Review of the Livestock Export Heat Stress Risk Assessment Model (HotStuff)

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Abstract

The HotStuff model was developed for the Australian livestock export industry to estimate and minimise the incidence of heat stress mortality in livestock during voyages to the Middle East. The model has been in operation since 2003 and the livestock export industry considered it timely to review the model, specifically the scientific basis for the algorithms and assumptions that underpin the core elements of HotStuff. The review panel conclude that whilst there are limitations in the data, the methodology and assumptions central to the model are sound, reasonable and supported by scientific literature. Several recommendations were made that aim to either engender greater confidence in the technical elements of the model or potentially improve the model's accuracy. Our key recommendation is to develop a system to validate and monitor the performance of the model predictions against actual aggregated voyage data over time. This will provide an objective mechanism for future refinement of the model which is clearly in the interests of the livestock export industry and animal welfare.

Executive summary

There are obvious animal welfare risks associated with the export of livestock to Middle Eastern countries. Notably, the risk of heat stress on vessels is a major issue particularly during the northern hemisphere summer. The Australian livestock export industry has been proactive in its attempts to develop practical solutions to manage such risks. In 2003, the HotStuff model was introduced to enable livestock exporters to predict the risk of heat stress mortality occurring during a voyage and to identify strategies to minimise these risks (e.g. reducing stocking densities, different genotype). The heat stress risk estimates are derived from the integration of: (i) wet-bulb temperature distributions en route and at port for the specific time of year, (ii) estimated animal mortality distributions for a given wet-bulb temperature adjusted for animal factors (liveweight, body condition, coat type (sheep) and acclimatisation zone) and (iii) ship and stocking density factors (i.e. that influence ventilation and therefore pen air turnover (PAT)).

Since its introduction, the HotStuff model has undergone several refinements, including the recent inclusion of the capacity to assess the risk of heat stress occurring during discharge at Middle Eastern ports (HotStuff Version 3.0). In view of this and the fact that model has been in operation for five years now, the livestock export industry deemed it appropriate and timely to review the model.

A review panel with expertise in animal welfare physiology, climatology, engineering and statistics was established to specifically examine the scientific basis, methodology and assumptions of the core elements that underpin the HotStuff model. Within the review, the following key questions were addressed:

- whether the HotStuff model algorithms and parameters are supported by scientific literature and MLA-LiveCorp R&D reports.
- whether assumptions within the HotStuff model are reasonable and justified.
- whether implementation of the HotStuff model adequately manages mortality risk associated with heat stress.

The panel acknowledges that there are deficiencies in the available data used to develop HotStuff, particularly those from animal heat stress studies which explore interactions with factors known to influence the susceptibility of animal mortality due to heat stress. Nevertheless, the best available data have been utilised and the biological assumptions have been revised in light of new evidence. As additional biological data on heat stress and mortality in Australian-type livestock becomes available, it should be considered for its applicability and usefulness for incorporation and refinement of the HotStuff model. The voyage/climate database used to derive the wet bulb temperature distributions is far more extensive but there would be benefits in undertaking some further analyses to identify the likelihood of possible biases, trends or cycles within the data. Further justification or evidence for the 1^{o}C downward reduction of the voluntary observing ships (VOS) temperature in the database is required. From an engineering perspective, pen air turnover is clearly the critical parameter and to improve the accuracy of these estimates within the model it is recommended that audits of ventilation properties on vessels be undertaken as a priority.

Overall, the panel concluded that the methodology and assumptions underpinning the HotStuff model are sound, reasonable and supported by scientific literature. The model developers have followed well-defined and logical principles of adaptive management in the presence of uncertainty.

In a complex model such as HotStuff, the levels of underpinning scientific data will vary between components. However, the key feature of adaptive management is rigorous monitoring of performance and this is the key recommendation of the panel. Specifically, the need for validation of existing assumptions and monitoring of the model's predictions against actual aggregated voyage data is required. The latter in particular, provides the only real mechanism to evaluate performance of the model but more importantly, it potentially enables objective refinement of the model to facilitate improved predictive accuracy. Further recommendations are made that aim to either engender greater confidence in the technical elements of the model or potentially improve the model's accuracy in the future.

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1 Background

The risk of heat stress during the export of Australian livestock to the Middle East, particularly during the northern hemisphere summer, is a significant animal welfare issue. In recognition of this and in the interests of improving animal welfare, the Australian livestock export industry developed a Heat Stress Risk Assessment Model (HotStuff) which was implemented in 2003. HotStuff assists exporters with the planning and mitigation of the risk of mortality due to heat stress and its application is an essential criterion governing the approval of a voyage.

The model is based on the integration of four core elements relevant to the sea transportation of livestock, namely:

- Animal physiology – Specifically, this includes the understanding of the principles of thermoregulation and heat exchange between livestock and their environment. Furthermore, based on the best available evidence, the identification of thresholds where specific classes of livestock experience heat stress.
- Engineering – Understanding the principles of fluid dynamics in the context of ventilation systems fitted to livestock export vessels as well as the physical design of these ships.
- Climatology – Using the best available data to estimate climatic conditions along the routes and destinations of livestock vessels.
- Statistics – Utilising the range of input data from the above three elements, to accurately estimate the probability of heat stress and mortality occurring.

The HotStuff model has undergone several refinements since its implementation. The most recent of these (HotStuff Version 3.0) now provides the capacity to assess the risk of heat stress occurring during discharge at Middle Eastern ports. In view of this and the fact that model has been in operation for five years now, the livestock export industry deemed it appropriate and timely to review the model.

2 Project objective

To undertake a comprehensive review of the scientific basis of the core elements (animal physiology, engineering, climatology and statistics) that underpin the HotStuff model.

3 Methodology

A review panel was established to formerly review and evaluate the HotStuff model. The panel comprised the following members:

Dr Drewe Ferguson (Co-ordinator). Principal Research Scientist, CSIRO Livestock Industries Animal Health and Welfare Stream.
Dr Andrew Fisher. Principal Research Scientist, CSIRO Livestock Industries Animal Health and Welfare Stream.
Dr Robert Casey. Principal, RT Casey Pty. Ltd., Consulting Mechanical Engineers.
Dr Barry White. Consultant, Agricultural Economist with experience in climate analysis and climate risk research management.
Mr Bob Mayer. Senior Biometrician, Qld Department of Primary Industries and Fisheries.

As background, the panel were provided with the following reports relevant to the development and revision of the HotStuff model and the livestock export industry.

MLA Final Report SBMR.002 – Investigation of the ventilation efficacy on livestock vessels (MAMIC Pty Ltd).
MLA LiveCorp Final Report LIVE.116 – Development of a heat stress risk management model (Maunsell Australia Pty Ltd).
MLA LiveCorp Report LIVE.212 – Investigation of ventilation efficacy on live sheep vessels (Maunsell Australia Pty Ltd).
MLA LiveCorp Report LIVE.228 – Upgrade of biological assumptions and parameters used in the HS risk management model (Maunsell Australia Pty. Ltd.).
MLA LiveCorp Report LIVE.246 – National livestock export industry shipboard performance report 2007 (Dept. of Agriculture and Food, WA).
MLA LiveCorp Report B.LIV.0249 – HotStuff Version 3.0 – Revision for Port Risk (Maunsell AECOM).

Following evaluation of these, the panel met with Dr Conrad Stacey and Colin Eustace of Maunsell AECOM (28 Oct – Barry White, 4 Nov 2008 entire panel) to discuss the development and application of the model. Sonia Correy from Maunsell AECOM was also at the meeting on 28 Oct.

After consideration of all the available information, the following review was prepared. In the context of this review, the panel addressed the following important questions as outlined in the terms of reference:

- Whether the HotStuff model algorithms and parameters are supported by scientific literature and MLA/ LiveCorp R&D reports?
- Whether the assumptions within the HotStuff model are reasonable and justified?
- Whether implementation of the HotStuff model adequately manages mortality risk associated with heat stress?

4 Review

The HotStuff 3.0 model enables exporters of Australian livestock to the Middle East to estimate the risk of heat stress occurring during a voyage. The heat stress risk estimates are derived from the integration of; (i) wet-bulb temperature distributions en route and at port for the specific time of year, (ii) estimated animal mortality distributions for a given wet-bulb temperature adjusted for animal factors (liveweight, body condition, coat type (sheep) and acclimatisation zone) and (iii) ship and stocking density factors (i.e. that influence ventilation and therefore pen air turnover (PAT)). This is illustrated in the following figure extracted from the B.LIV.0249 HotStuff Version 3.0 Final Report. It is important to emphasise that this is a risk management model and not one that attempts to predict outcomes from any one particular voyage.

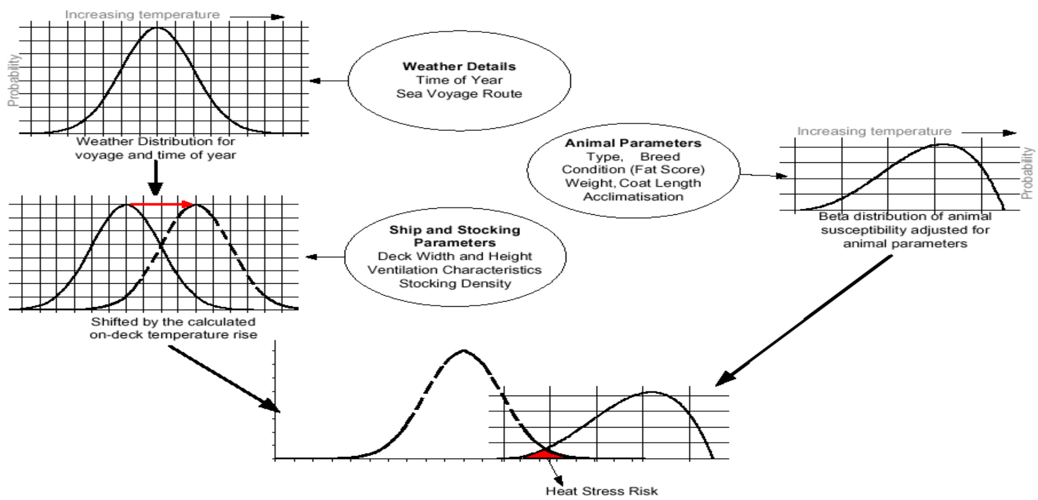

Figure 2-1: Summary of the Risk Estimate Methodology

The following review examines the methodology and key assumption used in the development of HotStuff 3.0 and discusses this in the context of animal physiology, engineering, climatology and statistics.

4.1 Animal Physiology

4.1.1 Introduction

The HotStuff Model estimates the risks of mortality for livestock on voyages from Australia to the Middle East. The model also incorporates mitigation strategies, such as reduced stocking densities and positioning a vessel to optimise crosswinds. However, at the heart of the model is a need to identify the thermal conditions which represent a risk to the life of different classes of livestock. Thus, the success of the model is dependent on accurate data and modelling concerning animal physiology and heat-induced mortality.

