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HEALTH^2: A Holistic Environmental Assessment Lay Tool for Home Health

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Abstract

Although the adverse health effects of poor indoor air quality on occupants from mold and dampness in indoor environments are well described, there is no reliable empirical tool to evaluate indoor mold and dampness levels in the home for use by the medical profession and health safety regulatory bodies. The economic impact to society approaches $ 40 billion a year in North America alone from the cost of health care and workplace lost productivity. Mobilizing corrective action necessitates an acceptable home environment evaluation method. This paper proposes a reliable empirical model and tool, the **H**olistic **E**nvironmental **A**ssessment **L**ay **T**ool for **H**ome **H**ealthiness, and develops guidelines for its use as a tool to evaluate and rank mold and dampness related indoor environmental conditions associated with known respiratory health outcomes. **HEALTH^2** was calibrated using theoretical homes and then validated using data from 269 home evaluations where occupant health and the home environment factors were collected. Results suggest the model can be used as an early detection tool to assist in determining indoor environment risk factors associated with respiratory illness from mold and dampness. Empirical modeling and this tool can assist environmental professionals in determining improvement scenarios beyond general industry prescription and assist regulatory bodies in setting home health guidelines. The **HEALTH^2** model challenges the dominant view and suggests that damp/moldy environments are measurable and the impact to society is sufficient to necessitate prompt medical and regulatory action.

Key words/phrases: building factors, damp and moldy environment, environmental model, home health, indoor air quality, mold, respiratory symptoms.

1. Introduction

The adverse health effects of poor indoor air quality (IAQ) on workers from mold and dampness in indoor environments are well recognized by environmental professionals and worker compensation boards but without measurable limits for acceptability. Despite its regulation in workplace and public environments, health safety regulatory bodies have been limited by building science knowledge gaps and privacy rights legislation to facilitate empirical based corrective measures for residential environments. Qualitative assessment with no measurable methods or means for in-depth analysis and residential restrictions limits opportunity to address significant health, economic, and productivity issues in society.

This paper proposes a reliable prediction tool for health risk due to mold and dampness through the **H**olistic **E**nvironmental **A**ssessment **L**ay **T**ool for **H**ome **H**ealthiness (**HEALTH^2**) model. This is accomplished by empirically linking building environments with health effects using building science factor assessment to reliably evaluate critical environmental conditions pertaining to respiratory health. Towards this, the paper focuses on residential indoor environments with three purposes: 1) present the development of the **HEALTH^2** model and guidelines for use as a tool to fill the knowledge gap; 2) calibrate the model to reflect realistic results; and 3) summarize results of initial **HEALTH^2** model validation.

2. Previous work

Indoor dampness and mold growth are risk factors to occupant health (Antova et al. 2008, WHO 2009, NYSTMTF 2010). Respiratory disease and particularly flu-like symptoms, wheeze, cough, upper and lower respiratory symptoms are associated with mold exposure (Koskinen et al. 1999, Krieger et al. 2010, Mendell et al. 2011, AIHA 2013). Reduction of mold and dampness in homes improves occupant health and reduces frequency of urgent clinical visits (Burr et al. 2007, Bernstein et al. 2008, Takaro et al. 2011, AIHA 2013). Recent research directly associates indoor mold burden and particular molds to the onset and exacerbation of asthma in children (Reponen et al. 2011, 2012). Overall, asthma incidence has more than doubled between 1980 and 1995 (CDC 2005). Yet building standards and regulations do not address the control of molds and dampness in indoor environments (WHO 2009). Timely remedial measures in at-risk homes and work places are critical to disease avoidance and reduction in population sickness, an increase in occupant well-being, and reduction in the overall burden on society (Fisk et al. 2010). The impacts are significant, with an estimated 20–50% of housing stock affected, totaling over ten million homes in North America (Zock 2002, Jaakkola 2002).

Mold and moisture are ubiquitous and exist under most conditions to varying extent. There are no generally accepted empirical means to measure indoor mold and dampness conditions and set objective outcomes (Worksafe 2013). The risk of health consequence is yet to be defined but risk assessment may provide a solution until definitive limits are developed. Indoor air quality (IAQ) regulation and assessment requirements pertaining to mold legislated for commercial, institutional, and public buildings to maintain worker health is a complaints driven process. The process lacks in empirical measurement for assessment and validation. Withdrawal of complaint (without merit) or instituting methods to reduce future complaints/issues by fiat are the instituted resolution methods (US EPA 2013, Worksafe 2013). Consequentially, environmental remediation of mold and dampness where legislated is generally based on prescriptive solutions, qualitative in nature, based on previous methods that are open to interpretation. Without means to delve deeper into cause and effect, the consequence is a lack of progress in the reduction of significant health and economic impacts in our society. Canadian health care costs due to moldy and damp environments approach $1 billion, with an estimate of over $9 billion annually in the USA. Including lost productivity in the workforce, the impact exceeds $40 billion in North America (Health Canada 2007, WHO 2009, Fisk et al. 2010). Without quantitative based regulation a reliable empirical indoor environment risk assessment tool is needed to evaluate and provide guidance for the reduction of environment induced respiratory disease from mold and dampness.

Haverinen (2002) proposed using scientific method to understand environmental effects on unhealthy occupants and comparing study results. A housing environmental assessment model with empirical validation has been suggested as a basis for improving respiratory health from mold and dampness

(Keall et al. 2010, 2012). Predicting building related respiratory symptoms with environmental exposure response relationships and suggesting indices of exposure to dampness and mold can support action to prevent building-related respiratory disease (Park et al. 2004). The models developed to date to evaluate the risk of mold causing health impacts in homes have shortcomings (Vereecken & Roels 2012). These shortcomings include non-conclusive, non-predictive conditions, and an incomplete evaluation method to assess environmental factors that comprise indoor environments.

3. Methodology

A four step process was used to develop the **HEALTH²** model, including: 1) identification of key building environment and lifestyle IAQ risk factors from epidemiological and building science research linking respiratory distress to dampness and mold growth; 2) analysis of factors using relational factor association to identify and assemble inter-relationships and correlations; 3) model formulation to provide structure to the model, assess and rank the environmental factors based on building science and expert knowledge; and 4) calibration, using theoretically generated indoor IAQ factor values spanning a measured domain. These steps are described in more detail below.

3.1 IAQ factor identification

The indoor environmental models found in literature fall into four categories: deterministic; predictive; index; and dose response (Table 1). Environmental characteristics and methods are introduced, but no one model addresses the indoor environment as a whole. To a greater extent Haverinen et al. (2001, 2003, 2006) identifies housing characteristics, but not building factors, that predict health response from a simple moisture damage classification. This research adds to the current literature by suggesting the extent of moisture damage and health response may be more fully defined if correlated to the key building factors that comprise the indoor environment to predict conditions more specifically.

Indoor environments are affected by building envelope, ventilation, filtration, and moisture, exacerbated by nutrient levels and occupant load that allow mold growth (CMHC 2013, USEPA 2013). The building envelope defines the extent of the conditioned living environment and protects the indoor environment from external elements (CMHC 2013). Moisture and airborne debris control is managed by indoor and external ventilation and extent of air filtration (ASHRAE 2007). A well designed building envelope reduces the risk of moisture intrusion and defines the dew point location for dampness analysis (WHO 2009, US HUD & CMHC 2013). Mold does not exist without both moisture and nutrients present (Park et al. 2006). Moisture and nutrients are source factors for mold growth. Molds obtain nutrients by decomposing organic sources inherent in building components, such as cellulose, exacerbated by dirt and organic debris from occupant storage and poor home hygiene levels (WHO 2009, US HUD 2009, Health Canada 2010, Vesper 2011). With mold proliferation a function of moisture and nutrient levels, poor quality ventilation and filtration systems lead to poor indoor environments (WHO 2009). These primary elements amplify the effects of mold growth.

