ARTICLE

HEALTH²: A Holistic Environmental Assessment Lay Tool for Home Health

C. Hostland, R. Sadiq, G. Lovegrove, and D. Roberts

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 Holistic Environmental Assessment Lay Tool for Home Healthiness, 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. HEALTH² 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 HEALTH² model challenges the dominant view and suggests that damp and moldy environments are measurable and the impact to society is sufficient to necessitate prompt medical and regulatory action.

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

Résumé : Même si l'on connaît bien les effets indésirables d'une mauvaise qualité de l'air à l'intérieur des bâtiments, résultant de la présence de moisissures et d'humidité, sur la santé de leurs occupants, il n'existe toujours pas d'outils empiriques fiables, permettant d'évaluer les niveaux d'humidité et la quantité de moisissures à l'intérieur des maisons, à disposition du corps médical et des organismes de réglementation en matière de santé et de sécurité. Cela a des répercussions économiques sur la société se chiffrant à près de 40 milliards de dollars seulement en Amérique du Nord, montant qui correspond aux coûts des systèmes de santé publics et à la perte de productivité dans le monde du travail. Pour pouvoir prendre des mesures visant à résoudre ce problème, il est nécessaire d'employer une méthode acceptable d'évaluation de la qualité de l'air dans les maisons. Le présent article propose un modèle et outil empirique fiable, l'Outil pratique d'évaluation globale et d'amélioration de la qualité de l'air dans les maisons (*Holistic Environmental Assessment Lay Tool for Home Healthiness* ou HEALTH²), et donne des instructions permettant de l'utiliser comme un outil d'évaluation et de mesure de la qualité de l'air intérieur, en fonction de la présence de moisissures et d'humidité responsables de problèmes respiratoires connus. HEALTH² a été étalonné à l'aide de modèles théoriques de maisons, puis validé au moyen de données provenant de 269 évaluations de maisons et portant sur la santé des occupants et aux paramètres de l'air intérieur. Les résultats ont montré que le modèle peut être utilisé comme outil de détection préliminaire permettant de déterminer les facteurs de risque présents dans l'air intérieur et associés à des maladies respiratoires causées par les moisissures et l'humidité. La modélisation empirique et cet outil peuvent aider les experts en qualité de l'air intérieur à définir des méthodes visant à améliorer celle-ci et dépassant les exigences générales de l'industrie. Ils peuvent également permettre aux organismes de réglementation de fixer des directives en matière de qualité de l'air intérieur. Le modèle HEALTH² vient remettre en question les théories dominantes en la matière et montre que les moisissures et l'humidité sont quantifiables et que l'ampleur de ce problème rend nécessaire la prise rapide de mesures médicales et réglementaires. [Traduit par la Rédaction]

Mots-clés : paramètres du bâtiment, présence d'humidité et de moisissures, modèle de qualité de l'ait intérieur, qualité de l'air dans les maisons, qualité de l'air intérieur, moisissures, symptômes respiratoires.

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.

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This paper proposes a reliable prediction tool for health risk due to mold and dampness through the Holistic Environmental Assessment Lay Tool for Home Healthiness (HEALTH²) 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 HEALTH² 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 HEALTH² model validation.

2. Previous work

Indoor dampness and mold growth have been identified as risk factors to occupant health (Antova et al. 2008; WHO 2009; NYSTMTF 2010). Ill-health in the form of respiratory disease and flu-like symptoms, wheeze, cough, upper and lower respiratory symptoms are associated with indoor mold exposure (Krieger et al. 2010; Mendell et al. 2011; AIHA 2013). With the reduction of mold and dampness in homes, occupant health is improved and the frequency of urgent clinical visits is reduced (Burr et al. 2007; Bernstein et al. 2008; Takaro et al. 2011; AIHA 2013). Specifically, recent research directly associates indoor mold burden and particular molds to the onset and exacerbation of asthma in children (Mendell et al. 2011; Reponen et al. 2011, 2012; Kennedy and Grimes 2013); and 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% with a population weighted average of 47% of housing stock affected, totaling over ten million homes in North America (Zock et al. 2002; Jaakkola et al. 2002; IAQ 2014).