4.1.2 Methodology used in HotStuff (including assumptions and quality of data)

Choice of wet bulb temperature as the critical environmental variable
Animals lose heat by a variety of heat transfer mechanisms, including radiation, convection and evaporation. Under hot conditions, evaporative cooling methods assume greater importance, as the body tries to lose heat to maintain homeostasis through thermoregulation. Evaporative cooling methods include sweating and panting, in which heat is lost by increased amounts of air passing through the moisture-rich respiratory passages. Cattle are able to lose somewhat more heat through sweating than sheep, but both species are heavily dependent on panting.

Because the effectiveness of evaporative cooling mechanisms declines rapidly as relative humidity increases, air temperature is not a good measure of the level of thermal challenge for livestock unless relative humidity is low to moderate. In addition, it is more common for heat stress in animals to arise through a combination of elevated temperature and humidity. Accordingly, environmental measures of heat challenge for animals typically include both temperature and humidity components.

One commonly-used such measure is the Temperature-Humidity Index (THI) (e.g. West, 1994). The THI combines air temperature and relative humidity in a formula and was originally developed as an index of thermal comfort for humans, and subsequently modified for livestock. The HotStuff model uses a slightly different measure - that of wet bulb temperature. In this measure, the bulb of a thermometer is typically covered by a sock which is kept wet via the wicking action of water being drawn up from a reservoir. The evaporation of water from the sock cools the bulb of the thermometer, but as humidity increases, this evaporation declines, and wet bulb temperature increases relative to dry bulb temperature. Typically, the wet bulb temperature is less than the dry bulb temperature unless there is no evaporative cooling. The developers of the HotStuff model examine the case for using wet bulb temperature in one of their earlier reports (SBMR.002). In this report, they also examine, for completeness, the utility of a little known third measure - that of the Equivalent Temperature Index (ETI). The ETI combines dry bulb temperature, relative humidity and airspeed in a defined formula. The developers of HotStuff demonstrate that the ETI generally conforms to the wet bulb temperature, whereas the THI, which is used more commonly in livestock heat stress evaluation, is closer to a midpoint between the wet bulb and dry bulb temperatures.

Despite the THI being used more commonly, the developers' decision to use wet bulb temperature as the critical environmental measure for determining risk of heat mortality in livestock on board ships is sound. The THI, as identified by the developers, is thought to be closer to the impact received by animals that may be in direct sunlight.

Solar radiation striking an animal grazing in hot conditions will be better reflected by the existing dry bulb temperature than by the wet bulb temperature, and thus the THI achieves a balance between the heat-inducing effects of solar radiation, and the heat-reducing effects of evaporative cooling. For animals on board ship, solar radiation is not an issue, and thus the wet bulb temperature is a very good indicator of the effects of the heat load on the animals arising from air temperature as modified by the effects of their evaporative cooling mechanisms under different relative humidities. In short, the cooling effect of the wet sock on the thermometer bulb mimics the evaporative cooling effects for the animals of panting and sweating, and both thermometer and animal have these cooling effects lessened by increasing humidity.

Data used to identify critical wet bulb temperatures

The HotStuff model is designed to identify the risk of actual mortality, rather than the risk of simple heat stress. Therefore, the data to identify critical wet bulb temperatures needs to have been collected in events or studies in which sheep and cattle either actually died, or came so close to death that the wet bulb temperature at which they would have died can be estimated with reasonable confidence. Furthermore, the studies or events used in the data collection must have used species and classes of livestock that are similar to animals exported from Australia to the Middle East.

The developers of the HotStuff model correctly state that these requirements necessarily result in a relatively limited dataset. Furthermore, it would be extremely unlikely that the application of Australian laws on animal experimentation would permit the heat-induced mortality of meaningful numbers of livestock for experimental reasons. Additionally, the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes also expressly proscribes research for the information of Australian organisations (but deemed unethical in Australia) being conducted in another country simply to avoid Australian animal experimentation laws.

However, the stated limitations of the size of the dataset do not mean that it is not useful or that it should not be used. The HotStuff developers list and detail the events and experimental studies used in the identification of critical wet bulb temperatures for cattle (page 26 of Report LIVE.116) and sheep (page 27 of Report LIVE.116). It is not within the scope of this review to examine the conduct of each of these studies themselves, but rather to examine how the resulting data have been used for the HotStuff model.

Report LIVE.116 outlines data from 6 events or studies for *Bos taurus* cattle and 3 events/studies for *Bos indicus* cattle. For sheep, there are 4 datasets from events involving Merino sheep and 1 event with Awassi sheep. In each case, the HotStuff developers have identified key independent variables influencing the result (acclimatisation temperature, body weight, coat and fat score), as well as recording the actual or accurately estimable “Mortality Limit” (ML) – the wet bulb temperature above which the animal was dead. An additional dependent variable - the “Heat Stress Threshold” (HST) is also presented. This is defined as the maximum wet bulb temperature at which the heat balance of the animal’s deep body temperature could be controlled by bodily heat loss mechanisms, although the HST is not in itself used in the HotStuff model. Each study or event is presented as the actual data, plus estimated ML and HST for scaled data on variations in acclimatisation temperature, body weight and coat length. The process for scaling the data is reviewed in a later section.

Examination of the total dataset used in LIVE.116 and the initial development of the HotStuff model indicates that while it is not extensive, it provides useful coverage of the key animal types and gives a good indication of the critical wet bulb temperature thresholds.

The actual voyage mortality events, although extremely regrettable in their own right, at least have served to provide some data to develop systems for preventing more such incidents.

Data scaling and assumptions for livestock classes and acclimatisation
Although the dataset of mortality and near-mortality events for livestock in conjunction with wet bulb temperature is useful, each set of data is for a particular class of livestock in terms of body weight, condition, coat or wool length and pre-heat challenge acclimatisation temperature. Accordingly the developers of the HotStuff model have undertaken a scaling procedure from each core dataset in order to estimate relevant ML for such animals at different condition scores, coat lengths and acclimatisation temperatures. For example, the estimated scaling factor for condition score ranges from 0.9 for condition score 1, to 1.2 for condition score 5 for both sheep and cattle. Although these scaling factors are based on estimates, they reasonably reflect existing knowledge that animals in fatter body condition are less heat tolerant. Similarly, the standard (shorn) sheep embarking on a voyage to the Middle East has a scaling factor of 1, whereas this is increased to 1.12 if the wool is greater than 25 mm in length, reflecting the reduced heat tolerance of such an animal if transported.

Acclimatisation temperature is known to have a significant effect on heat tolerance of livestock under all circumstances (Silanikove, 2000). The scaling factor for acclimatisation wet bulb temperature ranges from 0.79 (fully acclimatised to the challenge temperature) to 1.26 (completely unacclimatised), and because temperature is a continuous variable (unlike say condition score), the developers have correctly altered the scaling by a slope factor for each degree of acclimatisation. The slope factor is -0.0235 per degree of acclimatisation, which is initially difficult to understand until one calculates that it is derived from a 20ºC range in wet bulb temperature from acclimatised to unacclimatised, adjusted in a linear fashion between the two scaling points of 0.79 and 1.26.

The 20ºC range appears reasonable from the extensive wet bulb temperature data for origins, voyage routes and destinations that is considered in a number of MLA-LiveCorp reports (e.g. SBMR.002, LIVE.116, LIVE.212, B.LIV.0249) and the scaling values at each end of the range of 0.79 and 1.26 also do not conflict with the relatively limited data. A question arises as to whether a linear adjustment of the scaling factors represents the best approach, but given the restrictions of the dataset, it is reasonable to assume the simplest relationship. Assuming a non-linear relationship would risk a greater departure from reality if one chose the wrong curve shape.

Updating of biological data
The developers of the HotStuff model provided a subsequent report to MLA-LiveCorp (LIVE.228), titled *Upgrade of biological assumptions and parameters used in the HS risk management model*. The report examined additional datasets that had become available since the original development of the HotStuff model (LIVE.116).

The data from two cattle heat stress studies conducted in climate rooms at the University of Queensland with *Bos taurus* cattle was examined. Although these studies did not stress cattle to the point where ML could be derived, the HotStuff developers considered the data to see if it was compatible with the HST values used in LIVE.116. The developers (correctly) concluded that the HST values that could be derived from the two University of Queensland studies were consistent with the HST values in the studies and calculations considered in LIVE.116. Although, this information is not able to be directly incorporated into HotStuff (which uses mortality), the new information supports the relevance of the data used for the development of HotStuff, given that both HST and ML were presented in LIVE.116 and the HST is supported by the later data.

Data from a series of observations of 9 voyages with sheep and cattle (LIVE.223) were also considered with regard to HST, however this information, although broadly consistent with the HST values in LIVE.116 had some internal inconsistencies, and thus was of limited usefulness in updating or testing the model. Specifically, there was considerable variation in apparent HST between two voyages with similar classes of sheep, possibly related to difficulties in accurately determining respiration rate. Similarly, in cattle, very low respiration rates were recorded in one voyage despite the presence of high end wet bulb temperatures. Accurate measurement of respiration rates particularly when the animal is panting (ie. high wet bulb temperatures) is difficult. It would appear that accuracy was an issue in these sheep and cattle voyages and therefore, these data were not considered further in the upgrade of the biological parameters within the model.

Data from two heat stress studies conducted at Murdoch University were also examined. A study with sheep suggested no need to revise the HST values, but a study with dairy cattle indicated that the HST values for *Bos taurus* dairy cattle could be revised upwards slightly from those originally used. The HotStuff developers assumed that the ML values for such cattle could also be correspondingly increased in the HotStuff model, and this is a fair conclusion, given our level of understanding of the close relationship between HST and ML in livestock.

The LIVE.228 analysis also appropriately considered current published scientific literature on heat stress in livestock, although none was of sufficient relevance to be considered for testing against the HotStuff HST and ML values. However, the concept of testing the model against new knowledge as it arises, and updating the model as necessary, is important and should not be overlooked.

Probabilistic model for risk calculation

Because HotStuff is aimed at calculating and minimising the *risk* of mortality of livestock due to heat stress during shipment to the Middle East, simply knowing an ML value is not sufficient to assess probable mortality levels. Accordingly, a probabilistic model, based on the risk of mortality as wet bulb temperature increases towards a calculated ML, is needed.

The developers of HotStuff have approached this problem by assuming a probability distribution of mortality as wet bulb temperature increases towards ML. They have used a skewed beta distribution, rather than a normal (or gaussian) distribution. In fact, the choice of any particular distribution of livestock mortality with increasing wet bulb temperature represents an assumption, because we simply do not have data of sufficient precision and quantity to know the exact nature of the distribution. In any case, it would be unethical to hope to collect it because it would involve cattle and sheep studies where 100% mortality occurred through heat stress.

So, what are the arguments for or against the choice of a beta distribution as used by the developers of HotStuff? From a biological perspective, the type of non-symmetric distribution chosen by the developers, with its longer tail toward the lower end of the wet bulb temperature axis, is not unreasonable. This is because in any sample, there are likely to be weaker animals that succumb earlier to heat stress, but there are unlikely to be many animals that can survive beyond certain limits - i.e. there is likely to be weakness at enduring heat stress, but there is unlikely to be “strength” in enduring temperatures beyond biological limits. This results in the shorter tail of the beta distribution towards the upper end of the wet bulb temperature axis - essentially the remaining animals would be dying *en masse* once the temperature increased beyond a certain point.

