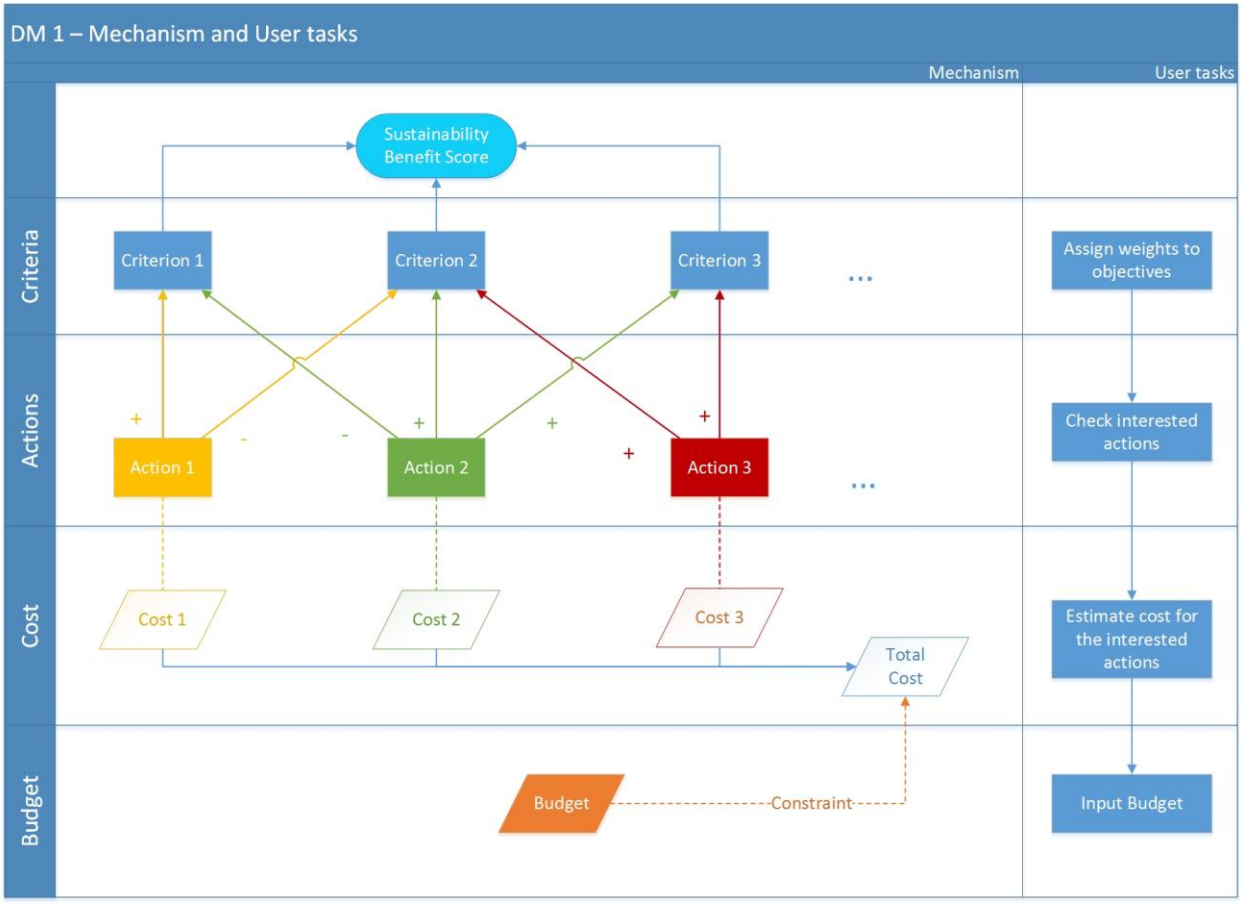


Figure 3-2 Mechanism of DM 1

Figure 3-3 is a simplified and partial example of DM 1 to provide further explanation of the mechanism. In the real tool, there are more criteria and more actions than those shown in the figure. Imagine the homeowner is interested in three potential renovation actions: install a heat pump, buy a new fridge, and add insulation to walls. A heat pump provides heating and cooling as needed, thus it contributes to the criterion "Thermal Comfort". On the other hand, a heat pump consumes lots of energy, thus it has a negative impact on "Energy Saving". Similarly, a new fridge will add to functionality but use some energy. Adding insulation to walls is good for "Thermal Comfort", "Acoustic Comfort" and "Energy Saving" to different degrees. The homeowner

estimates that he or she may spend $3,600, $2,000 and $5,000 for the three actions, respectively, and he or she has a budget of $9,000 for the whole renovation project. His or her preferences on the different sustainability criteria are indicated by the weights in the figure.

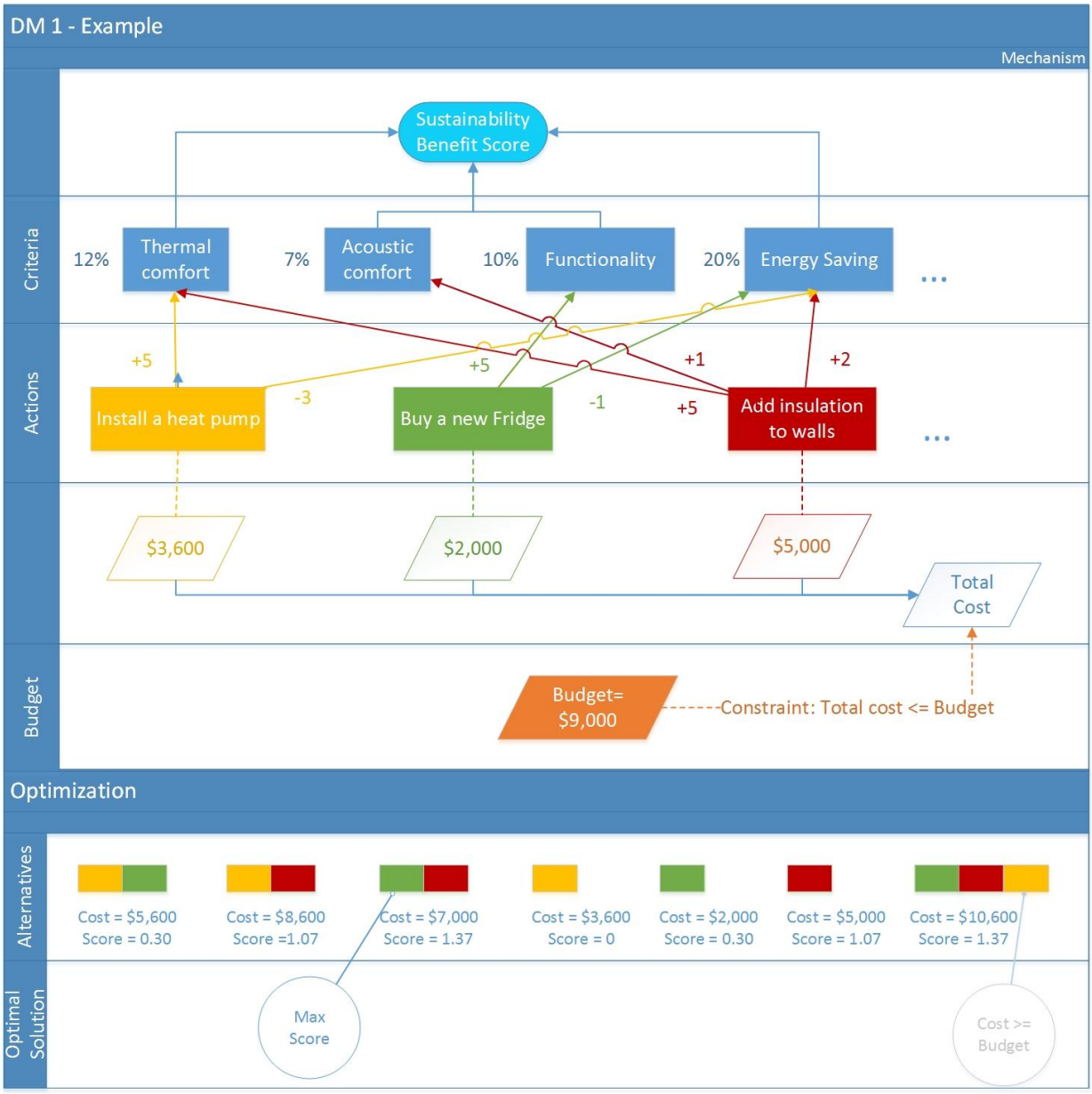


Figure 3-3 Partial example of DM 1

There are six combinations of the three actions, as shown in the row of "Alternatives" under "Optimization" in Figure 3-3. Each solution has a total cost and a total sustainability benefit score.

Take the first alternative solution, for example:

$$Cost = \$3{,}600 + \$2{,}000 = \$5{,}600$$

$$Score = [(+5) \times 12\% + (-3) \times 20\%] + [(+5) \times 10\% + (-1) \times 20\%] = 0.30$$

Excluding the alternative solution "do all the three actions" in which the cost is over budget, the optimal solution is to buy a new fridge and add insulation to walls. Obviously, if the weights are changed, different actions are checked, the costs of the actions are changed, or the budget is different, the final optimal solution will be different.

The mechanism of DM 2 is similar, but two rows are inserted between the criteria and the actions, as shown in Figure 3-4. Each action has more than one product alternatives. Each criterion can be represented by different indicators. Indicators are features of the products. The various product alternatives for a given action are all associated with the same set of indicators. For example, the two alternative products that can be selected for Action 2 (the yellow and the green) are associated with Indicator 3 of Criterion 1, Indicator 2 of Criterion 2, and Indicator 1 of Criterion 3. In terms of the two new rows, user activities include selecting products of interest and inputting the values of indicators.

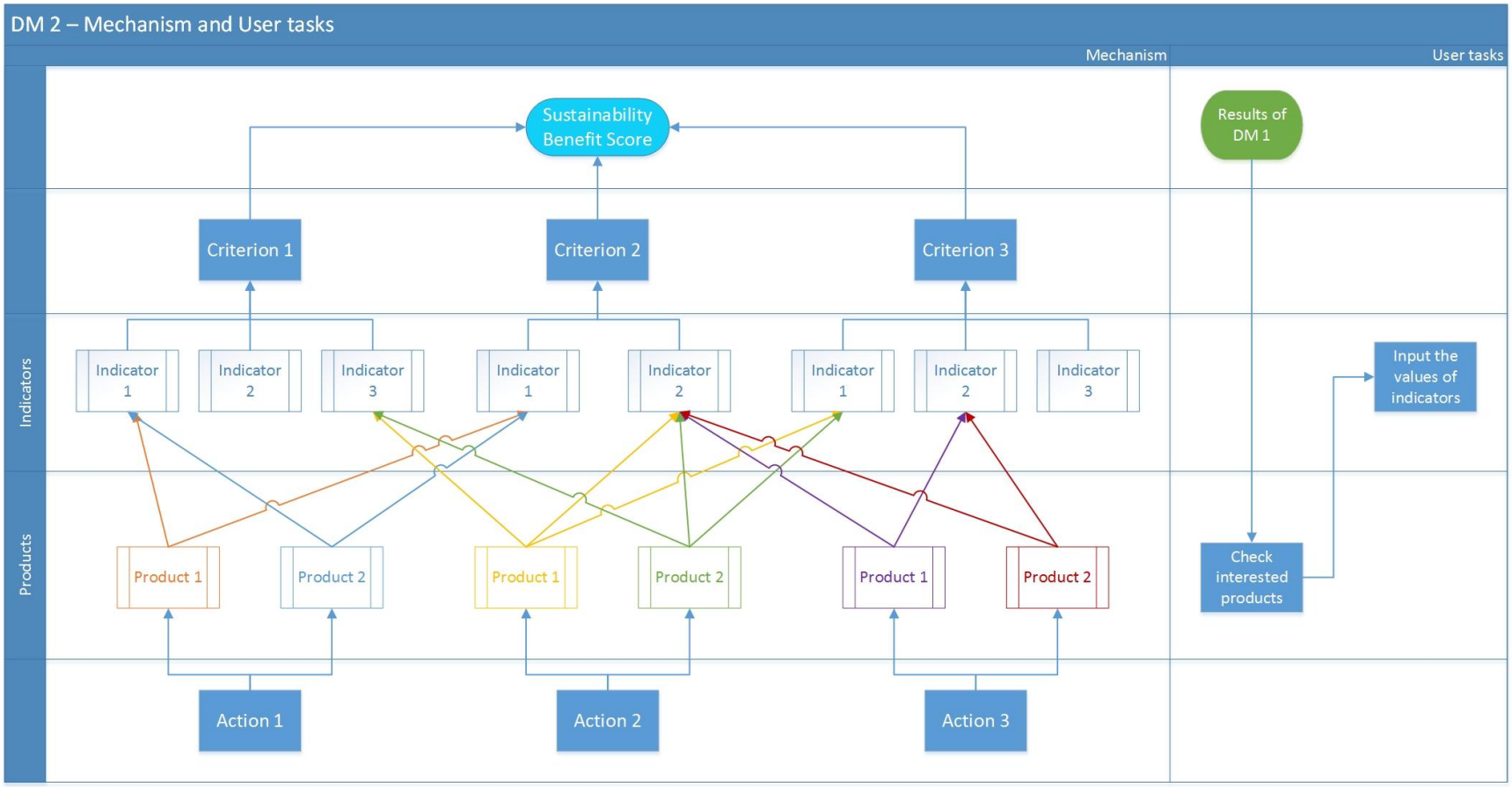


Figure 3-4 Mechanism and user activities in DM 2

3.3 Use Case Diagram

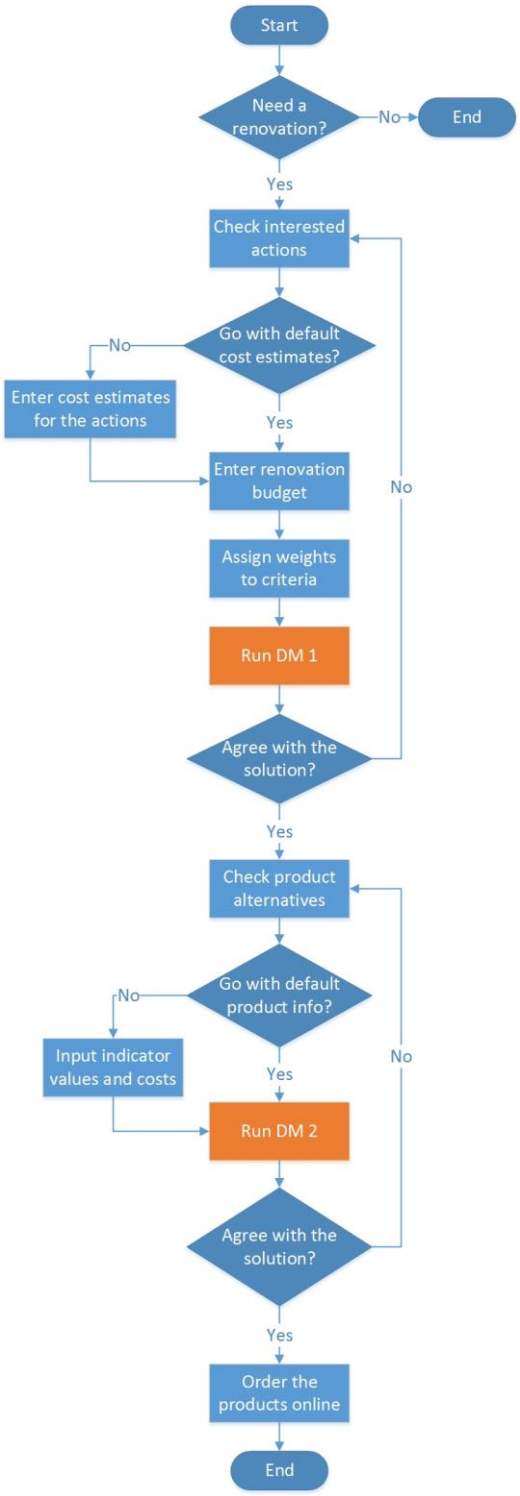


Figure 3-5 SWAHO flowchart

Figure 3-5 SWAHO flowchart combines the user activities identified in Figure 3-2 and in Figure 3-4. It shows the process of using SWAHO from the point of view of the users – homeowners. The solution to DM 1 is a set of renovation actions. The solution to DM 2 is one product for each action.

A Use Case Diagram, one of the Behavioral UML (Unified Modeling Language) diagrams for software development, is the simplest representation of the user's interactions with the system. A Use Case Diagram (Figure 3-6) was created based on the user activities from Figure 3-5. It shows the interactions in the SWAHO system, which include not only the ones between the user and the system, but also the database-system and web-system interactions. The rectangle on the left represents the DM 1 system while the rectangle on the right represents the DM 2 system. The blue bubbles are the events happening in the system—that is, the use cases. The lines in between represent the relationships.

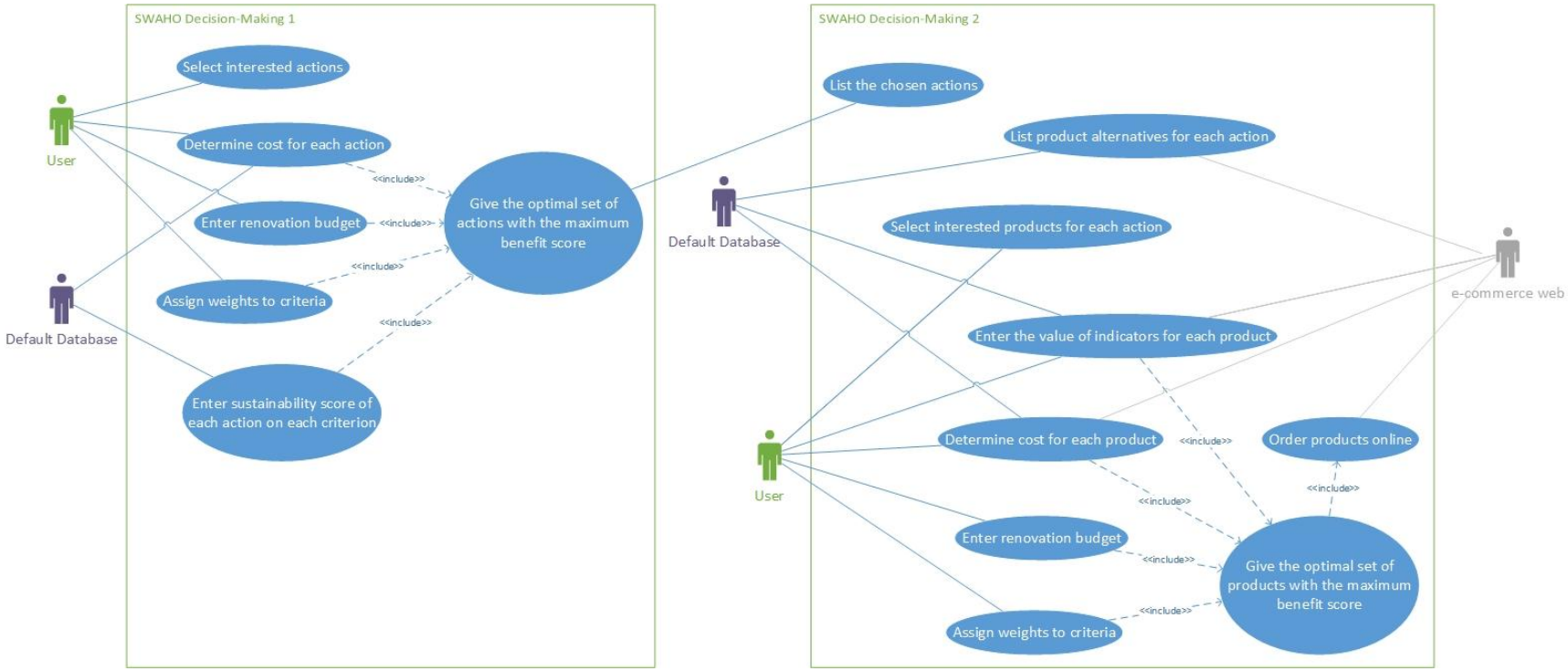


Figure 3-6 Use Case Diagram of SWAHO

As Figure 3-6 shows, in DM 1, the user is required to perform four tasks:

1. Select the actions of potential interest;
2. Determine cost for each action;
3. Enter renovation budget;
4. Assign weights to criteria.

The SWAHO database provides default cost estimates for the actions. Users can change the cost if they know the local average cost. The SWAHO database also pre-sets the sustainability scores of each action to each criterion. The four elements—the costs of the actions, the weights of criteria, the budget, and the sustainability scores—enable the optimization calculation for DM 1. The result of DM 1 is the start point of DM 2.

In DM 2, the SWAHO database, together with the e-commerce website, can provide a list of product alternatives for each action from the results of DM 1. There are five tasks for the users:

1. Select products of interest for each action;
2. Enter the indicator values for each product;
3. Enter cost for each product;
4. Enter renovation budget;
5. Assign weights to criteria.

In task 2, some indicator values can be input automatically from online sources, while others may need input from the user. In task 3, users can either enter cost or agree with the cost provided by SWAHO database or e-commerce websites. For task 4 and 5, users either stick with the budget and weights that they have entered for DM 1 or adjust the budget and weights.

Similar to DM 1, the four elements—the costs of the products, the weights of criteria, the budget, and the indicator values for the products—enable the optimization calculation for DM 2. The results of DM 2, the products suggested, are linked to e-commerce order pages.

3.4 Sequence Diagram

Use Case Diagrams are from the user's point of view, while Sequence Diagrams are from the software developer's point of view. Sequence Diagrams are another UML diagram that shows how objects operate with one another and in what order in the software. SWAHO could have been developed using any software platform, but the prototype was developed in Microsoft Excel. Therefore, the Figure 3-7 shows ideally how information and commands flow between the Excel sheets and the e-commerce websites.

In Figure 3-7, the flows happen in the time sequence from top to bottom. The e-commerce web line and related information flows are gray because this part is out of the research scope and thus the links between e-commerce system and SWAHO may not be as simple and direct as shown in the diagram.

The DM 1 phase was developed into a real tool as a prototype, which is introduced in detail in Chapter 4.