In addition to housing component factors, the literature identifies family lifestyle and non-adherence to environmental prevention guidelines as a significant risk factor for onset or exacerbation of asthma and respiratory disease (CDC 2005, US HUD 2005-12, CMHC 2013). Nutrient development, odor, and excess moisture developed from human activities including cooking and bathing, population size, and occupant burden (storage levels and types, moisture generation, systems utilization), are shown to be modifier factors in the development of mold growth in moist environments (US EPA, US HUD, CMHC 2013). Alternately, outdoor air is critical to reduction of indoor contaminants and extent of environmental tobacco smoke (ETS) as part of airborne particulate loading in general (US HUD 2006 & 2009, WHO 2009). Airborne mold measurement due to conflicting opinions from the literature and a lack of consensus among regulating bodies on specific numerical recommendations was excluded as a factor in the modeling (Worksafe BC 2002, WHO 2009, Mendell et al. 2011, CMHC 2013, US EPA 2013).

Combined, these source and modifier factors provide a holistic view of an indoor environment from which health impact risk may be predicted based on building environment as a complete system, rather than its individual parts, within a science of reasoning (Meriam-Webster 2013).Table 2 summarizes these as the

13 primary risk factors that have been identified as the key indoor environment characteristics, utilizing the fundamentals of building science to provide a comprehensive assessment.

3.2 Analysis of factors

Figure 1 summarizes a cognitive mapping exercise that revealed environmental and health relationships from field knowledge, which helped to align constituent parts in the model. Cognitive mapping is used to accumulate spatial knowledge, allowing the "mind's eye" to visualize images in order to reduce cognitive load and enhance learning. This type of spatial thinking can also be used as a metaphor for non-spatial tasks using spatial knowledge to assist in the processing of the task (Ross 2004). The mapping exercise exposed key environmental factor associations and levels of factor significance. This process exposed health sickness as an output factor and that a relative association existed between the various environmental input factors and occupant health results that could form an analytical model.

The overall association between source and modifier factors and how they combine to form an output value is presented in Figure 2 following from factor identification and relationship analysis based on the premise that:

1) nutrients and moisture as prime source factors must combine first to generate mold before site conditions can affect (amplify) proliferation;
2) the remaining factors are prime modifiers that amplify the effects of mold growth from nutrient and moisture combination;
3) sub factors describe different prime nutrient and moisture or modifier sources or conditions;
4) whereas sub factors are considered additive, significant proliferation of mold growth is of a multiplicative nature that would not be represented reasonably by addition of prime factors;
5) the cumulative of all source and modifier factors combine by multiplication after all factor treatments are concluded;
6) sufficiently moldy and damp environments contribute to residential respiratory sickness.

Table 3 presents the 16 source and modifier factors and sub factors developed from the analysis of factors, derived from the 13 primary indoor environmental building condition and lifestyle risk factors (Table 2). The input values for the model factors and sub factors allow for the widest possible range of specific building conditions determined from direct site inspection and/or analysis or remote assessment by occupant interview.

Non-mold related environmental impact factors such as chemicals, VOCs, mVOCs, and radon are excluded in this research, except for environmental tobacco smoke (ETS), a known major contributor to onset or exacerbation of respiratory disease. Although it is not contingent on mold or moisture in the indoor environment per se, researchers typically adjust for ETS in mold and dampness studies. Each factor was then given a value range based on which level of building condition it fits into over the ranges possible (Supplemental Page S2).

3.3 Model formulation

With the identification and assessment of the relevant IAQ factors, and the ranking of factor inter-relationships, the factor analysis relationship diagram for the **HEALTH^2** model shown in Figure 2 was developed. An analytical structure was then determined necessary to be overlain on the relationship diagram to develop a model structure with empirical results.

Decision making theory using multi-criteria decision making, fuzzy logic, and the analytical hierarchy process (AHP) were all examined as tools for formulating the model structure from process flow, determining factor weighting, and organizing the process output. AHP with a pair wise analytical approach through prioritization was chosen. Its benefit was determining the relative merit of members of a set of alternatives, as opposed to selecting a single alternative or merely ranking them. The analytic hierarchy process (AHP) is a structured methodology for organizing and analyzing otherwise complex issues. This capability distinguishes the AHP from other decision making techniques (Fraser et al. 2009). The factors and relationships are known. Weighting is a knowledge-based determination. Output is a numerical compilation of weighted factors.

Utilizing AHP, pair wise comparison of the factors and sub factors to determine their relative weights and ranking was undertaken. Three levels of AHP were applied in this structure to complete the source and modifier analysis based on the IAQ factor input (sub factor) values identified. The resultant third level source and modifier values are the result of the multiplication of weighted values, independent of each other, subsequently multiplied together to develop the HHI score (Figure 3).

Line by line site condition input is provided at the sub factor level on the HEALTH2 model structure input template (supplemental page S2). This produces sub factor composite values that become input column factor values modified by the various regional cognitive matrix criteria or weights (eg. single family residences, central BC/ lower mainland area urban climates – Supplemental Page S3) and compiled into source and modifier values. Refer to Figure 4 for an example of a multiplier matrix for indoor house hygiene levels with the normalized weighting vector value for the model.

The resulting source and modifier values are multiplied together to obtain the Home Healthiness Index (HHI) for the particular home (Figure 3). The **HEALTH^2** data input and output process flow diagram for the model is provided in Figure 5. This includes a health outcome based on health score results.

The extent to which respiratory illness is caused by mold and dampness in indoor environments is discussed in literature and summarized above. The **HEALTH^2** model empirically assesses the indoor environment for extent of mold and dampness contamination with a resultant index score. The prediction of health risk follows from site specific data analysis. This is accomplished with the development of a resident health score (RHS) derived from health response correlated to the HHI in a particular home. Initially a 5 level environment scale was set. A 2 or 3 level scale was found to be too coarse; a larger scale range not defendable. A 5 level scale was chosen in relation to respiratory conditions observed in the literature. A score of 1 indicates the respondent has no respiratory health issues. A score of 2 identifies minimal respiratory health issues by the respondent such as cough or light wheeze. A score of 3 indicates the respondent is somewhat or lightly hindered by respiratory issues with consistent coughing and wheeze requiring limited medication and mild inhaler use. A score of 4 indicates the respondent is hindered by function affecting heavy cough, loss of breath, and persistent wheeze that requires prescription medication and consistent doctor visits. A health score of 5 indicates the respondent has uncontrolled asthma with unplanned emergency room visits and extended hospital stays with heavy medication.

3.4 Model calibration

To verify test results, the HHI value should be comparable to similar types of homes with similar indoor environments; but dissimilar under different environmental conditions. For example, an environmentally impacted home would measure a significantly higher HHI than a clean, well-cared for home with little to no adverse environmental or lifestyle conditions. The **HEALTH^2** model was calibrated as such using a theoretical set of specific environmental conditions based on a wide range of well-known indoor environments, including: house #1 - lower standard; house #2 - mid-standard; and house #3 - premium standard for the Okanagan region of British Columbia.

