Application of a transient hygrothermal population model for house dust mites in beds: assessment of control strategies in UK buildings

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This paper discusses the capabilities and the application of an innovative combined hygrothermal and population model to assess the impact of building design and occupant behaviour on house dust mite populations in a mattress. The combined model is the first of its kind able to predict the impact of hourly transient hygrothermal conditions within a 3-dimensional mattress on a population of 'wild' *Dermatophagoides pteronyssinus* mites. The modelling shows that the current drive for energy efficiency in buildings might lead to an increase in house dust mite infestations in UK dwellings. Further research is needed to accurately determine the size of these effects and to adequately evaluate any trade-offs between energy efficiency measures and health outcomes.

Keywords: House dust mites, ventilation, beds, energy efficiency, dwellings

1. Introduction

House dust mites (HDM) can be found in beds, carpets and soft furnishings, and exposure to their allergenic faeces and dead body parts can lead to adverse health outcomes such as sensitisation and exacerbation of rhinitis, dermatitis and asthma symptoms (National Academy of Sciences, 2000). House dust mites feed on human skin scales and thrive in warm and humid environments. Since they absorb moisture from the air, mites dehydrate and will eventually die if kept in an environment where the relative humidity (RH) is lower than a critical value for a sufficiently long time (Crowther and Wilkinson, 2008). This critical low RH is often referred to as the *Critical Equilibrium Humidity* (CEH), which is temperature-dependent for *Dermatophagoides farinae* (DF), the most common species in the US (Arlian and Veselica, 1981). Some evidence exists that a similar temperature-dependence of CEH also occurs for *Dermatophagoides pteronyssinus* (DP), the most common species in the UK (Crowther *et al*., 2006). Temperature also affects HDM egg-to-adult development times (i.e. lower temperatures giving rise to longer development times).

Since house dust mites are dependent upon favourable hygrothermal conditions to thrive, building design and occupant behaviour (i.e. heating and ventilation patterns) can affect HDM infestations. For example, it has been suggested that the rise in UK asthma levels may be due to recent changes in the building stock, where excessive airtightness in housing may

have resulted in high moisture levels which create favourable conditions for house dust mite infestations (Howieson *et al*. 2003). In this context mechanical ventilation with heat recovery (MVHR) has been advocated as a possible way to control excessive levels of indoor moisture and HDM infestations (Howieson *et al*. 2003). However, it is difficult to prove the clinical efficacy of MVHR in the field (Gøtzsche *et al.* 2006), since the costs associated with the required sample sizes are high.

Although it is generally accepted that mites thrive in humid environments, there is some controversy as to whether the hygrothermal conditions required to prevent mite infestations can feasibly be achieved in UK housing in practice. This is partly because most studies on hygrothermal conditions and mite survival have been conducted under steady-state environments, with mites reared over many generations under ideal hygrothermal conditions and with an 'unnatural' diet. Consequently the resultant laboratory data are not necessarily applicable to real life situations. For example, studies have shown that laboratory-reared mites reproduce and develop faster than 'wild' mites, except when under environmental stress, and that food quality/quantity is a significant factor - particularly in sub-optimal conditions (Hart *et al.* 2007). Furthermore, indoor hygrothermal conditions are highly variable, depending on outdoor conditions as well as on building characteristics and occupant behaviour. This makes it difficult, in some circumstances, to reduce relative humidity to levels which are

consistently below CEH for long enough. A study where mites were kept under transient hygrothermal conditions found that they were able to survive when exposed to brief spells of high RH, even though the daily average RH was still below critical levels (de Boer *et al*. 1998). Thus, although it is theoretically feasible to control mite infestations by modifying the hygrothermal conditions of their habitats, it is not a simple matter to establish how to achieve this in practice. Furthermore, a number of studies (including UK-based studies) have concluded that beds are an important source of mite allergen exposure, since mite allergen concentrations are typically highest in beds (Simpson *et al.* 2002). However, hygrothermal conditions in beds are very variable, depending upon a number of interacting factors, such as: climate; building characteristics (especially insulation and air-tightness); heating and ventilation patterns; occupants' moisture production; type of mattress; length of time the mattress is occupied, etc. Therefore, it is difficult to estimate hygrothermal conditions of mattresses based on room conditions alone.

Although the current energy efficiency drive for the UK building stock has been advocated as a potential hazard with respect to HDM infestations, it is not straightforward to assess whether energy efficient dwellings are particularly at risk from HDM infestations. For example, although low ventilation rates may result in higher moisture concentrations, higher insulation levels should also increase indoor temperatures, potentially

producing lower relative humidities. On the other hand, low indoor temperatures caused by poor insulation levels may result in favourable high RHs, but also unfavourable low temperatures. Furthermore, mite microclimates (e.g. within a mattress) are not necessarily identical to room conditions at all times, as previously mentioned.

Due to the complexities and the large number of variables discussed above, a modelling approach is required in order to establish: a) how such variables interact and affect mite survival, and b) which building features and occupant behaviours are most responsible for either giving rise to mite infestations in beds or, conversely, controlling them. First of all, a mattress model is needed to assess the impact of building features and occupant behaviour on a bed's hygrothermal conditions, which in turn can then be used as input for a mite population model. Apart from the model developed by Cunningham (2009), most existing HDM population models (Cunningham, 2000; Crowther et al., 2006; Biddulph *et al*., 2007) are steady state models which are potentially unable to accurately predict the impact of transient hygrothermal conditions (such as those occurring in real beds) on mite populations – particularly if these conditions are very close to CEH. Furthermore, existing bed models are either one-dimensional steady-state (Pretlove *et al*. 2005), or if transient (e.g. Cunningham *et al.* 2004), do not take into account the spatial variations in hygrothermal conditions within a mattress. This could be important, since studies have found that the density

of the mite population is highest near the surface of the mattress, and that mites are not evenly distributed within it (de Boer and van der Geest, 1990).

This paper discusses the application of a newly developed combined hourly transient hygrothermal population model, comprising of a mattress model (Lectus) and a population model (Popmite). The model suite is the first of its kind able to predict the impact of hourly transient hygrothermal conditions within a 3-dimensional mattress on a population of 'wild' *Dermatophagoides pteronyssinus* mites. Detailed information on the models is provided in separate papers being prepared by the authors. In this paper the model suite is briefly described and then used to assess the impact of building features and occupant behaviours on HDM populations in UK beds (London area). The model capabilities and limitations are discussed, and the model is used to evaluate whether greater energy efficiency measures might lead to excessively high levels of HDM infestations in beds. An overview of the models is provided in the next section.

2. Introduction to the Models

2.1. The Mattress Model: Lectus

The Lectus computer model is a transient 3-dimensional model of the heat and moisture vapour movements within a mattress. The model mattress can be made of many layers of different materials, and can be described by a flexible 3D grid, which allows different layers to have a varying number of

nodes for higher local resolution. The boundary conditions on the sides, bottom and top surface of the mattress when unoccupied are made to follow the room air hygrothermal conditions subject to a time lag, according to the following equation.

$$T^n = T^{n-1} - \Delta T^{n-1}\left(1 - 0.5^{t/k}\right) \qquad [1]$$

where T^n is the bed temperature at the time interval n; T^{n-1} is the bed temperature at the time interval (n-1); ΔT^{n-1} is the temperature difference between the bed and the room, at the time interval (n-1); n is the time interval in minutes; t is the time step in which room conditions are available in minutes (e.g. every 60 minutes); k is a constant, corresponding to the time it takes for the ΔT^{n-1} to be halved. In Lectus, it is assumed that ΔT^{n-1} is halved every hour (k=60 min). The same formula applies in Lectus for the decay of the vapour pressure. This assumption is based on empirical observations from an instrumented bed, and was later confirmed by fieldwork observations.

When the mattress is occupied, the upper surface temperatures and an excess of vapour pressure are set to a predefined representative pattern of values (Figure 1), determined by experiments with volunteers on an instrumented test bed. For example, when the bed is occupied it is assumed that on the surface zone corresponding to the torso area the temperature is 34 ºC and the Vapour Pressure Excess (VPX) is 1000 Pa. VPX is the difference in vapour pressure between the mattress's boundary condition,

and the room's. These assumed values can be varied. Predictions of hourly temperature and relative humidity are made throughout the mattress cells for a user-defined time step (typically 1 hour). The room conditions utilised in Lectus can be either measured values, or predictions from any hygrothermal building simulation programme providing hourly predictions.

