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The vulnerability of refrigerated food to unstable power supplies

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Abstract

This paper describes a simplified model for estimating the vulnerability to spoilage of a number of refrigerated foods in households, resulting from interruptions to the electricity power grid. The tool is demonstrated on a sample of three foods (milk, chicken and fish) in India, which historically has suffered significant interruptions. The effect of interruptions is quantified in terms of tonnage and monetary value of potential losses, in a number of simple scenarios. These losses are estimated for rural and urban areas of each Indian state. Our model indicates that extensions to the duration of power supply interruptions increases potential losses in domestic refrigerators, and that these losses are considerable when compared to losses expected in previous stages of the food supply chain. The current model's estimation of weight of food lost may be converted to a nutritional value, which opens an opportunity for new multidisciplinary areas of research.

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Keywords: food waste; food loss; refrigeration; grid supply; power interruption

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1. Introduction

In recent decades, although there have been significant improvements made to the productivity of agriculture, losses and wastage of food are still common in many agricultural systems, food supply chains (FSC) and in households. Food losses, in India, occur predominantly during the early stages of the FSC, with significant amounts of food becoming unfit for human consumption due to poor handling and a lack of suitable transport. In general, as household income increases, losses and waste shift towards the consumer. As a result, it is likely that losses due to excessive temperatures in household refrigerators may account for a larger proportion of overall FSC losses (including the consumer), than in the same FSC supplying poorer households.

Work by Parfitt et al. [1], citing Grolleau [2], has asserted that food 'losses' occur prior to the retail stage of a food supply chain, and that food 'waste' occurs in either the retail or consumer stages of the chain. Grolleau's definition of food losses post-harvest, is broad and implies that it also encompasses 'waste' stating, "Food loss refers to total modification or decrease of food quantity or quality which makes it unfit for human consumption." [2 Section 2.2]. More recently, the Food Loss and Waste Protocol [3] leaves the definition of waste and losses to the users of the protocol, according to where the food could possibly end up, concentrating on material types and their destinations. The protocol requires its users to quantify the losses and waste by weight, whereupon they may then also establish the loss/waste "in terms of environmental impact, nutritional content or financial implications" (p.17).

Note that because this research work is concerned only with refrigerated food that has reached the consumer, this would be classed as 'food waste' under Parfitt et al's [1] existing definition. However, it might also be argued that the degradation of refrigerated food, resulting from interruptions of electricity supplies to household refrigerators, ought to be classified as 'food losses', in the same way that food failing to make its way into a chilled supply chain would be classed as food losses. The argument here is that the consumer has not wasted the food because he/she was not in full control of the circumstances that caused the food to perish, which might be seen as similar to a farmer being unable to get their produce into the chill chain due to circumstances beyond their control.

Refrigerators are generally one of the first white goods appliances to be purchased when a household can afford to own and operate one [4]. The incentive to own a refrigerator is also affected by access to an adequately reliable electricity supply [5] and due to the continuous nature of a refrigerator's operation, this usually means that the electricity supply needs to be from a grid, rather than from a generator. Consequently, this research does not consider refrigerators that are drawing power from a generator and all refrigerators in the model are assumed to be connected to the mains power grid without backup.

Although refrigerators can be common – particularly in urban areas – how they are used can vary considerably in terms of the foods stored within them and the duration of that storage, as indicated by research in the cities of Bangkok and Hanoi, by Smits and Rinkinen [6]. The study showed that the types of food stored in refrigerators were subject to the purchasing decisions of households, which were influenced by a number of complex issues, including levels of trust in the food's origin. As supermarkets penetrate markets, changes in the quality control of food products can occur, due to the supermarkets' requirements for a more standardized shelf life and brand reputation. Thus, changes in diet resulting from increased affluence, access to new food products and the increased ability to store perishable food add to the complexity of establishing exactly what is in consumer refrigerators. Such subtleties are beyond the limited scope and resources of this work, so some assumptions have been made about shopping and storage patterns for the foods modelled.

2. Model development

Models are reliant upon both their data inputs and the model design. At the conception of this model, the precise nature of any data that might be accessible was not known, thus the framework of the model was constructed to allow detailed inputs to be used, or alternatively develop assumptions in accordance with academic and grey literature.