From another perspective, the choice of a beta or a normal distribution actually matters relatively little in terms of the symmetry (or lack thereof) of the distribution curve, because it is not the entire distribution with which we are concerned in the application of the HotStuff model. Specifically, we are not interested in the risk of 100% mortality (the whole distribution curve), or even of 50% mortality, both of which would be an animal welfare catastrophe. The limit chosen in the application of HotStuff is the risk of a 5% mortality rate for a livestock class. The selection of the 5% limit is outside the scope of this physiological review - it is more of an ethical, political and economic question as to what constitutes the mortality rate that one wants to have a significant probability of avoiding. However, the relevance of the 5% limit in the consideration of the probabilistic mortality model is that it is only the very left hand edge of the distribution curve that is relevant, and the key issues are the spread of that far left side of the curve, and its position on the wet bulb temperature axis.

The developers of the HotStuff model have assumed that the spread of the left hand tail of the probability distribution is proportional to the susceptibility of the class of the animal to heat-induced mortality. That is, it is proportional to the size of the difference between the calculated ML and a nominal upper body core temperature of 40.0ºC (which is consistent for all animals). Thus, animals with a lower ML also have a greater spread of the beta probability distribution. This is biologically relevant, because, for example, animals with an ML of 33ºC may start to die at 31 ºC, whereas animals with an ML of 36 ºC may not start to die until 34.5 ºC. Figure 4.1 illustrates these points.

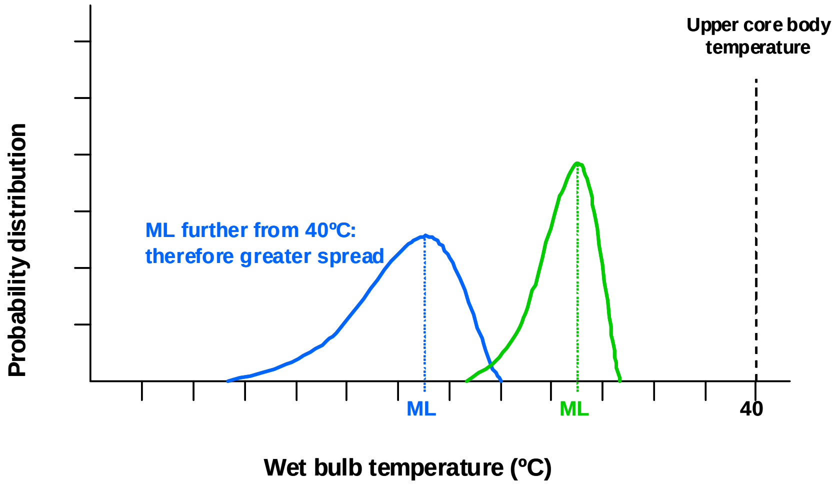

Figure 4.1. Probability distributions for heat-induced mortality for two classes of livestock. The blue line represents animals (e.g. *Bos taurus*) that are more susceptible than animals represented by the green line (e.g. *Bos indicus*).

4.1.3 Model accuracy or applicability

The data and calculations used in the HotStuff model for identifying the critical values for heat-induced mortality and the distribution of the accompanying incidence of mortality are supported by biological knowledge and reasonable assumptions derived from existing knowledge. Although the model does not take duration of heat exposure directly into account, this is a reasonable position given that the temperature and humidity conditions when at their worst are unlikely to fluctuate greatly over a short time, the relative conservatism of the model in seeking to safeguard animal welfare, and the possibility of introducing greater error by attempting to build in duration of stress.

Given that there is not a lot of data on mortality with heat stress for the model, there is even less data on duration effects for similar conditions.

4.1.4 Recommendations

- As additional biological data on heat stress and mortality in Australian-type livestock becomes available, it should be considered for its applicability and usefulness for incorporation and refinement of the HotStuff model.

- Mortality is clearly the ultimate measure of an animal's welfare (or lack thereof). However, it is recognised that it is not the only measure of welfare in response to heat challenge and that some consideration should be given to protecting animals that might otherwise suffer severe heat stress but not actually die. Some consideration of this issue is built into the selected threshold of a 2% chance of a 5% mortality event (i.e. these low values should provide some protection against undue stress in the animals). Consideration should also be given to utilising the HST values that have been developed, but not actually applied in the output and use of the HotStuff model.

4.2 Engineering – Evaluation of the thermodynamic and fluid modelling and assumptions

4.2.1 Introduction

The basis for the risk assessment in the HotStuff program, is via a comparison of the wet bulb temperature to which the animals are exposed, to a limiting value of wet bulb temperature. Thermodynamic and fluidynamic modelling are used to establish the wet bulb temperature that the animals are likely to be exposed to en-voyage and at discharge port(s). As such, the methodology and the assumptions embedded in the thermodynamic and fluidynamic modelling would have an impact on the validity of the approach. Therefore, these aspects are examined within this section.

4.2.2 Methodology used in HotStuff

The overall principle on which the calculation is performed to determine the value of wet bulb temperature to which the animals are exposed is relatively simple. Firstly, ambient conditions for a specific location are established via weather modelling and this allows a determination of an ambient value of wet bulb temperature. Then an increase to the ambient value of wet bulb temperature (ΔT_{wb}) is calculated via the equation:

$\Delta T_{wb} = 3.6 \times C \times M \times h / (\rho \times PAT)$ Eq. 1 [from 6.1 of LIVE116]

where C is the constant of proportionality relating ΔT_{wb} to the internal energy rise.
M is the liveweight in the particular weight zone (kg/m^2)
H is the 'per mass' rate of metabolic heat
ρ is the density of the air (1.2 kg/m^3)
PAT is pen air turnover (m/hr)

The addition of this increase to the ambient value of T_{wb} equates to the wet bulb temperature to which the animals are exposed. This value of wet bulb temperature is termed “On-Deck Wet Bulb Temperature” in more recent reports and will be adopted for the remainder of this report.

The form of the equation that calculates the increase of wet bulb temperature above ambient conditions aligns to a conservation of energy calculation, which holds as one of the primary tenets in fluidynamic and thermodynamic modelling. As such, it forms a strong basis on which to make the calculation.

Heat source quantification
The overall heat release from the animals within an area is taken to result from metabolic processes, and this has been equated to the live mass of the animals within that area via the terms h (the per mass rate of metabolic heat) and M (the live weight in the area). The accuracy of the calculation is therefore reliant on the accuracy of the animal based metabolic heat release terms.

Values such as:

2 W/kg for *Bos indicus* cattle
2.4 W/kg for *Bos taurus* cattle
3.2 W/kg for sheep

are nominated in LIVE.116 at section 6.1 as the values adopted for h in Eq. 1 above. The overall heat release is also dependent on the live weight of the animals, however it is likely that this is a far more deterministic parameter and therefore, the animal based specific metabolic heat release (h) is most likely to be the limiting factor in determining the accuracy of the metabolic heat release terms.

Additional heat from decomposing manure was reported in SBMR.002 section 2.1.1. However, the authors found that the heat generated via this source for “normal” manure pads was not significant. No quantification of the results was presented and as such, it is not possible to make an independent interpretation of their results. However, in the absence of information to the contrary, their conclusions are accepted.

Heat addition to the air flows via fan and ducting inefficiencies was discussed in report SBMR.002 at section 2.1.1. There, heat addition via the intake fans and their consequential flows was nominated as being typically 5% - 15% of the metabolic heat release from the animals. Outwardly this would form a significant contribution to the overall heat added to the airflow around the animals, especially at the upper end of this limit. This contribution has not been included in the HotStuff model. Inclusion of such terms would introduce a raft of complications. A great deal of difference can exist in the physical nature of inlet fans, ducting systems and ducting velocity and it would not automatically follow that all fans and ducts could be modelled as having the same relative amount of loss. As such, inclusion of an appropriate amount of loss would be dependent on an engineering audit of the ventilation installation.

Finally, heat addition to the airflow via radiant energy was discussed in section 2.1.1 of SBMR.002 where wall and ceiling temperature effects were discussed. Temperatures of 36°C for wall or ceiling panels were claimed to result in a 1% increase in the amount of heat to be rejected by cattle, whereas 50°C temperatures increased this percentage to 15%. This contribution has not been included in the HS model. However, some experimental justification for ignoring this form of heat contribution is put forward in section 2.12 of LIVE.212. Here a comparison is made between apparently similar pens for the experimentally measured wet bulb temperature. The results appear to show little significant difference in wet bulb temperature (Figure 0.24) even though one pen is beneath a 50^{o}C roof and the other is not. However, as noted in LIVE.212 this result was taken on a moderate voyage where the overall wet bulb temperature rise was tempered by strong natural ventilation. As such, the potential may exist for this form of heat addition to have a significant impact in still air, especially when at port during the discharge phase.

4.2.3 Quantification of air flow rate

The calculation of the wet bulb temperature rise is dependent on the volumetric air flow. Importantly, the air itself absorbs the heat generated within a pen and this leads to a temperature rise of the air. Pen Air Turnover (PAT) is put forward in Eq. 1 above, as a single parameter quantifying the amount of air flowing through a pen. Even though it is expressed as a single parameter, it belies a complexity of phenomena.

Mechanical ventilation
The simplest form of airflow to quantify is the component provided by mechanical ventilation. Data describing the amount of air delivered to various points throughout the ship would need to be determined during the design phase of the ventilation system. This follows as this data is needed to select and construct the fans and duct work in the first place in order to meet volumetric flow requirements. It appears that such data is provided through the ship owners as an input to the HotStuff program as a means of describing PAT. However, it is not clear if this data has been taken from design calculations, has come from an independent source or if it has been subjected to confirmation via some independent experimental audit of the vessel.

Importantly, data taken from design calculations are often conservative to allow for uncertainties in the actual installation. This may in fact open up the possibilities for some vessels which have relied on design data, to increase their nominated values of PAT. This would only be discovered through an experimental audit of the ventilation system by well qualified personnel. The benefits that may flow from this process would flow to the owners of the vessels. Conversely, variations in the installation of the ventilation system, especially ducting, can result in areas of lower than expected through-flow of air and an engineering audit may well find such areas.

The prime benefit of conducting an engineering audit of the ventilation system is the increased certainty with which data can be relied upon. The HotStuff model makes an estimate of parameters relevant to the risk to the animals, however, the estimate is reliant on the accuracy of many parameters, especially air flow from mechanical ventilation. As such, the accuracy of the risk estimate is also reliant on the accuracy of these parameters.

Cross wind ventilation
The benefits of cross wind ventilation to open pens en-voyage appear self evident from data presented in LIVE.212. It is also apparent from information presented in LIVE.116 at section 5.4.2 where it is noted that crosswinds in excess of 1 m/s overwhelm most mechanical effort, for open decks.

En-voyage, cross wind ventilation would have some element of controllability to it, in that it would generally be possible to navigate the vessel in such a way as to generate significant cross winds. As such, cross wind ventilation is a controllable parameter. This allows ship's personnel to react to adverse conditions that can affect the mortality rate during the voyage.