House #1 is modeled as a contemporary two to three bedroom 1970's bungalow on a heated crawlspace meeting the basic building code requirements for its day with a low insulation level poorer quality building envelope; non-insulated dirt crawlspace with no ventilation; single pane aluminum sliding windows; electric baseboard heat; no mechanical ventilation or filtration; no outdoor passive fresh air; inhabited by a small single family. House #2 is a last 1980s mid-standard single family home constructed with a better quality building envelope, increased insulation levels, added mechanical ventilation and fresh air supply with a forced air furnace, kitchen and washroom extraction fans, and double pane thermally broken windows. House #3 is a newer constructed single family premium standard residence with an air/vapor tight building envelope, high insulation levels, mechanical fresh air and recirculatory air handling systems, advanced mechanical air filtration, higher quality thermal windows, high efficiency heating and mechanical ventilation, reduced carpeting, and ventilated storage areas.

Each home was evaluated with the **HEALTH^2** model over four IAQ factor value scenarios for a total of 12 (3x4) test applications to assess the input factor valuations (ie the HHI range), and the output predicted (ie the RHI range). Scenario one: pristine, clean environment, light occupancy, and well maintained with some attention to indoor air/environment quality (clean and dry environment). Scenario two through four identify specific nutrient and moisture loads systematically introduced into the home. Scenario two: poor level of maintenance, low level of care (increased nutrient base), higher occupancy load (larger family or multi-family residence), and no attention to indoor environment quality. Scenario three: Scenario one with an active moisture event (> 48 hrs.) and visible mold growth. Scenario four: Scenario two with an active moisture event (> 48 hrs.) and visible mold growth.

The **HEALTH^2** model calibration results (Table 4) reflect expected outcomes in general. Low or substandard building environments are more susceptible to the development of indoor fungal contaminants (higher HHI and associated health impacts) than higher quality building environments. This is consistent with literature where introduction of nutrients through lack of hygiene, excess storage, building systems overload, and moisture at varying degrees has been associated with mold growth (Kercsmar et al. 2006, Antova et al. 2008, Jacques 2011).

A clean and pristine premium home (HHI 0.9) is very unlikely to have a health affecting environment, but becomes moderately likely with a change of conditions that include poor maintenance, increased occupants and storage, and corresponding nutrient loading from poor housekeeping (HHI 8.3). It then becomes a likely environment for ill-health with the addition of active moisture intrusion (HHI mid. 25.5). With the pristine clean environment, a water event longer than 48 hours elevates the home in the model from “unlikely” to “moderately likely” (HHI mid. 11.2) to have a health affecting environment.

The lower standard home, with a substandard building envelope, and non-existent ventilation and filtration system that is “unlikely” (HHI 8.8) becomes ”likely” with an occupant/ storage overload and reduced care and maintenance of the space (HHI 20.2). This increases to a high value (HHI mid. 50.0) with a moisture event extending over 48 hours. From an overview of the value outputs, it appears the HHI scores fall into a 4 scale range of 0-10 indicating a very unlikely to unlikely adverse environment for all three housing types; 10 – 20 moderately likely; 20-30 likely; to 30+ very likely to have a health affecting environment for the mid and low quality housing stock. These theoretically calibrated scores and qualitative health determinants were then assessed and validated using actual real world data.

4 Model validation

The calibrated **HEALTH^2** model was validated using data developed from two sources: 1) Okanagan BC residential environmental site inspections conducted from 2007 – 2013; and 2) remote assessment via e-survey of home buyers who bought between 2005 and 2012 to mitigate the bias from the first source of homeowners with perceived problems (Table 5). Direct on site review entails a rigorous assessment by a professional trained in assessing indoor environments for mold and dampness using the investigative templates identified in supplemental pages 1-3 for data capture and analysis. For the historical data used in this study, the investigative templates were earlier versions. Future occupant interviews will be conducted using the newly developed questionnaire to reduce self-selection bias. The e-survey study was approved by UBC human ethics review committee.

The resident health score (RHS) and home health index (HHI) were compared using the difference of means of the variables with multi-variance analysis (ANOVA) for independent samples. The null hypothesis definition was that no relationship existed between the damp and moldy environmental condition of the home (HHI) and health condition of the resident (RHS). The results reject the null hypothesis and affirm the alternate hypothesis that the increase in indoor environment mold and dampness measured by HHI correlates to the increase in respiratory ill health of the occupant as measured by RHS. The analysis of variance (ANOVA) results derived from computer simulation (SPSS

Statistics 22 and Microsoft excel 2013) provides a 99% confidence level with $F_{0.01,2,266}$ = 4.61 < 282 that the alternate hypothesis is valid (Figure 6).

The goodness of fit value of 0.68 indicates the data points fit a quadratic curve and that the observed outcomes replicate the model by explaining 68% of the variability of the resident health score (RHS). This suggests that 32% is explained by other health risk factors, which are speculated to be unique personal health conditions, genetics, gender, age, or ethnicity, which could be considered in future research.

The data results in Figure 6 also indicate that the HHI values for the combined data generally correlate with the following theoretical health condition boundaries: HHI of 0-10 indicating the home is health safe from environment derived respiratory conditions with an RHS of 1 or 2; HHI of 10-20 indicating a chance of light respiratory issues with an RHS of 3; HHI of 20 – 32 indicating possible function affecting environments with an RHS of 4; and, HHI of +32 scores indicating a potential for moderate to severe respiratory issues with an RHI of 5. These results are summarized in Table 6.

5. Concluding remarks

Human health can be affected by mold and damp conditions in home environments, but no reliable empirical tool exists to conduct quantitative assessment to determine risk. To date this knowledge gap has led guidance documents to limit action to the elimination of dampness and mold in indoor environments alone. However this approach is problematic, in that: 1) mold and moisture are ubiquitous and acceptable as well as necessary under certain conditions; 2) it can lead to incorrect conclusions and waste health care and repair dollars; 3) it does not address actual insitu conditions; 4) it does not connect the extent of harmful effects of indoor mold to occupant health; and 5) it does not define limits above which mold and moisture is considered a problem to health, leading to societal and health care inaction. The solution is a dynamic interplay between building environment, building systems, building maintenance, and occupant load that can be accomplished through modeling.

HEALTH² is the first comprehensive building environment factor-based model that can be used as a tool to provide reliable empirical results to accurately predict resident health impact risk from indoor mold and dampness. This empirical tool is founded on a holistic overview of the indoor environment to support proactive environmental impact evaluation, helping to close the knowledge gap and quantify qualitative evaluations scientifically. Conceptual application of the model in this paper demonstrates it's potential.

Results from the **HEALTH²** model development, calibration, and validation tests suggest a statistically significant association exists between specific home IAQ indoor environments and lifestyle conditions and potential resident health outcomes. The model predicts respiratory sickness from indoor mold and dampness in 68% of the data and is validated statistically to a 99% significance level suggesting the **HEALTH²** model is a reliable empirical tool to evaluate resident IAQ and predict potential health risk levels.

The benefits of a useful indoor environmental assessment tool include: 1) supporting the development and enactment of public policy on indoor housing improvement initiatives; 2) providing a basis for compliance monitoring and remediation scope and verification; 3) supporting research into the quality of new and existing housing stock as a basis for the development of more healthy environments; 4) extending the model to public and commercial environments for empirical analysis and validation; and 5) setting more defined boundaries and limits on extent of remediation required.

Limitations with the model include a simplified approach to indoor environments by eliminating other environmental factors from the assessment. Bias is introduced if occupant or site data is used from mail in surveys or telephone interviews. Accuracy of professional site review assessment depends on expertise levels. Factor relationships are region specific based on housing type and occupant use patterns. The model does not address specific health sensitivities and their reliance on certain environmental triggers although reverse engineering may provide insight. Some model factors are simplistic due to limited technical information and site gathered data to date. The model is specific to population health and cannot predict the individual health condition of occupants. People with immune-compromised conditions, congenital respiratory problems, or acquired sensitivities to certain molds will be affected by their indoor environments more severely than those without these conditions. Future study will adjust results for gender, age, ethnicity, ETS, and unique medical conditions to derive specialized or more specific results.