2.1. Data inputs

Data on typical census topics, such as regional/state population numbers and the urban/rural split, were obtained from government statistics. Climatic data inputs came from monthly mean dry bulb temperatures for each state [7]. Monthly consumption of food was sourced at the same level of detail, as was ownership of refrigerators. Data on grid reliability was available for a small number of Indian states and network operators, which have some detailed and accessible data, but for the majority of states, such data were inaccessible in the time frame of the project. The principal information extracted from the Indian state-level data was: population density; the urban/rural split of population; and numbers of households [8].

Indian data for household consumption of each foodstuff per month are taken from a government report on consumer consumption and ownership of goods and services [9], which is then recalculated as a weekly amount. This includes the mass or volume, and the cost of each foodstuff. What is not clear from the above report is to what extent food bought through the informal economy is accounted for, though the report states that it "… covers milk directly obtained from cow, buffalo, goat or any other livestock. Milk sold in bottle or polypack, as well as readily drinkable flavoured and bottled milk, is included." such that the amount of each food could be greater, but seems unlikely to be less. The amounts given in the report are taken at face value, as a data input to the model.

Data on the ownership of refrigerators was sourced from the Indian government survey of household consumption of goods and services, with separation of rural and urban populations in each state [9]. There are various designs of refrigerator, but less reliable data on the extent of ownership of each design in each area of study. For example, there are now refrigerators that incorporate phase change materials to help maintain recommended temperatures for prolonged periods after power has been interrupted. The effect of refrigerator types on spoilage rates has not been modelled and a generic refrigerator is used to calculate rates of food degradation.

For India, data on the reliability of grid electricity supplies in each state are drawn from the World Bank [10]. These data are limited, but cover each Indian state, thus overcoming the inconsistencies of data availability at the level of the state or distribution network operator. These data also align with various other state-level sources of data about food consumption and refrigerator ownership. The majority of network operator information would not allow such a good alignment of datasets, as the networks seem to rarely align with state boundaries. The World Bank state-level grid data include the average number of power interruptions and the average duration of interruptions in each month.

The source of information on the rate of deterioration of food comes from the FRISBEE project [11], which is a consortium of EU partners who have undertaken extensive research of primary and secondary data, collating these data into a tool designed to examine the rate of bacterial growth, and hence food decay under different conditions. This tool was principally used here to extract various parameters (including initial microbial count, microbial limits, chemical indices and sensory indices) to be used to determine the remaining shelf-life of the studied foodstuff. Milk, chicken and fish were chosen as the food types to model, as these are all consumed to a greater or lesser degree in most states. The choice was also constrained by the food types that were currently available in the FRISBEE model.

Assumptions have been made about the length of time that each food has already spent in a properly maintained chilled supply chain. These assumptions may be updated with better estimates, or values derived from recorded data, but are currently set at ten hours in chilled transport and forty-eight hours in a retail location (based on information obtained from Tassou et al, [12]. The model allows these arbitrary default periods to be altered should more updated data become available.

2.2. Assumptions and caveats

The model assumes that all of the relevant food is stored in the fridge, but this assumption may be less perfectly robust when applied to India. In particular, it is not known what proportion of a household's consumption of the target foods is consumed soon enough after purchase to not warrant refrigeration. The model also assumes that there is an average amount of the given foodstuff in the refrigerator, when a power outage occurs: i.e. half of the purchased food has been consumed and half is left in the refrigerator. Clearly, this may not be the case for a specific household, but assuming that the days households purchase their food are spread evenly across the week, the average amount of food in all fridges will be the same, given a weekly shopping trip. It would be possible to model the amount of food in the refrigerator, on a given day, should data about patterns of when food is bought become available. In theory, this could then be aligned with the patterns of when power outages occur (again, subject to data access).

In addition to the three sample foods, the mass of the other foods in the weekly shopping basket, which are deemed likely to be stored in the refrigerator, is also calculated. This mass is required when modelling the rate at which the contents of the refrigerator warm up, as the greater the thermal mass, the slower the warming. The mass of these other refrigerated foods is calculated in the same manner and from the same sources as for the case study foods. Again, it may be that some of the non-case study food assumed to be in the refrigerator, is not stored there, or other foodstuffs are refrigerated, which would affect the rate of warming of the contents of the refrigerator.