However, it is not possible to control cross wind ventilation in-port, as it would be entirely dependent on the prevailing direction and strength of winds occurring at the port, as well as the direction of the ship when it is tied up alongside a dock. Therefore, cross wind ventilation in-port is not a controllable parameter. Moreover, the aim of the HotStuff model is to provide a prediction of the probability of mortality of animals, prior to departure from Australia. If the mortality rate on open decks can be significantly affected by cross wind ventilation in port, and cross wind ventilation in port can not be relied upon, it would be prudent to make no reliance on cross wind ventilation in port. This is a strategy that would err on the side of caution, and aligns with conservative engineering practice and lends support for Maunsell's decision to not attempt to account for cross winds in port for open deck vessels within the HotStuff model.

Buffetting ventilation
Buffeting generated air flow is mentioned in section 2.3 of B.LIV.0249. This is where large vortex patterns are produced from the front of the vessel and can travel down the sides of the vessel. This would then generate local regions of high and low pressure with consequential localised flow between neighbouring cells. However, the overall level of the air flow that could be generated from this source would be highly dependent on the level of obstruction to the flow from internal structure, animals and any other impermeable objects. It would also be linked to the timescales that are available to establish this flow, that is, if the vortex pattern results in rapid movements of vortices down the sides of the ship, it is unlikely that there would be sufficient time to establish any significant flow into the ship that would penetrate to any significant width into the ship. Finally, separation type flows which give rise to such a mechanism tend to be highly reliant on the geometry of objects and as such would most likely be specific to each vessel. As such, it would be necessary to perform a detailed analysis of each vessel to determine what benefit might be derived from buffeting ventilation, if at all.

Jetting
Jetting has received a number of mentions in the various reports to date. This is where a spatial distribution of air flow occurs over a pen or some other localised area, with consequential localised peaks in air velocity. Intuitively, mechanical ventilation must give rise to some level of jetting as the mechanics of providing forced air flow to the pens is reliant on this air flow being delivered from discrete points, and this would give rise to localised areas of high air flow.

Currently, HotStuff uses a zero'th order parameter to evaluate air flow, namely PAT. This is where the overall net air flow is uniformly distributed over an area and as such carries with it the assumption that all points within this area have an equivalent level of air flow. On the other hand, jetting would provide a spatially resolved air flow in that the level of air flow across some area would be determined. As such, jetting would be reliant on some form of audit to provide spatial information about the air flow. Therefore the benefits that may flow from jetting would only come at the expense of such an audit.

Secondly, jetting may provide localised benefit to some areas within pens, however, the overall net airflow within a pen would ostensibly be the same as the nominal PAT. Therefore the benefits to localised areas with high air speed would come at the expense of other areas that must have localised low air speed. It may turn out that an audit of the spatial air flow in pens will reveal areas that have greatly improved airflow, however, it might also reveal areas with dangerously low air flow.

Finally, the benefits of jetting would depend on the proportion of animals that are exposed to high air flow at some point in time. As long as the benefits from such exposure would exceed the negative

impact that might arise from exposure in low flow areas of the pen, then there would be a net benefit to the animals. This would be reliant on the animals moving around in the pens and as such would be tied into animal behaviour and stocking density.
It would be prudent to make some form of evaluation to determine if there is a net value in jetting, before inclusion in the model would be warranted.

The project B.LIV.0240 investigated the potential benefits that may arise from jetting. There, a jetting factor was derived which represents the relative amount of heat rejection from an animal with and without jet-type air flow. Generally, this factor was above unity for the range of parameters investigated which forms a strong basis to continue with the process for inclusion of jetting factors in the HotStuff model.

Some limitations were borne out in this work in that the air flows described in B.LIV.0240 were for pens cross ventilated with equally spaced vents above the animals backs and so vessels (or even pens) which do not conform to such a ventilation format may not see the same benefits due to jetting. Also, the jetting factors were averaged over a pen area and atypical cases may arise where very high benefits in one portion of the pen are achieved at the expense of other sections elsewhere. This might potentially give rise to higher heat stress in such dead zones. However, it would be relatively straight forward to properly account for such non uniform pens via an audit of vessels by well qualified personnel that are familiar with the principles of jetting.

Mention is made in B.Liv.0240 for jetting factors to be normalised against the industry average for the fleet. From the second paragraph of the executive summary, it appears that this has been put forward as a means of maintaining the level of agreement between the HotStuff model's prediction of heat stress events. This may have some statistical relevance however it is not based on the physical nature of the fluid dynamics nor in the thermodynamics.

4.2.4 Open deck modelling

The Computational Fluid Dynamic (CFD) modelling described in section 5 of LIVE.116 appears exhaustive. The commercially available Fluent package was used for the computations and this program finds very strong acceptance both commercially and as a research tool in academia.

The efforts to make an animal representation go well beyond simple geometric representation as moisture, energy, momentum and blockage effects are all included. Although the results of the CFD would be dependent to some extent on the stocking rate and geometries of individual animals, it would be far beyond the scope of such a CFD effort to investigate a wide range of such geometries as such a parameter set would be too large to cope with, in a reasonable fashion. Also, it would be expected that as stocking densities increase, the homogeneity of any specific region would also increase making the results less dependent on the animal geometry.

Two very important points arise from the CFD work. Firstly, the relative effect of cross wind ventilation on open deck air flow is clearly demonstrated, in Figure 5.1 of LIVE.116. There it supports earlier experimental conclusions that good cross winds have the potential to overwhelm mechanical ventilation. Secondly, a lower limit to air flow is established via natural convection. That is, even when no mechanical ventilation is present, the buoyancy driven air flow will result in some air movement, albeit at very low effective PAT, as shown in Figure 5.2 of LIVE.116.

4.2.5 Proportionality constant

The term “C” appears in Eq. 1 above and has been assigned a value of 0.23^{o}C/kJ/kg (section 6.1 of LIVE.116). This constant of proportionality equates to the increase of wet bulb temperature with increases in energy.

As outlined in Appendix C of LIVE.116, the total energy released from metabolic processes has been proportioned such that some is liberated as sensible heat and some as water and this means that for each increase in energy there is also an increase in the amount of water added to the air. Importantly, this means that the water content of the air is assumed to increase in proportion to the energy increase.

This process appears to have been simplified by assuming all the metabolic heat is added to the total mixture enthalpy and ignores proportions of water and sensible heat. Since lines of total mixture enthalpy lie very nearly parallel to lines of wet bulb temperature on a psychrometric chart (commonly used to represent humidity in air), this approximation would be valid because the HotStuff model is only reliant on wet bulb temperature, irrespective of humidity ratio or other animal-related characteristics. Moreover, in the range of 25^{o}C to 35^{o}C (dry bulb) total enthalpy varies by approximately 0.23^{o}C/kJ-kg-dry-air, in accordance with the quoted value for C in Eq. 1. As such, it is considered appropriate.

4.2.6 Appropriateness of thermodynamic and fluidynamic modelling

The use of an energy conservation basis to determine increases of wet bulb temperature is considered to be sound. The model assumes a homogeneous distribution of airflow across a pen and in the absence of data that specifies a spatial distribution, this zero’th order approach must be accepted.

Quantification of the airflow has considered all expected forms of ventilation such as mechanical ventilation, cross winds, buffeting and natural convection. Mechanical ventilation stands as the most easily quantifiable of these forms of ventilation. Moreover through experimental and CFD programs, contributions that can be gained from the other forms of ventilation have been quantified. This aspect of the modelling appears to be thorough. Moreover, relative contributions from each source have been compared and in this fashion the likely gains that can be made by consideration of other forms of ventilation were ranked.

One important point is warranted here, the HotStuff model currently stands as a global approach to estimating the mortality risk aboard vessels that carry livestock. There is a great deal of geometric variability in vessels as well as variability in other mechanical attributes of mechanical ventilation systems aboard various vessels. By considering more and more details of specific vessels it might be possible to increase the accuracy of the determination of on-deck wet bulb temperature, however, this would come at a cost of needing to perform detailed surveys or modelling of the specific vessels. Moreover, it would also make the analysis specific to a particular vessel and as such the HotStuff model would lose much of its universal applicability. Therefore, the appropriateness of the universal approach of the HS model is a question of the intent of the HotStuff model in that if it is intended to serve as a universal predictive tool then it is considered to have fulfilled this role.

As noted in B.LIV.0249, cross winds at port were ignored for open decks and the on-deck wet bulb temperature only considers mechanical ventilation.

Earlier findings have clearly indicated that cross winds can have a significant contribution to overall ventilation levels on open-decks. It would be possible to include some form of consideration of cross winds in port as this would ostensibly be the same as cross wind inclusion en-voyage. However, port based cross wind information would best be incorporated from data taken at the port as it would be reliant on the wind direction, ship direction, local gust velocity and other parameters that are best assessed from direct measurement. This would negate much of the predictive role of the HotStuff program as port based assessment could only be made after the ship has arrived in a particular port and this occurs after the ship has left Australia. Additionally, as a control measure, it would be reliant on the ability of a ship's crew to react to adverse conditions and unless this can be relied upon, then the HotStuff model's output would only be a tool for predicting negative outcomes and not a tool for preventing them, in-port.

4.2.7 Model accuracy or applicability

The model formulation based on thermodynamics and fluidynamics is heavily reliant on input from sources that come from outside these two disciplines. This is particularly true for the inputs from animal physiology as well as from weather based data. As such, the accuracy of the HotStuff model is heavily reliant on the accuracy of these two sources.

It is possible that by refining aspects of the fluidynamics and thermodynamics that a greater level of information can be determined, such as spatial information about individual decks in the form of jetting. However there is no guarantee that such a process would necessarily increase the accuracy of the prediction as even in a refined format, it is still reliant on input from animal physiology and weather based data.

The best indicator of performance accuracy is to run the HotStuff model for sets of known conditions. In this sense, detailed data taken from actual voyages would need to be made available as input to the HotStuff program and then the output from the HotStuff model could be directly compared to actual mortality rates on a long-term 'average' level. This would have the added benefit of allowing "fine tuning" of parameters within the HotStuff model. This is discussed in more detail under Section 4.5.

4.2.8 Recommendations

- The HotStuff model currently uses a globalisation of air flow throughout the internal spaces of a vessel such that PAT is spread uniformly throughout a pen. It is possible that jetting or some other spatially resolved fluid flow may show non-linear forms of cooling (in relation to air velocity) and therefore have benefits that have not yet been accounted for. It is recommended that studies into the potential for jetting should be undertaken to quantify the potential benefits that may arise. It would only be prudent to incorporate jetting and other forms of spatial resolution of airflows if they show significant benefit over and above what is currently forecast by the HS model. Moreover, this benefit would come at the cost of making spatially resolved airflow assessments of individual vessels, which is likely to be both expensive and time consuming.

- Given the importance of PAT to the HS model, audits of vessels' ventilation systems should be recommended to owners.

- Given that the assumption of zero wind at port is contentious, it is recommended that an analysis of port weather data be undertaken. A sample of the limited available port wind data should be analysed to provide an initial assessment of the likelihood of calm conditions at high levels of wet bulb temperature and strengthen the justification for the assumptions for open deck situations at port.