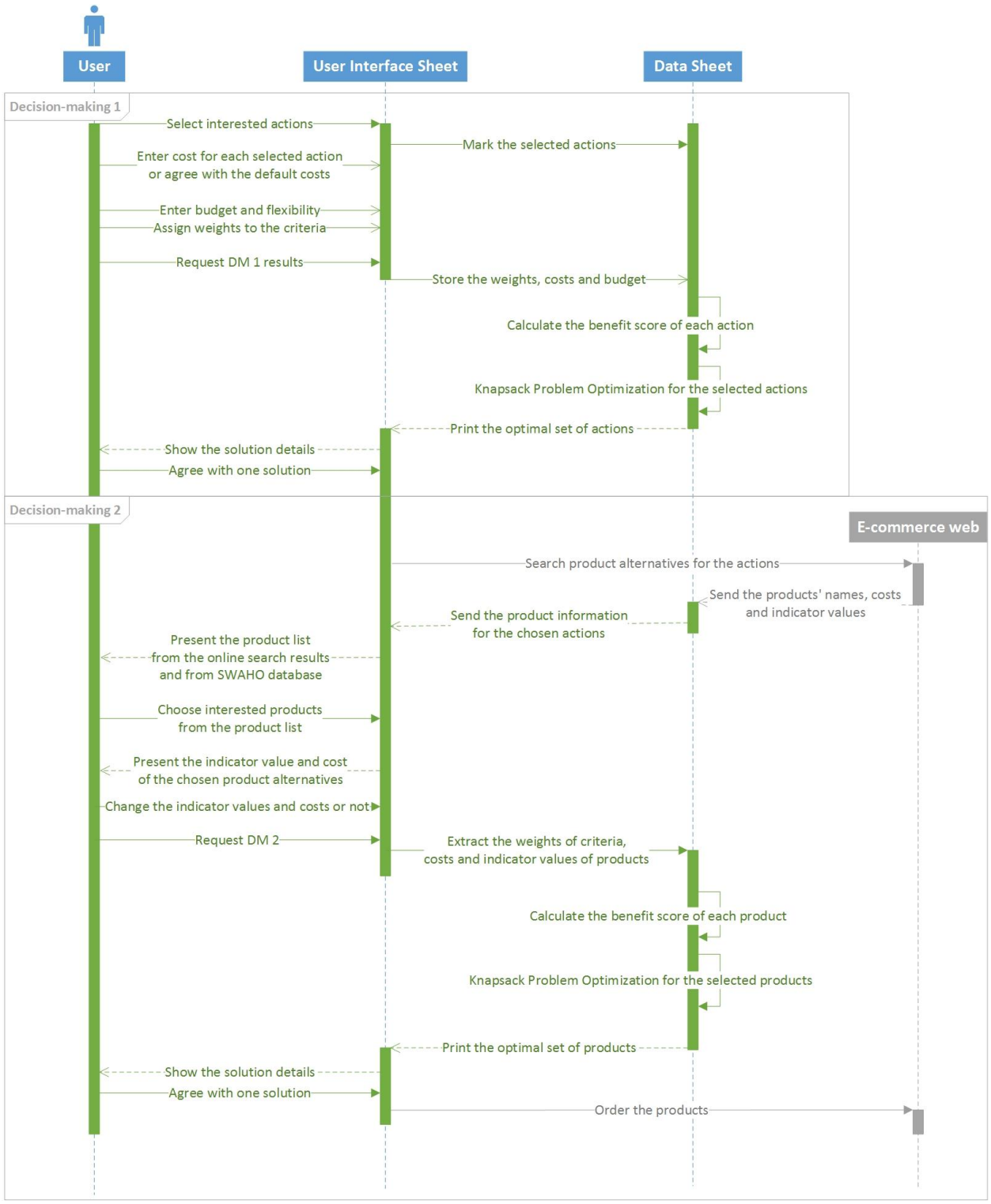


Figure 3-7 Sequence Diagram of SWAHO

Chapter 4: SWAHO Development – Excel Prototype

A prototype of SWAHO was developed using Microsoft Excel Visual Basic for Applications (VBA) to solve the DM 1 problem – "Given a set of actions that are of potential interest to a homeowner, which actions should the homeowner do to achieve the maximum sustainability?" This chapter describes the functions that are included in the prototype and how they were developed.

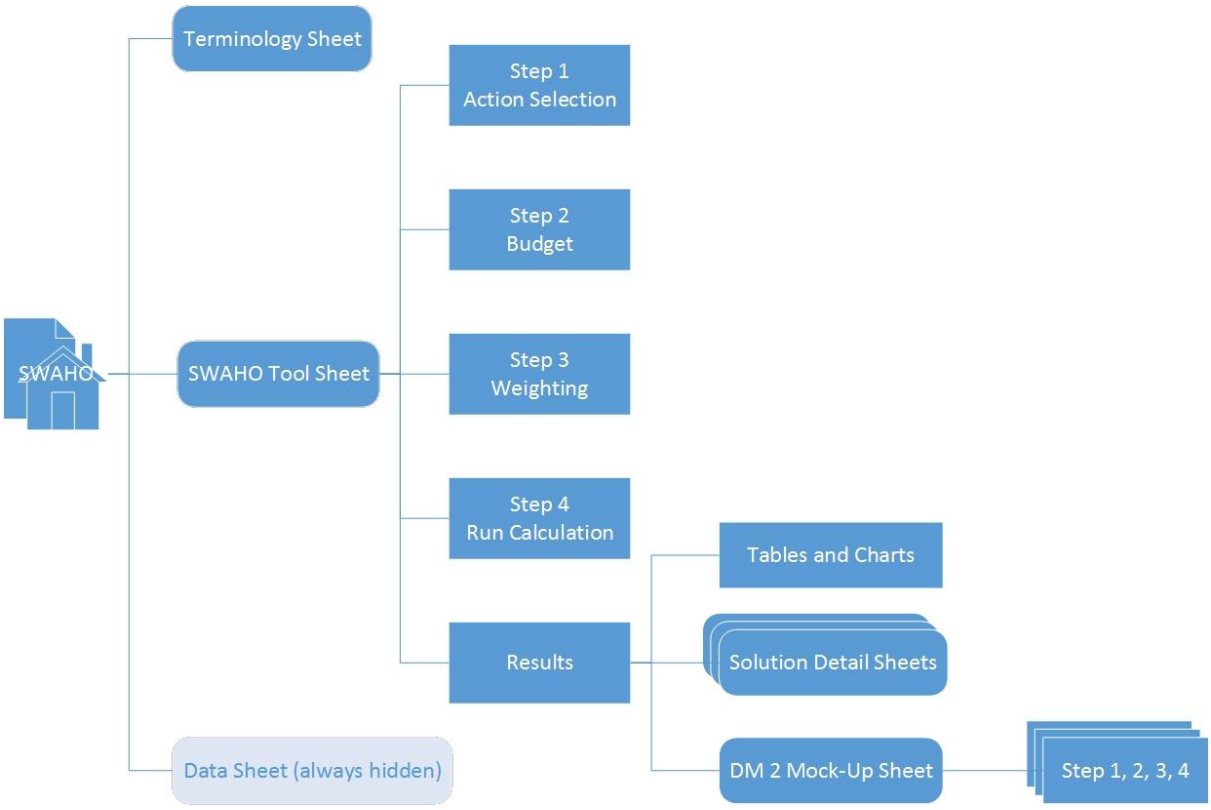


Figure 4-1 Elements of SWAHO prototype in Excel

When a user opens the Excel file of SWAHO, he or she will see two sheets named "Terminology" and "SWAHO Tool" respectively. The terminology sheet contains Figure 3-1. It is provided to help the user understand the terms. The "SWAHO Tool" sheet is the main user

interface. A data sheet is always hidden in the background for data collection and calculation. There are five areas on the "SWAHO Tool" sheet: Step 1 to Step 4 and the Results area. Besides tables and charts to present the results, the Results area contains buttons that link to sheets with further solution details and a DM 2 mock-up sheet.

Section 4.1 introduces the user interface of the SWAHO tool, followed by sections digging into the main components of the prototype: the action list, the criteria list, the scoring mechanism, the mathematical optimization algorithm, and a mock-up of DM 2.

4.1 User Interface

The "SWAHO Tool" sheet is the user interface for DM 1. It can be divided into an input area and an output area.

4.1.1 Input Area

The input area consists of four steps:

- Step 1: Check Interested Actions;
- Step 2: Enter Budget;
- Step 3: Assign Weights;
- Step 4: Run Calculation.

Figure 4-2 to Figure 4-5 are the screenshots of the four steps, followed by introduction and description of the steps.

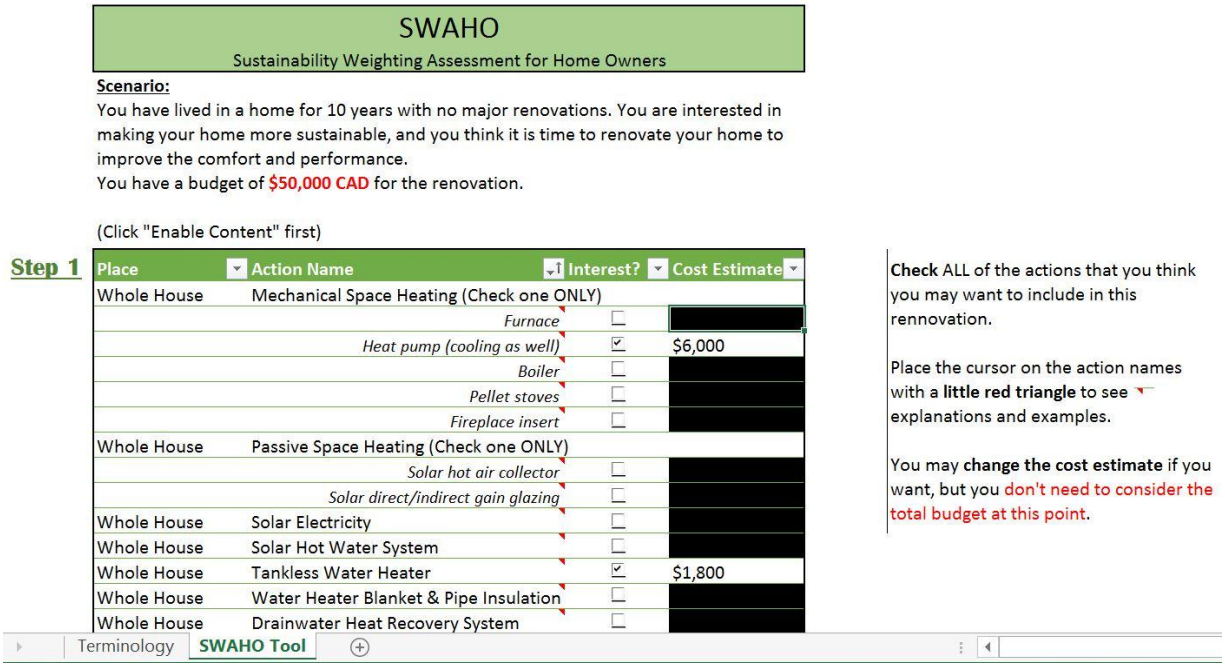


Figure 4-2 Screenshot of input area – step 1 of DM 1

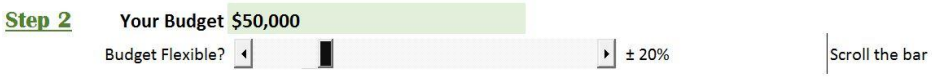


Figure 4-3 Screenshot of input area – step 2 of DM 1

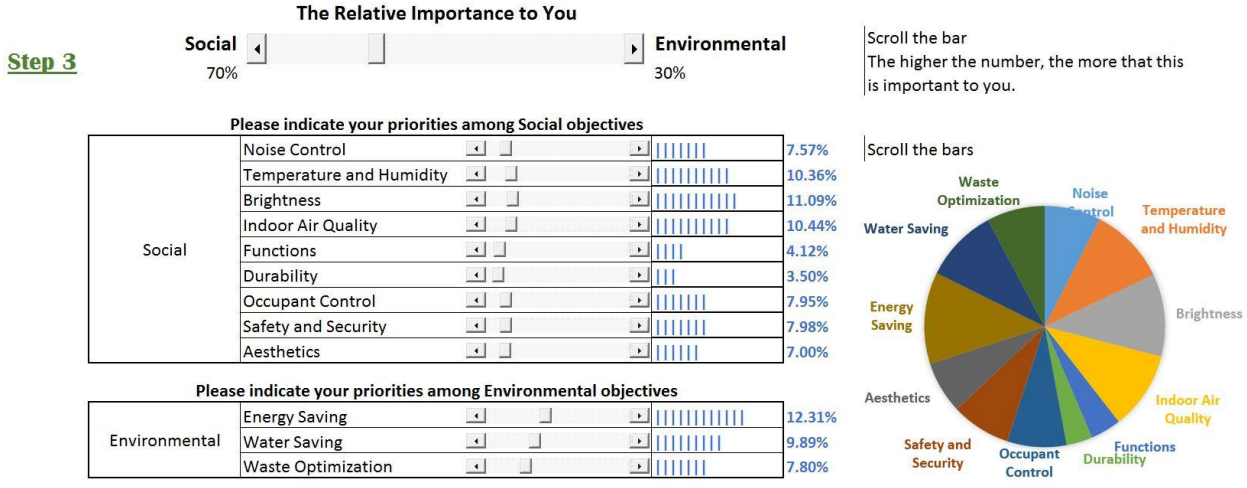


Figure 4-4 Screenshot of input area – step 3 of DM 1

Figure 4-5 Screenshot of input area – step 4 of DM 1

In Figure 4-2, the top area that provides a description of a scenario is for testing purpose only. It would be omitted in normal tool use. The texts on the right with a vertical black line are instructions for Step 1. By default, all the actions are unchecked. Users can check the checkboxes and change the cost estimates, as they wish. Section 4.2 provides more details to Step 1.

In Figure 4-3, users enter their budget for the whole renovation project in the green cell. If they drag the scrollbar to indicate budget flexibility, they will receive results for three cases. If, for example, they indicate a $50,000 budget and 20% flexibility, their final results will show Solution 1 for the case of $50,000 budget, Solution 2 for the case of $40,000 budget ($\$50{,}000 - \$50{,}000 \times 20\%$), and Solution 3 for the case of $60,000 budget ($\$50{,}000 + \$50{,}000 \times 20\%$). This function is to address the uncertainty of budget in reality.

In Figure 4-4, users first drag the scrollbar on the top to indicate the relative value that they place on social criteria and environmental criteria, and then drag the scrollbars below to indicate preferences among each group. Social criteria consist of nine aspects, while environmental criteria consist of three aspects. The twelve criteria add up to 100% in total. The default setting assigns equal weights to all the twelve criteria. The blue bars, the percentage numbers, and the pie chart show the weights in real-time as the user drags the scrollbars. The reason why the criteria are grouped instead of mixed is twofold: to encourage users to consider sustainability from two aspects, social and environmental, and to make it relatively easier to decide about weights. Section 4.3 provides more discussion on the criteria.

Figure 4-5 shows the last step – click “Get Solutions” to run the optimization. “Clear Everything” is the option to go back to default setting.

4.1.2 Output Area

After running the calculation, results are exhibited in the output area. Figure 4-6 is the screenshot of the output area provided some random inputs. There are two parts in the output area: the bottom part shows actions suggested for three cases; the top part provides comparisons between the three solutions.

Figure 4-7 is a closer look at the bottom part. The blue “Solution 1” is for the base budget case, the orange “Solution 2” is for low budget case (base budget less budget flexibility), and the gray “Solution 3” is for high budget case (base budget plus budget flexibility). Each solution lists the actions suggested, the budget, the total cost of actions suggested, and the total sustainability score. The button “See Details” links to the corresponding solution detail sheet, which is introduced later in this dissertation.

Figure 4-6 Screenshot of output area of DM 1

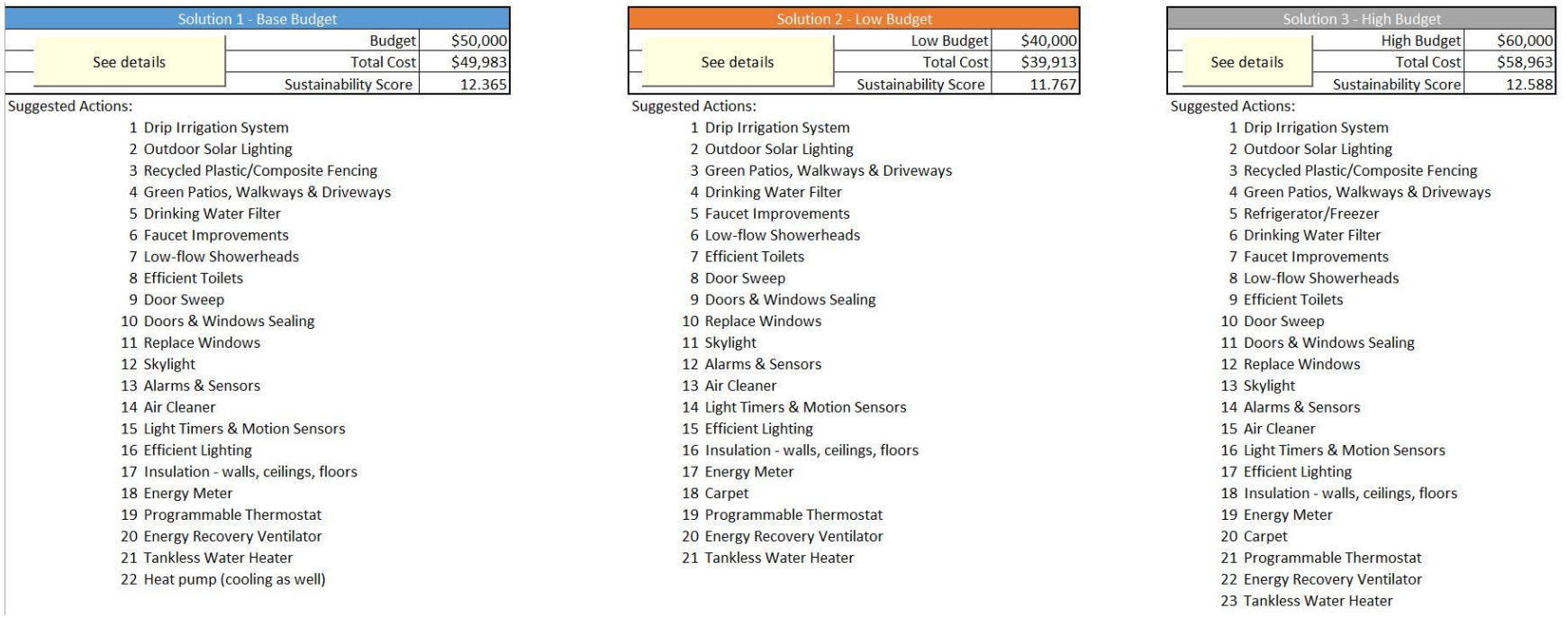
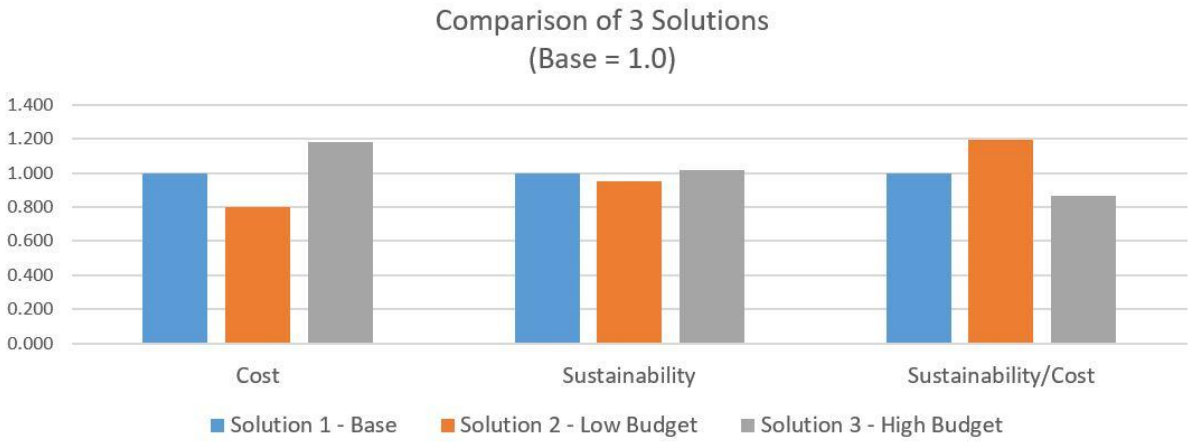


Figure 4-7 Example of three solutions



(a)

(b)

Figure 4-8 Example of the comparison charts

The top part includes two comparison charts (Figure 4-8).

As described in Section 2.4.2, the mathematical model treats the optimization as a cost-benefit analysis, where cost represents the economic pillar of sustainability and benefit embodies social pillar and environmental pillar of sustainability. Here, in the prototype, the word

“sustainability” is the short expression of “sustainability benefit” or “sustainability score” that covers social and environmental aspects. Therefore, Figure 4-8 (a) compares the cost, sustainability score, and score/cost by normalizing the three solutions to a base budget solution (therefore, the value of the base solution is 1.0). In addition, Figure 4-8 (b) is a spider chart that shows the sustainability scores of sustainability criteria earned by the three solutions. The closer to the periphery a point is, the more benefit is earned for the sustainability criterion. For instance, Figure 4-8 (b) shows that the base budget solution (blue line) has more benefit than the other two solutions in “Temperature and Humidity” and “Indoor Air Quality” but less benefit in “Energy Saving” and “Aesthetics”.

The button “See Details” for Solution 1 in Figure 4-7 will open the “Solution 1 Details” sheet as shown in Figure 4-9. The table on the top (Figure 4-9 (a)) presents the post-weighting sustainability score of each action (the rows) for each criterion (the columns). The green bars represent positive scores, while the red bars represent negative scores. The blue bars on the right are the total scores of each action. This table informs the user which action is more sustainable according to his or her perception of sustainability and why. The chart at the bottom (Figure 4-9 (b)) illustrates the scores across the twelve criteria earned by this solution. Users can grow the sense that in what aspects they have more wins.

Similarly, there are “Solution 2 Details” sheet and “Solution 3 Details” sheet with the same action detail table and criteria score chart. Furthermore, there is a button named “Product Selection Mock-Up” on the top-left corner in Figure 4-6. This button leads to DM 2 mock-up sheet, which is introduced in Section 4.6.

Figure 4-9 Example of "Solution 1 Details" sheet

4.2 Sustainable Actions and Products

This section provides more information about the step 1 in DM 1. Figure 4-10 shows the action list in the user interface sheet.

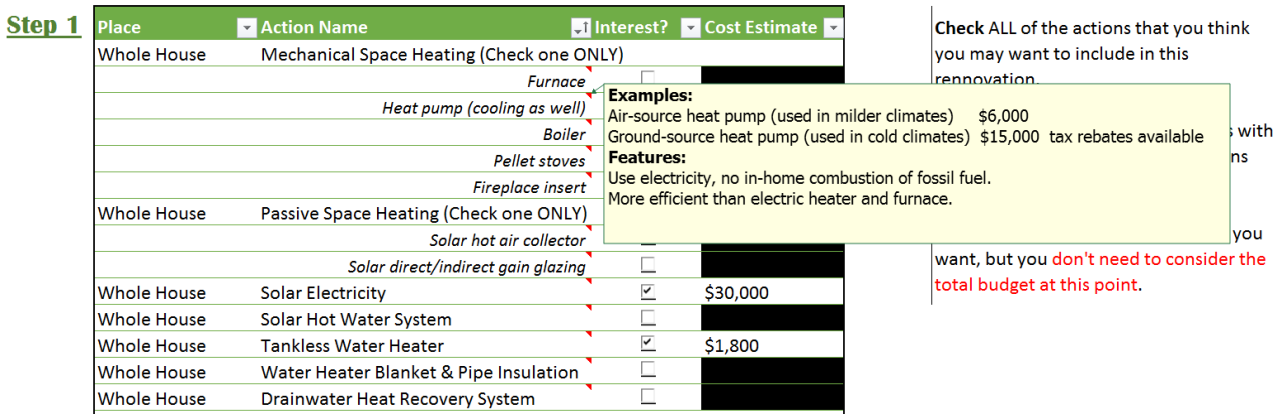


Figure 4-10 Screenshot of Step 1 in SWAHO

4.2.1 Action List

Renovation actions were collected from the review in Section 2.2, and only those actions that meet the following two criteria remained:

- They incur costs for the homeowner;
- They are common for a "home renovation".

For example, "properly set thermostat" is an action to save energy but it does not require any cost. "Sloping the soil" can naturally drain the water away from the house foundation and thus, to some degree, protect the house from moisture, mold and other damage to the structure. However, this is rather an action for a new house than an action for home renovation.