It may be the case that the precise properties of the foodstuffs chosen from FRISBEE, and assumed to be the same for the foodstuffs in the target countries, are in fact different due to variations in local species, methods of production, types of packaging and suchlike. This would affect the food decay rate as well as the thermal properties of the foodstuff, affecting the remaining shelf life. However, this could not be explicitly modelled in this study due to the lack of information available relating to the properties of the foodstuffs. Note that the data drawn from FRISBEE are for 'chicken fillet' and 'fish fillet', but have been applied to data for 'chicken' (or poultry) and 'fish', in the model. All refrigeration is assumed to maintain a temperature of 4ºC during normal operation and it is assumed that all milk has been pasteurised. There was no consideration given to food imports, mainly because the initial microbial count used in the study referred to the food location at the national level in the UK. For India, due to lack of data, the initial microbial count was assumed to be at the state-level, mainly due to the relatively large areas of each state compared to the UK.

The proportion of the weekly household consumption that never enters the chill chain is unknown. In India, there is a probability that, in some cases, the sample foods do not enter the chill chain at all. However, it would be relatively simple to build this capability into the model, should such information become available. In view of this the model estimates the total *potential* losses.

Due to the limitations of the data sources, seasonality in the availability of foodstuffs and how this affects the purchasing patterns of consumers, have not been included in the model. However, for the foodstuffs chosen for this case study, it seems likely that there is less seasonality than there would be for say fruit and vegetables. Though not investigated explicitly, it is probably feasible to build into the model a seasonal purchase function, given adequate data.

The model outputs do not cover all Indian states, primarily due to shortfalls in data. For some states, there are no results for urban areas, as the state consists entirely of an urban area, e.g. Delhi.

3. Results

The early results from the model quickly made it clear that without a power interruption, there would be no loss of shelf life for each food. This is common sense, as if the refrigeration is working properly, the shelf life should be maintained. The model uses scenarios to model food losses in the population of refrigerators and there are currently results for tonnage lost and the value of these losses. The scenarios chosen were:

- Business as usual (BAU), which gives the effect of current grid reliability and duration of interruptions.
- Scenario D2 assumes the same frequency of interruptions, but doubles their duration.
- Scenario D4 a quadrupling of the BAU duration of interruptions.
- Scenario C4, in which interruptions are unaltered, but the ambient temperature is increased by four degrees, to simulate a heatwave.
- Scenario D2 + C4 combining a doubling of interruption duration and a heatwave.
- Scenario D4 + C4 a quadrupling of interruption duration in combination with a heatwave.

For presentation here, scenarios are applied to week 28 of the year, when July summer ambient temperatures will be high. Clearly, lower ambient temperatures will affect the rate of food degradation, but the choice of this week is based on the likelihood of there being large loads on the supply grid, due to increased use of air conditioning, so this is approximately a worst case base scenario. However, as the model operates throughout the year, potential losses may be calculated for any week.

3.1. Scenario results

For the three foodstuffs modelled, the losses in tonnes have been calculated for both urban and rural regions of each Indian state that has adequate data. The results for business as usual (BAU) indicate there are no losses in this scenario, except for modest losses of fish (<10 tonnes) in Rajasthan. Results for a doubling of interruption duration are shown in Figure 1, indicating the increased vulnerability of the fish foodstuff, compared to chicken. Note that the amount of food that is vulnerable is also dependent upon the diet culture in each state, such that southern states tend to have a higher consumption of meat and fish than northern states.