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 BC 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 and issues by fiat are the instituted resolution methods (US EPA 2013; Worksafe BC 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 (Vereechen and Roels 2012). These shortcomings include non-conclusive, non-predictive conditions, and an incomplete evaluation method to assess environmental factors that comprise indoor environments. The assessment of mold is not uniformly addressed as, for example, mold on surfaces is assessed, but not aerosolized mold. As well, most models exclude the effects of health on results.

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 in the following sections.

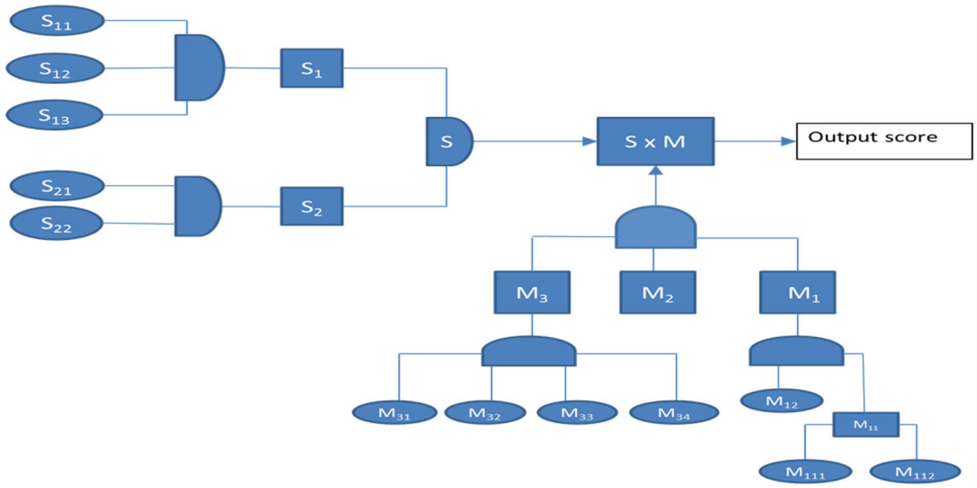
3.1. IAQ factor identification

The indoor environmental models found in literature fall into four categories: deterministic; predictive; index; and dose response. Environmental characteristics and methods are introduced, but no one model or models collectively address the indoor environment as a whole. To a greater extent Haverinen et al. (2001, 2003*a*, 2003*b*) and Haverinen-Shaughnessy et al. (2006) identified 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, nutrient load, and mold development correlates to degree of health impact. Further, the relationship may be more fully defined if health is correlated to the sum of specific building factors that comprise the indoor environment.

Indoor environments are affected by building envelope, ventilation, filtration, and moisture, exacerbated by nutrient levels and occupant load that allow mold growth (CMHC 2013*a*; US EPA 2013). The building envelope defines the extent of the conditioned living environment and protects the indoor environment from external elements (CMHC 2013*a*). 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 to reduce dampness effects (WHO 2009; US HUD 2013; CMHC 2013*a*). Mold does not exist without both moisture and nutrients present, making them source factors (Park et al. 2006). 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, 2006, 2007, 2009, 2013; CMHC 2013*b*). Nutrient development, odor, and excess moisture developed from human activities

Fig. 1. Factor relationship analysis diagram.



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 – dimensional lumber, paneling, plywood, OSB, particle type
M_1	Ventilation level – composite of M_{11} (composite of M_{111} to M_{112}) 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: Figure 1 represents the 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. The model factors are noted in the table above with each factor descriptor. These are then defined into source (S) and modifier (M) factors for clarity.

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 2013; US HUD 2013; CMHC 2013*a*). 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*a*; US EPA 2013).

Combined, these specific source and modifier factors are considered to approximate the building environment condition. Developing a predictive tool to measure health impact risk to the composite of these factors is considered in this paper.

3.2. Analysis of factors

The overall association between source and modifier factors and how they combine to form an output value is presented in Fig. 1 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;

Fig. 2. HEALTH² model structure.

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						
Filtrat. 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 ranking, and the final overall HHI score for the indoor environment under review.

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.