4.3 Climatology

4.3.1 Introduction

The model estimates risk of extreme heat stress from historical records of wet bulb temperature for the sailing and discharge portions of voyages that are typically of two to three weeks duration. This review is based on the report ‘HotStuff Revision for Port Risk’ (2008). The revision superseded the earlier version that had recognised deficiencies in estimating discharge port risk. The temperature distributions for the voyage are the key determinants of the heat stress risk. The model estimates the weather risk as measured by extreme wet bulb temperatures over a 12 hour period. The risk is modified using ship and stocking density parameters, and animal parameters to arrive at the risk for a specific voyage. Parameters such as stocking density can then be adapted to achieve an acceptable level of risk. The level has been set at a 2% or lower risk of mortality of 5% or higher occurring. The 2% risk is estimated using the 98th percentile of wet bulb temperature for the ‘worst case’ which is defined as the highest weather risk part of the voyage.

This section of the review will also cover animal acclimatisation, a parameter in the model based on the climate zones of the port of loading and the property of origin.

4.3.2 Methodology used in HotStuff

Choice of wet bulb temperature
Wet bulb temperature reflects the combined impacts of the dry bulb temperature as conventionally used and the humidity level as it affects an animal’s capacity to ameliorate heat stress. As shown in Section 4.1.2, wet bulb temperature is the most appropriate measure for this application for on–board heat stress risk. The model calculations are based on an estimate of the worst case wet bulb temperature likely to be experienced over a 12 hour period.

Acclimatisation wet bulb temperature data series
As shown in the LIVE.116 report, the software includes data to enable ready estimation of the mean monthly wet bulb temperatures for the property of origin and the port of departure. There is a facility to override means with actual data if that is readily available. As shown in Section 4.1.2, an allowance can then be made for the effects of acclimatisation. The wet bulb climatology is based on monthly means for all ports of departure and for 97 stations across Australia. The data were used to derive means for each month for 6 zones. The methodology is appropriate for determining the effects of acclimatisation.

Voyage wet bulb temperature data series
Distributions were developed for months and for the four most common voyage routes using the Voluntary Observing Ships (VOS) dataset from 1991 to 2008. The data set included over 500,000 observations. The data were cleaned using routine approaches to delete the small percentage of erroneous readings. A major downward correction of 1^{o}C was made to all data to allow for measurement inaccuracies. The correction was based on a comparison of VOS data with nearby reliable shore data. Details of the comparison have not been presented.

Wet bulb temperature distributions
The port-specific distributions of the data for each month were then estimated so that the ‘worst case’ could be defined for the sailing part of the voyage and for the port of discharge. The ‘worst case’ for the voyage is derived from the distribution representing the worst 12 hours of the journey including the port sections.

(The 12 hour period is approximately equivalent to a 250 nautical mile section of the route). Generally at least 500 data points were available to estimate monthly distributions and in particular the 98th percentile (There is a 2 percent chance of the 98th percentile being exceeded). The accuracy of this approach is discussed further within Section 4.3.3.

In closed deck vessels, the voyage risk based on the 'worst case' wet bulb temperature is the limiting risk because ventilation is the same at sea and in port. For open deck vessels at port, crosswind at port is assumed to be zero compared to an allowance for an effective cross wind of 5 knots during the sailing part of a voyage. Thus for open decks, the sailing risk or the port risk may be the limiting risk.

Risk assessment
The first step taken in the model is to specify a voyage by the date and place of departure and order of arrival at discharge ports. Voyage and discharge risks can then be calculated for each stocking line using the 98th percentile wet bulb temperature to define the 'worst case' 12 hour period for the relevant locations and months. There is no progressive or cumulative risk calculation based on duration of critical temperatures or the cumulative impacts of the most extreme risks other than the 'worst case'.

4.3.3 Accuracy and applicability of the model

Consideration of alternative approaches
For port risk, the original intention was to use sea surface temperature (SST) at the port of discharge on the basis that it would be a good proxy for wet bulb temperature when wind speed is zero. Reliable wind speed data is not generally available. However, this approach was not adopted because experience suggested there would be considerable variability in the risk of heat stress mortality between ports with a similar SST. That assessment is supported.

Wet bulb temperature climatology
The HotStuff model is an application that depends on a highly specific weather risk at a particular location. The future weather risk is based on a special purpose climatology summarising historic meteorological observations. The accuracy of the risk assessment depends on how appropriate the instrumentation is to the task and to what extent the calculated risk reflects the major expected climate patterns. No specifications are provided on the frequency of observations, for example whether the readings are 3-hourly and whether data is continuous. For general climate description, a period of 30 years is typically recommended and would be desirable for example, for assessing means and variability at an annual time scale. For HotStuff, the wet bulb temperature distributions are based on 17 years of data and typically, 500 data points for any given month. The sample size and the techniques used to assess the 'worst case' scenario are in general considered adequate for the purpose provided the sample data is shown to be free of bias, trends and cycles.

The general adequacy of the approach can be confirmed by reference to the seasonal and spatial variability of temperature data. Measures of climate elements at one location can be expected to exhibit gradual and coherent changes seasonally, and similarly particularly for spatial variability for maritime locations. The seasonal and voyage patterns for the median and 98th percentile are as expected and without anomalous months or locations. In addition smoothing has been used to interpolate for the few voyage segments with inadequate data. Given that the sample size appears adequate to derive coherent seasonal and spatial patterns, the question can be asked whether a smaller more localised sample could have been used to estimate port risk? This will be further considered in a section below on port risk.

Consideration of bias, trends and cycles in the wet bulb temperature data
The reduction of 1°C to VOS data is an adjustment for bias that is likely to have a major impact on risk estimates. But the adjustment is not based on a demonstrated rigorous analysis. The basis for the adjustment was to correct for the number of high readings which could have arisen from poorly maintained (wick allowed to dry out) or positioned (restricted air circulation) wet bulb thermometers. This contrasts with the findings by Kent et al (1993) in a North Atlantic analysis that the extent to which wet bulb readings were high depended on solar radiation and wind speed. The ship data were compared with data interpolated from numerical weather models. Similarly for this application, the VOS data could have been compared with climate reanalysis data now routinely available from numerical models provided the resolution is adequate. The accuracy of VOS data has been the subject of increased interest because of its value in climate change studies. There are other potential biases. The 'worst case' is defined by the 98th percentile. The 2 percent of events above the 98th percentile only correspond to 10 events. This small sample could have been analysed to check for other biases, for example, over representation of particular ships or seasons. The analysis could consider for example that the number of ships in the VOS has decreased in recent decades as ships become larger and voyages fewer. That could introduce a possible bias to data in the1990s. Another potential source of bias is the use of spatially sourced data to estimate climate and weather risk at a location. For example, an extreme event only occurring on one day could be duplicated in the 500 points or in the 10 extreme points if two VOS ships were in the sample for that day.

For most purposes and in this application, climate was traditionally assumed to be free of trends and cycles other than diurnal and seasonal. Climate descriptions are now likely to routinely consider trends and decade level variability due to recognition of the impact of climate change. Of particular relevance for this application, is the possibility that climate extremes are possibly changing more rapidly than means. Further, in some climates, extremes at the daily level are more likely when seasons are unusual. For example, extremes are more likely when climate forcings such as El Niño result in shifts in the frequency distributions of measures of seasonal climate. If such unusual seasons can be forecast, then a conditional distribution would be appropriate to estimate the 'worst case'.

Variability at a seasonal or decadal time scale recognises possible influences for example, from ENSO (El Niño Southern Oscillation). Whilst the sample size may appear adequate for daily data in the absence of demonstrated trends and cycles in a statistical sense, it is important to provide context and demonstrate how typical the climate experience of the last few years has been. Whilst it is unlikely that statistically meaningful relationships will be uncovered because of the short periods of record at an annual scale, it is important context.

Statistical techniques are available to test such hypotheses (using years, and/or routes/ports as replicates). Multivariate analyses can be used to see if years 'cluster' in any way, which could identify definite climatic 'phases'. If so, then these phases could have consistently more heat stress events.

The 12 hour duration for the 'worst case' risk assessment
As discussed in Section 4.1, the data on heat stress are insufficient to define with any precision the most appropriate duration to calculate the impacts of extreme wet bulb temperature. In any case the outcome is unlikely to be sensitive to the duration whether it is for example 12 or 24 hours. A high degree of correlation could be expected from one 12 hour period to the next. Thus a particular event could still be included in the 2 percent of critical wet bulb temperature events whether the event is defined as of 12, 24 or even 36 hour duration.

The extent to which there is a coincidence in the critical events should be checked to demonstrate that outcomes are unlikely to be sensitive to the definition of duration.

Revised port risk
The previous version of HotStuff did not have port-specific estimates and there were some inconsistencies in the treatment of voyage and discharge point risk. One distribution was used for Red Sea ports and one for the Persian Gulf although there were thought to be substantial differences between ports particularly in the Persian Gulf. The new version redefines port risk using the same approach as used to redefine voyage risk. Distributions of wet bulb temperature have been developed for each port. The VOS data were used to capture sufficient data points in a radius of the port to accurately assess critical wet bulb temperatures.

The port distributions were developed using a radius sufficient to capture 500 observations for each month. The report stated that was the number of observations needed for the distributions to stabilise. Therefore in general, there would appear to be little to gain from using a smaller area. However, there may be ports where VOS data may not be representative of conditions in port. In that case, further assessment is required of possibilities of using land-based observations to either check the accuracy of port data or to improve it. Note that assessment would also be relevant to the assessment of the general reduction of 1^{o} C to VOS data to correct for bias.

The new version also includes provision for the order of discharge ports and overall corrects the most serious deficiencies apart from the less than ideal approach used to estimate open deck airflow. Ideally statistics on wind should also be taken into account. The LIVE.116 Report did attempt a climatology of wind which would take into account the complex diurnal, seasonal and spatial patterns. However because calm conditions are likely to be often associated with high wet bulb temperatures, the joint distribution would need to be estimated. The task is clearly beyond what is feasible with existing data. It is not immediately clear the extent to which the airflow assumptions are conservative. The extent will depend on the degree of correlation of wind speed and wet bulb temperature at high values of wet bulb temperature. However, given that sailing risk is easier to manage than port risk, and assuming discharge mortalities are potentially significant, a conservative approach is warranted.

It is not clear from voyage statistics to what extent discharge mortalities also reflect heat stress. Any recommendation for further amendments would depend on the significance of heat stress related discharge mortalities and on how frequently port risk is the major risk. For the five years of data presented in the 2007 Performance Report (LIVE.246), discharge mortalities for sheep from Fremantle to the Middle East accounted for about 30 percent of mortalities. Contingent of the availability of quality voyage data, the voyage and model data could be further analysed as a pointer to heat stress risk at port.

Cumulative voyage risk
The model assumes that the 12 hour ‘worst case’ risk is an adequate representation of the risk of heat stress-related mortalities for the voyage. In some cases, the ‘worst case’ risk may be at the discharge port. In any case, there is no addition of the ‘worst case’ identified whilst sailing, the ‘worst case’ at port, and on other sailing days when extreme temperatures would have been a possibility. Generally, the chance of both the sailing risk and the discharge risk occurring is of course very small. The issue of cumulative risk only arises if there are several days of high wet bulb temperatures that are only 1 – 2^{o} C below the critical heat stress threshold. Although it can be argued that the calculation of a cumulative risk would be extraordinarily complex, it should first be demonstrated whether it is likely to be necessary.