The final action list in SWAHO ends up containing 47 renovation actions and one action named “other” where users are allowed to input any action not yet included in the list. To help the user understand the actions, explanations and examples are given for some of the actions using the pop-up comment boxes in Excel. In addition, the place (i.e., the part of a house) where a renovation action is deployed was listed as well in order to enable the renovation for a specific area. The places include whole house, envelope, bathroom, kitchen, laundry, and outdoor. Table 4-1 is the full list of renovation actions.

4.2.2 Cost Estimates

The cost estimates of the actions in Table 4-1 are either from the RSMeans books *Green Home Improvement* [13] and *Green Building: Project Planning & Cost Estimating*, 2002 [14] or from online resources. All the numbers are location adjusted and time adjusted. First, the cost estimates from the RSMeans books were adjusted for Vancouver and Canadian dollar by multiplying the location factor of Vancouver in the book [14], which is 1.05. Then the cost estimates were multiplied by the inflation rate from the year of publication to the year 2016. When the cost of an action is scale-related, the estimate is based on a 2-storey 2000 square feet house model. For example, the cost of flooring depends on the square feet of the floor. All the cost estimates include labor fees for removal of the old system and installation of the new system when necessary. The estimates are average costs in North America. However, costs vary a lot in different cities. Therefore, users can change the estimates if they have the confidence that the default number is not the case in his or her location.

4.2.3 Product List

It is impossible to develop a full list of renovation products for the renovation actions since numerous models and brands exist and new products keep coming to market. An approach that could be feasible for SWAHO would be to link it to e-commerce marketplaces where there is a specific business case for vendors to make updated products available. This e-commerce connection is within the conceptual design envisioned for SWAHO but has not been developed within the scope of this dissertation.

For the three actions in Table 4-1, *Mechanical Space Heating*, *Passive Space Heating*, and *Mechanical Cooling*, several different categories of products are listed below the action name because they are so different that they have different contributions to the sustainability criteria. In this case, they are not "products", but rather sub-actions. For example, "heat pump" means replacing the old heating system with a heat pump; "boiler" means replacing the old heating system with an in-floor water heating system along with an efficient boiler.

Although a full product list is not available, some common types of products are listed in the pop-up comment boxes (example in Figure 4-10). Table 4-1 shows the content in the comment boxes (explanations and/or examples), costs, and cost sources for the 48 actions in the prototype.

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (a)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Whole House	1	Mechanical Space Heating			
		Furnace	*Fossil fuel is burned to heat the air.* *Energy-efficient models are available.*	$4,600	[13]
		Heat pump (cooling as well)	***Examples:*** *Air-source heat pump (used in milder climates) $6,000* *Ground-source heat pump (used in cold climates) $15,000* *tax rebates available* ***Features:*** *Use electricity, no in-home combustion of fossil fuel.* *More efficient than electric heater and furnace.*	$5,750	Websites: HeatPumpPriceGuides, Fixr.com, QualitySmith.com
		Boiler	*Boiler burns fossil fuels or electricity to heat water, which is then distributed under your floor or through baseboard to provide space heating.* ***Features:*** *More efficient than forced air heating.* *The cost of fossil fuels is high.* *Consumes water.*	$5,310	[13]
		Pellet stoves	***Features:*** *No chimney.* *The fuel is made from waste material.* *Cleaner than wood stoves.* *Require occasional maintenance.* *Use electricity.*	$5,780	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (b)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
		Fireplace insert	*Use existing fireplace, but insert a firebox.* ***Features:*** *Increase the efficiency of wood-burning fireplaces about 65% to 70%.* *Reduce pollution emissions.*	$3,060	[13]
Whole House	2	Passive Space Heating			
		Solar hot air collector	*Collectors are mounted on south-facing exterior walls. Draw cold indoor air in, heat it, and blow warm air into the room.*	$2,950	[13]
		Solar direct/indirect gain glazing	*A section of south wall is removed and replaced with glazing. Cost for double glazed window, two panels wide:* *Direct gain system $2,468* *Indirect gain system $1,386*	$2,468	[14]
Whole House	3	Solar Electricity	*PV panels are installed on a south-facing roof. They produce electricity for home use and feed back to the grid.* *Cost: around $12 per watt capacity (including installation)*	$30,000	[13]
Whole House	4	Solar Hot Water System	*Collectors are usually mounted on the roof. Solar energy heats the water for domestic use, such as shower, dishwasher, etc.*	$11,450	[13]
Whole House	5	Tankless Water Heater	*No water tank. Heat water as needed.*	$1,800	[13]
Whole House	6	Water Heater Blanket & Pipe Insulation	*For water heaters with storage tank*	$25	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (c)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Whole House	7	Drainwater Heat Recovery System	*Drainwater heat recovery pipe takes advantage of the warm water flowing down the drains to preheat the water going into the hot water tank.*	$660	[14]
Whole House	8	Mechanical Cooling			
		Evaporative cooler	***Features:*** *Used in dry, hot climate* *Use electricity* *Slightly moisten air*	$4,900	[13]
		Air conditioning	*Used in all climates.* *Air conditioner needs to be replaced at 10 - 15 years old.* ***Examples:*** *Central air conditioning system* *Window/Wall air conditioner*	$5,500	Website: HomeAdvisor
		*Heat pump**	*If you have chosen a heat pump for heating, you can use it as an air conditioner in the summer, so you DON'T add any cost here.*	$0	-
		Fan	***Examples:*** *Ceiling fans $40 - $300* *Solar attic fans $350 - $800* *Regular attic fans ~ $100* *Whole house fan ~$1,700*	$300	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (d)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Whole House	9	Passive Cooling - Shades	***Examples:*** *Blinds* *Shades* *Drapes* *Curtains*	$900	[13]
Whole House	10	Passive Cooling - Radiant barrier	*Installed in attics to block heat in summer.*	$1,000	[13]
Whole House	11	Energy Recovery Ventilator	*Most cost-effective in climates with extreme winters or summers.* ***Examples:*** *Wall-mounted* *Window-mounted* *or in attics, utility rooms, basements, crawl spaces*	$1,300	[13]
Whole House	12	Programmable Thermostat		$250	[13]
Whole House	13	Green Flooring	***Examples:*** *Cork $22,420* *Bamboo $27,140* *Reclaimed wood $35,990* *All-natural linoleum $15,930* *Laminate $20,060* *Recycled-content tile $37,760*	$26,550	[13]
Whole House	14	Carpet	***Examples:*** *Recycled-content carpet $12,980* *All-natural wool carpet $39,530*	$26,255	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (e)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Whole House	15	Interior Wall Painting	*Use Low/No VOC paints.* *You can consider adding an insulating additive to paints.*	$10,000	[13]
Whole House	16	Energy Meter	*The Energy Detective (TED) displays real-time energy usage on an LCD screen.*	$350	[13]
Whole House	17	Insulation - walls, ceilings, floors	***Examples:*** *Cellulose* *Fiberglass made from recycled glass* *Rigid foam insulation* *Cotton batt insulation* *Loose-fill wool insulation* *Liquid foam insulation*	$5,400	[13]
Whole House	18	Radon Test and Mitigation	*Test and Analysis $35* *Mitigation System $1,400*	$35	[13]
Whole House	19	Efficient Lighting	*Replace light bulbs only or replace light fixtures as well.* ***Examples:*** *CFL (compact fluorescent light bulbs)* *LED lights*	$825	[13]
Whole House	20	Light Timers & Motion Sensors	***Examples:*** *Timer switch - shut off lights after the time you set.* *Motion-sensor switch - turn on lights when movement is detected.*	$625	[13]
Whole House	21	Indoor Plants	*Cost varies a lot depending on different types of plant and interior planters.*	$300	[14]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (f)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Whole House	22	Air Cleaner	***Examples:*** *Duct-mounted $1,220* *Stand-alone unit $250*	$250	[14]
Whole House	23	Alarms & Sensors	***Examples:*** *Freeze $538* *Fire $485* *Differential pressure (air) $740* *Differential pressure (water) $1,050* *Current Sensor $538* *Duct high temperature thermostat $707* *Duct smoke detector $875* *Carbon monoxide detector $88* *Carbon dioxide detector $248* *Security alarms $600* ***Please enter the total cost of your choices.***	$3,000	[14]
Envelope	24	Skylight	*Good for windowless spaces* ***Examples:*** *Tubular skylight (10"-14" diameter) $885* *Fixed traditional skylight (24"x48") $1,870* *Operable traditional skylight (44"x57") $2,260*	$885	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (g)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Envelope	25	Green Roofing	***Examples:*** *Recycled-content shingles* *Wood shingles& shakes* *Metal roofing* *Fiber-cement shingles & slate & clay tiles* *Rubber roofing*	$14,042	[13]
Envelope	26	Repair Windows	***Examples:*** *Heat-shrink plastic* *Exterior/Interior storm windows*	$1,500	[13]
Envelope	27	Replace Windows	***Configurations,*** *from most to least energy-efficient:* *Non-operable* *Casement* *Awning* *Hopper* *Single- and double-hung* ***Sash materials:*** *Wood* *Vinyl* *Aluminum* *Fiberglass* ***Number of panes of glass:*** *the more, the better.* ***U-factor:*** *the lower, the better.*	$6,372	[13]
Envelope	28	Exterior Storm Door		$484	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (h)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Envelope	29	Doors & Windows Sealing	*Caulk and weather-strip* ***Cost:*** *Materials only* *$140* *Materials + labor + markup* *$700*	$140	[13]
Envelope	30	Door Sweep	*A type of weather-stripping mounted on the inside bottom of a door*	$20	[13]
Bathroom	31	Efficient Toilets	***Examples:*** *Single-flush at 6 liters per flush (1.6 US gal; 1.3 imp gal) toilet* *Dual-flush toilet* *Flushmate-equipped toilet*	$500	[13]
Bathroom	32	Low-flow Showerheads		$50	[13]
Kitchen & Bathroom	33	Faucet Improvements	***Examples:*** *Add aerators* *$10 each* *Replace the whole faucet* *$240*	$20	[13]
Kitchen	34	Dishwasher		$1,200	[14]
Kitchen	35	Drinking Water Filter	*Purification and treatment on dirt, rust, odor, taste, scale and contaminants like fluoride, chlorine, etc.*	$1,115	[14]
Kitchen	36	Kitchen Range Hood		$600	Websites: IKEA, Costco, Lowe's, Home Depot
Kitchen	37	Refrigerator/Freezer		$2,000	[14]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (i)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Laundry	38	Clothes Dryer		$1,400	[14]
Laundry	39	Clothes Washer		$2,300	[14]
Outdoor	40	Green Patios, Walkways & Driveways	***Examples:*** *Permeable concrete pavers* *Pervious concrete* *Gravelpave* *Grasspave*	$1,240	[13]
Outdoor	41	Composite Decks & Porches		$4,012	[13]
Outdoor	42	Recycled Plastic/Composite Fencing		$24,662	[13]
Outdoor	43	Outdoor Solar Lighting	*Along walkways, around swimming pool*	$608	[13]
Outdoor	44	Solar Pool Heater & Cover		$4,720	[13]
Outdoor	45	Rainwater Collection Barrel		$170	[13]
Outdoor	46	Drip Irrigation System		$2,183	[13]

Table 4-1 SWAHO renovation action list, with explanations, cost, cost sources (j)

Place	No.	Action Name	*Explanations/Examples*	Cost	Cost Source
Outdoor	47	Greywater Recovery System	*Greywater is wastewater from sinks, showers, baths, clothes washing machine, and dishwasher.* *Greywater can be reclaimed, treated, and then used for exterior irrigation.* ***System Cost:** $6,600 - $13,200* *(including tank, pump & distribution lines, installation costs)*	$10,000	[14]
-	48	Other (Enter action name here)		$0	

4.3 Sustainability Criteria and Indicators

4.3.1 Criteria List

Each of the sustainability assessments reviewed in Section 2.3 incorporates a number of sustainability criteria. All of them are important, but SWAHO only addresses those that fit in the scenario of a home renovation project. Since the up-front cost represents the economic criterion of sustainability, other criteria are categorized into social criteria and environmental criteria. Social criteria are related to personal comfort and well-being at home, while environmental criteria address global environmental issues.

Table 4-2 shows the final list of criteria and their definitions. The criterion names in the second column are common names from the literature review. However, homeowner testers found some criterion names too obscure to understand. Therefore, the revised names in the third column are used in the user interface. Accordingly, the fourth column gives the definitions to the criteria.

Table 4-2 SWAHO sustainability criteria (a)

Category	Criterion Name	Criterion Name revised	Definition
Social	Acoustic Comfort	Noise Control	occupant satisfaction with the indoor acoustical environment, described in terms of sound proofing level and noise level, etc. [derived from ISO 16813:2006]
	Thermal Comfort	Temperature and Humidity	condition of mind derived from satisfaction with the thermal environment [derived from ISO 16813:2006]

Table 4-2 SWAHO sustainability criteria (b)

Category	Criterion Name	Criterion Name revised	Definition
Social	Luminous Comfort	Brightness	occupant satisfaction with the indoor visual environment, described in terms of illumination level [derived from ISO 16813:2006]
	Indoor Air Quality	Indoor Air Quality	quality of air inside a building, described in terms of odor, chemical, and biological pollutants [SOURCE: ISO 21929-1:2011]
	Functionality	Functions	addition to suitability or usefulness [derived from ISO 15686-10:2010]
	Durability	Durability	ability to retain in a state in which it can perform its required functions [derived from ISO 21929-1:2011]
	Occupant Control	Occupant Control	ability to change or adjust an aspect, such as temperature, lighting, the function of an object, etc.
	Safety and Security	Safety and Security	the condition of being free from harm [derived from Merriam-Webster]
	Aesthetics	Aesthetics	beautiful and pleasing in appearance [derived from Merriam-Webster]
Environmental	Energy Saving	Energy Saving	the relative amount of energy saved or created, compared to other actions
	Water Saving	Water Saving	the relative amount of water saved or created, compared to other actions
	Waste Optimization	Waste Optimization	efforts to take advantage of waste materials such as recycle, reuse and reclaim

One may notice that the number of environmental criteria is smaller than the number of social criteria. This is not because social concern is more important than environmental concern,

but rather because of the following reason. EPDs (Environmental Product Declarations) can provide comparable quantitative impacts of a product on a wide range of environmental issues, but unfortunately, there is no EPD for an action. Without EPD, SWAHO should include comparable environmental criteria that do not require physical measurements to determine the level of impact since SWAHO is a decision-making tool used prior to bringing actions into practice. As a result, some environmental issues could not be grouped into the environmental criteria in SWAHO. For example, global air quality is an environmental issue and the renovation construction process (removing the existing system, installation, etc.) may release harmful gas to the outdoor environment, but it was excluded from the environmental criteria because the influence can hardly be defined for different actions without actual measurements. Similarly, other issues such as acidification, eutrophication, and ozone layer depletion were excluded from the environmental criteria. However, "Indoor Air Quality" is related to personal comfort and human health and it is easier to measure compared to global air quality, thus it was categorized into social criteria.

4.3.2 Indicator List

Indicators are used in DM 2, which was not developed into the prototype tool. However, the author still made some effort to collect possible indicators for the sustainability criteria during the literature review. A proper indicator for SWAHO should meet two rules:

1. An indicator is associated with one or more renovation products;
2. For one product, there should be only one indicator to one criterion.

Quantitative indicators are retained whenever possible in order to exploit the essence of technical performance data and to enable direct information extraction from e-commerce websites.

However, in some cases where quantitative indicators are not feasible, qualitative indicators will be used. The value of qualitative indicators can be entered by the user or from historic average inputs. Table 4-3 provides a list of possible indicators for SWAHO. Some of the indicators are from the resources reviewed in Section 2.3, and the author came up with the rest of them in the list. This list needs refinement in the future.

Table 4-3 SWAHO indicators (a)

Criteria	Indicators	Type
Acoustic Comfort	Noise Reduction Coefficient (NRC) or Sound Absorption Average (SAA)	Quantitative
	Sound Proofing Level	Qualitative
	Decibel Rating (dBA) or Sone	Quantitative
	Operation Noise Level	Qualitative
Thermal Comfort	R-value/inch thickness	Quantitative
	Heating/Cooling Capacity (BTU/hour)	Quantitative
	Air Infiltration Rate (cfm/ft or cfm/ft^2)	Quantitative
	Contribution to Proper and Stable Temperature	Qualitative
	Contribution to Proper and Stable Humidity	Qualitative
Luminous Comfort	Total Lumens	Quantitative
	Addition of Daylight	Qualitative
Indoor Air Quality	Particle Filtration Percentage	Quantitative
	Air Delivery Rate (cubic feet/minute)	Quantitative
	VOCs (Volatile Organic Compounds) Emission Level	Qualitative

Table 4-3 SWAHO indicators (b)

Criteria	Indicators	Type
Functionality	Satisfaction Level of the Functions	Qualitative
	Addition of Functions	Qualitative
Durability	Extension of Life	Qualitative
	Ease of Maintenance	Qualitative
Occupant Control	Controllability	Qualitative
Safety and Security	Contribution to Safety and Security	Qualitative
Aesthetics	Aesthetic Level	Qualitative
Energy Saving	Power (Watts)	Quantitative
	Recovery Efficiency	Quantitative
	Energy Efficiency Ratio (EER)	Quantitative
	Energy Saving Potential	Qualitative
Water Saving	Water Use (gallons per load, gallons per minute, gallons per flush)	Quantitative
	Water Saving Potential	Qualitative
Optimize Waste	Percentage of Reusable Components	Quantitative
	Percentage of Recycled Materials	Quantitative

4.4 Scoring

As Section 2.4.3 stated, to enable knapsack problem optimization, each action *j* is equipped with a sustainability score S_j. This section describes how the SWAHO prototype calculates S_j.

Figure 4-11 illustrates the rationale behind S_j. The action denoted by *j* achieves sustainability benefit by having impacts on the sustainability criteria denoted by *k*. Thus we

introduce a stand-alone variable M_{jk}, which is the rating score of action j for criterion k. M_{jk} should be pre-set by the experts who have the knowledge of the renovation actions. In addition, weighting is used to address different personal perception of sustainability. Users can enter the weights for criteria, W_k. This way, S_j can be calculated using the Weighted Sum Method:

$$S_j = \sum_{k=1}^{m} M_{jk} W_k$$

where m is the total number of criteria. $m = 12$ in SWAHO.

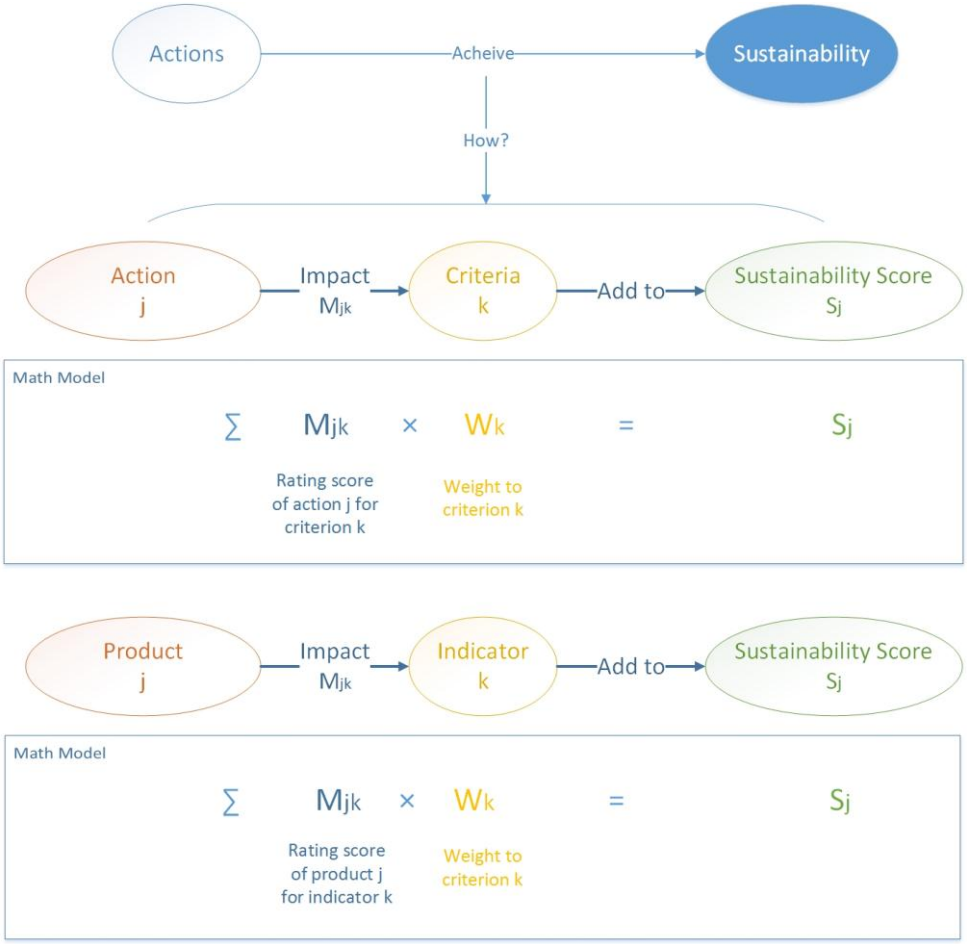


Figure 4-11 Mathematical deduction of sustainability score S_j

The scoring is the same for DM 2 except that the M_{jk} now represents the rating score of project *j* for indicator *k*. Each product *j* will have a score S_j.

M_{jk} is in a format of a positive or negative 5-star rating. The ratings are translated into scores accordingly, for background mathematical calculation. Table 4-4 shows the contrast between ratings and scores. M_{jk} is pre-set in DM 1, thus users will not see star ratings in the prototype, but they would see star ratings in DM 2 if developed.

Table 4-4 Sustainability benefit rating scores

Ratings										
Negative					0	Positive				
5 stars	4 stars	3 stars	2 stars	1 star	0	1 star	2 stars	3 stars	4 stars	5 stars
Sustainability Benefit Scores										
-5	-4	-3	-2	-1	0	1	2	3	4	5

4.4.1 Impacts of Actions on Criteria

Proper values of M_{jk} are a prerequisite for sound and credible decision-making results. Theoretically, the setting of M_{jk} should be a rigorous process such as expert focus group. However, this was not achievable due to the time limit. In this study, the author acted as the expert and pre-set the values of M_{jk}. The results of SWAHO tool at this point may not be exactly "true", but they should be close enough to prove the concept. M_{jk} should be independent of personal preferences or bias, thus M_{jk} reflects relative contribution or harm of an action compared with other renovation actions. Table 4-5 provides the full list of M_{jk} used in the SWAHO prototype.