Figure 1 also presents the 16 source and modifier factors and sub factors that we developed from the analysis of factors and derived from the 13 primary indoor environmental building condition and lifestyle risk factors. 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) assessment through 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 (i.e., 1–2, 1–10, etc.) based on its specific effect on the composite building condition and other factor relationships (supplemental Table S2[1]). The line item values are summed to a maximum amount (noted) and then inputted into the model for analysis.

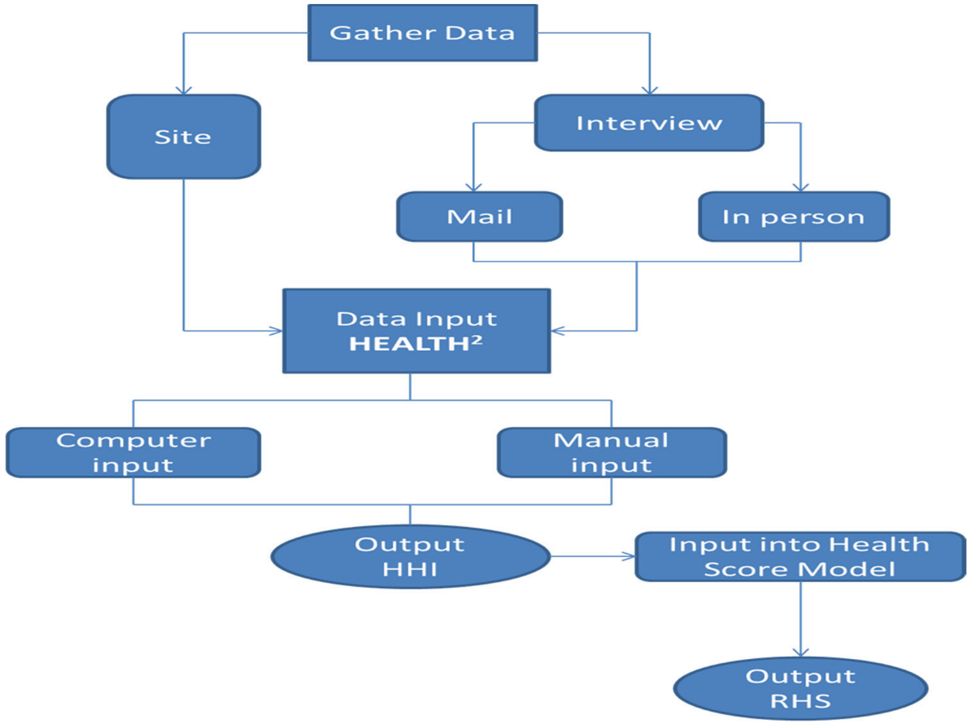
3.3. Model formulation

With the identification and assessment of the relevant IAQ factors, and the ranking of factor inter-relationships by the process noted below, the factor analysis relationship diagram for the HEALTH² model shown in Fig. 1 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. Analytical hierarchy process 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 (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 home healthiness index HHI score (Fig. 2).

Line by line site condition input is provided at the sub factor level on the HEALTH² model structure input template (supplemental Table S2[1]). This produces sub factor composite values that become input column factor values modified by the various regional cognitive matrix criteria or weights (e.g., single family residences, central BC and lower mainland area urban climates – supplemental Fig. S3[1]) and compiled into source and modifier values. A typical multiplier matrix is shown in supplemental Fig. S7[1]. The resulting source and modifier values are multiplied together to obtain the HHI for the particular home (Fig. 2). The HEALTH² data input and output process flow diagram for the

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjce-2014-0228.

Fig. 3. HEALTH² model process flow diagram.



Notes: This diagram outlines the HEALTH² model process from data gathering, model inputting, to home health index and resident health score output values.

Table 1. 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+

Note: Resident respiratory health is predicted based on home healthiness index (see also Fig. 4).

model is provided in Fig. 3. The flow diagram includes the health outcome model results 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 HEALTH² 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 as provided in Table 1. 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 HEALTH² 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 1970s 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 con-

Table 2. 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

*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.

structed 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 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 HEALTH² model over four IAQ factor value scenarios for a total of 12 (3 × 4) test applications to assess the input factor valuations (i.e., the HHI range), and the output predicted (i.e., the RHI range). Scenario one: pristine, clean environment, light occupancy, and well maintained with some attention to indoor air and 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 h) and visible mold growth. Scenario four: Scenario two with an active moisture event (>48 h) and visible mold growth.