The Lectus boundary conditions are used as input to a three-dimensional transient heat conduction and vapour diffusion model, to calculate the conditions at points within the mattress. An implicit finite difference scheme is used to model the transient temperature and vapour pressure conditions within the mattress. Only vapour diffusion is considered, i.e. the simplifying assumption is made that liquid water does not form within the mattress. The mattress is divided into a grid of finite elements, made up of horizontal layers. The elements in each layer have the same thermal conductivity, specific heat capacity, vapour diffusion coefficients, specific moisture capacity and density. All properties within an element are assumed to be non-directional, and do not vary as a function of temperature or moisture content. Heat transport by advection is not included in the model, nor is moisture buffering. A node is defined at the centre of each element; the temperature, vapour pressure and relative humidity are calculated at each node, given the boundary conditions imposed on the six surfaces of the mattress. Each node is connected to six neighbouring nodes, which may be surface nodes whose values are set by boundary conditions,

or other internal nodes within the mattress. Given the boundary conditions and initial conditions at each node, new conditions after the time step $\Delta\tau$ (s), at time $t+\Delta\tau$, may be calculated by applying the Gauss-Seidel iterative method to the finite difference scheme. Hence for temperature, T (^{o}C) for the *ith* node at time p+1:

$$T_i^{p+1} = \frac{\sum_j \frac{T_j^{p+1}}{R_{ij}} + \frac{C_i T_i^p}{\Delta\tau}}{\frac{C_i}{\Delta\tau} + \sum_j \frac{1}{R_{ij}}} \qquad [2]$$

where $C_i = \rho_i c_i \Delta Vol_i$, with ρ_i being the density (kg/m^3) of the *ith* cell, c_i its specific heat capacity (J/kgK) and $\Delta Vol_i = \Delta x_i \Delta y_i \Delta z_i$ its volume (m^3). R_{ij} describes the thermal resistance between the *ith* and the *jth* cells. If those cells are joined together in the z direction, then the thermal resistance is:

$$R_{ij} = R_i + R_j = \frac{dz_i}{2 \times dA_{ij} \times k_i} + \frac{dz_j}{2 \times dA_{ij} \times k_j} \qquad [3]$$

where dz_i is the length of the *ith* cell in the z direction, k_i is its thermal conductivity (W/mK) and dA_{ij} is the area connecting the *ith* and the *jth* cells.

Similarly for vapour pressure V (Pa):

$$V_i^{p+1} = \frac{\sum_j \frac{V_j^{p+1}}{Z_{ij}} + \frac{V_i^p \xi_i}{\Delta\tau}}{\frac{\xi_i}{\Delta\tau} + \sum_j \frac{1}{Z_{ij}}} \qquad [4]$$

where $\xi_i = \rho_i \varsigma_i \Delta Vol_i$, with ς_i being the specific moisture capacity (kg/kgPa) of the *ith* cell, and Z_{ij} the vapour diffusion resistance per unit area (Pa·s/kg) between the *ith* and the *jth* cells. Again, if those cells are joined together in the z direction, and with δ_i being the vapour diffusion coefficient of the *ith* cell (kg/m·s·Pa), then the vapour resistance is:

$$Z_{ij} = Z_i + Z_j = \frac{dz_i}{2 \times dA_{ij} \times \delta_i} + \frac{dz_j}{2 \times dA_{ij} \times \delta_j} \qquad [5]$$

A comparison of Lectus predictions with fieldwork data shows that the model reproduces similar temperatures and vapour pressures as those recorded in the test beds. For example, both monitored and modelled data demonstrated that one of the areas most favourable for dust mite growth is 1-2 cm below the top surface, under the chest area. For this area of the mattress, Figures 2 and 3 show the comparison between measurements and predictions of respectively temperature and vapour pressure in a sprung mattress monitored every 10 minutes over 20 days. Predictions were calculated by using the monitored conditions for the room and for the top mattress surface, in order to accurately represent the sleeping pattern of the occupant. Figure 3 shows that, for the cell selected, Lectus tends to over-predict at high vapour pressures, which correspond to the times when the bed is occupied. This might be due to a combination of factors, such as the change in geometry and material's property during mattress occupation, and the occupant's movement. A differential sensitivity analysis also showed

that the difference between measurements and predictions fell well within the range determined by the impact of uncertainties in input variables and of error measurements (Ucci, 2007).

For the boundary conditions, the validation exercise showed that there is an agreement between predicted and average monitored results. However, there is also a degree of variability in hygrothermal conditions monitored on the bed surface, both within and across individuals, due to a combination of: differences in heat and moisture output during sleep (e.g. moisture intake before sleep or different body temperatures during sleep cycles); clothing levels; different hygrothermal properties of mattresses, duvets and pillows; sleeping position (particularly for the head); and movement levels during sleep (also affected by mattress size). Consequently, although on average the boundary conditions assumed in Lectus are sufficiently representative of fieldwork data, a *range* of conditions are likely to occur in reality. The impact of this range is discussed in the scenarios modelling section.

2.2. The House Dust Mite Population Model: Popmite v.7d

The hygrothermal conditions recorded in a real mattress and predicted by Lectus vary by large amounts on the time scale of an hour. Transition matrix population models, for example Cunningham (2009) and models using continuous age distributions such as Popmite (Biddulph et al 2007) are unable to cope with these rapidly fluctuating conditions. They can

be set up to run with a time step of an hour, but they rely on the population in the next hour being solely dependent on the population in the last hour and the current hygrothermal conditions. In reality the population in the next hour will also depend on the current hydrated state of the mites. For example a fully hydrated mite is able to survive for a long period of time in adverse conditions compared to a dehydrated mite. The Popmite model has therefore been further developed to account for the hydrated state of the mites and is therefore the first population model able to predict the effect of transient hourly hygrothermal conditions on a population of *Dermatophagoides Pteronyssinus* (DP) mites. A paper on this new version of Popmite is currently being prepared by the authors. Version 7.d of Popmite was used for the study described in this paper.

Modifications to the steady state model from Biddulph *et al* (2007) include a dependence on the moisture content of mites on its eating rate and therefore, for adult females, egg production rates. The eating rate together with the temperature also drives the development rate of juvenile mites. Moisture losses and gains are modelled in detail simulating the complex moisture retention mechanisms (described in the literature, e.g. Arlian and Veselica, 1981) occurring when the air RH goes below the CEH. As moisture is lost from the mite slowly in dry conditions, death only occurs when mites have lost more than half of their normal fully hydrated water content (Arlian and Veselica, 1979), which can be after many hours

depending on the dryness of the atmosphere and the previous hydration state of the mite. This mechanism also allows the mites to recover very quickly once the RH has returned above the CEH.

Popmite therefore requires species-specific information on the effect that hygrothermal conditions have on parameters such as the feeding rates of each life cycle phase of a house dust mite. Much of the information can be found in the scientific literature (e.g. Arlian, 1977), but only some of these key parameters are based on laboratory experiments with 'wild' DP mites (i.e. not reared in laboratory conditions) feeding on a natural diet of skin and dust (Hart et al., 2007). A complete description of the mite population's age structure and moisture contents is required at the beginning of each simulation. Popmite is then able to provide a prediction of the numbers of eggs/juveniles/adults on an hour-by-hour basis given the hourly hygrothermal conditions of the habitat (both mattress surface and inner cells). Figure 4 shows a typical output of the Popmite model, with a starting population of 100 eggs kept under certain hygrothermal conditions for 30 days. The plot shows the number of mites as a function of time.