Table 4-5 Impacts of actions on criteria (a)

Action Name	Acoustic Comfort	Thermal Comfort	Luminous Comfort	Indoor Air Quality	Functionality	Durability	Occupant Control	Safety and Security	Aesthetics	Energy Saving	Water Saving	Waste Optimization
Mechanical Space Heating												
Furnace	0	5	0	-1	0	0	0	0	0	-4	0	0
Heat pump (cooling as well)	0	5	0	1	0	0	0	0	0	-3	0	0
Boiler	0	5	0	0	0	0	0	0	0	-2	-2	0
Pellet stoves	0	2	0	-1	0	0	1	0	1	-2	0	3
Fireplace insert	0	2	0	1	0	0	0	0	0	-1	0	0
Passive Space Heating												
Solar hot air collector	0	3	0	0	0	0	0	0	0	4	0	0
Solar direct/indirect gain glazing	-2	2	3	0	0	0	0	0	1	3	0	0
Solar Electricity	0	0	0	0	0	0	0	0	0	5	0	0
Solar Hot Water System	0	0	0	0	3	0	0	0	0	4	0	0
Tankless Water Heater	0	0	0	0	3	0	0	0	0	2	0	0
Water Heater Blanket & Pipe Insulation	0	0	0	0	0	3	0	0	0	1	0	0
Drainwater Heat Recovery System	0	0	0	0	0	0	0	0	0	2	0	0

Table 4-5 Impacts of actions on criteria (b)

Action Name	Acoustic Comfort	Thermal Comfort	Luminous Comfort	Indoor Air Quality	Functionality	Durability	Occupant Control	Safety and Security	Aesthetics	Energy Saving	Water Saving	Waste Optimization
Mechanical Cooling												
Evaporative cooler	0	4	0	-1	0	-1	2	0	0	-2	-2	0
Air conditioning	0	4	0	2	0	0	2	0	0	-3	0	0
*Heat pump**	0	0	0	0	0	0	0	0	0	0	0	0
Fan	-2	2	0	0	0	0	3	0	-1	-1	0	0
Passive Cooling - Shades	0	1	0	0	0	0	3	1	1	1	0	0
Passive Cooling - Radiant barrier	0	1	0	0	0	1	0	0	0	1	0	0
Energy Recovery Ventilator	0	1	0	3	0	0	0	0	0	2	0	0
Programmable Thermostat	0	4	0	0	0	0	5	0	0	2	0	0
Green Flooring	0	0	0	-1	0	3	0	3	2	0	0	3
Carpet	1	1	0	-2	0	-3	0	3	3	0	0	1
Interior Wall Painting	0	0	0	-2	0	3	0	0	3	0	0	0
Energy Meter	0	0	0	0	0	0	2	0	0	1	0	0

Note*: Heat pump can provide cooling as well. The impacts of it have been addressed by “heat pump” entry under “Mechanical Space Heating”, thus the impacts of “heat pump” entry under “Mechanical Cooling” are all zero.

Table 4-5 Impacts of actions on criteria (c)

Action Name	Acoustic Comfort	Thermal Comfort	Luminous Comfort	Indoor Air Quality	Functionality	Durability	Occupant Control	Safety and Security	Aesthetics	Energy Saving	Water Saving	Waste Optimization
Insulation - walls, ceilings, floors	5	1	0	0	0	0	0	0	0	2	0	0
Radon Test and Mitigation	0	0	0	4	0	0	0	0	0	0	0	0
Efficient Lighting	0	0	5	0	0	0	0	0	0	2	0	0
Light Timers & Motion Sensors	0	0	0	0	0	0	4	0	0	1	0	0
Indoor Plants	0	0	0	2	0	0	0	0	5	0	0	0
Air Cleaner	0	0	0	5	0	0	0	0	0	-1	0	0
Alarms & Sensors	0	0	0	0	0	0	2	5	0	0	0	0
Skylight	0	-1	4	0	0	0	0	0	2	-1	0	0
Green Roofing	0	1	0	0	0	3	0	0	0	0	0	3
Repair Windows	0	1	3	0	0	0	0	0	0	1	0	0
Replace Windows	0	2	5	0	0	1	3	0	0	1	0	0
Exterior Storm Door	0	1	0	0	0	0	0	1	0	1	0	0
Doors & Windows Sealing	2	1	0	0	0	1	0	0	0	1	0	0
Door Sweep	2	1	0	0	0	1	0	0	0	1	0	0

Table 4-5 Impacts of actions on criteria (d)

Action Name	Acoustic Comfort	Thermal Comfort	Luminous Comfort	Indoor Air Quality	Functionality	Durability	Occupant Control	Safety and Security	Aesthetics	Energy Saving	Water Saving	Waste Optimization
Efficient Toilets	0	0	0	0	3	0	3	0	0	0	5	0
Low-flow Showerheads	0	0	0	0	-2	0	0	0	0	0	5	0
Faucet Improvements	0	0	0	0	0	0	0	0	0	0	3	0
Dishwasher	0	0	0	0	5	0	0	0	0	-1	-2	0
Drinking Water Filter	0	0	0	0	3	0	0	3	0	0	0	0
Kitchen Range Hood	-1	0	0	3	0	0	0	0	0	0	0	0
Refrigerator/Freezer	0	0	0	0	5	0	0	0	0	-1	0	0
Clothes Dryer	-1	0	0	0	5	0	0	0	0	-1	0	0
Clothes Washer	-1	0	0	0	5	0	0	0	0	-1	-2	0
Green Patios, Walkways & Driveways	0	0	0	0	3	-2	0	0	3	0	3	0
Composite Decks & Porches	0	0	0	0	1	3	0	0	3	0	0	3
Recycled Plastic/Composite Fencing	0	0	0	0	0	3	0	5	0	0	0	3
Outdoor Solar Lighting	0	0	3	0	0	0	0	0	3	1	0	0
Solar Pool Heater & Cover	0	3	0	0	0	0	0	1	0	5	0	0

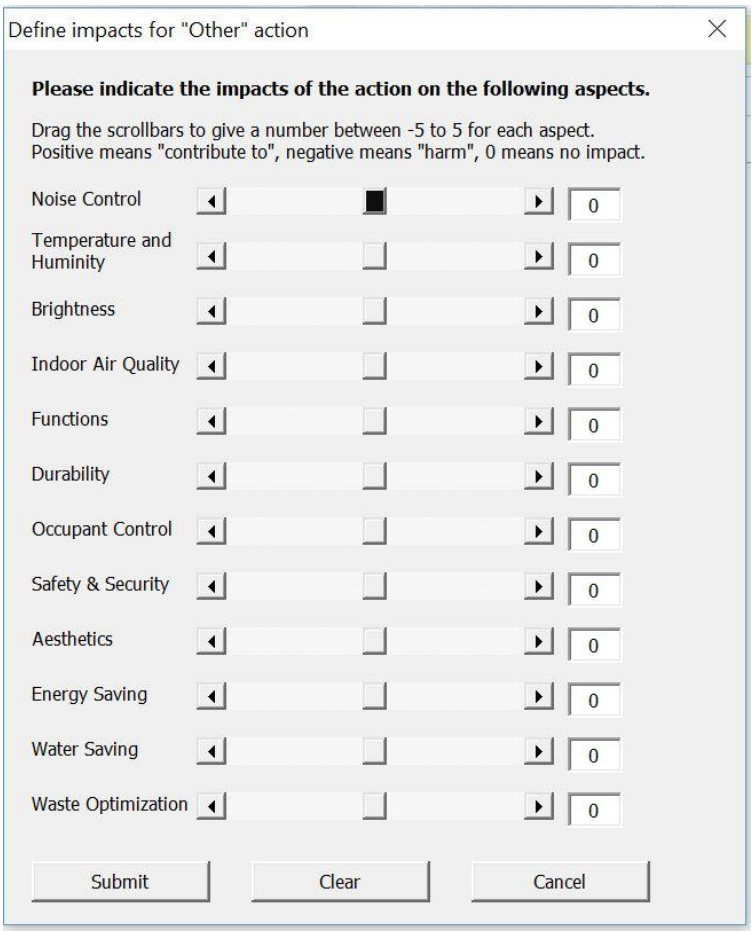
Table 4-5 Impacts of actions on criteria (e)

Action Name	Acoustic Comfort	Thermal Comfort	Luminous Comfort	Indoor Air Quality	Functionality	Durability	Occupant Control	Safety and Security	Aesthetics	Energy Saving	Water Saving	Waste Optimization
Rainwater Collection Barrel	0	0	0	0	0	0	2	0	0	0	3	0
Drip Irrigation System	0	0	0	0	3	0	2	0	0	0	3	0
Greywater Recovery System	0	0	0	0	3	0	2	0	0	0	5	0
Other (Enter action name here)	0	0	0	0	0	0	0	0	0	0	0	0

Users are allowed to enter one customized action. The default values of M_{jk} for the customized action "Other" are zero (the last row in Table 4-5).

Outdoor	Drip Irrigation System	☐	[redacted]
Outdoor	Greywater Recovery System	☐	[redacted]
-	Other (Enter action name here)	☑	$0

(a)



(b)

Figure 4-12 Screenshots of entering "Other" action

If the user checks the "Other" action (Figure 4-12(a)), a window will pop up to let the user input the impacts of the new action (Figure 4-12(b)) by giving scores between -5 to 5 to each criterion. After submitted, the impact values will be stored in the data sheet. Meanwhile, the user can change the action name and its cost estimate.

4.4.2 Impacts of Products on Criteria

Product-level decision-making (DM 2) was not developed into a working prototype tool. This section is to demonstrate how to determine M_{jk} for each product in theory.

If SWAHO was linked to the e-commerce system, it would be able to extract quantitative indicator values, such as power (watts) and percentage of recycled material, from the product webpages. For some qualitative indicators that are independent from the current user's input, such as operation noise level and ease of maintenance, SWAHO could trace the historical inputs from the previous users and present the average value for each indicator. For those qualitative indicators that require input from the current user, such as satisfaction level of the functions, there would be places for the user to enter the values.

All the values obtained above are original indicator values, which then can be translated into 5-star rating scores based on a conversion table that defines rating rules. Table 4-6 gives a conversion table for demonstration purposes, but actual, meaningful conversion rules would need to be determined by experts. A specific example using the rules above can be found in Section 4.6.

Table 4-6 Example of indicator's conversion table

Score	Sound Absorption Average	Operation Noise	R-value/inch thickness	Power (Watts)	Water Use (gallons/load)	Percentage of Recycled Materials
-5		Extremely Noisy	-	>3000	>50	-
-4	-	Very Noisy	-	1001-3000	41-50	-
-3	-	Noisy	-	501-1000	31-40	-
-2	-	Somewhat Noisy	-	101-500	21-30	-
-1	-	A Little Noisy	-	0-100	<=20	-
0	-	Not Noisy	-	-	-	-
1	0-0.24	-	<3.0	-	-	0-20%
2	0.25-0.49	-	3.1-4.0	-	-	21%-40%
3	0.5-0.74	-	4.1-5.0	-	-	41%-60%
4	0.75-0.99	-	5.1-6.0	-	-	61%-80%
5	>=1	-	>6.0	-	-	>=81%

4.5 Mathematical Optimization

As analyzed in Section 2.4.2, DM 1 is a basic 0-1 knapsack problem and DM 2 is a multiple-choice knapsack problem. Knapsack problems have a history of more than one century. Several algorithms are available to solve the problem. Dynamic Programming algorithms are less affected by the kind of data sets and are generally more efficient than other algorithms [59]. This section will introduce how Dynamic Programming algorithm was used to solve the DM 1 problem.

4.5.1 Mathematical Expression of SWAHO Decision-Making Problems

DM 1 is described as: Given a set of *n* actions, each action *j* ($1 \leq j \leq n$) with a cost c_j and a sustainability benefit score S_j, determine what actions to do to maximize the total sustainability benefit while making the total cost under the budget *B*.

DM 1 can be expressed as:

Maximize

$$\sum_{j=1}^{n} x_j S_j$$

Subject to

$$\sum_{j=1}^{n} x_j c_j \leq B$$

Where

$$x_j = \begin{cases} 1, & Action\ j\ is\ selected \\ 0, & Action\ j\ is\ not\ selected \end{cases}$$

DM 2 is described as: Given *k* actions denoted N_i, each action *i* with a set of products *j* ($j \in N_i$), exactly one product must be chosen from each action set N_i, to maximize the total sustainability benefit while making the total cost under the budget *B*.

The mathematical expression of DM 2 is:

Maximize

$$\sum_{i=1}^{k} \sum_{j \in N_i} x_{ij} S_{ij}$$

Subject to

$$\sum_{i=1}^{k} \sum_{j \in N_i} x_{ij} c_{ij} \leq B,$$

$$\sum_{j \in N_i} x_{ij} = 1, \qquad for\ all\ 1 \leq i \leq k$$

Where

S_{ij} – Sustainability benefit score of product *j* of action *i*

c_{ij} – Cost of product *j* of action *i*

$$x_{ij} = \begin{cases} 1, & Product\ j\ of\ Action\ i\ is\ selected \\ 0, & Product\ j\ of\ Action\ i\ is\ not\ selected \end{cases} \quad for\ all\ 1 \leq i \leq k\ and\ all\ j\ \in N_i$$

4.5.2 Application of Dynamic Programming

A Dynamic Programming algorithm can be applied to both DM 1 and DM 2. However, DM 2 is not discussed here as it is out of the scope of development.

Dynamic Programming uses recursive equations, which can be defined in the following way [59].

In DM 1, the number of actions *n*, the costs c_j and the budget *B* are integers, whereas the sustainability scores S_j are real numbers.

For each integer m $(1 \leq m \leq n)$ and for each integer z $(0 \leq z \leq B)$, we can define:

$$\boldsymbol{f_m(z) = \left\{ \sum_{i=1}^{m} x_i S_i \mid \sum_{i=1}^{m} x_i c_i \leq z, x_i = 0, 1 \; for \; i = 1, \ldots, m \right\}} \qquad \textbf{Equation (4-1)}$$

$f_m(z)$ represents the solution to the sub-problem: the highest total sustainability benefit score given *m* actions and the remaining budget *z*.

From Equation (4-1) we have:

$$f_1(z) = 0, \qquad for \; 0 \leq z < c_1;$$

$$f_1(z) = S_1, \qquad for \; c_1 \leq z \leq B.$$

The recursive equations for the m-th stage $(m = 2, \ldots, n)$ are given by:

$$f_m(z) = \begin{cases} f_{m-1}(z), & for \; 0 \leq z < c_m \\ \max\{f_{m-1}(z), f_{m-1}(z - c_m) + S_m\}, & for \; c_m \leq z \leq B \end{cases} \qquad \textbf{Equation (4-2)}$$

Utilizing Equation (4-2), we can compute the value $f_m(z)$, with $m \geq 2$, when the value $f_{m-1}(z)$, at the (m-1)-th stage, are available. In other word, Equation (4-2) creates the relation between the sub-problem given *m* actions and the sub-problem given *m-1* actions. It answers the question: shall we select the m-th action?

If the cost of the m-th action, c_m, is greater than the remaining budget z, we cannot select the m-th action. The result $f_m(z)$, the highest score given *m* actions, will be the same with the result given *m-1* actions, $f_{m-1}(z)$. If the cost of the m-th action, c_m, is less than or equal to the remaining budget z, we need to consider selecting the m-th action or not. If we do not take the m-th action, the result will be the same as the result given *m-1* actions, that is, $f_{m-1}(z)$. If we take

the m-th action, the result will be $f_{m-1}(z - c_m) + S_m$, that is, the score of the m-th action (S_m) plus the highest score $f_{m-1}(z - c_m)$ given the *m-1* actions before the m-th action and given the remaining budget $z - c_m$.

Below is a simple example.

Problem: There are three actions, 1, 2, 3. Decide what actions to do to maximize the total sustainability score. The budget $B = \$900$.

- Action 1: cost $c_1 = \$200$, score $S_1 = 1.5$;
- Action 2: cost $c_2 = \$500$, score $S_2 = 2.2$;
- Action 3: cost $c_3 = \$300$, score $S_3 = 1.8$;

From Equation (4-2) we have

$$f_3(900) = max\{f_2(900), f_2(600) + 1.8\}$$

Then

$$f_2(900) = max\{f_1(900), f_1(400) + 2.2\}$$

$$f_2(600) = max\{f_1(600), f_1(100) + 2.2\}$$

We know directly that

$$f_1(100) = 0 \qquad \text{//Do not take Action 1}$$

$$f_1(400) = f_1(600) = f_1(900) = 1.5 \qquad \text{//Take Action 1}$$

Therefore, we have

$$f_2(600) = \max\{1.5, 0 + 2.2\} = 2.2$$ // Do not take Action 1, Take Action 2

$$f_2(900) = \max\{1.5, 1.5 + 2.2\} = 3.7$$ //Take Action 1 and Take Action 2

$$f_3(900) = max\{3.7, 2.2 + 1.8\} = 4.0$$ // Do not take Action 1, Take Action 2 and 3

The solution $f_3(900)$ is "Do not take Action 1, take Action 2 and Action 3", and the highest possible score is 4.0. The result can be proved by checking all the possible combinations where the total cost is less than the budget $900:

- Take Action 1 only: cost = $200, score = 1.5;
- Take Action 2 only: cost = $500, score = 2.2;
- Take Action 3 only: cost = $300, score = 1.8;
- Take Action 1 and 2: cost = $700, score = 3.7;
- Take Action 2 and 3: cost = $800, score = 4.0;
- Take Action 1 and 3: cost = $500, score = 3.3.

When the number of actions and the budget number are large, dynamic programming algorithm will show its advantage in reducing the number of calculations.

In Excel VBA coding, the following variables in Table 4-7 were defined for dynamic programming calculation.

Table 4-7 Variables in Excel VBA for dynamic programming

Variable Type	Name	Value
Integer	itemN	The number of actions that are taken into consideration
Long (very large integer)	budgetHigh	$Budget \times (1 + flexibility)$
Long (very large integer)	budget	$Budget$
Long (very large integer)	budgetLow	$Budget \times (1 - flexibility)$
One-dimensional Array	cost(i)	Cost of action i, $i = 1\ To\ itemN$
One-dimensional Array	Si(i)	Sustainability Score of action i, $i = 1\ To\ itemN$
Two-dimensional Array	d(i,j)	The highest total score given i actions and j budget. $i = 0\ To\ itemN, j = 0\ To\ budgetHigh$
Two-dimensional Array	path(i,j)	path = 1 if the i-th action is selected; path = 0 if the i-th action is not selected. $i = 0\ To\ itemN, j = 0\ To\ budgetHigh$
Long (very large integer)	TTC	The total cost of all the selected actions

Because the base budget case and the low budget case are sub-problems of the high budget case, we can run the calculation once for the high budget case and then print solutions for the three cases. After writing values for itemN, budgetHigh, cost(i) and Si(i), and initializing all d(i,j) and path(i,j) to zero, dynamic programming calculation was conducted by the following codes.

```
For i = 1 To itemN
    For j = 0 To budgetHigh
        d(i, j) = d(i - 1, j)
        If j >= cost(i) Then
            If d(i, j) < d(i - 1, j - cost(i)) + Si(i) Then
                path(i, j) = 1
                d(i, j) = d(i - 1, j - cost(i)) + Si(i)
            End If
        End If
    Next j
Next i
```

Figure 4-13 Excel VBA codes for dynamic programming

To print the solution (actions selected, total cost and total sustainability score), we can check path(i,j) backwards, from path(itemN, budgeHigh) to path(0,0).

```
j = budgetHigh
i = itemN
TTC = 0

Do While i > 0
    If path(i, j) = 1 And j >= 0 Then
        'print the action name on main sheet...
        'print the name and detailed scores on solution sheet...
        TTC = TTC + cost(i)
        j = j - cost(i)
    End If
    i = i - 1
Loop
'print total cost and total score on main sheet
```

Figure 4-14 Excel VBA codes for printing results

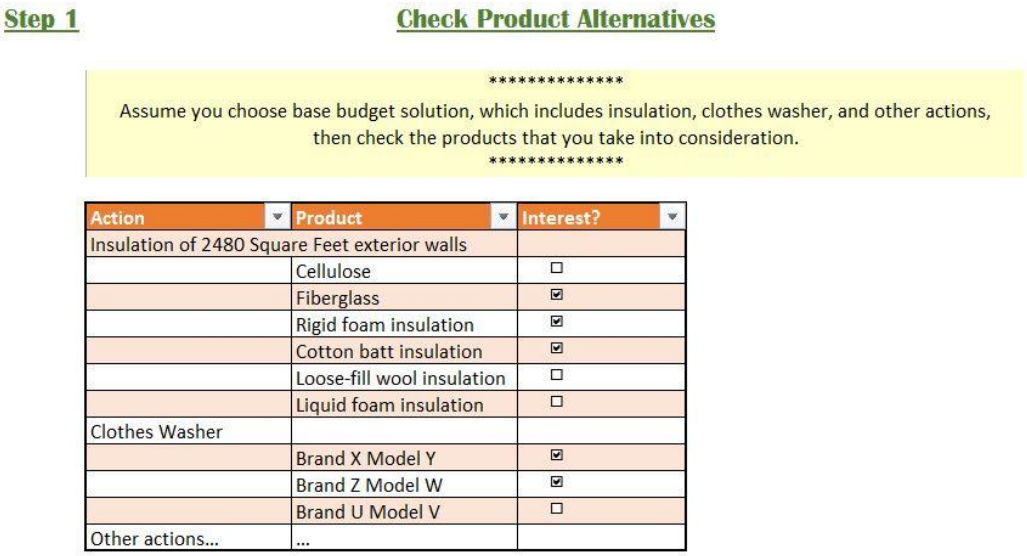
Some of the codes in Figure 4-14 were replaced with explanations (the green lines started with ') to make them understandable. To print the solution for the base budget case, set j = budget and run the routine. To print the solution for the low budget case, set j = bedugeLow and run the routine again.

4.6 Mock-Up of DM 2

Although DM 2 was not developed into a working prototype, a mock-up sheet was created in the prototype to help the users understand DM 2 in testing. There are four steps in DM 2:

- Step 1: Check Product Alternatives;
- Step 2: Input Indicator Values;
- Step 3: Run Calculation;
- Step 4: Order Online.

Below are screenshots of the mock-up sheet. The sheet explains how DM 2 works. It is not a design of the user interface of DM 2. The process of DM 2 is more complex than DM 1 since DM 2 involves various product alternatives and information flows from e-commerce websites. Thus, the user interface of DM 2 should be carefully designed in the future in order to be user-friendly. Some suggestions regarding user interface design are available in Chapter 5.



Step 1 **Check Product Alternatives**

****

Assume you choose base budget solution, which includes insulation, clothes washer, and other actions, then check the products that you take into consideration.

****

Action	Product	Interest?
Insulation of 2480 Square Feet exterior walls		
	Cellulose	☐
	Fiberglass	☑
	Rigid foam insulation	☑
	Cotton batt insulation	☑
	Loose-fill wool insulation	☐
	Liquid foam insulation	☐
Clothes Washer		
	Brand X Model Y	☑
	Brand Z Model W	☑
	Brand U Model V	☐
Other actions...	...	