A simple example will illustrate the difference between one 'worst case' risk of a 2 percent chance of an extreme daily wet bulb temperature and a longer period of exposure to a similar albeit slightly lower level of risk. The example considers the overall chance of at least one event greater than the 98th percentile occurring over a period of 7 days. During the extreme parts of a voyage it would not be uncommon to experience periods of several days of high risk because the risk and the climate generally only changes slowly with distance. The statistical chance (assumes the risk is constant over the period) of one or more 98th percentile event occurring over a seven day period is about one in seven (The chance of more than one extreme day over a seven day period can be calculated by first calculating the chance of no occurrence. For any one day that is 98%, because 98% of days are equal to or less than the 98th percentile. For six more days the chance is 0.98 multiplied by 0.98 six times, that is 0.87 or a 87% chance. More than one event in seven days, is therefore a (100-87) or 13%, by coincidence about a one in seven chance). The implications for mortalities related to heat stress might be complex and uncertain because of either possible acclimatisation or increased susceptibility from the first event and because of correlation between successive temperatures. However the example clearly demonstrates that further analysis and evaluation of the assumption that the 'worst case' scenario adequately reflects overall voyage risk is warranted.

4.3.4 Recommendations

- The VOS data used to estimate the 'worst case' risks be more clearly defined and checked for biases, trends and cycles that may be relevant to estimating future risks; the check should include seasonal, decadal and climate change influences and provide rigorous justification for the 1^{o}C downward adjustment made to VOS data.

- The climatological and physiological justification be provided for using the worst case over 12 hours as a measure of risk by considering for example, coincidence or correlation with worst case risk events assessed over longer periods.

- The approach of estimating cumulative voyage risk based on the 'worst case' needs to be justified by the extent to which 'worst case' risk approximates cumulative risk. This could be assessed in the first instance for example, by a comparison of the 'worst case' identified whilst sailing, the 'worst case' discharge port risk, and whether there were several other occurrences of high levels of sailing risk.

- A sample of the limited available port wind data be analysed to provide an initial assessment of the likelihood of calm conditions at high levels of wet bulb temperature and strengthen the justification for the assumptions for open deck situations at port.

- There is a need to compare and evaluate the VOS and land-based climate data (at each port) to identify the most suitable data for the estimation of port risk within the model.

4.4 Statistics

4.4.1 Introduction

The statistical issues relating to climate have already been adequately addressed in Section 4.3. The following sections relate to specific statistical issues in the animal response area and in how the various risk components have been incorporated together.

4.4.2 Animal response data

Scientific data on HST and ML (in terms of wet bulb temperature) have been sourced from research publications and reported observed cases. For the purposes of the model, a distribution form (for mortality probabilities at increasing wet bulb temperatures) was needed for different species of exported animal (sheep, cattle, goats), types (breed, gender, age, size), condition and coat/fleece status. A Beta distribution is a standard statistical distribution type and is considered appropriate and biologically relevant (refer Section 4.1.2).

The LIVE.228 Report addressed this issue of updating the Beta distributions based on more recently available research studies on heat stress. Most of the data were 'analysed' by plotting respiration rates against wet bulb temperature and then assessing heat stress thresholds 'by inspection' of these plots. These plots generally showed a flat response to increasing temperature (where the animal was 'comfortable' and able to maintain body temperature), until a point where the pattern started taking an upward movement (assessed visually). A more accurate statistical method would have been to fit bent-stick models to the data, which would estimate these points more accurately than by eye, and also have associated standard errors to show how accurately they had been estimated. In addition, a meta-analysis of these break point temperatures, across animal types, could be carried out to see if any distinct patterns could be identified. If so, then these could possibly be used to extrapolate temperature values for animal types not included in these studies.

The MLA report 'Investigation of the Ventilation Efficacy on Livestock Vessels' (SBMR.002, July 2001) was provided to the review team as additional information. This report comes up with numerous 'principal findings' and 'other significant outcomes' but almost no actual data has been presented. The report claims 'A number of new figures and tables are . . . presented as a result of both analysis of the total data set and of revisiting voyage data in new contexts'. Unfortunately, this report did not present either this data, or details of how it was 'analysed'. Conclusions such as 'had generally much higher respiration rates' and 'are clearly well above and well below the trend respectively' indicate that no statistical analyses were carried out on the data. Such analyses would improve the the scientific confidence of the conclusions.

A similar report 'Investigation of Ventilation Efficacy on Live Sheep Vessels' (LIVE.212, April 2004) was provided. This report presented the scientific data recorded on two monitored sheep shipments to the Middle East in 2002. Graphs are presented on

- rectal temperature rises in response to increasing wet-bulb temperatures (up to 35^{o}C for different breeds, sexes, wool length, size
- wet and dry bulb temperatures and relative humidity experienced on different decks during the voyages
- animal body weight changes.

The trends in some of these graphs are important to the HotStuff assumptions, but the conclusions in the report are not backed up with any statistical analysis. Statements such as 'Figure 0.8 indicates that', 'were generally higher', 'was the same as, or slightly lower', 'no measurable difference' should be backed up with actual probability statements to improve the scientific credence.

In the LIVE.246 report 'National Livestock Export Industry Shipboard Performance Report 2007', comprehensive mortality data are presented for all cattle, sheep and goats transported in 2007. It also presents some data from 1985-2006 for comparison purposes.

It has variously broken up the mortality data into categories : C = class of animal (within species, e.g. adult wethers in sheep), L = loading port, D = country of destination, M = month of year, Y = year, H = half of year, V = specific vessel. In 2007 there were a total of 66 voyages shipping sheep, and 281 voyages shipping cattle. The 'sheep' part of the report has presented 'main effect' averages for each of the above factors, and, in various tables and figures, given 'interaction' figures for YxV, YxLxV, LxC, YxMxL, YxLxVxH. This indicates that the authors felt that at least some of these factors were not 'additive', but had interactive effects. This could be confirmed by subjecting the data to statistical analysis. Some mortality data were also reported for cattle exported to SE Asia from 1995 to 2007, involving 1057 different voyages.

In summary, it seems that a lot of potentially useful data has been collected and collated, but it would appear that it has not been subjected to rigorous statistical analysis, or considered across all aspects. If this is the case and the data were statistically analysed it may not necessarily change the underlying assumptions drawn from the data. However, it would facilitate improved confidence in the assumptions. It is also recommended that in the context of validation and monitoring of the model (refer Section 4.5) that appropriate statistical advice be engaged to ensure statistical rigor.

4.4.3 Assessing mortality risks

The HotStuff model combines specific vessel details with the long-term climate distributions, and heat generation specific to animal type, condition and stocking density to arrive at a predicted wet bulb temperature distribution for each deck/class of animal on that deck, for particular times of a voyage, and also while docked at a port of discharge. This temperature distribution is then compared with the relevant mortality level temperature Beta distribution for the class of animal, to give statistical estimates of 'expected mortality' rates, and also to answer specific questions such as 'what is the probability that the mortality rate will exceed a set limit?'. The statistical methodology for this is sound.

The diagrammatic representation of this 'distribution matching' process in Figure 2-1 on page 8 of the MLA-LiveCorp Report B.LIV.0249 is intuitively good, but misleading. It implies that the shaded area where the 2 distributions overlap represents the 'heat stress risk'. In fact, this does not represent how either the 'estimated mortality' or the 'risk' probabilities have been calculated. For example, the left hand side of the shaded area is simply an area under the left tail of the Beta distribution, while the right hand side is an area under the Normal distribution. The temperature at which the 2 curves intersect has no special significance.

On page 11 of the B.LIV.0249 report, it states, 'The heat stress risk for both the sailing and the discharge components of the voyage must be satisfied for all stocking lines'. This means that HotStuff does independent predictions, and that the two are independent. There are two issues/concerns here. Firstly, is it not the 'overall' likelihood of mortality (from loading to discharge) that matters? Secondly, can this be assessed from the separate estimates (e.g. simply combining the estimates assuming that they are independent)? If animals are heat stressed during a very hot part of the voyage, and some die, are the remaining ones:

(i) more heat tolerant (than the ones which died) to hot conditions, so that their Beta distribution has moved to the right in terms of being exposed to further heat challenge?
(ii) now more acclimatized to hotter conditions?
(iii) weakened by the experience, and so their Beta distributions have moved to the left?
(iv) not affected in terms of ability to respond to future hot conditions?

This is likely to be extremely difficult to address, and may not be important enough to evaluate, unless validation exercises indicate that the model really needs to incorporate this.

4.4.4 Recommendations

- That the climate data continue to be collected along the livestock export transport routes and at all ports of discharge, and compared statistically with the distributions currently used in the model. If necessary, the new data could be added to the existing data, or, if real changes are detected, completely new distributions should be developed.

- That regression models be fitted to the data presented in LIVE.228 Report to more accurately determine wet bulb temperatures at which different classes of animal start to experience stress.

- That statistical methods be used to compare past predicted values (expected mortality levels, probabilities of exceeding set levels) with actual mortalities on vessels, for ‘in transit’ and ‘while at ports of discharge’. This can be done for specific routes, ports, classes of animal, times of year, and possible other factors as well.

- That past recorded mortality figures be statistically analysed using the factors referred to above.

4.5 Validation and monitoring

A common theme that has emerged during the course of this review of the HotStuff Model is the need for validation of existing assumptions and monitoring of the model’s predictions against actual voyage data. The latter in particular, provides the only real mechanism to evaluate performance of the model but more importantly, it potentially enables objective refinement of the model to facilitate improved predictive accuracy.

The HotStuff model has been operational for over five years, and it is likely that a substantial data set has been collected on actual voyages - particulars of vessels, routes, times, animal cargoes, climatic conditions experienced, in/on deck wet-bulb temperatures and heat-related animal mortalities. It is now opportune to see to what extent this data can be used to check or validate the model. Of course, the main caveat here is that any validation would still be contingent on the availability of high quality voyage data. In particular, vessel wet bulb data and heat-stress mortalities during the voyage (including discharge). If the data can be accessed and it is of sufficient quality and specificity then a comparative analysis of the ‘actual’ incidence rate of mortalities with those predicted by the model would be very informative. This would indicate whether the model has been under or over conservative. Such validation can be done on different scales, from ‘very broad’ to ‘very specific’. The following provide some examples.

4.5.1 Different levels of validation

The broadest scale is to check the ‘overall’ probabilities estimated by HotStuff for each ‘case’ against any mortalities experienced (and accurately recorded) for that group of exported animals, provided that the mortalities can be attributed to heat stress and not to other primary or contributory causes. The next level of validation is to look at the ‘expected mortality’ rates predicted by HotStuff, which are not currently used in the decision making process, but statistically are very useful.

Of course, one of the major ‘unknowns’ in the prediction process involves the actual temperatures which are expected during the voyage and discharge. This variable can be eliminated from the validation process using past records, because after the event we will know the actual temperatures experienced. This will enable validation of sub-components of the model to be done more precisely. The following sections will describe how such levels of validation might be carried out. This will also serve to identify what future voyage data is essential, and what is desirable, for most effective future monitoring.