In order to test Popmite's predictions, an innovative 'mite caging' technique was developed as a way of overcoming sampling and ethical issues related to the monitoring of mites in a real environment. In theory, it is possible to examine mite survival rates under realistic conditions by infesting real beds with a known number of mites and then sampling the live

mites after a certain monitoring period. However, this is both unacceptable ethically, and almost impossible to monitor in reality since sampling live mites can be difficult (as discussed in Section 6). The ‘mite bags’ technique utilised in this study involves caging a known number of live mites with food in a mite and allergen-proof sealed ‘bag’ (similar in size and appearance to tea bags), made from porous material. The ‘mite bags’ are coupled with loggers measuring hygrothermal conditions and placed in real mattresses in various locations (e.g. top surface and within its depth). In each monitored location, 3 bags are installed for repeatability purposes. After six weeks the equipment is retrieved and the number of live mites in each bag is counted, and then compared with the model’s predictions. It should be noted that only adult mites and large juveniles can be counted, as eggs and early juveniles are very small and do not move and are therefore impossible to count with a microscope against a background of food. The comparisons with the model are therefore only with adults and late juveniles. Although the excess food supply and the lack of freedom to move are unrealistic, this technique gives the opportunity to use real occupied beds as ‘incubators’ (in a way that is acceptable on ethical grounds), where mite growth can be examined in relation to real transient conditions, and compared to the population model predictions.

In the validation study, 20 adult ‘wild’ DP mites (1:1 males and females) were encapsulated in each mite bag, together with ‘natural’ food

(1:1 by weight skin and dust). Figure 5 illustrates the comparison between Popmite's predictions and measurements (average of 3 mite bags in each location) resulting from 69 sets of mite bags which were installed in 16 dwellings at various locations within the mattress and in the bedroom. The graph shows that the model tends to over-predict but the correlation is rather good when considering that Popmite is predicting biological phenomena, which usually have noticeable variability. Furthermore, Popmite can predict the impact of transient conditions on a population of 'wild' DP mites more accurately than the steady-state model MPI from Crowther *et al.*, 2006 (comparison between mite bags measurements and MPI predictions: R^2=0.49, versus 0.58 for Popmite predictions).

Experiments have shown that mite growth is ultimately limited to approximately 12,000 mites per gram of food (Wilkinson et al. 2002) and, if the distribution of skin scale within a mattress is known, the model is able to take account of this restriction. Unfortunately we lack such data and consequently, for this study, it was assumed that there were no restrictions on mite growth due to food or space availability. Similarly, due to lack of sufficient information, the model does not currently take account of mite movement between cells or migration into or out of the mattress.

3. Methods

This section describes the methodology and assumptions adopted for the scenarios modelling. This involved modelling a base-case bed within a base-

case dwelling, and subsequently changing one building feature (or occupant behaviour) at a time, in order to assess the impact of changes in bedroom conditions on the bed's mite population growth. The mite predictions for the bed in each scenario are then compared with the base-case predictions. The predicted energy consumption of each scenario is also compared with the baseline consumption. Lectus was adopted for predicting hygrothermal conditions in a bed from given room conditions and its predictions were then utilised in Popmite in order to assess their impact on mite growth. The energy use predictions and the hourly room conditions (required as inputs for the Lectus model) were obtained by using the building simulation program EnergyPlus (version 2), which has been validated against various standard methods (US Department of Energy, 2007). EnergyPlus was selected because moisture adsorption/desorption of the internal surfaces can be modelled in this program, with the Effective Moisture Penetration Depth (EMPD) model (Keresteciogl*u et al.*, 1990). The EnergyPlus materials library was utilised in order to define the EMPD properties of the indoor surfaces.

The base-case dwelling simulated in EnergyPlus is a 2-bedroom mid-floor flat in the London area, with an occupancy of 4 people (2 adults and 2 children), 2 exposed walls, a floor area of 45 m^2 and a volume of 108 m^3, and design features compliant with the 2006 Building Regulations (ODPM, 2006a and 2006b). This building type (flat) was selected since

some authors have suggested that modern dwellings might be partly responsible for the rise in asthma prevalence in the last decades due to an increase in airtightness with resulting higher levels of indoor moisture (Howieson *et al.*, 2003). Due to their small volumes and small exposed wall areas, flats can have rather low background infiltration rates. Furthermore, large concrete panel systems – often utilised in the construction of flats – have a low permeability, compared with other construction types (Stephen, 2000). Table 1 summarises the main features of the base-case dwelling, whilst Table 2 summarises the changes made to the base-case model (i.e. the different scenarios).

Table 2 shows that for each variable modified in the base-case dwelling, two options were considered (respectively with a higher and a lower value than base-case), so that a typical *range* of input variables could be examined. In each case, the values for option 1 and 2 were chosen as representative of ranges found in real dwellings. For example, in the "moisture input" case, option 1 corresponds to "wet occupancy", while option 2 corresponds to "dry occupancy" (following the definition given in BSI, 2002). In addition to the options illustrated in Table 2, a balanced mechanical supply and extract ventilation system with heat recovery (MVHR) was also applied to the base-case flat (in replacement of the extract fan), in order to assess its impact on mite growth in beds. Two MVHR options (see Table 3) were tested: 1) option one, with ventilation rates compliant with Part F 2006

Building Regulations requirements (ODPM, 2006b); and 2) option two, with greater ventilation rates (40% greater than option one). A range of mattress boundary conditions was also investigated in the scenarios modelling by considering 'best case'[1] and 'worst case'[2] scenarios (see Table 5). The range is based on findings from fieldwork measurements (Ucci, 2007).

The 12 months hourly hygrothermal conditions predicted by EnergyPlus for each of the options described so far were utilised as inputs in the Lectus model. In particular, the EnergyPlus results from Bedroom 2 were utilised, since this bedroom had a greater occupancy per floor area than Bedroom 1 (i.e. greater moisture concentration). The mattress modelled in Lectus is a 15 cm thick homogenous single mattress, with material properties equivalent to foam. These properties were collated from a number of published sources and are summarised in Table 4, together with the other input variables utilised in the base-case Lectus model. A sensitivity analysis of the Lectus model showed that changes in mattress properties have no dramatic impact on the model's predictions, when compared to changes in room and boundary conditions. Therefore changes in mattress properties were not included in the scenarios modelling. The mattress simulated in Lectus was divided into 4 layers, with thicknesses of (from the top to bottom of the mattress): 2.5 cm, 2.5 cm, 5 cm and 5 cm. The upper two layers were thinner than the other two, in order to test the finding based on

[1] Lower temperature and lower vapour pressure excess (worse for mites)
[2] Higher temperature and higher vapour pressure excess (better for mites)

preliminary measurements that the most favourable location for mite growth in a homogeneous bed is at 1-2 cm below the top mattress surface. In the Lectus model, each mattress layer was divided horizontally into 5x5 cells, corresponding to a total of 100 cells. It was found that doubling the number of cells for each mattress layer did not produce significantly different results.

The output from Lectus hourly conditions were used as input to Popmite, with the starting date in each 12-month simulation run being the 1st August, since mites thrive in late summer-early autumn. Another key input for Popmite is the starting population in each mattress cell. However, currently there is limited information on the exact number and distribution of live mites in a mattress, mostly due to difficulties associated with sampling live mites (see Section 6). Consequently, the starting population in each modelled mattress cell was assumed to be 10 'wild' DP mite couples (20 adult mites in total), with a spread of all ages. The impact of a larger starting population (200 mites per cell) and of a different simulation start date (1st November) for the predictions were also investigated. The next section illustrates the base-case results.

4. Base case results

Table 6 shows a summary of the hygrothermal conditions predicted by EnergyPlus for Bedroom 2 of the base-case dwelling, whose predicted energy consumption for ventilation and heating was 4278 kWh/year. The

corresponding prediction after 12 months was an average of 137,000 mites per mattress cell, with a dramatic variation within the mattress (standard deviation: 526,000) and predicted numbers reaching a maximum of more than two million mites per cell in some of the cells in the top mattress layer (area shaped like a cross corresponding to the chest, groin, legs and arms, e.g. see Figure 1). On the other hand, in the same area but on the mattress's upper surface, mite predictions were not just lower, but nil. This is because - as already shown by previous studies (Cunningham *et al.*, 2004) - when the bed is occupied the additional moisture due to the sleeper is counteracted by the occupant's high body temperature, which produces low RHs. As a result, conditions on the mattress top surface (under the body) are too hot and dry for the mites to survive. On the other hand, in the layers below the mattress top surface, the excess moisture from the body does result in greater RHs than room conditions which, combined with suitable temperatures, facilitates mite growth. This is particularly true for the top mattress layer, which appears to be the most favourable location for mites. This is unfortunate, since this location is also likely to have plenty of food (skin scales) from the bed's occupant. Figure 6 shows the temporal variations in mite predictions for these two mattress areas (inner and surface cells corresponding to groin area). It was found that even with a starting population of 200 mites, mite predictions for the surface cell would be nil after 12 months.