Figure 4-15 Mock-up of DM 2, step 1

Color coding:	Required Input	Optional Input			
	Input Original Indicator Data				
Action	Insulation of 2480 Square Feet exterior walls			Clothes Washer	
Product	 Fiberglass roll	 Denim Insulation Multi-Purpose roll	 XPS Rigid Foam sheathing	 Brand X Model Y	 Brand Z Model W
Cost	$1,810	$2,778	$2,852	$1,500	$1,048
Noise Control	Modest sound proofing	Very Good sound proofing	Modest sound proofing	Somewhat Noisy	A Little Noisy
Temperature and Humidity	R-3.33/inch	R-3.35/inch	R-5/inch		
Brightness					
Indoor Air Quality					
Functions				Very satisfied with capacity and functions	Satisfied with capacity and functions
Durability					
Occupant Control					
Safety and Security					
Aesthetics					
Energy Saving	Energy Star Certified	Energy Star Certified	Energy Star Certified	Average 160W per load	Average 90W per load
Water Saving				20 gallons per load	26 gallons per load
Waste Optimization	65% recycled content	100% recycled content	20% recycled content		

Figure 4-16 Mock-up of DM 2, step 2 (a)

What you will see - Rating Scores				
Insulation of 2480 Square Feet exterior walls			Clothes Washer	
				
Fiberglass roll	Denim Insulation Multi-Purpose Roll	XPS Rigid Foam sheathing	Brand X Model Y	Brand Z Model W
$1,810	$2,778	$2,852	$1,500	$1,048
3 ★★★	5 ★★★★★	3 ★★★	-2 ★★	-1 ★
2 ★★	2 ★★	3 ★★★	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	5 ★★★★★	4 ★★★★
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
2 ★★	2 ★★	2 ★★	-2 ★★	-1 ★
0	0	0	-1 ★	-2 ★★
4 ★★★★	5 ★★★★★	2 ★★	0	0

Figure 4-16 Mock-up of DM 2, step 2 (b)

Color coding: Required Input | Optional Input

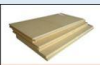
	Input Original Indicator Data					What you will see - Rating Scores				
Action	Insulation of 2480 Square Feet exterior walls			Clothes Washer		Insulation of 2480 Square Feet exterior walls			Clothes Washer	
Product	 Fiberglass roll	 Denim Insulation Multi-Purpose roll	 XPS Rigid Foam sheathing	 Brand X Model Y	 Brand Z Model W	 Fiberglass roll	 Denim Insulation Multi-Purpose Roll	 XPS Rigid Foam sheathing	 Brand X Model Y	 Brand Z Model W
Cost	$1,810	$2,778	$2,852	$1,500	$1,048	$1,810	$2,778	$2,852	$1,500	$1,048
Noise Control	Modest sound proofing	Very Good sound proofing	Modest sound proofing	Somewhat Noisy	A Little Noisy	3 ☆☆☆	5 ☆☆☆☆☆	3 ☆☆☆	-2 ★★	-1 ★
Temperature and Humidity	R-3.33/inch	R-3.35/inch	R-5/inch			2 ☆☆	2 ☆☆	3 ☆☆☆	0	0
Brightness						0	0	0	0	0
Indoor Air Quality						0	0	0	0	0
Functions				Very satisfied with capacity and functions	Satisfied with capacity and functions	0	0	0	5 ☆☆☆☆☆	4 ☆☆☆☆
Durability						0	0	0	0	0

Figure 4-16 Mock-up of DM 2, step 2 (c)

Step 3 **Run Calculation** Get Solution

****

The star ratings, together with your budget and weights, will be used for background calculation.
Similar to what you got previously,
you will get suggestions for products, like below.

****

Solution 1 - Base Budget	
Budget	$30,000
Total Cost	$29,902
Sustainability Score	15.609

No.	Suggested Action	Suggested Product
1	Insulation - walls	Denim Insulation Multi-Purpose roll
2	Clothes Washer	Brand X Model Y
...	...	...

Figure 4-17 Mock-up of DM 2, step 3

Figure 4-18 Mock-up of DM 2, step 4

Assume that the solution in DM 1 suggests the homeowner to take two renovation actions: to insulate the exterior walls and to buy a new clothes washer. SWAHO will present all the product alternatives for the two actions. Users can check the products that he or she is interested in, as shown in Figure 4-15.

Next, for each product that is checked, input areas will pop up for the cost and the indicators of the twelve criteria. For each action, some criteria areas are mandatory while others are optional. For example in Figure 4-16 (a), "Noise Control", "Temperature and Humidity" and "Energy Saving" are required for insulating materials (marked in darker green); "Noise Control", "Functions", "Energy Saving" and "Water Saving" are mandatory for a clothes washer. The original indicator values and the cost of each product are filled out automatically using the information from a product webpage or SWAHO database, if available. Users should enter the value of certain indicators such as the satisfaction level of a product. Then, based on the conversion rules (example as Table 4-6), the original indicators will be presented by 5-star ratings (see Figure 4-18 (b) and (c)).

Before going to Step 3, users have the opportunity to adjust budget and weights that they have entered for DM 1. If they do not want to change them, SWAHO will use the budget and weights, along with the star rating scores in Step 2, for optimization calculation.

As Figure 4-17 shows, after selecting "Get Solution", the user will see one product suggested for each action. If they are satisfied with the results, they can order the products suggested through the links to the product webpages (Figure 4-18). If they do not like the products suggested, users can review the product details, re-check the products of interest, adjust weights, budget or indicator values, and re-do the calculation (see flowchart Figure 3-5).

Up to this point, Chapter 3 and Chapter 4 have answered the first research question "How to develop SWAHO?" The next chapter will evaluate the developed SWAHO framework and prototype.

Chapter 5: Evaluation

After developing SWAHO, the research question left is

Is SWAHO a good path to support green renovation decision-making?

The word "good" means

1. SWAHO has some benefits over existing paths.

   To examine this point, a user evaluation that involved meetings and surveys was conducted to collect users' opinions on the concept of SWAHO and their suggestions for the prototype tool (see Section 5.1).

2. The renovation solutions suggested by SWAHO are reasonable.

   While SWAHO identifies "optimal" solutions for a given set of information, the facts that this information is not (and never can be) a complete set of all relevant sustainable renovation data and that some of the data is necessarily subjective mean that the solution is not an overall optimum recommendation for the home renovation. Therefore, the success criteria used is that the system provides reasonable recommendations given the available information. To examine this point, a self-evaluation analyzed the results of 144 scenarios to discover any potential illogical results, and furthermore, to identify patterns that may lead to suggestions for the homeowners (see Section 5.2).

Section 5.3 concludes and discusses the results from the two evaluations.

5.1 User Evaluation

The user evaluation was designed with the intent to provide some evidence for the benefits of SWAHO. The evaluation plan was approved by the UBC Behavioral Research Ethics Board. Section 5.1.1 describes the procedures of the user evaluation, Section 5.1.2 presents the results of the questionnaire, Section 5.1.3 discusses the statistical validity of the results and other general observations and comments from the testing, and Section 5.1.4 summarizes the users' suggestions on the user interface of the tool.

5.1.1 Design

Objectives

The purpose of the user evaluation is twofold: to assess the hypothesis that the proof-of-concept SWAHO approach has some advantages over existing paths for green renovation, and on the other hand, to collect feedback and requirements for user interface design.

As Figure 1-1 shows, three paths were considered: Path 1 – unaided decision-making, Path 2 – professional consultancy and Path 3 – SWAHO. The benefits of SWAHO might be the following:

1. Provide more sustainable decisions compared to path 1;
2. Make homeowners more likely to pursue a green renovation compared to path 2;
3. Address homeowner's individual perception of sustainability;
4. Advocate concerns about the environmental and social sustainability;
5. Stimulate building and furnishing industry.

Methods

The user evaluation involves four methods as follows.

1. Face-to-face meeting

The author organized one-on-one, face-to-face meetings with the testers, where she introduced the idea of SWAHO and how to use the tool. Over the course of the meeting, the author wrote down all the doubts, confusions, and suggestions from the tester. the Preliminary testing plans avoided a face-to-face meeting to reduce the influence of the author on the testers. However, preliminary test showed that it was impossible for the tester to use the tool without an introduction because of technical problems (Excel problems), user interface design, and the homeowner's lack of knowledge in the green renovation field. Therefore, a face-to-face meeting was the only feasible way at that point. The following three methods were involved in the meeting.

2. Introduction Video

A short animation video was created to introduce the basic concept of SWAHO. Animation video with humor and light music are comfortable and easy to understand. It frees the potential stress that a tester may feel from participating a research testing. This may increase the sense of involvement, and therefore, the testers may be more likely to come up with suggestions. The video is 1-minute-15-second long. Some screenshots of the video are shown in Appendix A.

3. User Testing

The testers were given a scenario, based on which they used the SWAHO prototype to make renovation decisions. The results were saved in the Excel file for further analysis.

4. Online Survey

A questionnaire was created using UBC online survey tool, FluidSurveys. Testers were asked to fill out the survey to give feedback. The full questionnaire is attached in Appendix B. There are two parts. Questions in Part A compare SWAHO to path 1 or to path 2. Respondents specify their level of agreement or disagreement on a Likert scale (Strongly Agree, Agree, Neutral, Disagree and Strongly Disagree) for a series of statements. Questions in Part B are about the user experience of the tool.

Evaluation Procedures

The author carried out the following procedures during the meeting.

1. The author explained the procedures to the tester. Testers signed the Consent Form.
2. The tester watched the introduction video.
3. The author further explained the idea of SWAHO by showing the tester Figure 1-1 and presenting the tester with the SWAHO DM-0 tool, which is intended to mimic the unaided path.
4. Opening the prototype SWAHO DM-1, the author guided the tester through the functions of SWAHO.
5. The tester used SWAHO DM-1.
6. The author explained the mock-up sheet of DM 2.
7. The tester completed the online survey.

The SWAHO DM-0 Excel file looks similar to the prototype, but it only includes a list of actions and their cost estimates (no budget, weighting, or calculations are used). This is to simulate

the unaided path for green renovations, where people need to investigate each sustainable action by themselves and make tradeoffs between the actions to prevent going beyond the budget.

A scenario is given in SWAHO DM-0: "You have lived in a home for 10 years with no major renovations. You are interested in making your home more sustainable, and you think it is time to renovate your home to improve the comfort and performance. You have a budget of $50,000 CAD for the renovation." In a preliminary test, the tester found it impossible to make the decisions in SWAHO DM-0, since, in reality, it takes a long period to develop interests in some renovation actions and to make the final decisions. Therefore, other testers were not asked to make decisions using SWAHO DM-0.

In the SWAHO DM-1 Excel file, users were given all the functions as introduced in previous chapters. The same scenario was given in SWAHO DM-1. This time, however, users do not need to consider how sustainable each action is and how to make the total cost under the budget. Instead, they just need to check the actions that appear good for his or her purpose of renovation. The time they used to make the decision was recorded in the SWAHO DM-1 Excel file.

Recruitment of Testers

Since the current version of SWAHO is designed for the context of a house, the tester should be someone who has lived in a house for many years so that he or she can understand the renovation actions. Besides, the tester should be interested in green homes. People under the age of 19 were excluded from the testers.

The potential testers were recruited from the University Sustainability Initiative and Sustainable Building Science Program at UBC through a snowball sampling method, which means

the author first identified a few testers who then provided the contact information of other potential testers and so forth. Once the potential tester agreed to join the evaluation, a meeting was scheduled for the testing.

Number of Testers

The population of all the potential testers is very large (all home owners). Given the time allotted to testing, however, a total of eight testers took part in the user evaluation. One preliminary test provided oral feedback only, while the other seven testers completed the online survey and provided oral feedback. Although the number of samples is relatively small, it turned out that the answers to each question were uniform without much variation (see Section 5.1.2). This shows that the results are of strong indication of proof of concept. Moreover, one of the purposes is to collect qualitative suggestions for the user interface. Since the number of new suggestions decreased dramatically as more evaluations were completed (see Figure 5-1), eight tests did provide a good coverage of requirements for the user interface. Of course, more testers with diverse age and diverse culture background should be approached in the future to improve the tool.

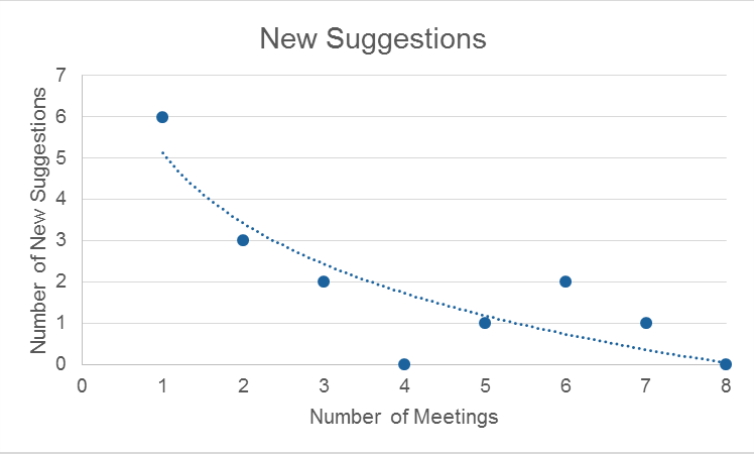


Figure 5-1 Number of new suggestions vs. Number of meetings

5.1.2 Survey Results

PART A. Do you agree or disagree with the following statements?

This part is to compare the three paths of green renovations as shown in Figure 1-1. Path 1 is unaided decision-making; Path 2 is professional consultancy; Path 3 is SWAHO. Below are responses to each question.

1. SWAHO provides more sustainable decisions than unaided decision-making.

Response	Chart	Percentage	Count
Strongly disagree		0.0%	0
Disagree		0.0%	0
Neutral		0.0%	0
Agree		42.9%	3
Strongly Agree		57.1%	4
		Total Responses	**7**

All the testers agreed that in general, SWAHO could help them make more sustainable decisions than making decisions on their own.

2. Compared to unaided decision-making, with SWAHO, I am more likely to consider Environmental impacts during renovation.

Response	Chart	Percentage	Count
Strongly disagree		0.0%	0
Disagree		0.0%	0
Neutral		0.0%	0
Agree		71.4%	5
Strongly Agree		28.6%	2
		Total Responses	**7**

All the testers thought that SWAHO encouraged them to consider environmental impacts.

3. Compared to unaided decision-making, with SWAHO, I am more likely to consider Social impacts during renovation.

Response	Chart	Percentage	Count
Strongly disagree		0.0%	0
Disagree		0.0%	0
Neutral		28.6%	2
Agree		42.9%	3
Strongly Agree		28.6%	2
		Total Responses	**7**

Testers have given generally positive responses to this question, but the percentage of "Agree" plus "Strongly Agree" is lower than that in Question 2. Looking at the two questions together, it is indicated that, without SWAHO, some people may address concerns about some social criteria but they are less likely to consider environmental impacts. Therefore, SWAHO can foster people to consider the two sides of sustainability and it has a larger effect on the environmental side.

4. I am more likely to pursue green renovation given Path 3 than given Path 2.

Response	Chart	Percentage	Count
Strongly disagree		0.0%	0
Disagree		0.0%	0
Neutral		0.0%	0
Agree		71.4%	5
Strongly Agree		28.6%	2
		Total Responses	**7**

5. I prefer to use Path 3 than to use Path 2.

Response	Chart	Percentage	Count
Strongly disagree		0.0%	0
Disagree		0.0%	0
Neutral		0.0%	0
Agree		57.1%	4
Strongly Agree		42.9%	3
		Total Responses	**7**

Question 4 asks that, given professional consultancy and SWAHO, which path makes the tester more willing to pursue a green renovation. Question 5 asks that if the tester is certain to pursue a green renovation, which path does he or she prefer. In both questions, testers responded preference on SWAHO to professional consultancy, even though professional consultancy provides more technical results. One of the testers said, "SWAHO is definitely helpful because consultancy requires more money and time." She also questioned whether consultants would oversell products.

PART B. About SWAHO

6. Do you think SWAHO catches your preferences about sustainability?

Response	Chart	Percentage	Count
Yes		100.0%	7
No		0.0%	0
		Total Responses	**7**

7. Do you like the actions and products proposed by SWAHO?

Response	Chart	Percentage	Count
Yes		100.0%	7
No		0.0%	0
		Total Responses	**7**

If you don't like the results, why?

(N/A)

8. Did SWAHO help you understand green renovation?

Response	Chart	Percentage	Count
Yes		100.0%	7
No		0.0%	0
		Total Responses	**7**

Question 6, 7 and 8 show that all the testers thought SWAHO addressed their preferences on sustainability, they were satisfied with the results proposed by the tool, and they highly appreciated that SWAHO helped them understand green renovation.

9. Do you think, if SWAHO links to e-commerce, it will benefit the building products companies?

Response	Chart	Percentage	Count
Very unlikely		0.0%	0
Unlikely		0.0%	0
Uncertain		14.3%	1
Likely		42.9%	3
Very likely		42.9%	3
		Total Responses	**7**

Some testers were very positive in this question. They stated that SWAHO had a great chance to market a brand. The tester who answered "uncertain" argued that SWAHO would benefit some companies but not others – it would help the ones to which SWAHO links.

10. Any suggestions to SWAHO?

The responses to this question are discussed in the following sections.

5.1.3 Testing Results and Comments

Statistical Assessment of the Results

Although the number of testers was small (n = 7), the fact that there was unanimous agreement (either agree or disagree) on most of the questions, and unanimous "neutral or agree" on the remaining questions, gives a very high statistical confidence that a true population median would agree with the survey questions. For example, if we take the Linkert scale value of "Agree" to be the minimum threshold for agreement (i.e., a response of "Agree" or "Strongly Agree" is above the threshold for agreement, while a response of "Neural", "Disagree", or "Strongly Disagree" is below the threshold for agreement), then, for a sample size of 7 and 0 samples below the threshold, the probability that the actual median value is below the threshold is 0.5% [60]. That is, since seven out of seven responses indicated agreement with a statement, there is 99.5% probability that a true population median would agree with the statement (this assumes that the results were a fair sample of the target population).

Decision Duration

The time that the testers used to finish the decision-making (until they click the button "Get Solutions") was recorded in the Excel files. The average time was 12.14 minutes. In reality, users

may look into details of the solutions and re-run the calculation, thus the time for decision-making may be longer. However, it is apparent from the testing that SWAHO will save much time compared to either unaided decision-making or professional consultancy.

The comments from the testers are categorized and discussed below.

About the Approach

One tester suggested that the video could be slower since there was no thinking time. The video in the evaluation was created as a shallow introduction that did not require users to think deeply. Nevertheless, if the video is used as a "product manual" in the future, the pace and content of it will need modifications.

In addition, it was reported that users need some knowledge background of home improvement techniques to be capable of using the tool. Testers would like to have some hand-holding when using the tool, such as a chat line or a phone to clarify questions. It may be that, in order to use SWAHO effectively, homeowners would need to be guided through the tool in the way that the author guided the testers. However, improved user interface and assistance elements may address these issues.

About the Tool

Testers found SWAHO good at identifying issues that were important to them. The weighting process forced them to think what criteria were more important. Moreover, the solution proposed by SWAHO provided a second check. For example, one tester found that she did not earn much score in "Indoor Air Quality". This was because she did not check any actions that

would contribute to “Indoor Air Quality” in Step 1. By SWAHO, she became aware of some important actions that she had ignored before.

Testers repeatedly pointed that the tool was great as a self-exploration tool – people can play around the tool on the bus, at home, etc. With a few tries on the tool, they could quickly find some useful renovation actions that would address their real concerns.

However, one tester said that the tool was not able to address some special cases. For example, she lives in a heritage house and the windows are beautiful, so they will not replace the windows anyway. This concern is not reflected in the weighting. Although this case can be solved simply by checking “Repair Windows” instead of “Replace Windows” in DM 1 Step 1, it is true that people may have some special considerations that the tool is not able to address. This is one of the limitations, but it is not seen as major because SWAHO provides suggestions rather than definitive actions.

5.1.4 Suggestions for User Interface

Apart from general comments above, most of the feedback related to the usability of the prototype. This feedback was valuable in terms of future development of SWAHO, although user interface issues were not the focus of this research. These problems are discussed below.

General User Interface

The Excel file was a prototype. Testers suggested that a mobile application or website would be more user-friendly. Especially for DM 2, showing all the product alternatives at a time is too overwhelming. An interactive interface could show products and related information one-at-a-time as needed.

Checking Actions

Testers had difficulty understanding some of the green actions, despite the pop-up box of explanation and examples. Pictures, website links, and maps might help. For instance, the soil in Vancouver contains very little radon, thus homeowners in Vancouver may not need a "Radon Test and Mitigation". In this case, a radon map could be attached to the action name to inform the user whether to check the action.

Furthermore, testers need aids to estimate the cost. For example, it would be better to have a box that allows entering the square feet and other configuration data of the house so that the cost estimates could adjust automatically.

Testers would like to know more when they check the actions. For example, how much electricity cost will the action save in the long term? In the case where the current fridge is still functioning, what are the cost saving and sustainability benefits of purchasing a new one versus using the old one? It turned out that users were cautious about the validity of the numbers. Future development of SWAHO should be more prudent and provide numbers with explicit context and source.

Another common feedback is that the location of the house can significantly influence the decision. For example, for a house on a business street, the impact of a large window on acoustic comfort will be significantly different from that for a house in a quiet neighborhood. Similarly, the impact on safety will be different for a house in a safe community and for a house in a downtown area. To address the location issue, the tool could either offer different sets of impacts or allow users to adjust the impacts when they check the interested actions.

About Weighting

Testers were unfamiliar with the criteria names. Therefore, some terms were changed as shown in Section 4.3.1 to be more understandable. Definitions of the criteria with nonprofessional language may be helpful as well. The group name "social" triggered some disputes. Although it is a common word used in triple bottom line of sustainability, a tester said she often related "social" to welfare and justice. She would prefer using the word "livability" as the group name. It is important and challenging to replace jargons with proper words. Surveys in the future may investigate how nonprofessionals interpret different terms and thus help rephrase the names of the criteria.

Another comment from almost all the testers was about the weighting scheme. Weighting conveyed a misconception that increasing one criterion meant sacrificing the others. Testers said every criterion was important to them, thus it was hard to think which criteria were more important. Moreover, some testers thought the weighting numbers (percentages) were meaningless. For instance, a tester gave 6% to brightness and 3% to safety but she could not understand what it meant that brightness was twice important than safety. Testers provided some suggestions to solve these difficulties with weighting, such as dragging sectors of a pie chart to weight, categorizing the social criteria to some sub-groups, or using qualitative words instead of numbers.

In addition, one tester noticed that her goals for each product varied. For instance, acoustics is important for a dishwasher but less important in some other products. However, the basic concept of SWAHO is to enable tradeoffs between renovation actions based on the same criteria. More complex calculation scheme may be able to address the concern of varied criteria, for example, by categorizing actions and assigning different sets of weights to them.

About the Results Area

The numbers beside the action names in the results area were misleading (see Figure 4-7). They were included only for enumerating the total number of actions suggested, but some testers thought they were the ranks of the actions. Indeed, testers would like to see a rank of actions so that they would only pay attention to the top ones. Moreover, testers would like to see the "quick wins", for example, the actions that gave a high score and minimal effort.

In DM 2, one tester said that it would be great to link to multiple product webpages when clicking "order" in SWAHO. In addition to that, one tester suggested that perhaps SWAHO could show availability in retail stores in the area as well. These comments show that users want controls over the selection of the products, although SWAHO was designed to free users from the task of manually selecting best alternatives.

5.2 Self-Evaluation

Although there is no "right" (i.e., absolute optimum) solution for the most sustainable actions, it is possible to test if the results of SWAHO are reasonable. The self-evaluation aimed to test the reasonableness. The design of the self-evaluation is introduced in Section 5.2.1, while the results are analyzed in Section 5.2.2.

5.2.1 Design

Corresponding to the three steps in DM 1, three input variables were defined: budget, renovation type and personal priority, each variable with several values. The self-evaluation was to run SWAHO with different combinations of the input variables and analyze the results.

Figure 5-2 Screenshot of Self-test

The input variables and their optional values are shown in Figure 5-2. The output results collected were the total cost and sustainability score. VBA code was used to run the test and print the results.

There are six values for the *budget* variable: $10,000, $30,000, $50,000, $70,000, $100,000 and $150,000. Budget flexibility was set zero.

The *Renovation Type* relates to action selection – people with different renovation purpose have interests in different actions. Six types of renovation were defined.