The HEALTH² model calibration results provided in Table 2 reflect expected results 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 h 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 and (or) 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 h. 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 HEALTH² model was validated using data developed from two sources: (1) Okanagan BC residential environmental site inspections conducted from 2007 to 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. The data summary is provided in Table 3. 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 Tables S1 and S2 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 (Fig. 4) with a sample size of 269.

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 Fig. 4 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 1.

5. Concluding remarks

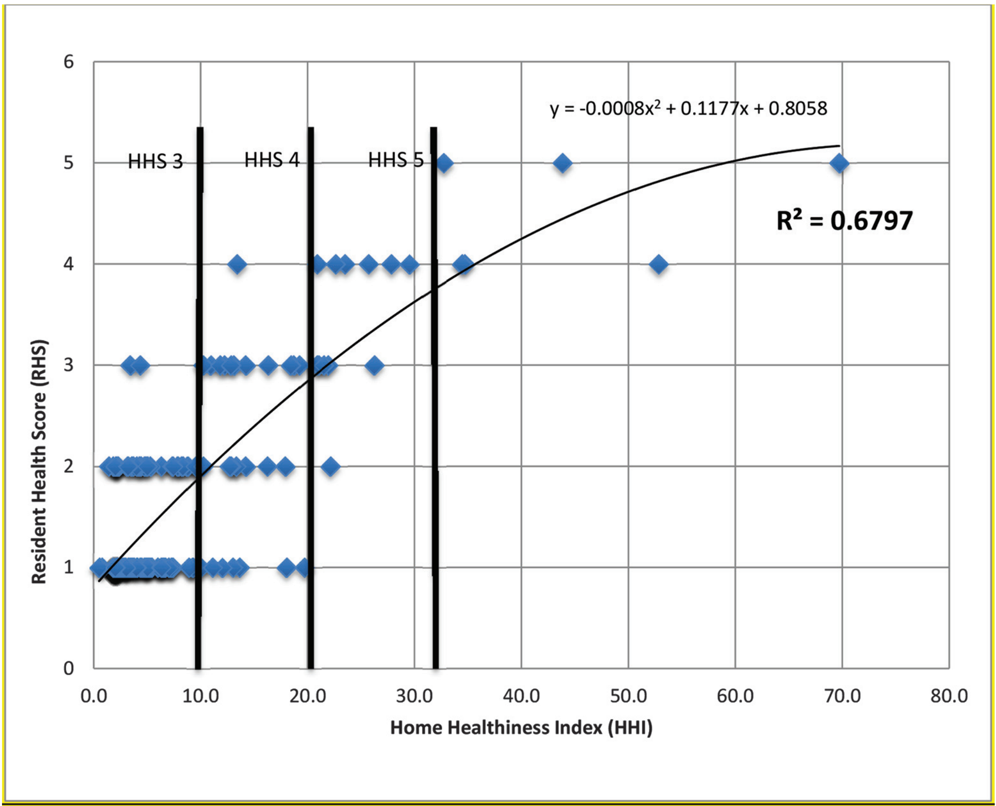
Human health can be affected by mold and damp conditions in home environments, but no reliable empirical tool exists to con-

Table 3. 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
Ave.	1	Ave.	2.84	Ave.	1.63	Ave.	7.55	Ave.	1.46	Ave.	6.25

Note: 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 to 2013 (historical).

Fig. 4. Relation between observed HHI input and predicted RHS.



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. Sample size = 269.

duct quantitative assessment to determine risk. The knowledge gap between health effects from damp and moldy environments and quantitative measures to substantiate those health effects has led guidance documents to limit action to the elimination of dampness in indoor environments alone. However this approach is problematic, in that: (1) mold can be present in a home without identifiable dampness that exhibits occupant ill-health effects; (2) the limitation can lead to incorrect conclusions and waste health care and repair dollars; (3) dampness alone does not address the variety and uniqueness of specific in situ conditions; (4) dampness alone does not connect the extent of harmful effects of indoor mold to occupant health; and (5) the action does not include attempting to 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 are 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 sensitivity 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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