As previously mentioned, for this study the simplifying assumption had to be made, through lack of adequate data, that there were no space/food restrictions, nor mite movements across mattress cells. Applying the maximum measured rate of 12,000 mites/g food (see above), 2.4 million mites would imply the availability of at least 200g of food within each of these cells, which may be unlikely in practice. Nevertheless, even if such very high numbers are unrealistic, they do demonstrate the favourable conditions and potential for mite infestation that some locations within a mattress can provide.

If the start date of the simulation is taken as the 1st November (start of heating season, less favourable for mites) rather than 1st August (ideal conditions for mites), the final number of predicted mites (after 12 months) for the mattress cell with the highest predictions is approximately 12% less than in the base case. Predictions also show that for those mattress cells with predicted nil mites in the base case, the final predicted population after 12 months is still nil, even if the starting population is 10 times higher than base-case (although it takes longer for all the mites to die). Users of the combined Lectus/Popmite model are therefore advised to take account of how the chosen population size, start simulation date and length of the simulation runs may affect their results.

5. Scenarios modelling results

In order to reduce computational times for the selected 20 scenarios, Popmite predictions for mite numbers in each scenario were only calculated for three representative mattress cells (out of 100 cells):

1) Cell A, with the highest baseline predictions in mite numbers (approx 2.8 million). This corresponded to the cell in the top mattress layer, under the groin area.
2) Cell B, with low baseline predictions in mite numbers (355 mites)[3]. This corresponded to the cell in the mattress third layer (from the top), next to the central chest area (i.e. one cell in from the edge).
3) Cell C, with baseline predicted mite numbers of 3570. This cell is located in the top surface, on the mattress edge, therefore having at all times the same hygrothermal conditions as the room.

Table 7 shows the mite and energy consumption predictions for all the scenarios detailed in Tables 2, 3 and 5. The results are given in terms of the *ratio* between the predictions for a specific scenario and the baseline predictions. The average temperature and RH values predicted for each of the three mattress cells in each scenario are provided in Figures 7 and 8. Table 7 shows that for some scenarios the mite predictions for the three mattress cells vary by different orders of magnitude. For example, in scenario 4 (permeability of 3 m^3/m^2h at 50 Pa, lower than base-case), the ratio of mite predictions to base-case predictions is: 269, 2540 and 31.7 respectively for cells A, B and C. Furthermore, in some cases a scenario leads to a *reduction* in predicted mite numbers for one cell, but to an *increase* in predicted mite numbers for another cell. For example, in

[3] Those few cells with very small (<10) or nil predictions were not considered suitable for the scenarios modelling, since it was assumed to be unlikely that the simulated changes in hygrothermal conditions would be sufficient to significantly affect the predictions in these cells.

scenario 1 (corresponding to a U-value of 1.6 W/m^{2}K, higher than base-case) the ratio of mite predictions to base-case is: 0.6, 8.8 and 0.6 respectively for cells A, B and C. This variability is due to threshold effects which are discussed further in section 6.

Since only three mattress cells were considered due to time and computational constraints, it is difficult to establish with certainty the exact order of magnitude in the overall reduction or increase in mite numbers due to specific scenarios for the mattress as a whole. However, by considering the total number of mites resulting from the sum of predictions for Cells A, B and C in each scenario, it is possible to establish whether a specific scenario is likely to lead to an overall reduction or increase, compared with the base-case. Table 8 shows the scenarios results ordered by the total number of predicted mites (sum of predictions for cells A, B and C). Even though the three cells represent a small percentage of the total mattress cells, it could be argued that they are representative and, by including the cell with the highest mite predictions (Cell A), are likely to identify those scenarios that have most effect on overall mite numbers.

Table 8 shows that the scenario with the greatest decrease of predicted mite numbers from base-case is a reduction of moisture at source, which is also accompanied by no energy penalty. On the other hand, fabric permeability also has a dramatic effect upon mite numbers, as well as on energy consumption. The option with the largest increase in predicted mite

numbers corresponds to a greater energy efficient dwelling than base-case, with more fabric airtightness and insulation levels. However, it should also be emphasised that the results presented in Table 7 and 8 are highly dependent on the characteristics of the base-case (including the weather conditions), and therefore extrapolation of these results should be done with some caution.

Whilst it is perhaps unsurprising that moisture production, ventilation and fabric permeability would dramatically affect mite predictions, Table 7 and 8 contain some unexpected and apparently contradictory results. It might appear surprising, for example, that a higher U-value should *decrease* predicted mite numbers whilst a lower thermostat setting should increase them (and vice-versa). These apparent contradictions are due to the complex ways temperature and RH affect mite growth (see Introduction) and to threshold effects which are discussed further in section 6. The predictions for MVHR might also appear surprising: although MVHR is often advocated as an effective method for moisture and HDM reduction, predictions suggest that the use of purge ventilation with high ventilation rates at targeted times (i.e. base-case: high volume extract fan) may be more effective at removing moisture than lower but continuous ventilation as in the MVHR case (see Tables 1 & 3 for comparative extract rates) – although greater ventilation rates do improve the MVHR's performance, as discussed below. However, it should be emphasised that the

base-case scenario assumes the use of extract fans at the exact times when moisture is being produced; this might not always occur in reality. It might also appear suspiring that the energy consumption associated with window opening (Table 7) is rather small. This is mainly because the heating system in the model is switched off overnight. Also, the amount of open windows for the base-case was relatively small, hence there would not be a dramatic difference in energy consumption once they are completely closed.

Table 7 and 8 also show the results of two alternative scenarios for the mattress boundary conditions (case 18 and 19, see Table 5 and 7). If 'best case' boundary conditions are selected, the mite predictions can be reduced by 30% (cell B) or even 90% (cell A), from baseline. If on the other hand the 'worst case' boundary conditions are selected, this can result in mite predictions being 10 times (cell A) or even 46 times (cell B) higher than baseline.

Table 7 and 8 results are obtained without imposing any limits to the mite population in each cell. This is because, as previously discussed, insufficient empirical data is available for meaningful input parameters on mite limits. However, if a theoretical limit of 2.4 millions mites per cell (based on 200 g of food, as previously discussed) is applied, changes from the base-case become less striking. However, no dramatic change in the order of the options presented in Table 8 is found – except for the MVHR Option 2, which moves up Table 8, with predicted mite numbers nearly

equal to the base case. As the limit for maximum mite numbers per cell is reduced further, MVHR Option 2 moves even further up Table 8. For a limit of 0.2 millions per mattress cell (equivalent to 17g of food), MVHR Option 2 would lead to a reduction in mite numbers from base-case of the same order of magnitude as the 'higher permeability' scenario (No. 3 of Table 7). However, the position in Table 8 of the MVHR Option 1, with lower ventilation rates, does not improve. The next section discusses the results and the model capabilities further.