- Retrofit: This type of renovation usually involves fundamental changes to the shell or mechanical systems with the purpose to save energy bills.
- Maintenance & Repair: This type of renovation includes actions on existing products rather than replacing or installing something new.
- Minor Additions: This type of renovation includes minor actions that do not require heavy installation or construction work, such as appliances and repair work.
- Try New Technology: This type of renovation incorporates new green technologies.
- Conservative: This type of renovation includes traditional renovation actions.
- Everything: This type of renovation checks all the actions on the list.

The actions included for each renovation type are checked in Table 5-1.

Table 5-1 Actions checked for different renovation type (a)

No.	Action	Retrofit	Maintenance & Repair	Minor Additions	Try New Tech	Conservative	Everything
1	Mechanical Space Heating						
	Furnace		✓				
	Heat pump (cooling as well)	✓ (air-sourced)			✓ (geothermal)		
	Boiler						✓
	Pellet stoves						
	Fireplace insert						
2	Passive Space Heating						
	Solar hot air collector						
	Solar direct/indirect gain glazing						
3	Solar Electricity						
4	Solar Hot Water System						
5	Tankless Water Heater						
6	Water Heater Blanket & Pipe Insulation						
7	Drainwater Heat Recovery System						

Table 5-1 Actions checked for different renovation type (b)

No.	Action	Retrofit	Maintenance & Repair	Minor Additions	Try New Tech	Conservative	Everything
8	Mechanical Cooling						
	Evaporative cooler						
	Air conditioning						
	*Heat pump**						
	Fan						
9	Passive Cooling - Shades						
10	Passive Cooling - Radiant barrier						
11	Energy Recovery Ventilator						
12	Programmable Thermostat						
13	Green Flooring						
14	Carpet						
15	Interior Wall Painting						
16	Energy Meter						
17	Insulation - walls, ceilings, floors						
18	Radon Test and Mitigation						

Table 5-1 Actions checked for different renovation type (c)

No.	Action	Retrofit	Maintenance & Repair	Minor Additions	Try New Tech	Conservative	Everything
19	Efficient Lighting						
20	Light Timers & Motion Sensors						
21	Indoor Plants						
22	Air Cleaner						
23	Alarms & Sensors						
24	Skylight						
25	Green Roofing						
26	Repair Windows						
27	Replace Windows						
28	Exterior Storm Door						
29	Doors & Windows Sealing						
30	Door Sweep						
31	Efficient Toilets						
32	Low-flow Showerheads						
33	Faucet Improvements						

Table 5-1 Actions checked for different renovation type (d)

No.	Action	Retrofit	Maintenance & Repair	Minor Additions	Try New Tech	Conservative	Everything
34	Dishwasher						
35	Drinking Water Filter						
36	Kitchen Range Hood						
37	Refrigerator/Freezer						
38	Clothes Dryer						
39	Clothes Washer						
40	Green Patios, Walkways & Driveways						
41	Composite Decks & Porches						
42	Recycled Plastic/Composite Fencing						
43	Outdoor Solar Lighting						
44	Solar Pool Heater & Cover						
45	Rainwater Collection Barrel						
46	Drip Irrigation System						
47	Greywater Recovery System						
	Total Cost of the actions checked	$121,824	$67,346	$20,702	$107,754	$62,083	$188,859

Personal Priority is the homeowner's value of sustainability reflected in the weighting. Different priority leads to emphases on different criteria. Certainly, there are numerous kinds of weights to the criteria, but in this self-evaluation, four types of priority were identified and their emphases are listed below.

- Comfort: Acoustic Comfort, Thermal Comfort, Luminous Comfort, and Aesthetics;
- Function: Functionality, Durability, and Occupant Control;
- Health & Safety: Indoor Air Quality, Safety and Security, and Thermal Comfort;
- Environment: Energy Saving, Water Saving, and Waste Optimization.

Table 5-2 shows the detailed weights for each type of priority.

Table 5-2 Weights for different personal priority

	Comfort	**Function**	**Health & Safety**	**Environment**
Acoustic Comfort	11%	6%	7%	6%
Thermal Comfort	15%	6%	12%	6%
Luminous Comfort	15%	6%	7%	6%
Indoor Air Quality	6%	6%	15%	6%
Functionality	6%	15%	6%	6%
Durability	6%	15%	6%	6%
Occupant Control	6%	15%	6%	6%
Safety and Security	6%	6%	15%	6%
Aesthetics	10%	6%	7%	6%
Energy Saving	7%	7%	7%	16%
Water Saving	6%	6%	6%	15%
Waste Optimization	6%	6%	6%	15%

5.2.2 Results

In total, there are 144 scenarios (6 budgets × 6 renovation types × 4 personal priorities = 144 combinations). The total cost and the total sustainability score for each scenario were recorded and analyzed below.

Results as per Budget

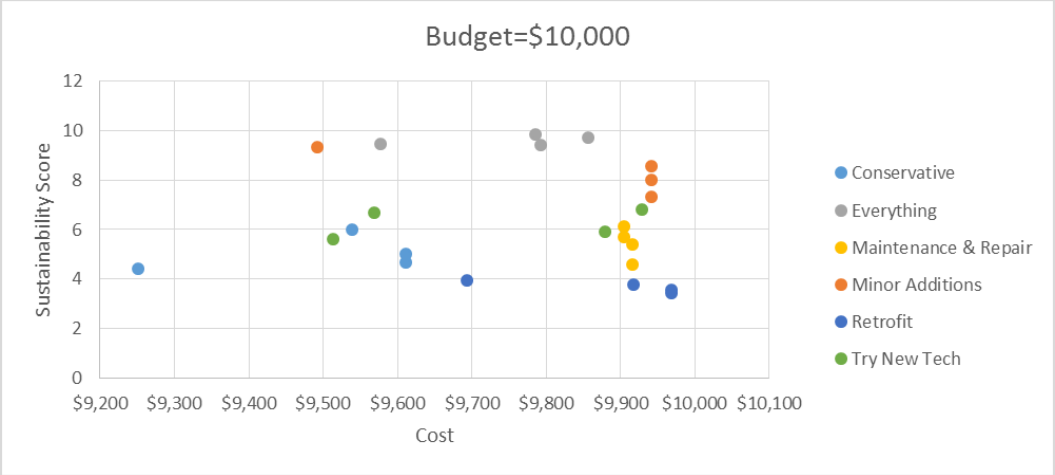


Figure 5-3 Self-test results as per budget (a)

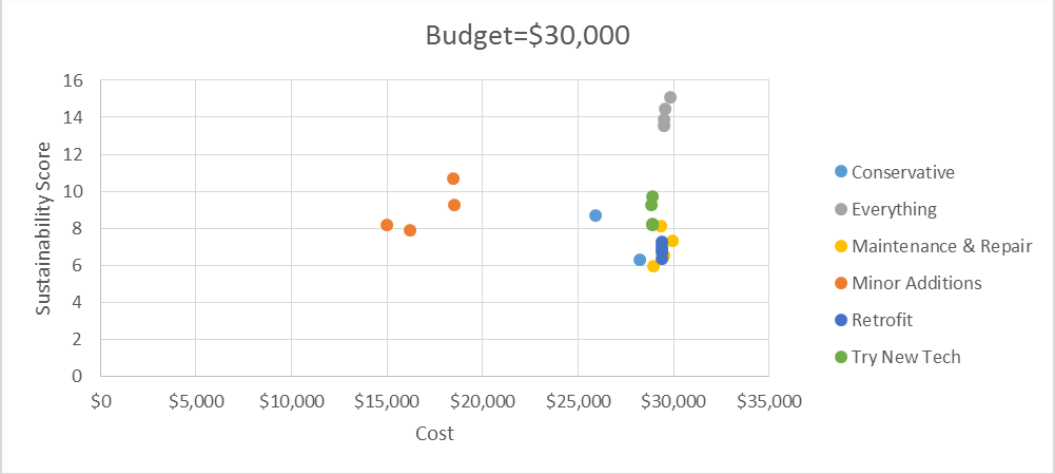


Figure 5-3 Self-test results as per budget (b)

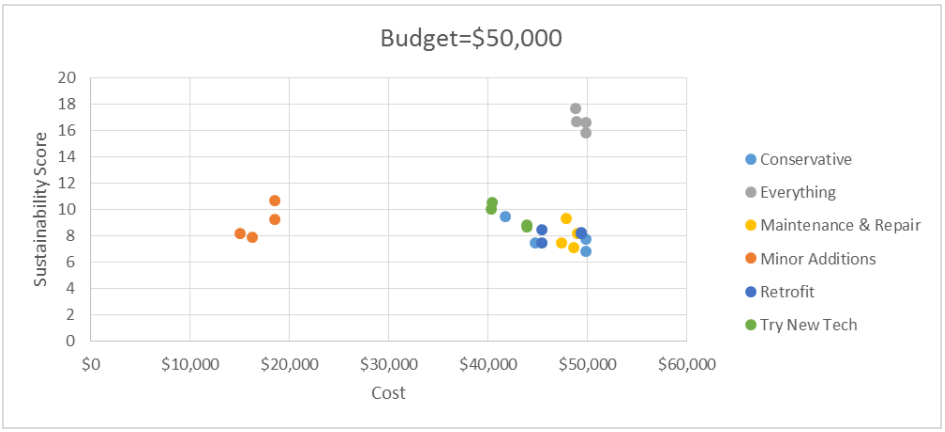


Figure 5-3 Self-test results as per budget (c)

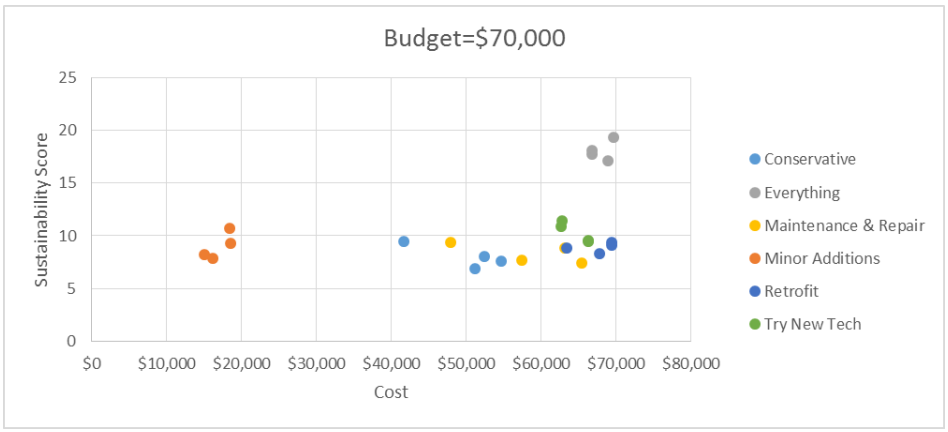


Figure 5-3 Self-test results as per budget (d)

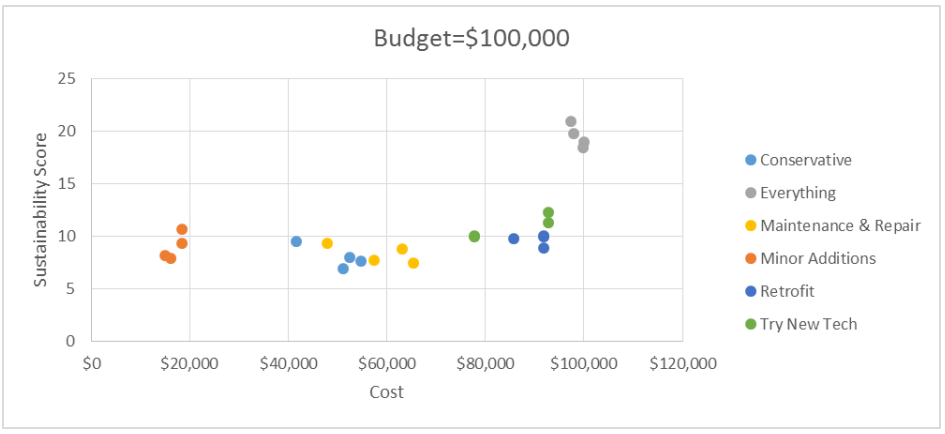


Figure 5-3 Self-test results as per budget (e)

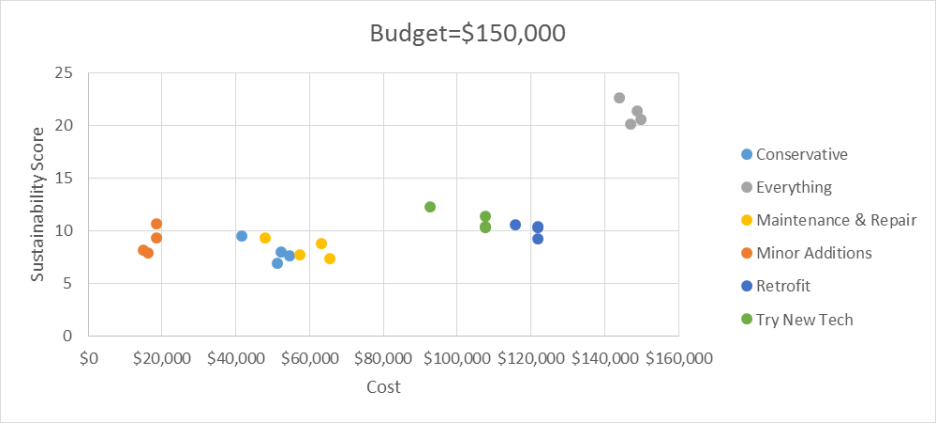


Figure 5-3 Self-test results as per budget (f)

Each figure in Figure 5-3 is a collection of scenarios with a specific budget. The color in those figures represents different renovation types. Each color has four dots, which represent the four personal priorities. As the budget increases, the dots become clustered by renovation type, because the total cost of the actions checked for a renovation type varies (see the last row in Table 5-1). For example, the cost of all the actions checked for *Minor Additions* is $20,702. When the budget is $30,000 or larger, the orange dots still cluster around $20,000.

Results as per Renovation Type

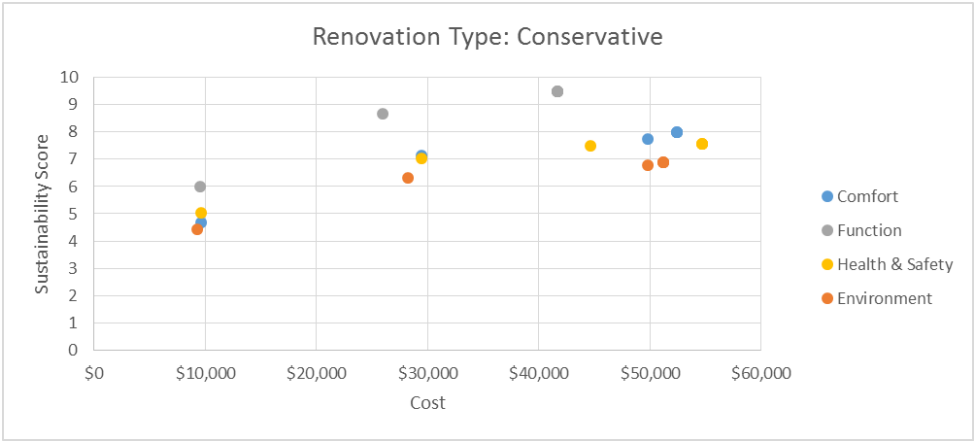


Figure 5-4 Self-test results as per renovation type (a)

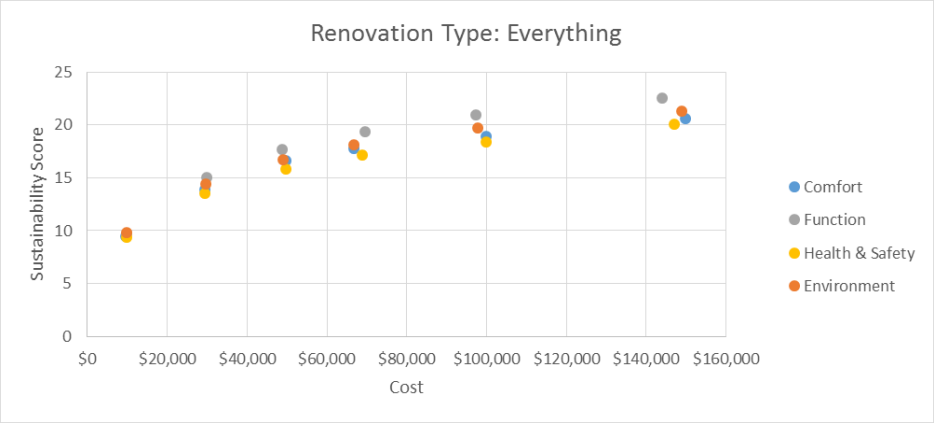


Figure 5-4 Self-test results as per renovation type (b)

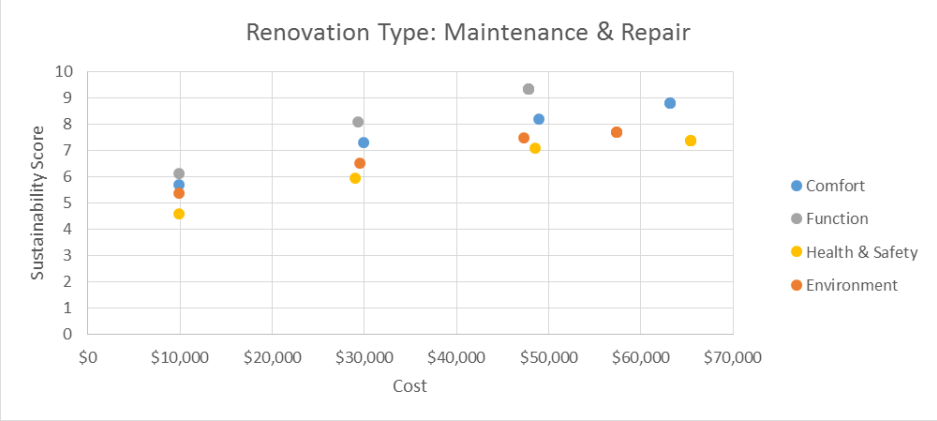


Figure 5-4 Self-test results as per renovation type (c)

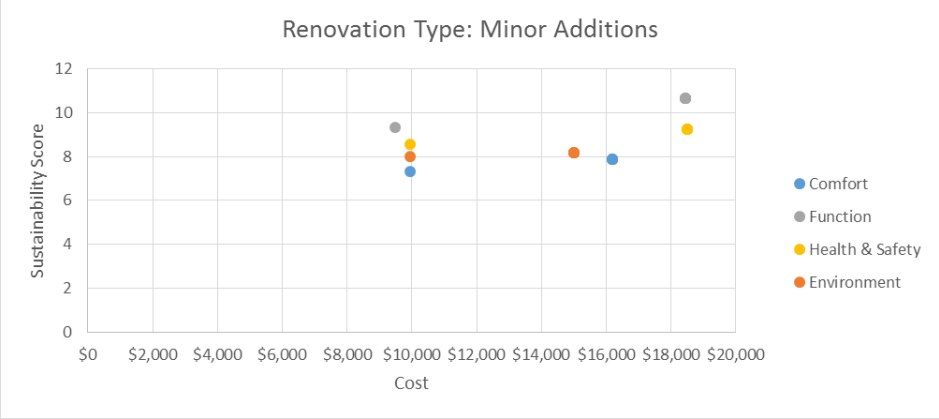


Figure 5-4 Self-test results as per renovation type (d)

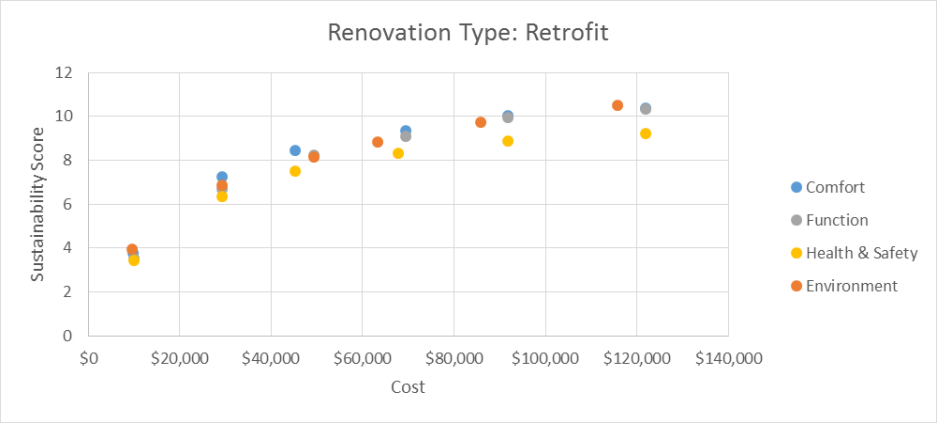


Figure 5-4 Self-test results as per renovation type (e)

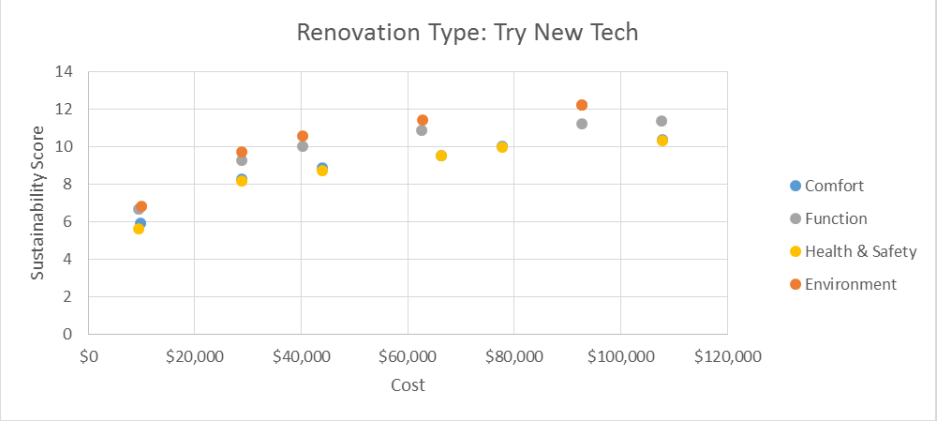


Figure 5-4 Self-test results as per renovation type (f)

Each figure in Figure 5-4 is a collection of scenarios with a specific renovation type. The color of the dots differentiates personal priority. Looking at a specific color in any of the figures (i.e., a specific renovation type and specific personal priority), there is an ascending curve that shows that the sustainability score increases as the cost increases. However, Figure 5-4 (d) does not show this curve because the dots for the scenarios with a $30,000 budget and those with larger budgets overlapped. Also, for the *Minor Additions* renovation type, the increase of expense does not add much to sustainability score. This is because the actions for *Minor Additions* mainly

contribute to functions (see Table 5-1). Thus, if one values *Comfort*, *Health & Safety* or *Environment*, he or she will not gain much sustainability score with these actions.

Similarly, for *Conservative* and *Maintenance & Repair* types of renovation (Figure 5-4 (a) and (c)), if *Function* is the priority, the sustainability score will be higher (the grey dots are higher than others are), because many of the actions checked in these two types of renovation improve the functionality. For *Try New Technology* type of renovation, the scenarios with personal priority on *Environment* earn more sustainability (the orange dots are higher than others are in Figure 5-4 (f)), because most of the new technologies help saving energy and water.

Figure 5-4 (b) and (e) present a good mixture of colored dots because *Everything* and *Retrofit* types of renovation incorporate a diversity of actions with no specific impacts on particular aspects. All the patterns identified above are in accordance with prediction.