4.5.2 Comparing observed incidence rates with the stipulated ‘less than 2%’ level.

As an example, suppose that there have been 5000 ‘cases’ where accurately recorded heat related mortalities have been recorded, and that in only 80 of these cases have there been mortalities of 5% or higher (giving an average incidence rate of 1.6%). In the ‘broadest’ validation process, this overall incidence rate can be compared with the HotStuff stipulation of ‘less than 2% incidence’. Constructing a 95% confidence interval (for the true incidence rate) based on an observed ’80 out of 5000’ results in a band from 1.3% to 2.0%. This would suggest that the model is about right, and probably a bit conservative (but see the following). Of course it is difficult to statistically evaluate a rather imprecise hypothesis such as ‘less than 2% incidence’. Moreover, it is recognised that heat-stress mortalities have not been recorded during voyages.

However, the overall operational experience of the very large number of voyages undertaken following implementation of the model probably supports the conclusion that the mortality risk has been managed within acceptable limits. This is subject to two provisos. One is that the range of the conditions experienced is adequate to cover possible future conditions. Secondly, that the model is not overly conservative. The applicability and adequacy of the model can be determined if two questions can be answered:

1) How typical were the weather conditions (in general and in terms of extreme wet bulb temperature) of the last five years in a historical context and relation to conditions likely to be experienced in the next decade?

2) To what extent is the success of the model in achieving low levels of mortalities over the last five years due to overly conservative assumptions?

The first question needs further analysis. The second question can be partly answered by a consideration of the mortalities for the last five years for sheep from Fremantle to the Middle East. There is a clear seasonal pattern; mortalities average about 0.6 percent to June and then double to over 1 % from August to October. The hottest months in the Middle East are generally from July to September.

The 2007 Industry performance review (LIVE.246) states ‘The main causes of sheep mortalities during sea transport were inanition and salmonellosis. These two causes accounted for about 75% of all mortalities aboard ship.’ Previous research (for example as summarised in LIVE.216 ,2003) has clearly demonstrated that prior nutritional history is an important contributor to the seasonal mortality pattern. Sheep coming from dry pastures for example at the end of the southern summer are at less risk in terms of inanition than sheep coming from greener pastures mid year. Therefore it is not known to what extent heat stress contributes to the seasonal mortality pattern. Some small contribution from heat stress because of the small risk over a large number of voyages would be qualitative evidence that the model was not overly conservative.

4.5.3 Comparing HotStuff ‘expected’ levels of mortalities with actual values

Regression methods can be used to compare these two sets of data, much more precisely than the single ‘overall incidence’ method suggested in 4.5.2. This will check if the model is predicting accurately over the whole range. For this analysis it requires that the cause of mortality has been diagnosed, specifically which deaths can be directly related to heat stress. It is recognised that this is not normal practice but it is recommended that the feasibility of developing a rapid and practical post-mortem protocol be explored.

It is difficult to estimate how many voyages would be required to undertake a meaningful analysis. However, a database of heat stress mortality records over a 12 month period (including the highest at risk months) would be a useful starting dataset for such an analysis.

4.5.4 Comparing predicted wet-bulb temperatures with those recorded

This will depend on whether sufficient reliable data is available on wet-bulb temperatures recorded during voyages. (Presumably the outside ambient temperatures for each voyage have been accurately recorded). However it will be a vital validation check on the engineering and animal heat transfer components of the model. Hence, for future monitoring these temperatures will need to be recorded, at least during the hottest parts of the voyage. Ideally, this would also include the recording of wet bulb temperature within decks during these hotter periods.

4.5.5 Checking maximum animal tolerance to heat

Any heat-related mortalities for specific groups of animals, while regrettable, will provide checks against the Beta-distributions for mortality levels. If accurate records can me made during the different stages of each voyage, such data could be used to test hypotheses such as whether animals’ response/tolerance to repeated heat stress is independent or cumulative (making them more or less tolerant to heat stress).

4.5.6 Recommendations

- That relevant data from Hotstuff predictions and livestock export reports be collated and subjected to series of validations as indicated above. Furthermore, that where weaknesses are identified in data needed for accurate validation, such data be identified as a priority for collection in future voyages. Statistical expertise should be engaged to undertake these analyses.

4.6 Response to issues raised by Industry in relation to HotStuff

Sections of the livestock export industry have flagged some concern with regard to the application of the HotStuff model. The following 17 issues/concerns were provided to the review panel to consider and comment on. The italicised response following each of the issues is based on the inputs from Maunsell AECOM and the review panel.

1. The authors acknowledge at paragraph 1.5.2 that there are a number of animal parameters which could well have significant effects on animal heat stress thresholds in relation to which there are limited data, or scope for further research. These are;

(a) influence of weight on the heat stress threshold of sheep:

(b) influence of weight on the heat stress threshold of cattle;
(c) heat stress threshold of crossbred versus Merino sheep;
(d) influence of bos indicus infusion on heat stress threshold;
(e) influence of acclimatisation of the heat stress threshold of sheep and cattle;
(f) influence on fat score on the heat stress threshold of sheep and cattle;
(g) metabolic heat production data.

Agreed there is limited animal data but the model is based on the best available data. The biological assumptions to HotStuff were upgraded in the new version (v 3.0) following the availability of more recent animal data (refer LIVE.228 report). It is recommended that this should be an on-going process as new data becomes available.

2. At paragraph 1.5.3 the authors state that HS version 2.1 has no allowance for air jetting or variation of ventilation along the deck, and comment that the vessel ventilation data on which the model is based remains largely unaudited.

This is true. An audit of the ventilation data is important in improving the reliability of risk estimate outcomes and a precursor to the incorporation of an allowance for jetting in the risk analysis. The panel recommends that such audits be recommended to ship owners. This in itself does not invalidate the existing operation of the model.

3. The crucial input for the heat stress threshold of animals is the wet bulb temperature, that is a combination of absolute temperature along with allowance for the rate of heat loss through perspiration and evaporation. However, at paragraph 2.2.1 the authors acknowledge that the quality of the data and recording of various temperatures varies widely. They note that error in reporting wet bulb temperature is that the wet bulb itself becomes dry or does not have air freely circulating around it. This would increase the reported wet bulb temperature. Although the authors have attempted to account for this there remains some room for improvement of the data in this regard.

The VOS database has been significantly augmented and incorporated within the new version of the model. The panel have recommended that further justification be provided to support the adjustment of wet bulb temperatures from the VOS database to align more closely with likely ambient temperatures.

4. In paragraph 2.4 the authors deal with the effect of acclimatisation at the port as opposed to acclimatisation of the property of origin. The authors conclude that if the animals have spent 2 weeks or more at the port then they are considered as being acclimatised to the port condition. If the animals have spent less than 4 days between the property of origin and sailing then the zone is taken from the property of origin. Between these two extremes, for animals that spend between 4 and 14 days in the port zone, the zone number entered should be the average of the zone numbers for the property of the origin and the port rounded down. There appears to be little if any scientific justification for this. It is based on what appears to be assumptions made by the authors. These assumptions don't appear unreasonable, however, they don't appear to be based on science. Having said that, given that most of the sheep exported come from only one of the climatic zones specified this may be more of an issue for cattle than sheep.

The acclimatisation methodology is based on Environmental Engineering in South African Mines, W.W. Malan, which discusses acclimatisation periods for humans. Of course there is limited animal data to allow meaningful conclusions to be drawn about acclimatisation.

However, we would agree that the assumptions are not unreasonable and the acclimitisation adjustment has a quite small effect in terms of risk.

5. There are a number of respects in which the method by which the authors evaluate the heat stress threshold and mortality limits of cattle and sheep appear somewhat lacking in scientific basis. The authors state that it is difficult to get good data on mortality limits thus the model is based on an estimate of the mortality limit the authors have chosen a “skewed beta function probability distribution” to estimate mortality units. Some reasons are given for this but these appear to be statistical assumptions rather than assumptions based on actual veterinary evidence.

While a mortality temperature distribution is an important part of a heat stress risk analysis, the available mortality temperature data are limited. The developers of HotStuff have approached this problem by assuming a probability distribution of mortality as wet bulb temperature increases towards mortality limit. They have used a skewed beta distribution, rather than a normal (or gaussian) distribution. In fact, the choice of any particular distribution of livestock mortality with increasing wet bulb temperature represents an assumption, because we simply do not have data of sufficient precision and quantity to know the exact nature of the distribution. In any case, it would be unethical to hope to collect it because it would involve cattle and sheep studies where 100% mortality occurred through heat stress (refer Section 4.1).

6. At paragraph 3.3.2 the authors attempt to address the effect of acclimatisation. They admit there is no physiological basis for assuming that the limits of wet bulb temperatures of 5º and 25º cause animals to be fully unacclimatised or fully acclimatised.

This assumption has a limited effect on the risk analysis since there are insignificant occurrences of wet bulb temperatures outside the given range.

7. Also at paragraph 3.3.2, the authors state that because sheep are only exported in large numbers from southern ports and therefore come from a limited range of climates it is difficult to establish an acclimatisation effect. For that reason they have adopted the curve appropriate to bos indicus cattle as applying to sheep.

Given insufficient sheep data appropriate for determining an acclimatisation effect, the best available option is to assume that the acclimatisation effect in sheep is similar to that in cattle for which there are available data. Under the circumstances the panel support this assumption.

8. At paragraph 3.5, the authors discuss the validation of their model from actual voyage data. Importantly, they state that because data from open decks are very difficult to analyse, and because mortalities on open decks were relatively low, they only analysed the closed deck data.

This is correct. However, it should be noted that one of the key recommendations arising from this review is the need for validation and on-going monitoring of the performance of the model. To enable this, it is critical that essential voyage data is collected across both closed and open deck vessels and that this may take some time to generate a suitable dataset that is amenable for analysis.

9. At paragraph 4 the authors state that the pen air turn over data from shipowners are variable in quality. They recommend detailed survey, and observe that nominal design figures are often lower than the actual figures as ship builders and fan suppliers allow a margin to ensure the

outcome does not fall below the specification. They state that a detailed survey would be likely in most cases to increase the assessed livestock loading for a given risk level.

Agreed. Refer 2.

10. Again, at paragraph 5.4.4 the authors acknowledge that risk management for open decks is very different than that for closed decks and there is a lack of useful wind statistics that makes it very difficult to make the model apply to open decks.

The Hot Stuff model applies to mechanically ventilated open decks in the same way as it applies to mechanically ventilated closed decks. However it currently ignores contributions to air flow from cross winds, in port, to open decks. The management of the risk to animals on open decks is necessarily different to closed decks as the ship's crew have some ability to control cross winds en-voyage to open decks. However this does not change the Hot Stuff model's predictive applicability to either closed or open decks. The review panel recommends that a sample of the limited available port wind data be analysed to provide an initial assessment of the likelihood of calm conditions at high levels of wet bulb temperature and strengthen the justification for the assumptions for open deck situations at port.

11. As you know the model is based on detailed statistical fluid dynamics and veterinary expert evidence. It may well be that experts in these fields reviewing the report may observe other deficiencies.

The review panel in their recommendations have acknowledged that the model is based on limited data but believe that the HotStuff developers have accessed the best available datasets. Moreover, assumptions underpinning the HotStuff model are sound, reasonable and supported by scientific literature. The panel has not identified any obvious deficiencies rather their recommendations are largely directly at enhancing the application of the model in the future.