6. Discussion

This paper illustrates the use of a newly developed combined transient hygrothermal and population model (Lectus and Popmite) for assessing the most effective psychrometric methods of HDM reduction in UK beds (London area). The scenarios modelling focused on the main building features and occupant behaviours which affect indoor hygrothermal conditions: insulation, airtightness, heating and ventilation patterns, and moisture production. The impact of changes in the Lectus mattress boundary conditions was also considered. The predictions showed that higher moisture production, lower permeability and lower ventilation rates from the base-case can dramatically increase predicted mite numbers in the mattress. Predictions also indicated some apparently contradictory results whereby higher U-values than base case would reduce mite infestations (and

vice-versa for lower U-values) but higher thermostat settings would significantly reduce mite growth (and vice-versa for lower thermostat setting). These apparent contradictions are due to: 1) marked threshold effects intrinsic in mite physiology (i.e. role of CEH and dependence of CEH on temperature); 2) the different roles that temperature and RH play on mite survival and growth; 3) the interdependence of temperature and RH in ambient air. For example, in low temperature conditions (e.g. as tend to be the case with higher U-values when the heating is off in winter), RHs might be higher and therefore humidity levels might be above CEH. However, temperature affects development times and hence mite populations might not thrive if temperature is particularly low, despite high RHs. In the case of higher thermostat settings, the opposite occurs: higher temperature might favour fast development times, but the resultant lower RHs might adversely affect mite growth more markedly. It is difficult to establish in abstract which of the two conflicting tendencies prevails (e.g. mite decrease due to low RH, mite increase due to high temperature), since this is largely due to threshold effects and to the size of these changes over time: this is where the importance of a transient model such as Popmite becomes evident.

The scenarios modelling results suggest that the current drive for greater airtightness should be implemented with some caution – particularly if suitable ventilation means are not provided or not utilised adequately by the occupants. With respect to MVHR, predictions suggest that for the

building type considered in this study, flow rates compliant with Part F 2006 may be less effective at reducing mite infestations in beds than targeted ventilation provided by extract fans with high extract rates. However, if limits on maximum mite numbers per mattress cell are imposed in the scenarios modelling, a marked improvement in the performance of MVHR systems with higher flow rates than the minimum required by Part F 2006 is observed.

For insulation levels, predictions suggest that lower U-values might be unexpectedly more conducive to mite growth in some cases. However, this finding might be dependent upon the specific base-case chosen in this study and further scenarios modelling should be carried out to assess whether this finding can be extended to other building types and scenarios. The modelling indicated that a number of options could reduce predicted mite numbers from baseline values: higher fabric permeability; windows open all night in the bedroom; prolonged use of extract fans; increased temperature for the thermostat setting; reduced moisture production rates. Unfortunately, all of these options (except moisture reduction at source) result in greater energy consumption, although windows open all night and longer use of extract fan may do so by relatively little.

Models such as Lectus/Popmite can be used to assess which combination of strategies is likely to result in the lowest levels of mite infestation for the least energy penalty. However, in order to achieve a

suitable balance between energy penalties and potential health risks, we need models that can predict not only mite population levels but also allergen levels in the home and the resultant occupant exposure to mite allergens. The authors are planning to develop an allergen model linked to Popmite, although considerable further information is required on the amount of allergen produced by mites under different hygrothermal conditions and how this allergen accumulates into reservoirs. More information is also needed on the dose-response relationship between HDM allergen exposure and health outcomes. In this respect it is unfortunate that the mechanism between HDM allergen exposure and adverse health effects (e.g. sensitisation, asthma onset/exacerbation, etc.) are currently not fully understood. For example, there is some controversy on the possibility of identifying meaningful threshold levels of exposure (Custovic and Chapman, 1998). Also, although the dose-response relationship between HDM allergen exposure and sensitisation is generally believed to be linear, some studies suggest that it could be bell-shaped in some circumstances (Schram-Bijkerk *et al.* 2006).

The modelling results revealed large variations in predicted mite numbers across the mattress cells at baseline (from nil to 2.8 million mites per cell), and in the various scenarios. It is therefore important to consider the impact of changes in hygrothermal conditions on the overall population in a mattress. However, it is notoriously difficult to estimate the overall

number of mites in a mattress, and non-destructive techniques such as vacuuming can be inaccurate (Hay, 1995). In addition, as noted above, the overall population carrying capacity of a mattress will be affected not only by the hygrothermal conditions in the mattress, but also by food and space availability, as well as by mite movement and population size (Wilkinson *et al.*, 2002). Unfortunately, none of these parameters can at present be satisfactorily modelled in Popmite due to lack of adequate data. If theoretical limits on maximum mite numbers per mattress cell are imposed, then changes from the base-case are not as dramatic, and some scenarios (notably MVHR at the higher ventilation rates) perform better than before. However, apart from this significant exception, the rankings shown in Table 8 are hardly changed.

Fieldwork validation of Popmite and of Lectus indicated a tendency to over-predictions for mite numbers and vapour pressures in conditions of high moisture levels. Even though this is likely to lead to overestimates, it should not affect results if they are analysed in a comparative manner. Furthermore, although Lectus assumptions for the boundary conditions are representative of fieldwork results on average, if a range of conditions is considered, the modelling results can be rather diverse. It should also be highlighted that due to the marked threshold effects and to the impact of seasons and population size, simulation start dates, initial population size

and baseline hygrothermal conditions can all have an effect on Popmite predictions.

Given all the above considerations, the combined hygrothermal population models illustrated in this paper should not be used to determine the exact number of mites or the magnitude of changes from base-case, but rather to compare options and determine whether a population is likely to be greater or smaller than a base-case.

7. Conclusions

This paper discussed the capabilities and application of a newly developed combined transient hygrothermal population model to assess the impact of building design and occupant behaviour on dust mite populations in a mattress. The combined model is the first of its kind able to predict the impact of transient hourly hygrothermal conditions within a 3-dimensional mattress on a population of 'wild' DP mites. The model predictions show that uncontrolled moisture production and measures such as lower permeability and lower ventilation rates can dramatically increase predicted mite numbers in the mattress. Lower U-values might also produce, in some circumstances, favourable conditions for mite growth. Therefore, the current drive for energy efficiency could potentially lead to adverse health effects in susceptible individuals – particularly if suitable ventilation means are not provided or not utilised adequately by the occupants. Although MVHR is often advocated as a method for moisture and HDM reduction, the use of

purge ventilation with higher ventilation rates at targeted times (i.e. extract fan utilised at the same time as moisture production) may be more effective at reducing mite infestations than smaller but continuous ventilation (MVHR). However, our analysis also showed that the performance of MVHR systems is affected by :a) the level of ventilation rates provided, and b) uncertainties in the overall mite carrying capacity of the mattress - hence further research is needed on this aspect. Further research is also needed to address the over-predictions of Popmite and of Lectus (vapour pressure in particular) at high moisture levels – although these over-predictions are unlikely to significantly affect comparative analyses such as those performed in this paper.

Results also indicate that the variability in mattress boundary conditions due to differences amongst individuals (e.g. sleeping clothing) can lead to significant differences in mite predictions. This study also emphasised that whilst moisture control (RH in particular) is often the key focus of intervention strategies for mite control in buildings, the role of temperature should not be underestimated when formulating such strategies.

Whilst the combined models are useful for assessing changes in predicted mite numbers from a base-case, at present they should be used to calculate relative changes rather than to determine the exact size of a population in a mattress or the absolute magnitude of an effect. In order to adequately evaluate any trade-offs between energy efficiency measures and

health outcomes, further research is needed. The current model has to be developed further to include: 1) the impact of restrictions in food and space availability on mite population growth; 2) the impact of food/space availability and of hygrothermal conditions on mite movement; 3) the impact of hygrothermal conditions on food consumption and allergen production. At the same time, a further understanding is required of the dose-response relationship(s) between exposure to HDM allergens and adverse health effects.

Despite the limitations discussed in this paper, and even though the lack of food and space restrictions in the model is unrealistic, until further detailed information becomes available on key parameters[4], the Lectus/Popmite 7d suite still represents the best available model for assessing the impact of transient hourly hygrothermal conditions on DP mite populations in a mattress.

[4] E.g. food, space, movement, typical population sizes per volume, allergen production under variable hygrothermal conditions.