The development and accumulation of site specific data using **HEALTH²** would add to the science and research already in place, perhaps providing certainty in the proactive identification and remediation of mold affected indoor environments. Residential access may be resolved through social contract with the patient for specialized respiratory care relief. Future work is necessary to determine a generally accepted mold sampling protocol for testing and analysis, and permissible mold exposure limits (PEL) that regulatory bodies can rely on for setting healthy indoor environment criteria.

Future data gathering and **HEALTH²** model applications will help to refine the model fit. Future research can include building factor sensitivity analysis and/or particular respiratory health conditions. This may also allow for the inclusion of more environmental stressors than dampness and mold as consequential health impacters, and more respiratory diseases for medical assessment. An opportunity for future research is to reverse engineer a home environment to determine the most cost effective or simplest option to remedy specific health affecting environments by running renovation scenarios through the **HEALTH²** model.

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public and private interest in indoor environmental quality and health may benefit Mr. Hostland and Healthy Homes IAQ indirectly; but the major benefactor will be society as a whole and mold and dampness affected occupants specifically.

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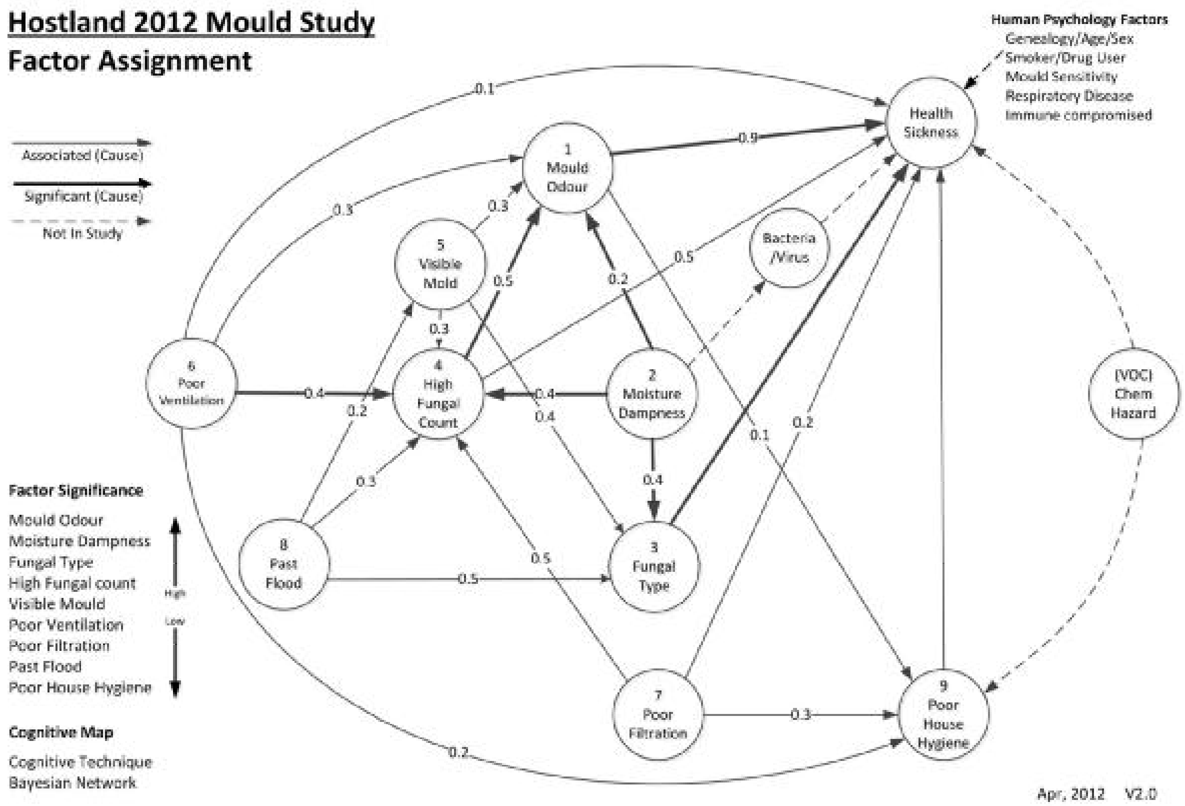
List of Tables:

List of Figures:

List of Supplemental pages:

Figure 1 Factor assignment cognitive map



Notes: Cognitive mapping was used to determine relationships and relative significance between key environmental and building factors based on field knowledge. From this, occupant health condition was determined to be an output (result). This was a first step in developing an understanding of the key factors that affect the health of occupants in indoor environments. The factor significance values have been usurped by AHP based relative weightings and the factors have been clarified and improved subsequently in the HEALTH2 (2013) model.

Matrix 1: Indoor house hygiene levels (0-9)

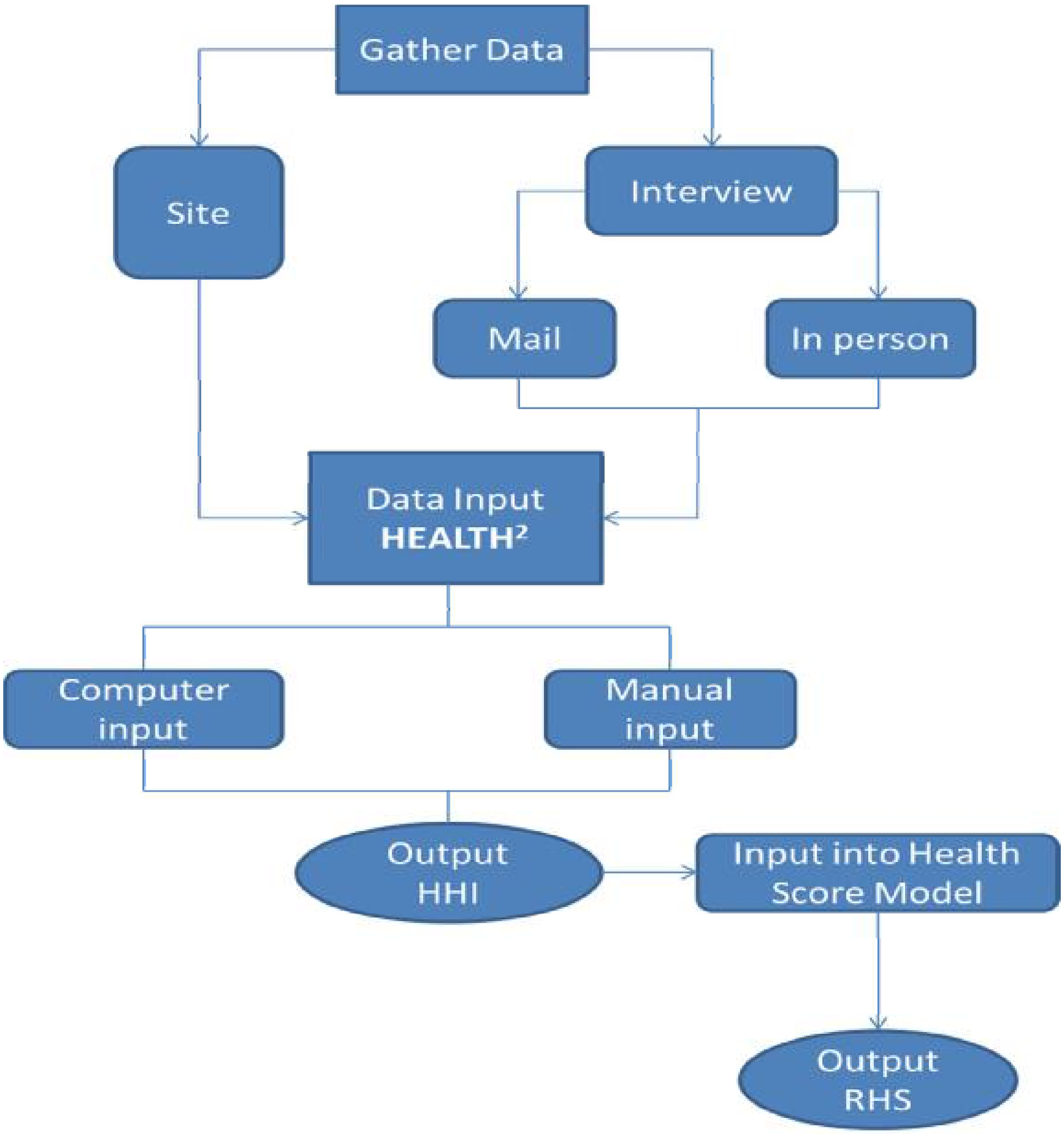
	M31	M32	M33	M34	Relative weight	Normalized relative weight
M31	1	2	0.2	0.3	0.589	0.099
M32	0.5	1	0.14	0.2	0.344	0.058
M33	5	7.14	1	1	3.656	0.615
M34	3.33	5	1	1	1.351	0.228
					5.939	1.000