12. The climatology data used by Maunsell causes some concern as it treats all Arabian Gulf ports similarly. Their reasoning, we believe, is that all vessels must transit the Straits of Hormuz to get into the Gulf, and the Straits are notoriously bad for severe heat and humidity conditions. Granted, but our contention is that the vessel is moving when transiting the Straits and therefore, when considering open deck vessels, this movement creates airflow through the sheephouse.

This issue has been addressed in the new version of the model – HotStuff 3.0.

13. When transiting the Straits there are also management tools available to the experienced Master operating in this region, including:

- Altering course several times to clear the sheephouse of stale air.
- Choosing a course to minimise heat and humidity pockets (e.g., sailing closer to the Iranian coast)
- Using portable fans in worst areas of the sheephouse.

Hot Stuff does not (and cannot) take into account the skill and experience of the vessel operator.

Agreed and it would be expected that the vessel Master would take such actions. However, these actions may still not mitigate against heat stress mortality under extreme climatic conditions (high wet bulb temperature with low wind velocity).

14. We know from practical experience that Kuwait port, although very hot, does not have the humidity issues that some other ports suffer and this is why we generally try to make Kuwait first port during periods of extreme weather and Muscat (the worst for extreme conditions) the final discharge port. Maunsells model does not recognise this – it treats all Gulf ports the same. Indicatively, despite the program offering a number of discharge ports as first port options it in fact only has parameters for two general destination regions being the Arabian Gulf and the Red Sea. Therefore changing discharge port rotation will not change the Heat Stress Risk Assessment but this strategy does (quite definitely) affect the voyage outcome (mortality wise) in practice.

It should be also remembered that the model is only relevant up until the first port of discharge. After this, operators would slacken off the cargo to give stock more room and, generally, a greater level of comfort.

The model no longer treats all Gulf ports similarly as the estimation of port risk has been incorporated in the new version. While redistribution of livestock is likely to have a positive effect in the reduction of heat stress risk, the difficultly in defining, prior to the voyage, how the redistribution will take place, makes useful implementation difficult. A workable methodology for redistribution deserves further consideration.

15. On what scientific basis was the critical wet bulb temperature for the different classes of livestock established. For example – was it a 'hot house' experiment involving say 10 sheep, high fat score, wool etc where ethics committees govern how far the experiment can go? We have many practical instances where despite the critical wet bulb being exceeded the stock do not die. Our concerns are:

- Was the livestock sample statistically relevant?
- What were the classes and condition of the sample?
- To what stage are experiments / trials allowed to proceed? - to discomfort or to death?

The animal experiments and data used in the biological elements of the model were documented in LIVE.116 and more recently in LIVE.228 when the models biological assumptions were upgraded. The heat stress thresholds were derived from both controlled animal experiments (based in climate rooms) and actual voyage data. Some of the controlled studies have since been published in scientific journals which indicates that the experimental design and methodology and interpretation of results has stacked up against scientific peer review.

The developers have utilised the best objective data available to them. It also must be stressed that under the regulations governing animal experimentation in Australia it would not be possible to conduct heat stress studies where a significant number of animals are allowed to die.

Mortality is the ultimate measure of an animal's welfare (or lack thereof). However, it is recognised that it is not the only measure of welfare in response to heat challenge and the panel has recommended that some consideration should be given to protecting animals that might otherwise suffer severe heat stress but not actually die.

Finally, if the panel's recommendation to conduct ongoing monitoring of actual versus predicted data is accepted, it will provide an opportunity to determine whether key thresholds and assumptions within the model are too conservative.

16 The model considers up to a 2% probability of a 5% mortality acceptable. Why is this considered appropriate? In interpreting the HotStuff printout, AQIS determine that the figure in the "5% Mortality Risk" column must be below 2%. Why not consider that the risk is acceptable if the expected mortality column is less than 2%.

It is our understanding that the criteria were based on industry consultation and advice. The methodology provides only the risk estimates, not the evaluation criteria, which was agreed to by industry after extensive consultation.

17. Practically, Version 3 of the HSRA model, penalises two tier open deck vessels to an reasonable degree. Al Kuwait, for example, has done 180 voyages. Its last Heat Stress event was in 1997 when alongside at Muscat (first port). Maunsell's Version 3 would penalise this vessel by, we estimate, up to 50% which is clearly ludicrous given this vessel's trading history.

It was interesting that AQIS' imposition of 15% stocking density reduction on two tier open deck vessels for the northern summer months of 2008 appeared to have the desired effect. They found that it reduced heat stress mortality levels to less than those of single tier decks without a single reportable HS incident.

Summarising, we think that Maunsell's methodology when considering open deck vessels is seriously flawed and in general the model appears ultra-conservative in many areas. Perhaps, for open deck vessels, modelling based on historical vessel data would be more appropriate than predictive modelling.

The most appropriate response to the points raised here is to once again reinforce the need for validation and monitoring as recommended by the panel. A rigorous evaluation of predicted versus actual voyage data is, in the panel's opinion, the only real way of determining whether the model is too conservative. More importantly, it will potentially enable objective refinement of the model to facilitate improved predictive accuracy.

5 Success in achieving objectives

The primary objective of reviewing the scientific basis of the HotStuff model has been completed. The findings of the review and the recommendations are detailed in this report.

6 Impact on meat and livestock industry – now and in five years time

The application of the HotStuff 3.0 model is viewed as a significant improvement in the context of improving animal welfare outcomes within the Australian livestock export industry.

This review has concluded that the data and assumptions underpinning the HotStuff model are sound, reasonable and supported by scientific literature. A key recommendation of the review was for that the model be subjected to on-going monitoring and evaluation. Through this process it is expected that the predictive accuracy and applicability of the model can be improved which will have obvious benefits to industry in the future.

7 Conclusions and recommendations

It is paramount that the livestock export industry be proactive in its efforts to improve animal welfare. To that end, the development and application of the HotStuff model is a significant practical advancement in the prediction and mitigation of livestock mortality events due to heat stress.

With regard to the data and assumptions used in the model, it is acknowledged that the derivation of livestock mortality limits and scaling factors (condition score, coat length, acclimatisation) is based on relatively limited datasets. Nevertheless, it is still the best available data and the assumptions used are sound and supported by biological knowledge. The opportunity to test the model against new data as it becomes available should be encouraged. However, it must be recognised that the generation of additional data from controlled animal studies will always be constrained by the ethical considerations governing animal experimentation.

The climate database for routes and ports is now far more extensive and the statistical methodology that has been applied is robust. One issue that requires further justification is the use of the $1^{o}C$ correction that is applied to the data as this adjustment will affect the estimation of mortality risk.

Exhaustive thermodynamic and fluid modelling has been undertaken in the development of the model. The relevant assumptions are sound but these could be improved through the incorporation of actual pen air turnover data form vessel ventilation audits.

Overall the management of heat stress has followed well-defined and logical principles of adaptive management in the presence of uncertainty. In a complex model such as HotStuff the levels of underpinning scientific data will vary between components. The key feature of adaptive management is rigorous monitoring of performance to provide feedback and to guide adaptive research and management strategies.

The third question within the terms of reference was whether implementation of the HotStuff model adequately manages mortality risk associated with heat stress? Our response has focused on monitoring and validation aspects on the basis they will be most relevant to evaluating the performance and facilitating improvements to the model. There are many other aspects that are relevant to successful implementation but they were not within the scope of this review. To that end, the panel recognises that it is quite important that the livestock export industry can access simple and practical support and extension material with regard to application of HotStuff.

Overall, the panel concludes that the data and assumptions underpinning the HotStuff model are sound, reasonable and supported by scientific literature. The following recommendations should not be interpreted as direct criticisms of the model. Rather, they are proposed in interests of potentially improving the accuracy and applicability of the model in the future.

Recommendations

The consolidated list of recommendations from the key sections of the review is as follows:

1. As additional biological data on heat stress and mortality in Australian-type livestock becomes available, it should be considered for its applicability and usefulness for incorporation and refinement of the HotStuff model.

2. Mortality is clearly the ultimate measure of an animal's welfare (or lack thereof). However, it is recognised that it is not the only measure of welfare in response to heat challenge and that some consideration should be given to protecting animals that might otherwise suffer severe heat stress but not actually die. Some consideration of this issue is built into the selected threshold of a 2% chance of a 5% mortality event (i.e. these low values should provide some protection against undue stress in the animals). Consideration should also be given to utilising the HST values that have been developed, but not actually applied in the output and use of the HotStuff model.

3. The HotStuff model currently uses a globalisation of air flow throughout the internal spaces of a vessel such that PAT is spread uniformly throughout a pen. It is possible that jetting or some other spatially resolved fluid flow may show non-linear forms of cooling (in relation to air velocity) and therefore have benefits that have not yet been accounted for. It is recommended that studies into the potential for jetting should be undertaken to quantify the potential benefits that may arise. It would only be prudent to incorporate jetting and other forms of spatial resolution of airflows if they show significant benefit over and above what is currently forecast by the HS model. Moreover, this benefit would come at the cost of making spatially resolved airflow assessments of individual vessels, which is likely to be both expensive and time consuming.

4. Given the importance of PAT to the HS model, audits of vessels' ventilation systems should be recommended to owners.

5. A sample of the limited available port wind data be analysed to provide an initial assessment of the likelihood of calm conditions at high levels of wet bulb temperature and strengthen the justification for the assumptions for open deck situations at port.

6. The VOS data used to estimate the 'worst case' risks be more clearly defined and checked for biases, trends and cycles that may be relevant to estimating future risks; the check should include seasonal, decadal and climate change influences and provide rigorous justification for the 1^{o}C downward adjustment made to VOS data.

7. There is a need to compare and evaluate the VOS and land-based climate data (at each port) to identify the most suitable data for the estimation of port risk within the model.

8. The climatological and physiological justification be provided for using the worst case over 12 hours as a measure of risk by considering for example, coincidence or correlation with worst case risk events assessed over longer periods.

9. The approach of estimating cumulative voyage risk based on the 'worst case' needs to be justified by the extent to which 'worst case' risk approximates cumulative risk. This could be assessed in the first instance for example, by a comparison of the 'worst case' identified whilst

sailing, the ‘worst case’ discharge port risk, and whether there were several other occurrences of high levels of sailing risk.

10. That the climate data continue to be collected along the livestock export transport routes and at all ports of discharge, and compared statistically with the distributions currently used in the model. If necessary, the new data could be added to the existing data, or, if real changes are detected, completely new distributions should be developed.

11. Contingent on the action taken on Recommendation No. 5, that regression models be fitted to the data presented in LIVE.228 to more accurately determine wet bulb temperatures at which different classes of animal start to experience stress.

12. Statistical methods be used to compare past predicted values (expected mortality levels, probabilities of exceeding set levels) with actual mortalities on vessels, for ‘in transit’ and ‘while at ports of discharge’. This can be done for specific routes, ports, classes of animal, times of year, and possible other factors as well.

13. The relevant data from future HotStuff predictions and livestock export reports be collated and subjected to series of validation analyses. Furthermore, that where weaknesses are identified in data needed for accurate validation, such data be identified as a priority for collection in future voyages. Statistical expertise should be engaged to undertake these analyses.

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