Results as per Personal Priority

Figure 5-5 Self-test results as per personal priority (a)

Figure 5-5 Self-test results as per personal priority (b)

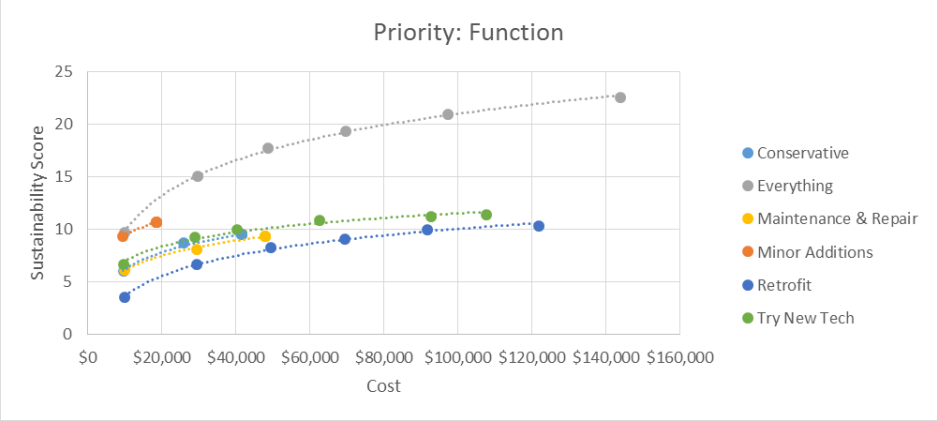


Figure 5-5 Self-test results as per personal priority (c)

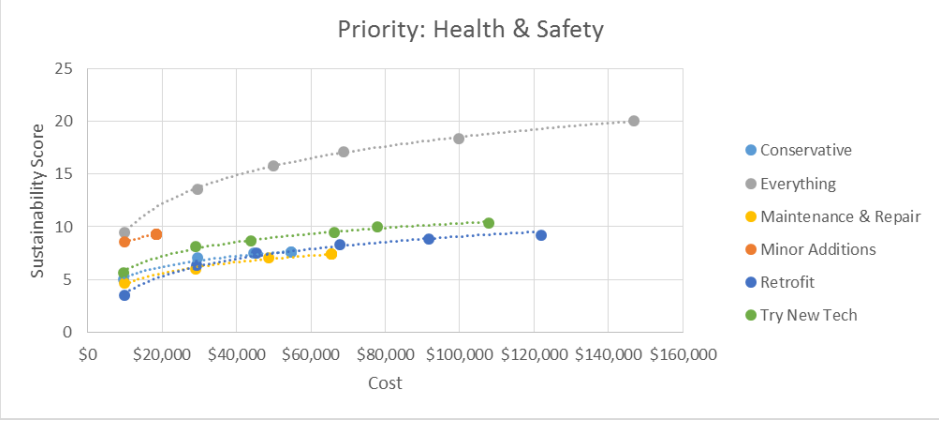


Figure 5-5 Self-test results as per personal priority (d)

The same curve appears in Figure 5-5 that sustainability increases as spending increases. It is also noticed that the tail of the curve tends to be flattened. This may be interpreted that we do not need to spend the entire budget and that lower-cost actions can make good contributions to sustainability. However, it does not mean that high-cost actions have no impact. The 5-star rating score is rather a qualitative classification than a quantitative classification. Therefore, 5-star rating scheme is good at differentiating "bad" and "good", but not good at differentiating different degrees of "goodness" (e.g., between "good" and "very good"). For example, small actions such as faucet aerators ($10 each) and Rainwater Collection Barrel ($170) have a rating "3" to Water Saving; big investment such as Greywater Recovery System (around $10,000) has a rating "5" to Water Saving, which is the biggest score achievable. If we compare the two kinds of actions in SWAHO, apparently small actions will bring more value (score per dollar). However, a Greywater Recovery System will save much more water than the small actions but it is hard to quantify the savings.

In summary, marginal utility is observed in the results, which means homeowners do not need to spend as much as they have to achieve sustainability. However, the marginal utility may partially result from the limitation of the 5-star rating scheme.

Influence from priorities

The basic idea of SWAHO is that different people have different priorities, thus the suggestions should be different. To check if SWAHO embodies the influence from priorities, one specific case was examined. For the case with *Retrofit* renovation type and $70,000 budget, the actions suggested for different priority were recorded below.

Table 5-3 Actions suggested based on different personal priority (Retrofit renovation type, budget $70,000)

Comfort	Function	Health & Safety	Environment
Greywater Recovery System	Greywater Recovery System	Greywater Recovery System	Greywater Recovery System
Drip Irrigation System	Drip Irrigation System	Drip Irrigation System	Drip Irrigation System
Composite Decks & Porches	Composite Decks & Porches	Composite Decks & Porches	Composite Decks & Porches
Green Patios, Walkways & Driveways	Green Patios, Walkways & Driveways	Green Patios, Walkways & Driveways	Green Patios, Walkways & Driveways
Replace Windows	Replace Windows	Replace Windows	Replace Windows
Green Roofing	Green Roofing	Skylight	Green Roofing
Skylight	Skylight	Alarms & Sensors	Skylight
Alarms & Sensors	Alarms & Sensors	Efficient Lighting	Alarms & Sensors
Efficient Lighting	Efficient Lighting	Radon Test and Mitigation	Efficient Lighting
Radon Test and Mitigation	Radon Test and Mitigation	Insulation - walls, ceilings, floors	Radon Test and Mitigation
Insulation - walls, ceilings, floors	Insulation - walls, ceilings, floors	Green Flooring	Insulation - walls, ceilings, floors
Interior Wall Painting	Interior Wall Painting	Drainwater Heat Recovery System	Interior Wall Painting
Drainwater Heat Recovery System	Drainwater Heat Recovery System	Tankless Water Heater	Drainwater Heat Recovery System
Tankless Water Heater	Tankless Water Heater	Solar hot air collector	Tankless Water Heater
Solar hot air collector	Solar hot air collector	Heat pump (cooling as well)	Solar hot air collector
Heat pump (cooling as well)	Heat pump (cooling as well)		

Table 5-3 shows that the actions proposed for *Comfort* and *Function* priorities are the same. Compared to the first two columns, with *Health & Safety* priority, Green Roofing and Interior Wall Painting were not recommended, but Green Flooring was suggested. By looking into the detailed scores in the Data sheet, it was found that Green Roofing did not have any impact on Indoor Air Quality and Safety, but it had a moderate score with earns from other aspects. The reason why Green Roofing was not suggested was that it was too costly. Interior Wall Painting was excluded from the recommendation because it had a negative impact on Indoor Air Quality (paints may emit volatile organic compounds) and thus the total score of it was very low. Green Flooring had a little bit negative impact on Indoor Air Quality (volatile organic compounds) but it contributed a lot to safety since most of the green flooring is resilient. Plus the scores earned for Durability, Aesthetics, and Waste Optimization, Green Flooring earned a very high score, thus it was recommended despite the high cost. The results for *Environment* Priority are the same as the first two columns except that heat pump was not recommended, because heat pump consumes a lot of energy and thus the overall score of it was negative.

Overall Assessment

The self-evaluation methodology—generating a wide range of scenarios and plotting the results—allowed the SWAHO results to be reviewed across a wide range of input values, and to determine some understanding of how the results will change as the inputs are changed in specific ways. This assessment does not prove that the results are optimum for all situations, but any results that were clearly un-expected would be found. No instances or patterns of results were found to be un-reasonable given the input information. In conclusion, the self-assessment results indicated that SWAHO produced reasonable results across a broad range of input situations.

5.3 Discussion and Limitation

All the survey responses were positive regarding the concept of SWAHO. It strongly indicates that SWAHO has the following benefits:

1. SWAHO can provide more sustainable decisions compared to unaided decision-making because SWAHO complements the limited knowledge of homeowners.
2. SWAHO increases homeowners' willingness to pursue a green renovation than professional consultancy because professional consultancy is more time-consuming and more expensive. This is in accordance with the assumption that the increase of convenience will encourage green renovation.
3. SWAHO advocates concerns on environmental impacts during renovation decision-making and, to some degree, encourages a focus on social impacts as well.
4. SWAHO addresses homeowner's individual perception of sustainability, and even further, help them to explore their real concerns.
5. SWAHO has a good potential to benefit the building and furnishing industry.

The self-evaluation demonstrates that the mathematical model of SWAHO—dynamic programming for knapsack problem—operates effectively since the results of all the 144 scenarios were reasonable. A close examination of one scenario reveals that SWAHO is capable of suggesting different actions based on different personal perception of sustainability.

Apart from above, some patterns were observed in the self-evaluation. Accordingly, suggestions for homeowners arise from these patterns:

1. High sustainability scores appear when personal priority matches certain renovation type. For example, *Conservative* renovation type with priority on *Function* tends to achieve a higher score than *Conservative* renovation with other priories achieve; *Try New Technology* renovation type with priority on *Environment* has a higher score than *Try New Technology* renovation with other priories. This pattern implies that it would be helpful if people think about the relation between their priorities of sustainability and their purpose of renovation. The application of this pattern may be, for instance, "I want to increase the functionality of my house, so I should take some traditional renovation actions or maintenance work rather than try new technology."
2. No matter with which kind of priority, the renovation type *Everything* always achieves the highest score compared to other renovation types. This indicates that restriction to a particular type of renovation action may handicap the potential sustainability. Therefore, when homeowners are unclear about their personal priorities, it is better to be open-minded and be interested in every possible renovation action.
3. A marginal utility (sustainability) curve has been observed across all the combinations of renovation type and personal priority. There was not much increase in sustainability score when spending more than $60,000 in the renovation. This pattern may be interpreted that homeowners do not need to invest as much as they have to aim for sustainability. Meanwhile, they should keep in mind that the marginal utility is partially due to the limitation of the 5-star scoring scheme.

In addition, both user evaluation and self-evaluation revealed some limitations of the SWAHO prototype:

1. The user interface should be more user-friendly and self-guided.
2. The language should be more nonprofessional for homeowners to understand.
3. The weighting process should be carefully designed to increase usability.
4. SWAHO is not able to address some special cases.
5. The 5-star scoring scheme is imperfect in terms of presenting the benefit of high-cost renovation actions.

A general takeaway from the meetings with the testers is that users demand more information to feel comfortable to trust the results. Likewise, they are conscientious to ensure the results are applicable to his or her specific context. With that said, there are two directions of future development of SWAHO:

1. An advice tool rather than a decision-making tool.

   Testers suggested treating SWAHO as an advice tool, akin to a mobile game. The aim of the advice tool will be to help homeowners explore possible renovation actions and give advice rather than to give the right decisions. A general database, as the prototype has, is acceptable for this type of tool.
2. A decision-making tool that is applicable to specific context.

   To provide optimal decisions to the users, the tool must be applicable to a specific context. There could either be different location versions, such as SWAHO-Vancouver or SWAHO-New York, each with the city database, or be a general tool that allows the user to adjust the data. This type of tool can replace the current two green renovation paths, as SWAHO was originally proposed. However, the development of the real tool will require a great deal of effort to collect valid and context-based data.

Both of the directions above are favorable. Testers appreciate the SWAHO prototype in terms of helping them understand green renovation, as well, they like the whole concept that integrates all the tasks from decisions on actions to ordering products online. Meanwhile, some testers showed the hesitation to trust the results and the desire for more information. This implies that, although they like the concept of SWAHO, they still want controls over the decisions. Perhaps a larger number of surveys can determine which direction of development is more desirable.

Chapter 6: Conclusion

6.1 Summary

This dissertation proposes an integrated path of green renovation for homeowners, as opposed to professionals in the form of a tool called SWAHO (Sustainability Weighting Assessment for Homeowners). SWAHO attempts to bridge the gap between homeowners' goal and their knowledge in terms of pursuing a green renovation. That is, the proposed path aims to provide easier sustainable decision-making for homeowners given the rationale that the increase of convenience to pursue a green home will encourage sustainable thinking among homeowners and, thus, help increase the sustainability performance of homes.

The SWAHO tool supports the homeowners assessing the tradeoffs among renovation actions and renovation products based on the homeowner's perception of sustainability. A conceptual model was designed that the SWAHO tool integrates all the tasks in pursuing a green home, from decision-making on renovation actions to ordering products on e-commerce websites. A prototype tool, which enables decision-making on renovation actions, was created using Microsoft Excel VBA.

SWAHO is comprised of three domains of knowledge: sustainable actions and products, sustainable criteria and indicators, and mathematical mechanism for decision-making. Literature review in the three domains included books and online resources about green actions and practices, a wide range of sustainability assessments, and mathematical mechanisms such as multi-criteria decision-making and knapsack problem. The literature review constituted the foundation of the main pieces of SWAHO.

A user evaluation consisting of surveys and meetings reported very positive feedback on the concept of SWAHO. Testers also provided many suggestions on the user interface design. A self-evaluation on 144 scenarios showed that all the results of SWAHO were reasonable, meaning that the mathematical model of SWAHO was effective. The two kinds of evaluations set forward the proof of concept that SWAHO is a good path for green renovation.

6.2 Contributions

This dissertation proposes a method to increase the sustainability of buildings from the perspective of homeowners. The main challenge, or in another word, the main contribution to knowledge, was to explicitly present the vague concept of sustainability, and furthermore, to promote optimization for sustainability. The two items below are considered to be the specific contributions.

1. A framework, or conceptual model, of SWAHO

   The framework is a brand-new approach for green renovation, which earned clear endorsements from the testers.

2. A prototype tool of SWAHO

   The prototype tool managed to use a mathematical model to demonstrate the relation between sustainable actions and sustainability objectives.

Both of the efforts contribute to the knowledge area of sustainable building assessment. However, they are distinctive from work done elsewhere, especially different from current prevailing sustainability assessments, such as building rating systems and life-cycle assessment. SWAHO focuses on a segment that is usually under-served, yet it remains the largest group of

people in building industry, the homeowners (homeowners refer to occupants as well in this dissertation). Moreover, SWAHO applies to post-construction phase whereas most of other sustainability assessments are conducted in the design phase. A summary of the differences are listed in Table 6-1.

Table 6-1 Comparison of building rating systems, LCA and SWAHO

	Building Rating System	**Life-Cycle Assessment**	**SWAHO**
For	Professionals, i.e., designers, engineers, etc.	Professionals, i.e., designers, engineers, etc.	Homeowners
Focus	Environmental and social aspects	Mostly on environmental aspect	Environmental, social, and economic aspects
Use phase	Mostly design phase	Design phase	Post-construction phase
Outcome	A report, a certificate	A report of one product or a building	A set of optimal actions and products

The work in this dissertation offers benefits for both nonprofessionals and professionals.

Benefits for Homeowners

The proposed path and tool will equip homeowners with green renovation practices and make it easy for them to pursue a green home. The tool also provides homeowners with the opportunity to explore their real concerns on sustainability. Furthermore, the tool cultivates sustainable thinking in homeowners' mind, which will potentially lead to a more sustainable lifestyle in the future. As a whole, SWAHO helps homeowners save bills while making good impacts on both social and environmental aspects.

Benefits for Professionals

Professionals are increasingly aware of the importance of occupants nowadays. If similar sustainability outreach to nonprofessionals is pursued in the future, this dissertation can provide useful guidance since many suggestions and requirements for user interface were collected in the user evaluation. Lessons learned in this research also tell professionals how to encourage sustainability among nonprofessionals.

6.3 Future Work

SWAHO has some limitations despite the general positive feedback. This leads to several areas of further research and development.

Further Research on the Framework

The conceptual model of SWAHO is a pilot that needs further research. For example, the feasibility of the link to e-commerce system, which is out of the scope of this dissertation, needs further investigation. An integrated path for green home renovation involves a large number of stakeholders, such as the e-commerce companies, the product manufactures, the delivery systems, and of course, the homeowners. There may be some legal concerns when dealing with the relationship between the stakeholders and SWAHO. In general, people are in favor of an approach to simplify the current path for green renovation. However, lots of challenges and unknowns exist prior to putting the approach into practice.

Future Development of SWAHO

To develop a mature software, a rigorous process of software development is required, which includes, but is not limited to, identification of need, planning, designing, testing, implementation, and maintenance. Surveys can help collect user requirements and identify core activities. A full set of UML diagrams can straighten out the structure of the software and guide the development of the software. UML diagrams are comprised of structure diagrams such as component diagram and object diagram, and behavioral diagrams such as activity diagram and use case diagram.

There is a great potential to improve the user interface design. A mobile application or website can replace the Excel file and other coding language could be used. Both the input area and results presentation should be more interactive and neat. Other specific suggestions for user interface are included in Section 5.1.4.

In terms of specific components of the SWAHO tool, the action names and criteria names need revision in order to be easily understood by nonprofessionals without compromising the original scientific meaning. In addition, the weighting process needs refinement to make homeowners more comfortable. Some suggestions have been discussed in Section 5.1.4. Other than those, an Analytic Hierarchy Process can support pair-wise comparison and Fuzzy Set Theory can enable qualitative inputs to the priority of criteria.

Moreover, although the knapsack problem plus a 5-star scoring scheme can successfully model the renovation optimization problem and provide reasonable results, there is a limitation in

capturing the benefits of comparatively high-cost renovation actions. Other mathematical mechanisms are worth investigation to find a more proper mathematical model.

In the current SWAHO prototype, the impacts of each action were entered by the author based on common sense without a strict validation. To increase the credibility, experts should be involved in pre-setting the background data, including the impacts of actions in DM 1 and the conversion rules for products in DM 2. The indicator list in DM 2 also needs refinement. A general future research question could be “how to determine the value of an action or a product”.

On the other hand, experts may not need involvement if SWAHO is able to extract historical data from user ratings. Like user ratings for hotels, for example, homeowners who have bought a product through SWAHO rate the product for different indicators. The average ratings for the indicators could be used for future calculation. This is a potential research direction as well.

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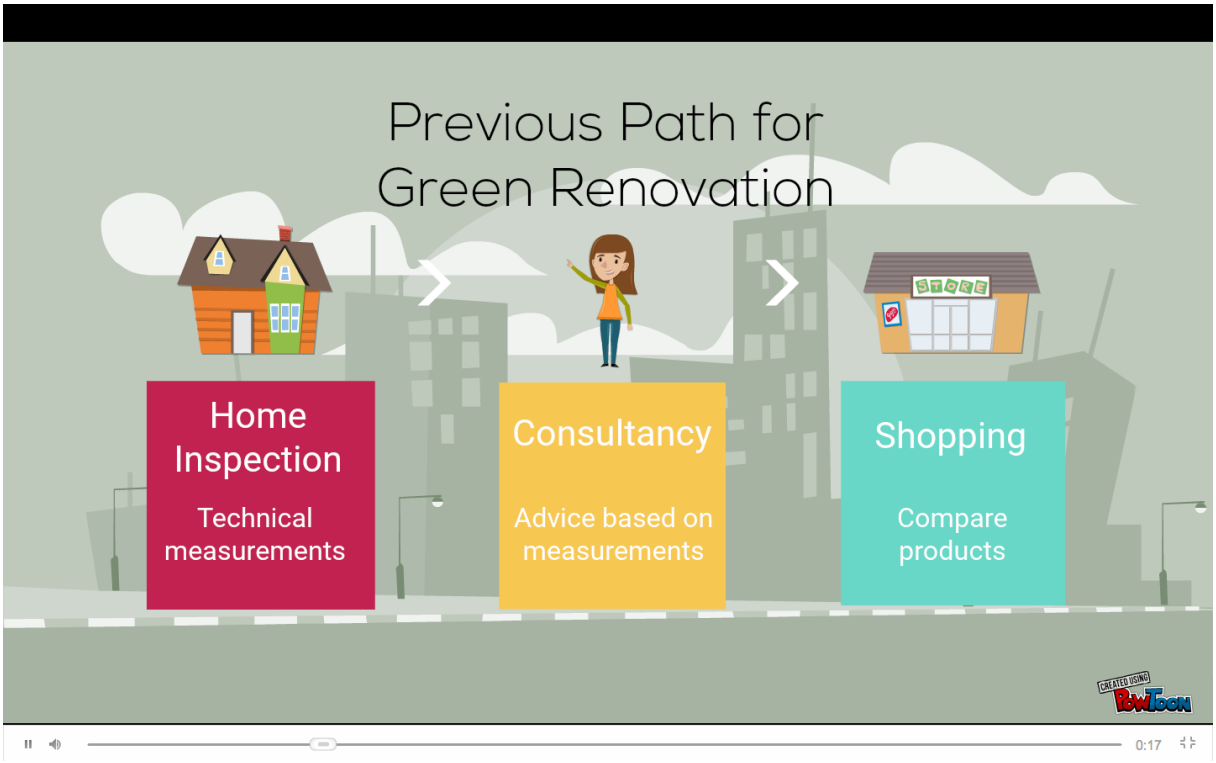
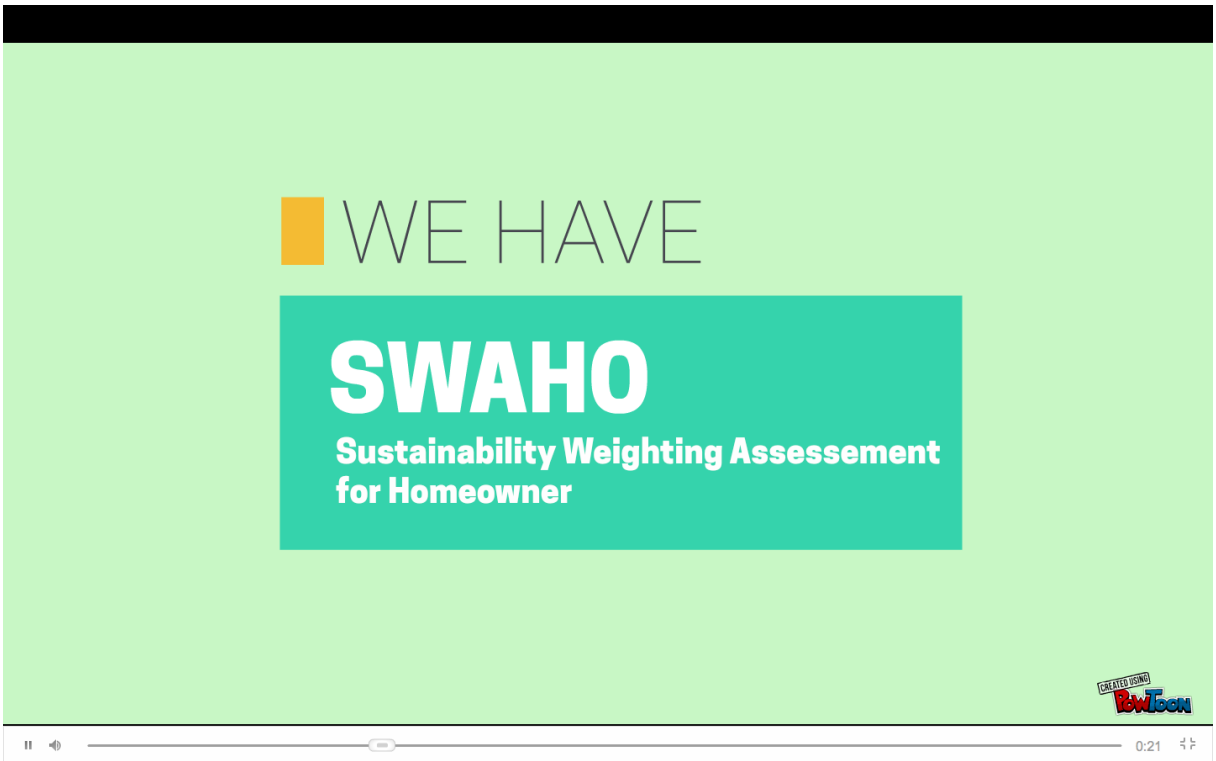
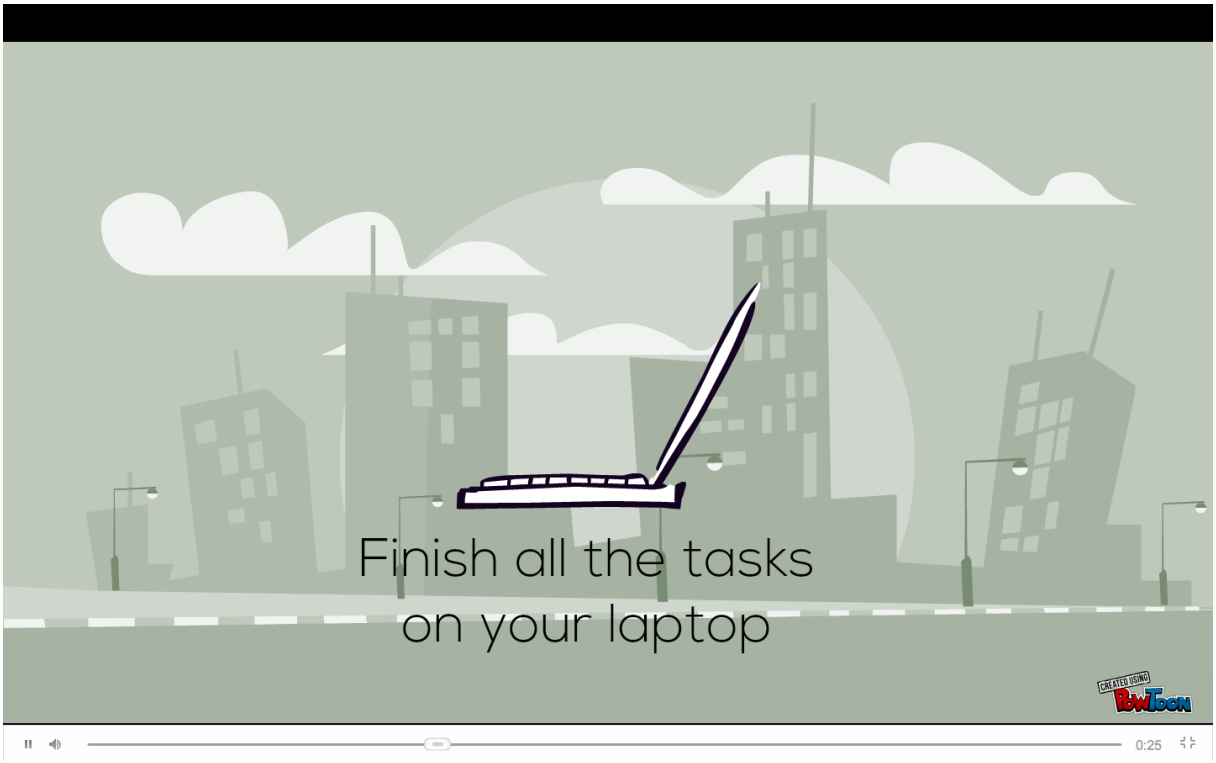
Appendices