Legend

M31	Dust/dirt/ETS level
M32	Occupant/ storage load
M33	Mold growth/odor/damp/rot
M34	Mold stain/ no odor/ dry

Notes: The multiplier matrix from the HEALTH2 model supports the knowledge based pair wise analysis to set factor weighting. Rationale and value setting is described in supplemental page one.

Figure 4 Example multiplier matrix



Notes: This diagram outlines the HEALTH^2 model process from data gathering, model inputting, to home health index and resident health score output values.

Figure 5 HEALTH^2 model process flow diagram

Table S1 AHP scoring scheme

Value scale comparing A to B

1/9 Extreme preference of B over A
1/7 Very strong
1/5 Strong
1/3 Moderate
1/1 Equal
3 Moderate preference of A over B
5 Strong
7 Very strong
9 Extreme

Matrix A Modifier - Indoor house hygiene levels (M_{31} – M_{34})

M31-M32 = 2 Moderate to equal preference of house hygiene over occupant/storage load

M31-M33 = 0.2 Strong preference of Mold growth over house hygiene levels

M31-M34 = 0.3 Moderate preference of Mold stain over house hygiene

M32-M33 = 0.14 Very strong preference of Mold growth over occupant/storage load

M32-M34 = 0.2 Strong preference of Mold stain to occupant / storage load

M33-M34 = 1 Equal preference Mold growth to mold stain

Matrix B Source – Moisture rating (S_{11} – S_{13})

S11-S12 = 4 Moderate to strong preference of active water to relative humidity

S11-S13 = 9 Extreme preference of active water over a past moisture event

S12-S13 = 5 Strong preference of relative humidity to past moisture event

Matrix C Modifier - Ventilation/ Filtration/ house hygiene (M_1 – M_3)

M1-M2 = 3 Moderate preference of ventilation over filtration

M1-M3 = 7 Very strong preference of ventilation over house hygiene

M2-M3 = 5 Strong preference of filtration over house hygiene

Matrix D Source - Nutrients rating (S_{21}, S_{22})

S21-S22 = 9 Extreme preference of loose cellulose over dense wood products

Matrix E Source - Moisture/ nutrient ($S_1 – S_2$)

S1-S2 = 5 Extreme preference of moisture over nutrient as without moisture, mold growth will not occur.

Matrix F Modifier - O/I Ventilation ($M_{11} – M_{12}$)

M11-M12 = 9 Extreme preference of outside air vs. indoor air circulation for Northern climates

Matrix G Modifier - Outdoor air ($M_{111} – M_{112}$)

M111-M112 = 5 Extreme preference of mechanical outdoor air over passive outdoor air

Notes: This supplemental page provides the comparative factor relationships for housing in the Okanagan, BC, Canada to determine relative weightings. This forms the basis for the accuracy of the regional HEALTH^2 model. The AHP scoring scheme will vary by region/ country based on specific characteristics of housing stock and quality of installation. Local environmental and building science expertise will be required to validate regional scoring schemes.

Table S2 HEALTH² model structure scoring input template

	Factor	Description	Maximum value	House value
1	**S11**	**Active Moisture (SC)**		
	a	> 48 hr water ponding	5	____
	b	roof/plumb leak < 48 hrs/ intermittent	1	____
	c	roof/plumb leak > 48 hrs/ reoccuring	3	____
	d	condensation on window glass	1	____
	e	Puddling water in window channel	3	____
	f	unvented operating clothes dryer	2	____
	g	moldy/ dirty humidifier	1-2	____
	h	blg surface SC 15-20%	1	____
	i	blg surface gt 1 sm SC 20-30%	2	____
	j	blg surface gt 1 sm SC gt 30%	4	____
	0 = best	**TOTAL (max 10)***		[ ]
2	**S12**	**Active moisture (RH - relative humidity)**		
	a	ave blg RH < 50%	0	____
	b	ave blg RH 50-55%	2	____
	c	ave blg RH 56-60%	4	____
	d	ave blg RH 61 - 80%	8	____
	e	ave blg RH 81%+	10	____
	0 = best	**TOTAL (max 10)**		[ ]
3	**S13**	**Past moisture history**		
	a	Flood < 48 hrs	1	____
	b	Flood 48-96 hrs	5	____
	c	Flood 96 hrs +	10	____
	d	Repaired water leak <48 hrs	0	____
	e	Grow op not professionally cleaned	10	____
	f	History of roof leaks	5	____
	g	History of plumbing leaks	5	____
	0 = best	**TOTAL (max 10)**		[ ]

4	**S21**	**Nutrient: paper/cardboard/dirt/dust**		
	a	Drywall at potential moisture source	4	____
	b	Exposed in-house dirt crawlspace	2-5	____
	c	OSB/particle board flooring	1	____
	d	Window sill debris	1	____
	e	Cardboard/ paper storage - light to heavy	1-2	____
	f	Plants - light to numerous	1-2	____
	0=best	**TOTAL (max 10)**		
5	**S22**	**Nutrient: wood**		
	a	Dim lumber ground/concrete contact	4	____
	b	Manuf'd lumber ground/concrete contact	5	____
	c	Manuf'd lumber exposed in crawlspace	3	____
	d	Manuf'd lum at potential moisture source	5	____
	e	Dim lumber at potential moisture source	5	____
	0=best	**TOTAL (max 10)**		
6	**M31**	**House Hygiene level**		
	a	Very Clean - dust free	0	____
	b	Visible light dust on surfaces	2	____
	c	Poorly cleaned - very visible dust	6	____
	d	Very poor	10	____
	e	Use of tobacco in the house (ETS)	5	____
	f	Use of central vacuum system	-2	____
	0=best	**TOTAL (max 10)**		
7	**M32**	**Storage/ occupant load**		
	a	Vacant	0	____
	b	Light	1	____
	c	Moderate	3	____
	d	Cluttered	5	____
	e	Excessive clutter	8	____
	f	Hoarder	10	____
	0 = best	**TOTAL (max 10)**		