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Table 1: Details of the base-case dwelling modelled in EnergyPlus

Element	Details
Floor area	45 m^2
Volume	108 m^3
Envelope leakage (permeability)	10 $m^3h^{-1}m^{-2}$ at 50 Pa
Envelope insulation (U-value)	*Walls*: 0.35 $Wm^{-2}K^{-1}$ *Windows*: 2.2 $Wm^{-2}K^{-1}$
Trickle vents (equivalent areas)	*Bedroom 1*: 10,000 mm^2 *Living Room & Kitchen*: 12,500 mm^2 in each room *Bedroom 2 & Bathroom*: 7,500 mm^2 in each room *Total*: 50,000 mm^2
Extract fan[#]	*Kitchen*: 60 L/s (intermittent use) *Bathroom*: 15 L/s (intermittent use)
Heating system	*Thermostat set point (living room):* 20 °C *Heating season*: 1st October to 31st May *Size of electric heaters*: 2 kW in each room *Hours heating per day*: 10 hours on weekdays, 17 hours at weekends.
Window opening	10% open (intermittent use)
Moisture input	Equivalent to 10 kg/day (moist occupancy*)
Outdoor climate	London (EnergyPlus weather file: Present-kew.epw)

*As defined by BSI, 2002; [#] Extract fan in use when moisture is produced

Table 2: Changes made to the EnergyPlus base-case model.

	Variable changed	Base-case	Option 1	Option 2
1	Permeability at 50 Pa	10 $m^3h^{-1}m^{-2}$	20 $m^3h^{-1}m^{-2}$	3 $m^3h^{-1}m^{-2}$
2	Walls U-value	0.35 $Wm^{-2}K^{-1}$	1.6 $Wm^{-2}K^{-1}$	0.25 $Wm^{-2}K^{-1}$
3	Window Opening (time)	10% open, intermittent times	As base case, but also open all night in bedrooms	Always closed in bedrooms
4	Extract fan (time)	Intermittent use	Additional 2 hours from base-case	Fans never used
5	Thermostat	20°C	22°C	18°C
6	Heating hours	10 hours at weekdays, 17 hours at weekends	12 hours at weekdays, 19 hours at weekends	8 hours at weekdays, 15 hours at weekends
7	Total daily moisture	10 kg/day (Moist occupancy*)	14 kg/day (Wet occupancy*)	5 kg/day (Dry occupancy*)

* BSI, 2002

Table 3: Details of options for the mechanical ventilation with heat recovery system (MVHR), added to the base-case dwelling instead of extract fan

Variable	Details
Sensible heat recovery	90%
Whole building ventilation rate **Whole building ventilation rate**	***Option 1***: 14.5 L/s ***Options 2 & 3***: 21 L/s
Continuous mechanical extract	**Kitchen, *Option 1***: 9.0 L/s (12 L/s boost); **Kitchen, *Option 2***: 13 L/s (18 L/s boost); **Bathroom, *Option 1***: 5.5 L/s (8 L/s boost); **Bathroom, *Option 2***: 8 L/s (11 L/s boost);
Continuous mechanical supply	**Living room, *Option 1***: 6.5 L/s (9 L/s boost); **Living room, *Option 2***: 9 L/s (12.5 L/s boost); **Bedroom 1, *Option 1***: 4 L/s (6 L/s boost); **Bedroom 1, *Option 2***: 6 L/s (8.3 L/s boost); **Bedroom 2, *Option 1***: 4 L/s (6 L/s boost); **Bedroom 2, *Option 2***: 6 L/s (8.3 L/s boost);
System boost period, week day	07:00 to 08:30, 18:00 to 20:30, 21:30 to 22:00
System boost period, weekend	08:00 to 09:30, 12:00 to 12:30, 18:00 to 20:30, 21:30 to 22:00

Table 4: Main mattress inputs for the Lectus model (base-case)

Input Parameter	Details
Density	36 $Kg \cdot m^{-3}$
Thermal Conductivity	0.06 $Wm^{-1}K^{-1}$
Heat Capacity	850 $Jkg^{-1}K^{-1}$
Vapour Permeability	2.33E-12 $kgm^{-1}s^{-1}Pa^{-1}$
Moisture Capacity	2.00E-05 $kgkg^{-1}Pa^{-1}$
Thickness	0.15 m
Time in Bed (per night)	8 hours

Table 5: Boundary conditions in Lectus, for the mattress top surface, when the bed is occupied.

Location	Base-case		Scenario 2 ("worst")		Scenario 3 ("best")	
	Temp. (°C)	VPX (Pa)	Temp. (°C)	VPX (Pa)	Temp. (°C)	VPX (Pa)
Under Pillow	23	400	24	550	22	200
Chest	34	1000	35	1300	33	700
Legs/Feet	34	1000	35	1300	31	640
Side	28	800	29	1080	26	520
Edge	(0)*	0	(4)*	100	(0)*	0

*Temperature difference between bed and room.

Table 6: Average and standard deviation of the temperature and RH predicted by EnergyPlus for Bedroom 2 in the base-case flat

Variable	Heating Season*	Non-Heating Season#
Bedroom 2: Temp., Average (°C)	18.1	20.3
Bedroom 2: Temp., St. Dev. (°C)	2.4	2.0
Bedroom 2: RH, Average (%)	52.1	68.7
Bedroom 2: RH, St. Dev. (%)	11.8	8.2
Outdoor: Temp., Average (°C)	8.0	16.7
Outdoor: Temp., St. Dev. (°C)	4.1	3.5
Outdoor: RH, Average (%)	79.9	72.5
Outdoor: RH, St. Dev. (%)	10.6	11.2

* 1st Oct. to 31st May; # 1st June to 30th Sept.

Table 7 Scenarios modelling results (presented as ratios in relation to base-case results)

Scenarios	Mite Predictions			Energy Consumpt.
	Cell A	Cell B	Cell C	
1) U-value: 1.6 W/m^{2}K	0.65	8.77	0.62	1.27
2) U-value: 0.25 W/m^{2}K	1.10	1.03	1.10	0.97
3) Permeability: 20 m^3/m^{2}h	0.08	0.38	0.20	1.58
4) Permeability: 3 m^3/m^{2}h	269.05	2538.55	31.73	0.55
5) Windows open all night	0.75	0.91	0.75	1.02
6) Windows closed	1.03	1.16	0.99	1.00*
7) Extract fan, longer use	0.45	0.35	0.58	1.07
8) No extract fan	5.49	54.37	2.43	0.89
9) Thermostat: 22°C	0.03	0.00	0.88	1.20
10) Thermostat: 18°C	5.41	15.50	0.41	0.80
11) Heating period: plus 2 hours	0.94	0.08	1.05	1.05
12) Heating period: minus 2 hours	5.59	54.24	0.82	0.94
13) Moisture: 14 kg/day	7.08	55.61	1.83	(1.0)[#]
14) Moisture: 5 kg/day	0.02	0.00	0.03	(1.0)[#]
15) MVHR, option 1	159.67	369.69	25.37	0.31
16) MVHR, option 2	20.43	0.00	0.07	0.33
17) U-value 0.25 W/m^{2}K and permeability 3 m^3/m^{2}h	312.63	3032.87	38.78	0.52
18) Boundary conditions: best case~	0.10	0.73	(1.0)[#]	(1.0)[#]
19) Boundary conditions: worst case~	10.11	45.91	(1.0)[#]	(1.0)[#]

[#]No changes expected; *Very small energy reduction; ~ See Table 5 for details

Table 8 Scenarios modelling results ordered by the sum of predicted mites for the three mattress cells (results presented as ratios in relation to base-case results)

No.~	Scenarios	Mite Predictions (total of cell A, B, C)	Energy Consumpt.
14	**Moisture: 5 kg/day**	0.02	(1.0) [#]
9	**Thermostat: 22°C**	0.03	1.20
3	**Permeability: 20 m^3/m^2h**	0.08	1.58
18	**Boundary conditions: best case**	0.10	(1.0) [#]
7	**Extract fan, longer use**	0.45	1.07
1	**U-value: 1.6 W/m^2K**	0.65	1.27
5	**Windows open all night**	0.75	1.02
11	**Heating period: plus 2 hours**	0.94	1.05
6	**Windows closed**	1.03	1.00*
2	**U-value: 0.25 W/m^2K**	1.10	0.97
10	**Thermostat: 18 °C**	5.40	0.80
8	**No extract fan**	5.49	0.89
12	**Heating period: minus 2 hours**	5.59	0.94
13	**Moisture: 14 kg/day**	7.08	(1.0) [#]
19	**Boundary conditions: worst case**	10.10	(1.0) [#]
16	**MVHR, option 2**	20.40	0.33
15	**MVHR, option 1**	159.53	0.31
4	**Permeability: 3 m^3/m^2h**	269.03	0.55
17	**U-value 0.25 W/m^2K and permeability 3 m^3/m^2h**	312.63	0.52

~Scenarios Number (from Table 7); [#]No changes expected; *Very small energy reduction

Figure Captions:

Figure 1: Lectus Model, top of the mattress boundary conditions for an occupied mattress.