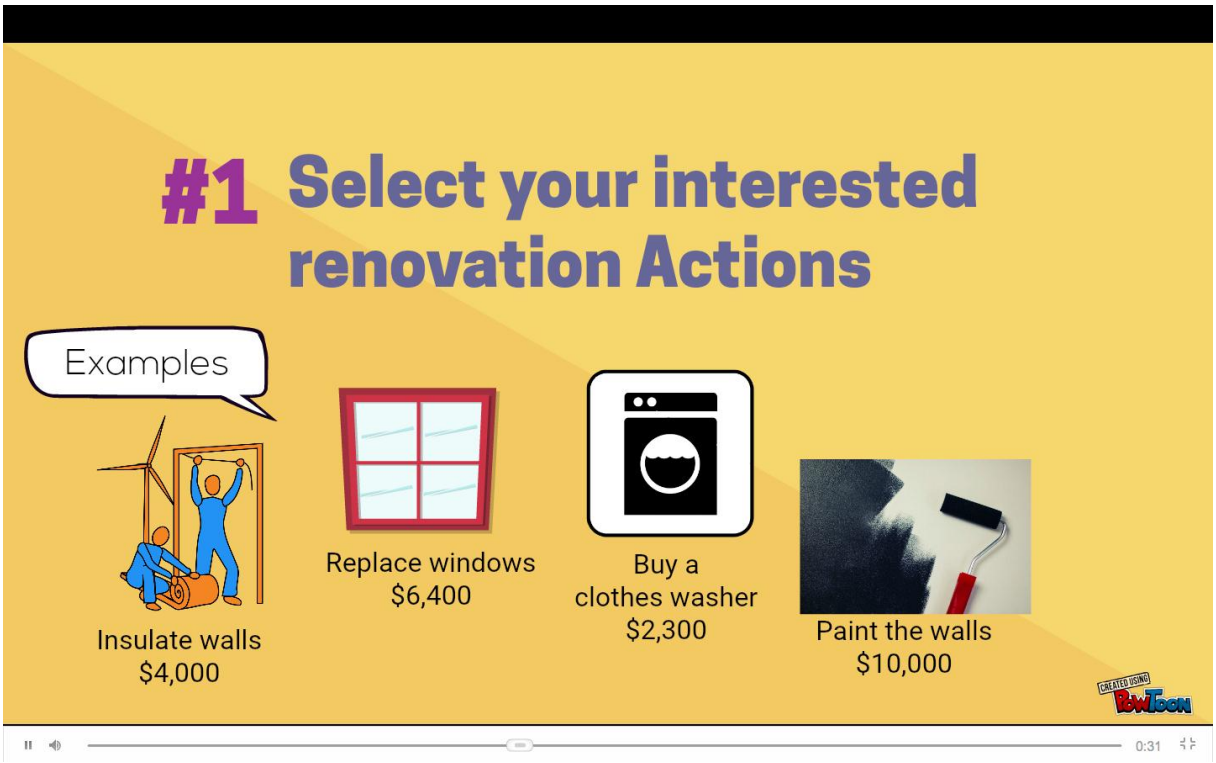
Appendix A SWAHO Introduction Video

The video was created on PowToon, a video maker website. Below are some screenshots.

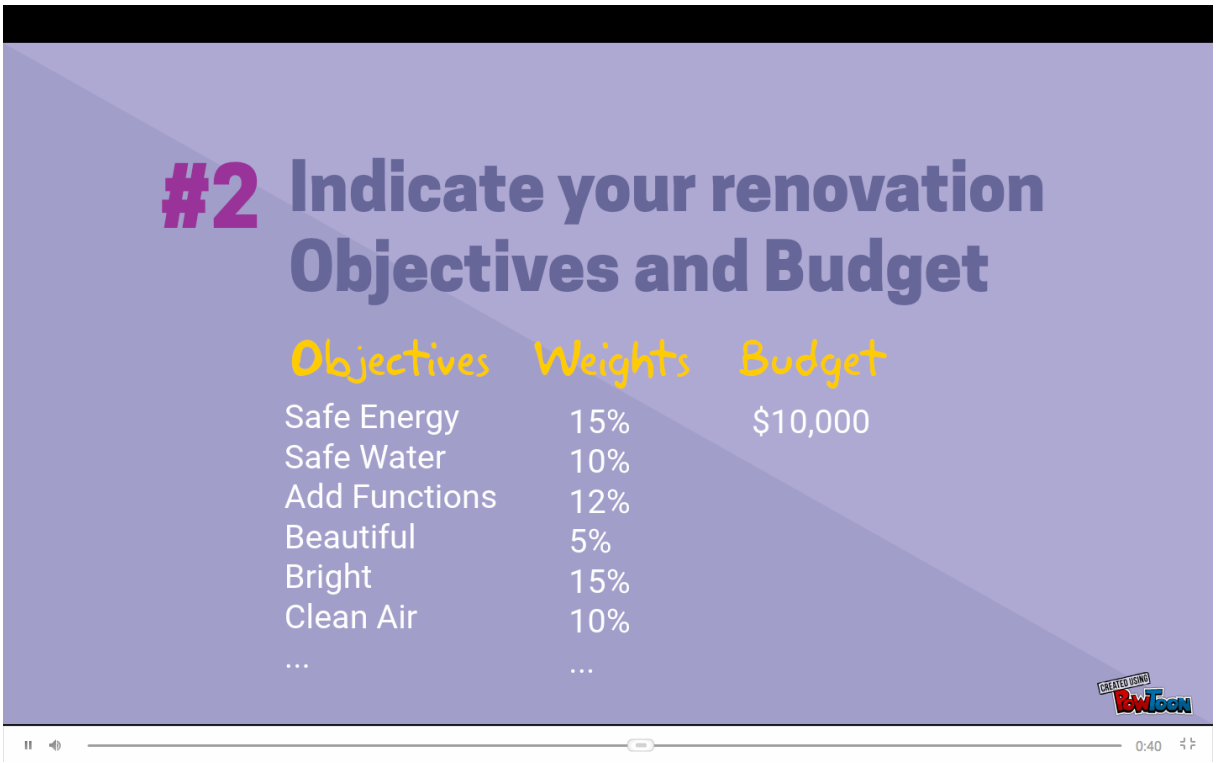

Previous Path for
Green Renovation
Home Inspection
Technical measurements
Consultancy
Advice based on measurements
Shopping
Compare products
STORE
CREATED USING POWTOON
0:17

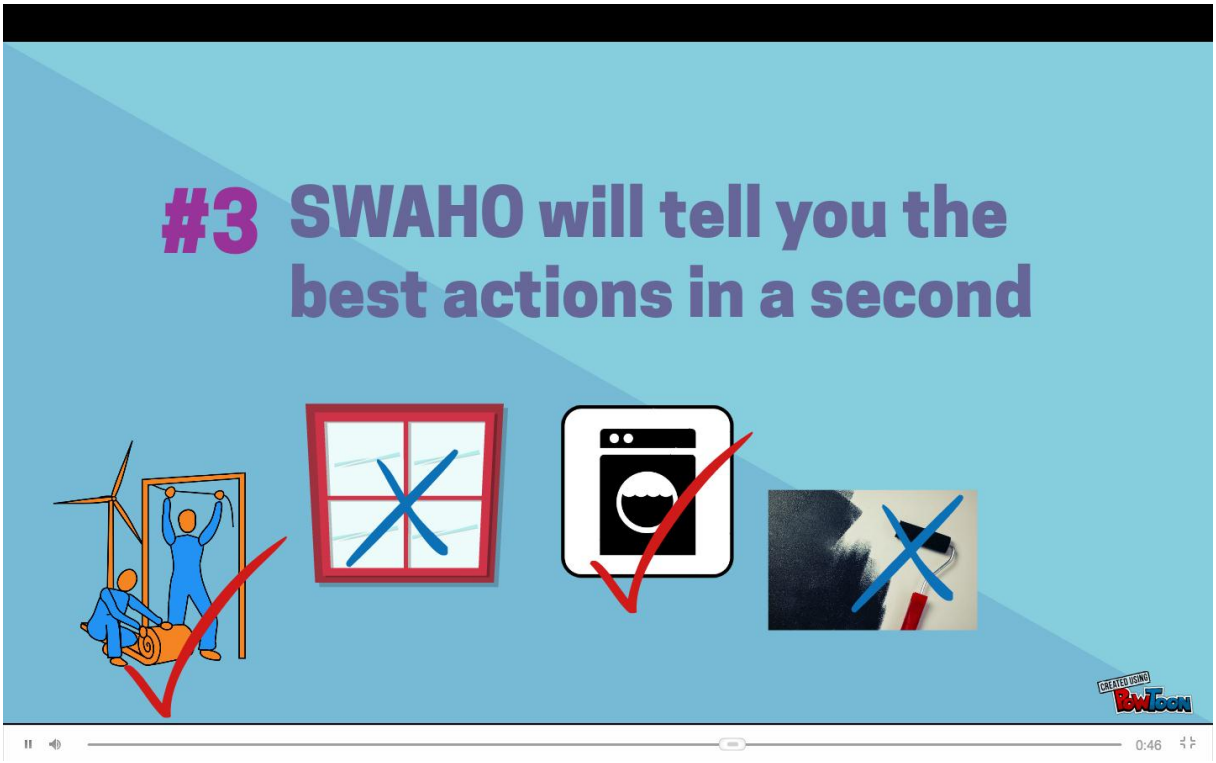

WE HAVE
SWAHO
Sustainability Weighting Assessement for Homeowner
CREATED USING POWTOON
0:21


Finish all the tasks
on your laptop
0:25


#1 Select your interested renovation Actions
Examples
Insulate walls
$4,000
Replace windows
$6,400
Buy a
clothes washer
$2,300
Paint the walls
$10,000
0:31

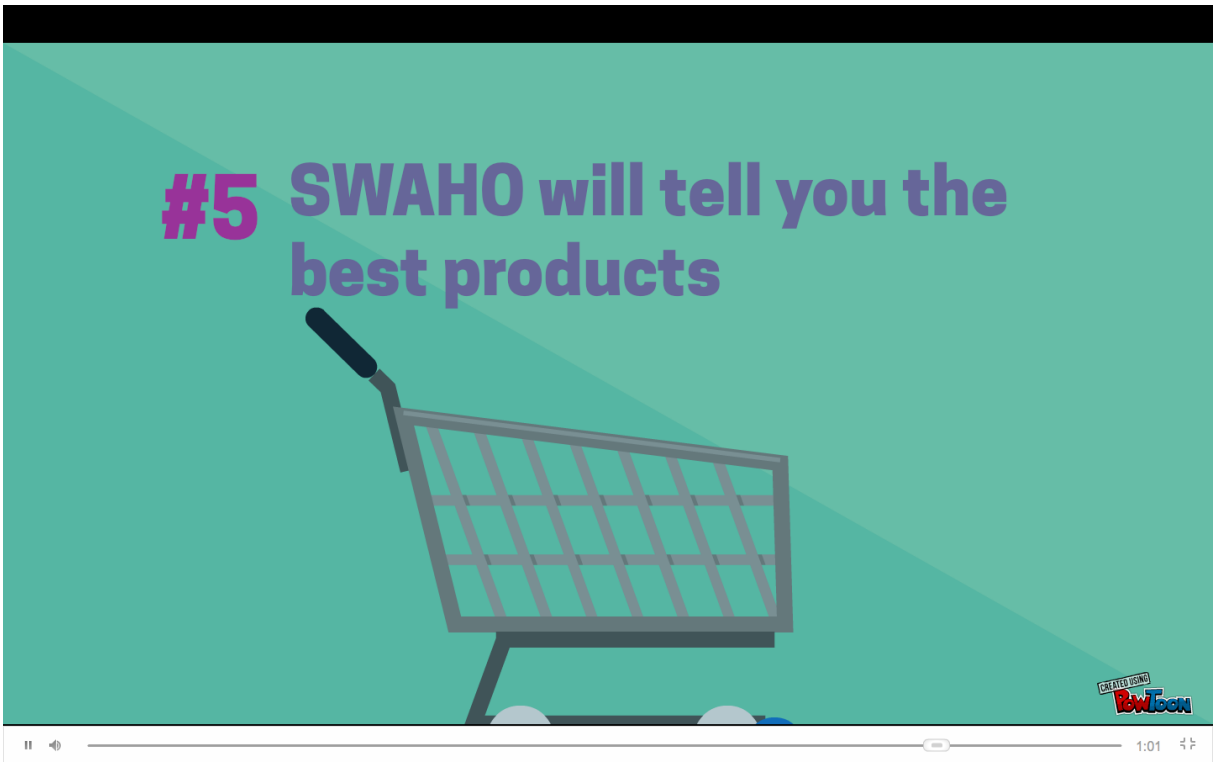

#2 Indicate your renovation Objectives and Budget
0:36


#2 Indicate your renovation Objectives and Budget
Objectives Weights Budget
Safe Energy 15% $10,000
Safe Water 10%
Add Functions 12%
Beautiful 5%
Bright 15%
Clean Air 10%
... ...
0:40

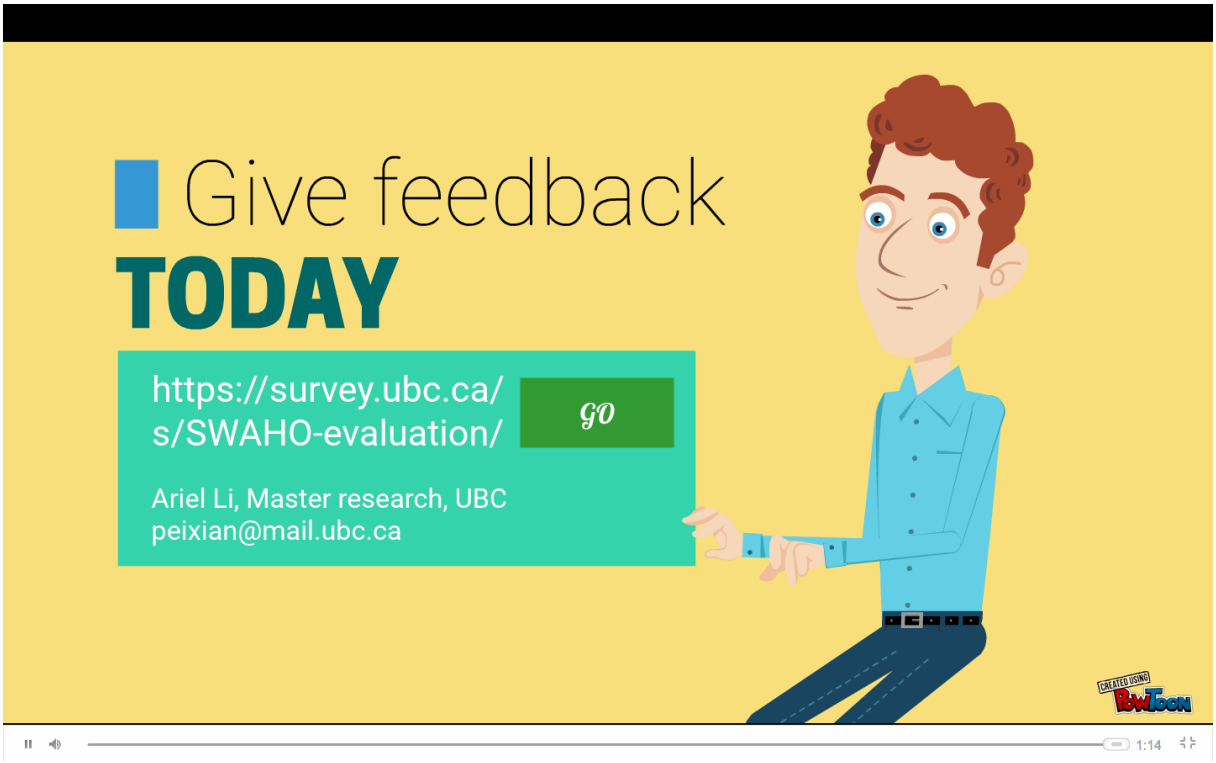

#3 SWAHO will tell you the best actions in a second
0:46


#4 Select alternative Products for actions
Examples
0:54


#5 SWAHO will tell you the best products
CREATED USING POWTOON
0:59


#5 SWAHO will tell you the best products
CREATED USING POWTOON
1:01


SWAHO
Easy
Customized
1:08


Give feedback
TODAY
https://survey.ubc.ca/s/SWAHO-evaluation/
GO
Ariel Li, Master research, UBC
peixian@mail.ubc.ca
1:14

Appendix B SWAHO Evaluation Survey

Link: https://survey.ubc.ca/s/SWAHO-evaluation/

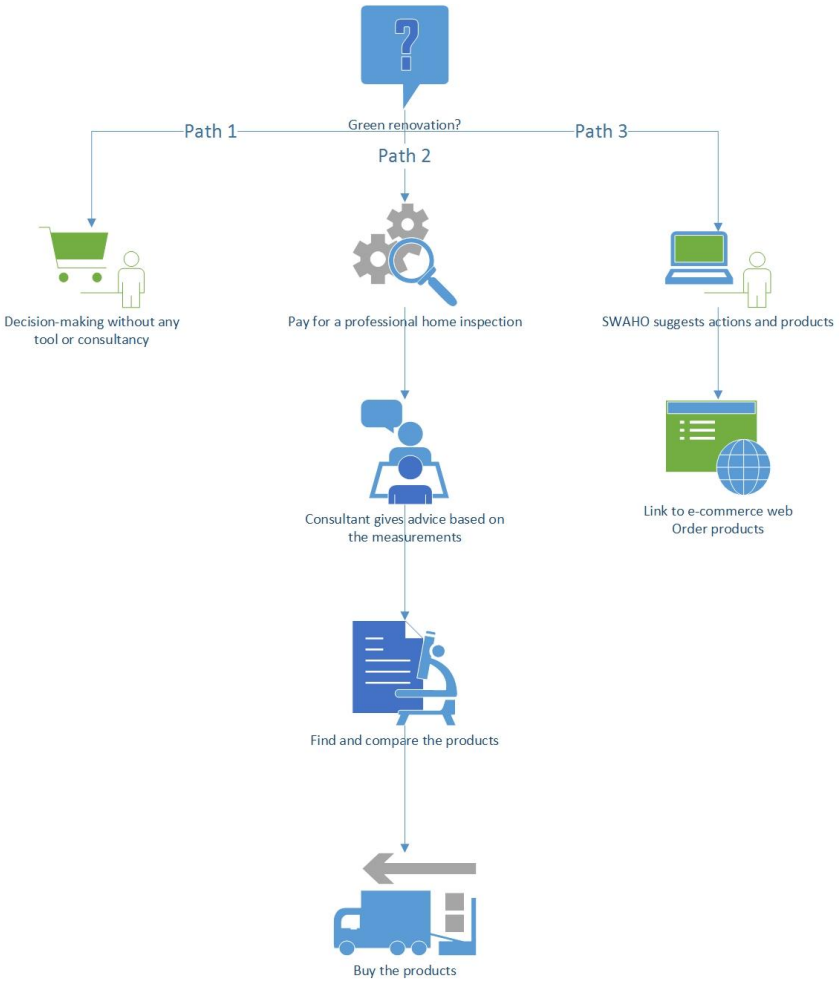
PART A. Do you agree or disagree with the following statements?

We are comparing **3 paths** to **Green Renovation**:

Path 1. Unaided Decision-making

Path 2. Professional Consultancy

Path 3. SWAHO tool



SWAHO provides more sustainable decisions than unaided decision-making.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly Agree

Compared to unaided decision-making, with SWAHO, I am more likely to consider ENVIRONMENTAL impacts during renovation.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly Agree

Compared to unaided decision-making, with SWAHO, I am more likely to consider SOCIAL impacts during renovation.

- ○ Strongly disagree

- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly Agree

I am more likely to pursue green renovation given Path 3 than given Path 2.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree
- ○ Strongly Agree

I prefer to use Path 3 than to use Path 2.

- ○ Strongly disagree
- ○ Disagree
- ○ Neutral
- ○ Agree

○ Strongly Agree

PART B. About SWAHO

Do you like the actions and products proposed by SWAHO?

○ Yes

○ No

If you don't like the results, why?

Did SWAHO help you understand green renovation?

○ Yes

○ No

Do you think, if SWAHO links to e-commerce, it will benefit the building products companies?

○ Very unlikely

○ Unlikely

○ Uncertain

○ Likely

○ Very likely

Any suggestions to SWAHO?