8	**M33**	**Visible mold growth*, rot, odor, damp**		
	a	Active mold growth < 1 m2	2	____
	b	Active mold growth < 10 m2	5	____
	c	Active mold growth > 10 m2	10	____
	d	Verified mold "odor"	5	____
	e	Active visible rot	3	____
	f	Activity and adjacent carpeting	2	____
	0 = best	**TOTAL (max 10)**		☐

9	**M34**	**Fungal stain, no odor, dry**		
	a	Fungal staining < 1 m2 total	1	____
	b	Fungal staining <10 m2 total	4	____
	c	Fungal staining totalling over 10 m2	8	____
	d	Carpeting adjacent to staining	2	____
	0 = best	**TOTAL (max 10)**		☐

10	**M2**	**Filtration (10 = none)**		
	a	None	10	____
	b	HEPA and or UV	0	____
	c	Pleated MERV 6+	2	____
	d	Spun fibreglas - basic	6	____
	e	Room HEPA/UV	1	____
	f	2 Room HEPA/UV	2	
	0 = best	**TOTAL (max 10)**		☐

11	**M111**	**Passive outdoor air exchange (10 = none)**		
	a	no fresh air duct to return plenum	4	____
	b	no min. 150mm open duct to exterior	4	____
	c	Majority of rooms have opening windows	0	____
	d	Few rooms have opening windows	2	____
	e	None	10	____
	0 = best	**TOTAL (max 10)**		☐

12	**M112**	**Mechanical outdoor air exchange (10=none)**		
	a	None	10	____
	b	HRV on continuous timer	0	____
	c	HRV on continuous timer - not functional	10	____
	d	HRV only on demand	3	____
	e	Washroom exhaust on switch	5	____
	f	Washroom exhausts connecting to light	2	____
	0 = best	**TOTAL (max 10)**		

13	**M12**	**Internal mechanical air circulation - room**		
	a	None	10	____
	b	F/A furnace on timer 4-6 hr a day	0	____
	c	Portable house fan - 1 room	9	____
	d	Portable house fan - 2 rooms	7	____
	e	F/A furnace - no timer	5	____
	0 = best	**TOTAL (max 10)**		

Notes:

*48 hour fungal growth criteria per IICRC S-520, NYSTMTF (2010)

*Mold growth area criteria per Worksafe BC guidelines part 4.79 (2012)

*Line item scores are additive to a maximum score of 10 for each factor

*Scoring values and range based on prof. experience

Table S3 Expert knowledge (cognitive) matrices

Matrices criteria: British Columbia single family residence, central BC/ lower mainland

Matrix A Modifier - Indoor house hygiene levels 0-9

	M31	M32	M33	M34	Relative wt	Normalized
M31	1	2	0.2	0.3	0.589	0.099
M32	0.5	1	0.14	0.2	0.344	0.058
M33	5	7.14	1	1	3.656	0.615
M34	3.33	5.00	1	1	1.351	0.228
					5.939	1.000

Matrix B Source - Moisture (0-9)

	S11	S12	S13	Relative wt	Normalized
S11	1	4	9	3.302	0.709
S12	0.25	1	5	1.077	0.231
S13	0.111	0.2	1	0.281	0.060
				4.660	1.000

Matrix C Modifier - Ventilation/ Filtration/ hygiene (0 - 9)

	M1	M2	M3	Relative wt	Normalized
M1	1	3	7	2.759	0.649
M2	0.333	1	5	1.186	0.279
M3	0.143	0.2	1	0.306	0.072
				4.250	1.000

Matrix D Source - Nutrients (0-9)

	S21	S22	Relative wt	Normalized
S21	1	9	3.000	0.900
S22	0.111	1	0.333	0.100
			3.333	1.000

Matrix E Source - Moisture/ nutrient (0-5)

	S1	S2	Relative wt	Normalized
S1	1	5	2.236	0.833
S2	0.2	1	0.447	0.167
			2.683	1.000

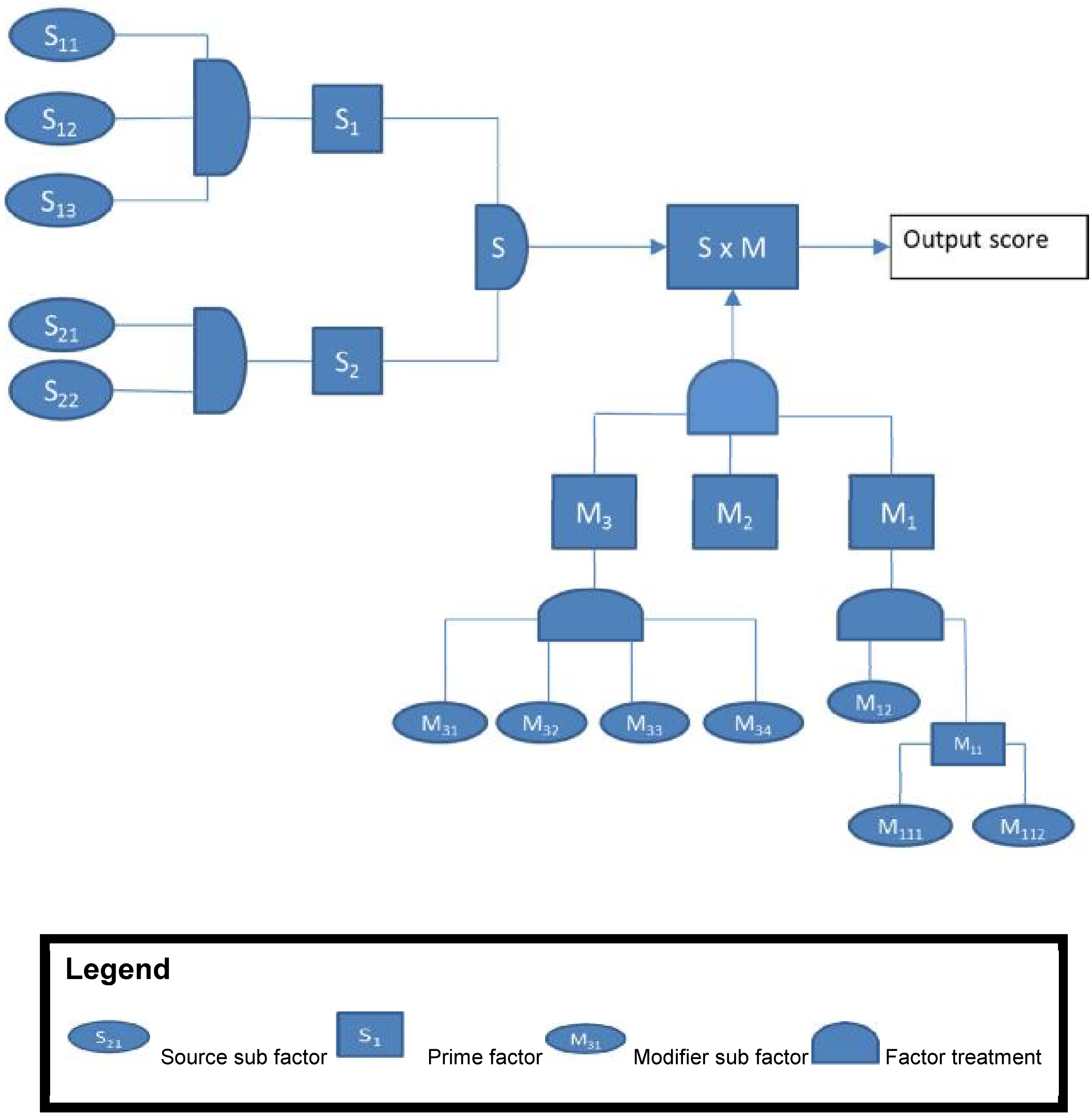
Matrix F Modifier - O/I Ventilation (0-9)