Figure 2: Lectus predictions and corresponding measurements of temperature under the chest area in the top layer of a sprung mattress monitored every 10 minutes over 20 days.

Figure 3: Lectus predictions and corresponding measurements of vapour pressure under the chest area in the top layer of a sprung mattress monitored every 10 minutes over 20 days.

Figure 4: Typical output from Popmite.

Figure 5: Popmite 7d predictions and measurements of caged live mites in 16 bedrooms and various mattress locations.

Figure 6: Popmite prediction over 12 months for the base-case: comparison of inner and surface mattress cells corresponding to groin area (the inner cell is 'Cell A' of Table 7 and 8).

Figure 7: Predicted average temperature (over 12 months) for the three mattress cells, for each scenario.

Figure 8: Predicted average relative humidity (over 12 months) for the three mattress cells, for each scenario.

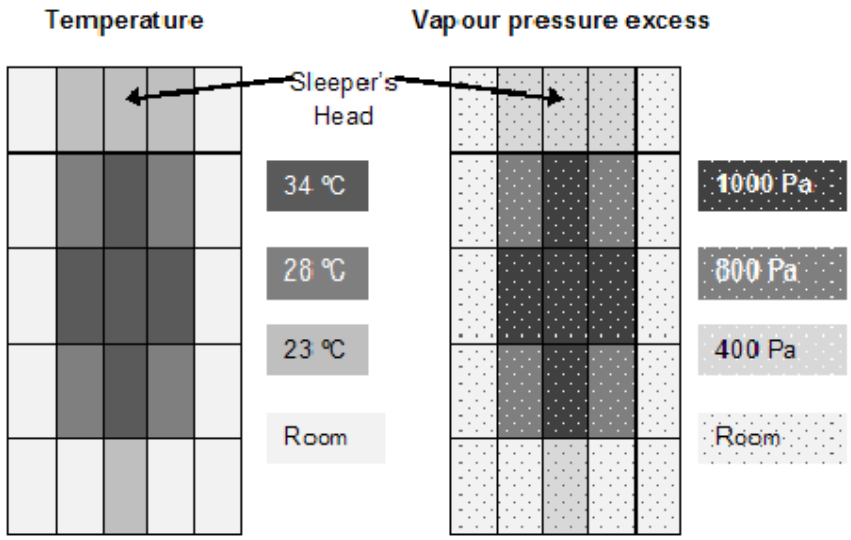

Figure 1

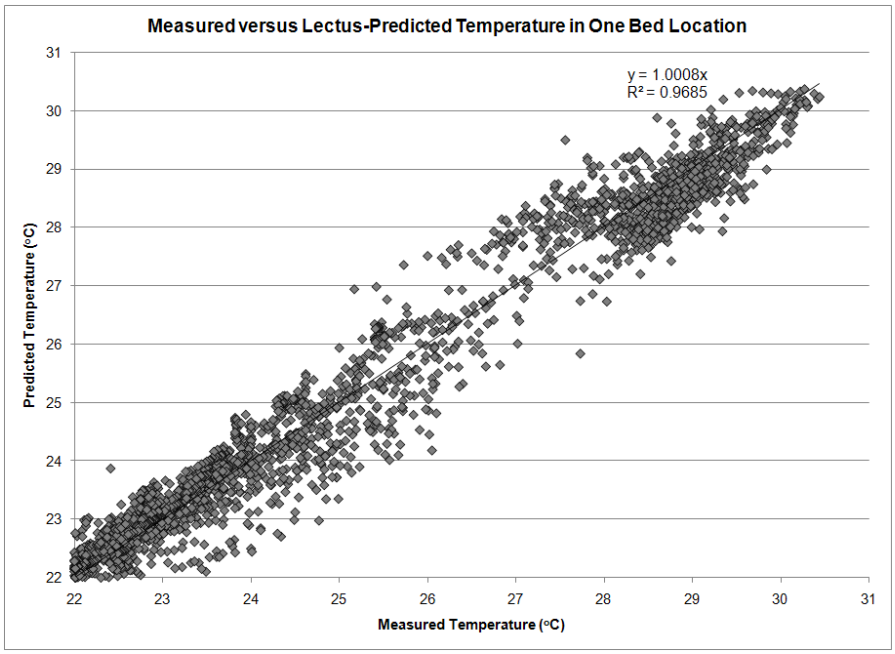

Figure 2

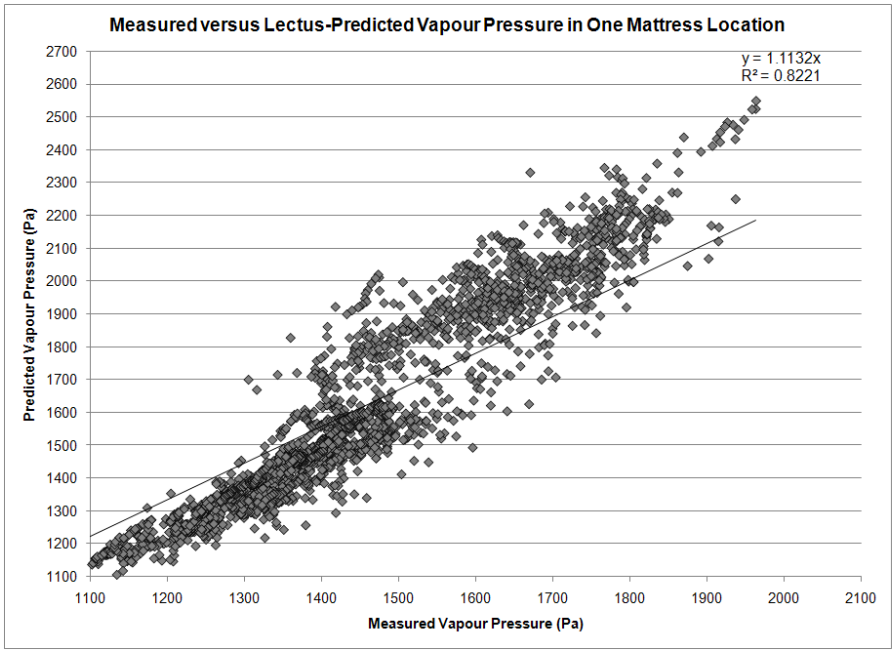
Measured versus Lectus-Predicted Vapour Pressure in One Mattress Location
y = 1.1132x
R² = 0.8221
Predicted Vapour Pressure (Pa)
Measured Vapour Pressure (Pa)
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100