	M11	M12	Relative wt	Normalized
M11	1	9	3.000	0.900
M12	0.111	1	0.333	0.100
			3.333	1.000

Matrix G Modifier - Outdoor air (0-5)

	M111	M112	Relative wt	Normalized
M111	1	0.2	2.236	0.167
M112	5	1	0.447	0.833
			2.683	1.000

Notes: AHP analysis: for each criterion (factor) the relative importance of the alternative for each pairwise comparison is assessed (See Table S1) in a matrix format. The criterion is given a value scale of 1-9 except for matrices E and G (1-5) representative of their relative importance to the other matrices based on local knowledge. The source matrices are B, D, and E. the other matrices are amplification types that magnify source impacts based on extent in the indoor environment (see Figure 5). The relative weightings are then normalized for HEALTH2 model input.



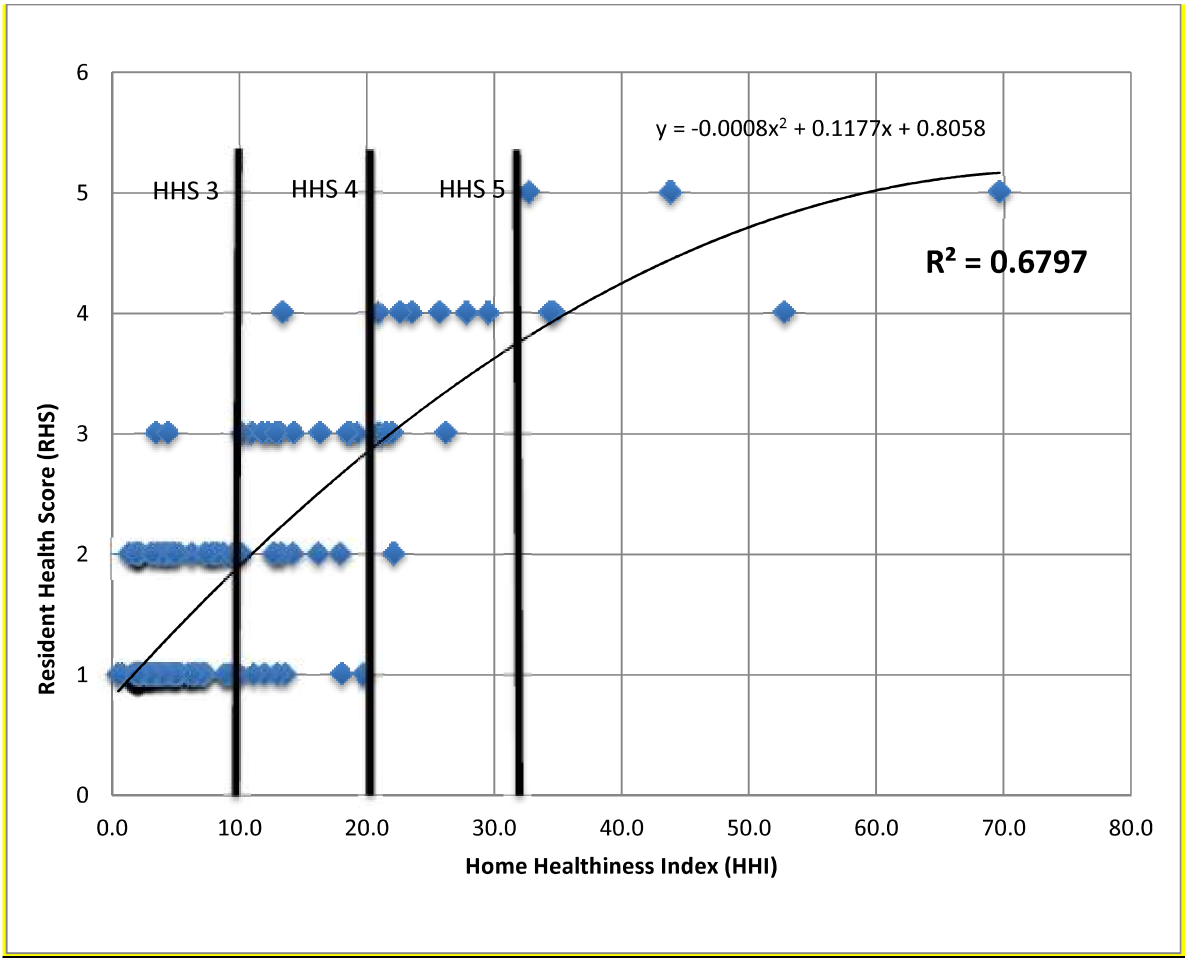
Notes: Figure 2 represents the initial concept of a process flow and factor relationship structure. Source factors are treated separately from modifier sub factors then combined to provide an output score for the home. Refer to Table 3 for sub and prime factor descriptions.

Figure 2 Factor relationship analysis diagram

Factor	Factor Input Values	Weight	Composite Results (CR)		CR		CR	HEALTH2 Output Score
Moisture rating								
S11	8	0.709						
S12	7	0.231	7.6					
S13	5	0.060						
Nutrient rating				0.833	7.9		7.9	
S21	10	0.900	9.5	0.167				
S22	5	0.100						
Particulate Load								
M31	5	0.099						HHI SCORE 36.4
M32	8	0.058	1.8					
M33	1	0.615						
M34	1	0.228						
Filtration rating M2	10		10	10 = none		0.649	4.6	
Ventilation rating						0.279		
M111	4	0.167	9			0.072		
M112	10	0.833	10=none	0.900	8.9			
M12	8		8	0.100				

Notes: A spreadsheet version of the HEALTH2 model showing input factors, AHP derived weights, and the final overall HHI score for the indoor environment under review.

Figure 3 HEALTH^2 model structure



Notes: The graph of data results shows the relationship between home healthiness (HHI) and predicted resident health is 68% explained by home healthiness and 32% explained by other health risk factors such as genetics, age, gender, etc. The graph suggests that environments with HHI scores greater than 20 are a respiratory risk for the residents. Alternately the data indicates residents with health scores of 4 or greater live in damp and mouldy home environments.

Figure 6 Relation between observed HHI input and predicted RHS

TABLE 1 – Existing indoor environmental assessment models/ tools

Name	Category	Reference	Qualities	Limitations
ERMI	Deterministic	Vesper et al. 2007	DNA based mold ID. Identifies moisture based molds and may allow for mold burden estimates.	Not health predictive. Does not include a visual assessment. Does not measure airborne molds.
Walk thru only	Deterministic	CMHC, Health Canada, US EPA 2012	Inexpensive. Immediate. Helpful in finding visual evidence. Can be health predictive.	Qualitative. Non-empirical.
IEA–Annex 14	Deterministic	Acco, Leuven 1990	Proposes a time dependent relative humidity threshold	Component of holistic assessment. Not health predictive.
Time of wetness	Deterministic	Adan 1994	Determines water availability/ WC/RH for mold growth.	Component of holistic assessment. Not health predictive. No general conclusion
Johansson mold growth indices	Deterministic	Johansson et al. 2010	Estimates mold growth on surfaces from RH and temp.	Component of holistic assessment. Not health predictive.
Fungal index	Deterministic	Abe et al. 1996	Environmental capacity for mold growth based on *e. herbariorum.*	Reliability questionable. Component of holistic assessment. Not health predictive.
VTT model	Predictive	Hukkan Viitanen 1999	Mold index for mold growth prediction model based on response time and material influence.	Based on various assumptions. Empirical. Component of holistic assessment. Not health predictive.
Isopleth models	Predictive	Ayerst 1969 Smith & Hill 1982 Clarke et al. 1999 Hens 1999 Sedlbauer2001	Based on RH, water activity, temperature, exposure time, mold risk inter-relationships.	Component of holistic assessment. Not health predictive.
RHI	Index	Keall et al. 2012	A count of housing characteristics linked to respiratory health of occupants.	Not inclusive of the house as a system. Linear assessment tool. Not flexible to home type variability.
HHI	Index	Healthyhousing. org.nz/research	House condition measurement tool of how likely occupants will suffer ill-health.	Study stage only. No detailed information provided for assessment.
I	Predictive	Haverinen et al. 2001-2006	Housing characteristics associated with excess moisture and consequential damages and health impacts such as asthma	Certain environmental characteristics compared to risk of moisture damage was favourable but not occupant health conditions (asthma).
HHSR	Deterministic	UK 2006 ISBN-10:185 1128965	Guidance on risk assessment approach to all house hazards	Broad brush, generic approach. Incomplete.
IEQAT	Dose/response	Ncube et al 2012	For environmental hazard assessments – chemical only	Requires fugacity coefficients and permissible exposure limits.
Other IEQ models	Deterministic	Chang et al 2009 Lai et al 2009	Inclusive of light and sound, thermal, IAQ. AHP based.	Based on quality of life, not ill-health based.

Notes: These models and tools assess elements of indoor environmental quality using deterministic, predictive, dose/response, and index methods. No one model or tool is predictive of the whole environment, but all support the identification or valuation of components of the indoor environment. Only the RHI model is health predictive.

Table 2 Key indoor environmental building condition factors

	Risk Factors	Description	Model Factor Symbol	Seminal References
	Visual dampness	Open water on surfaces	S_{11}	IOM 2004, Rockwell 2005, US HUD 2006, 2009, NYSTMTF 2010, US EPA 2013.
2.	Relative humidity	Active airborne moisture	S_{12}	Park et al. 2008, US HUD 2009, WHO 2009, Mendell et al. 2011, ASHRAE 2012
3.	Moisture history	History of water leaks or floods	S_{13}	Hostland 2013.
4.	Nutrient loose	Dust/cellulose/dirt	S_{21}	IOM 2004, ASHRAE 2007, US HUD 2009, Vesper 2011, US EPA 2013
5.	Nutrient dense	Wood, paneling	S_{22}	US HUD 2009, Vesper 2011
6.	Particulate load	Dust/ cleaning levels	M_3: M_{31}-M_{34}	CMHC 2012, US EPA 2012
7.	Occupant load	Storage/ clutter/ debris	M_{32}	US HUD 2006, Krieger et al. 2010, CMHC 2013, EPA 2013
8.	Mold growth*	Odor/rot/dampness	M_{33}	IOM 2004, Mendell M.J. et al. 2011
9.	Mold stain	No odor/ dry	M_{34}	NYSTMTF 2010, IICRC S-512
10	Air filtration	Filter type and capacity	M_2	ASHRAE 2007, WHO 2006, 2009
11	Passive outdoor air	Operating windows, fresh air piping.	M_{111}	BC building code 2009, ASHRAE 2007
12	Mechanical outdoor air	Air exchange on a timer or humidistat	M_{112}	Seppanen et al. 2002, ASHRAE 2007, US HUD 2006, 2009, WHO 2009. Sundell et al. 2011.
13	Air ventilation	Mechanical indoor air circulation.	M_1:M_{11}/ M_{12}	ASHRAE 2007, WHO 2006, 2009

Notes: This table provides the most recent references that support the 13 key building and environment factors that form the basis for the HEALTH² model. The relationship between the key factors and model symbols (noted as factors in the paper) are also provided. *Characteristic (factor) assessment can include air sampling for mold to estimate the likelihood of exposure (Dillon et al. 1999). Sampling, though, is discouraged for mold analysis due to the variability of results (USEPA 2001, CDC 2005).

Table 3 HEALTH^2 model source and modifier factors

Model Factor	Model Factor Description
S_{11}	active moisture – surface/solid (measured by moisture content MC)
S_{12}	active moisture – airborne (measured as relative humidity (RH)
S_{13}	past moisture – measured based on history and cause type
S_{21}	nutrient cellulose/organic – spun/glued drywall backing, cardboard/paper, dust/dirt
S_{22}	nutrient cellulose dense – dimen. lumber, paneling, plywood, OSB, particle type
M_1	Ventilation level – composite of M_{11} to M_{12}
M_2	Filtration - type and capability extent represented by integer values
M_3	House Hygiene - composite of M_{31} to M_{34}
M_{111}	Passive outdoor air exchange extent represented by integer values
M_{112}	Mechanical outdoor air exchange extent represented by integer values
M_{11}	Outdoor air supply – extent of type/amount represented by integer values
M_{12}	Mechanical indoor air circ. extent – extent of type/amount represented by integer values
M_{31}	Particulate load (dust/ETS) – extent of amount represented by integer values
M_{32}	Occupant/ storage load – extent of amount represented by integer values
M_{33}	Mold growth/rot/odor/damp extent – extent of amount represented by integer values
M_{34}	Mold stain/ no odor/ dry extent – extent of type/amount represented by integer values

Notes: The 13 key building condition factors (Table 2) form the basis for the 16 model factors with the symbols noted in the table above with each factor descriptor. These factors are then defined into source (S) and modifier (M) factors for clarity.

Table 4 Calibration of theoretical results

	Condition 1 Pristine	Condition 2 Overload condition	Condition 3 Pristine + water	Condition 4 Overload +water
low quality housing stock	8.8	20.2*	20.0-47.4* Mid 34.9	35.0-75.0* Mid 50.0
mid-range housing stock	1.2	10.4	9.8-52.1* Mid 21.4	21.3-54.0* Mid-44.6
Premium housing stock	0.9	8.3	7-28.3* Mid 11.2	20.1-34.2* Mid 25.5

Notes: * conditions are considered likely to very likely to have mold contamination that may cause severe respiratory health issues. A range of values for likely to very likely was calculated with a mid-point value noted to indicate the sensitivity of certain site effects to cause a wide range of values.

Table 5 Data Summary

E-Survey (n=74)				Historical (n=195)				Combined (n=269)			
Health Score		House Score		Health Score		House Score		Health Score		House Score	
low	1	low	2	low	1	low	1.8	low	1	low	1.8
high	1	high	11.1	high	5	high	69.7	high	5	high	69.7
average	1	average	2.84	average	1.63	average	7.55	average	1.46	average	6.25

Notes: Data developed from two sources: 1) remote assessment via e-survey of home buyers who bought between 2005 and 2012; and 2) Okanagan BC residential environmental site inspections conducted from 2007 – 2013 (historical).

Table 6 Resident Health Score (RHS) description with corresponding Home Healthiness Index (HHI) score

Resident Health Score (RHS)	Description	Corresponding Home Healthiness Index (HHI) score
1	no respiratory health issues	0-10
2	minimal respiratory health issues	0-10
3	light respiratory issues (hindrance)	10+
4	Moderate respiratory issues (function affecting)	20+
5	severe respiratory issues (hospital)	32+

Notes: Resident respiratory health is predicted based on home healthiness index (see also Figure 6).