Figure 3

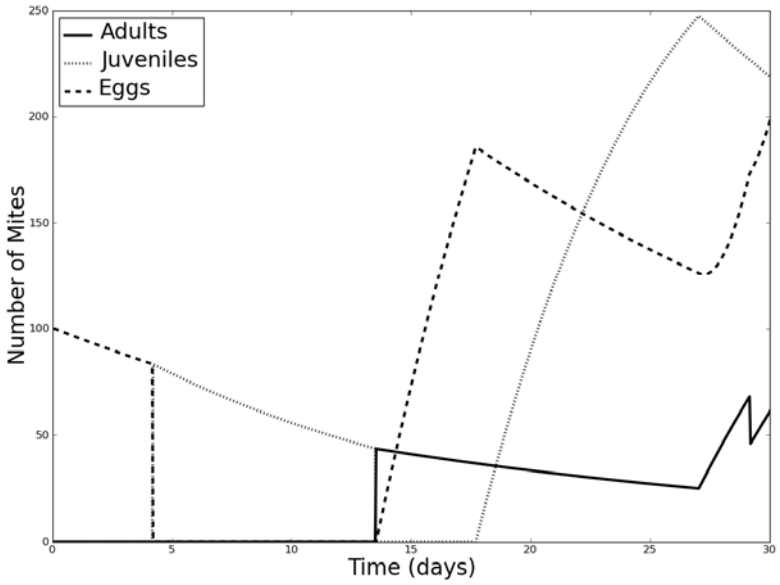

Figure 4

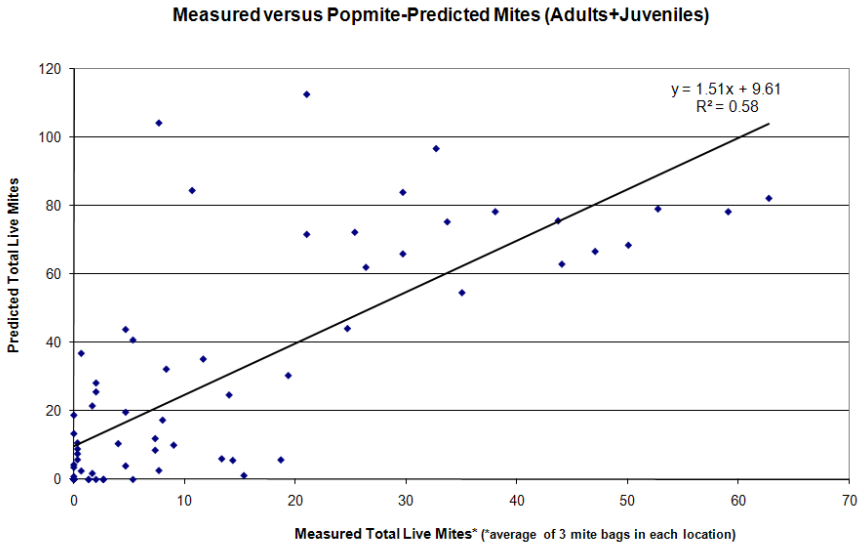

Figure 5

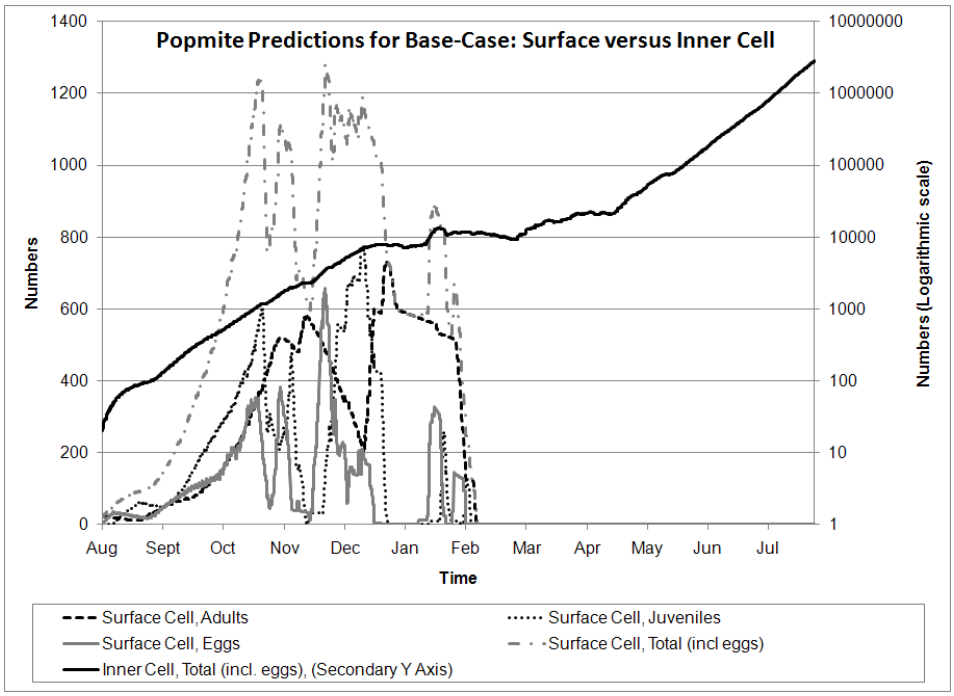
Popmite Predictions for Base-Case: Surface versus Inner Cell
Numbers
Numbers (Logarithmic scale)
Time
1400
1200
1000
800
600
400
200
0
10000000
1000000
100000
10000
1000
100
10
1
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Surface Cell, Adults
Surface Cell, Juveniles
Surface Cell, Eggs
Surface Cell, Total (incl eggs)
Inner Cell, Total (incl. eggs), (Secondary Y Axis)

Figure 6

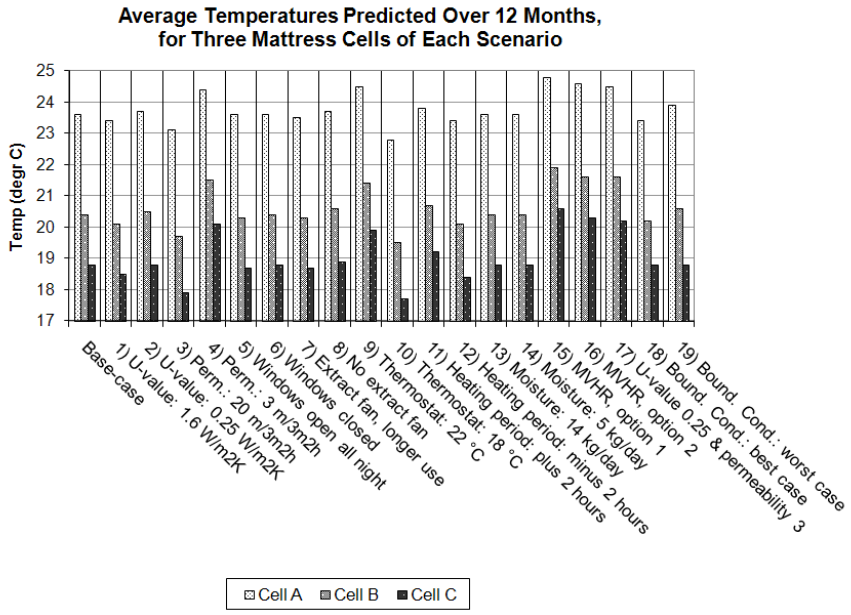

Figure 7

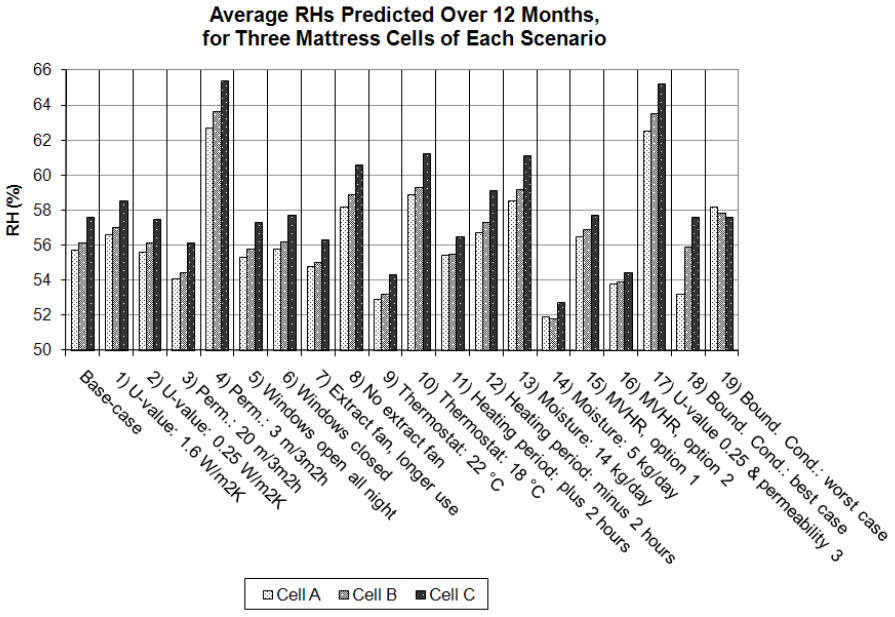

Figure 8