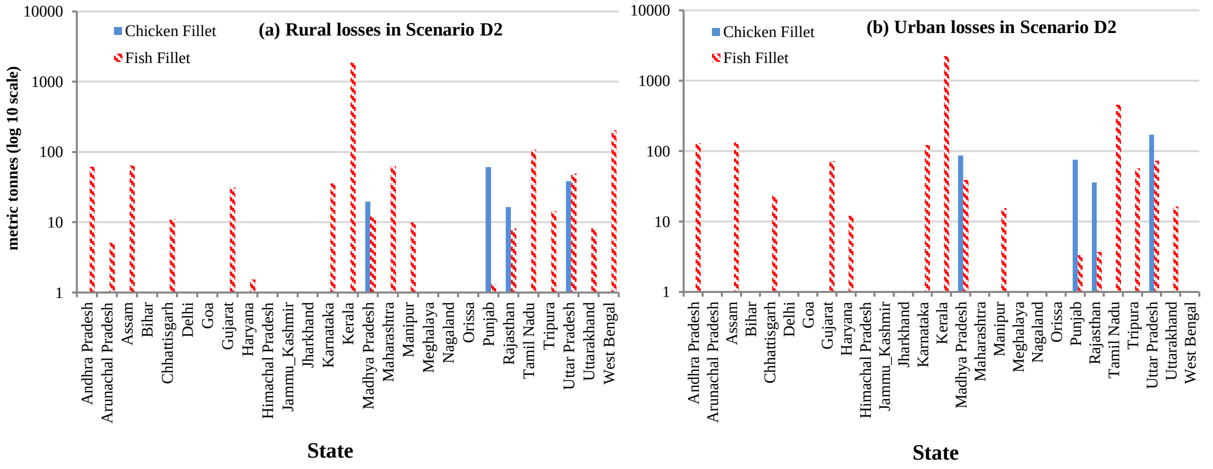

Figure 1: Potential losses in rural (a) and urban (b) regions of Indian states, based on a doubling of the duration of supply interruptions.

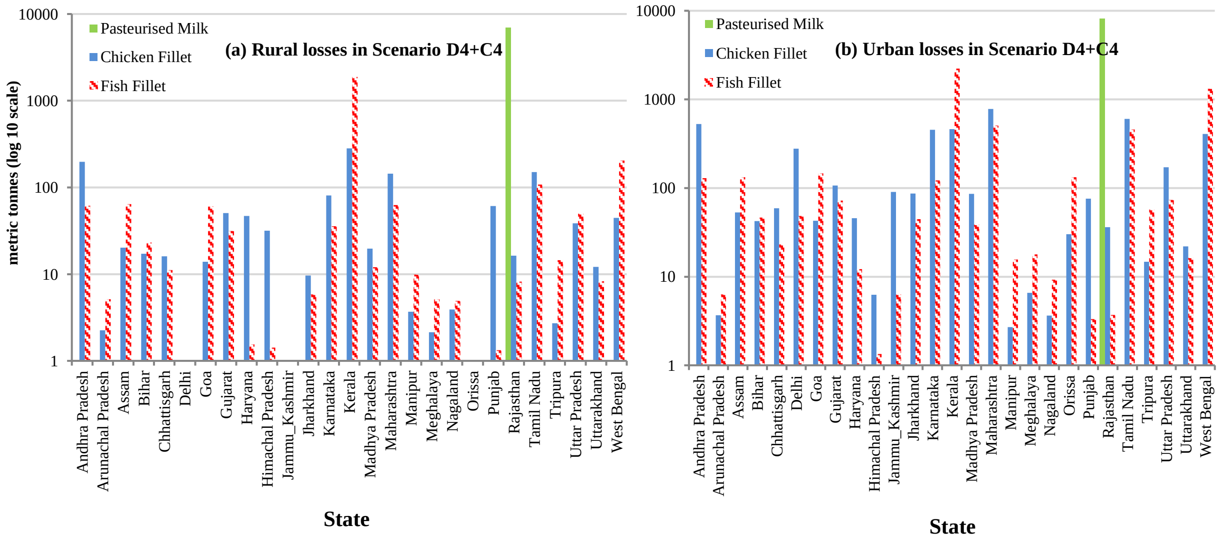

Figure 2: Potential losses in rural (a) and urban (b) regions of Indian states, based on a quadrupling of the duration of supply interruptions and a 4ºC increase in the mean ambient temperature.

Figure 2, above, shows the model's results for an extreme scenario for a quadrupling of the interruption duration coupled to a heatwave with ambient temperatures 4ºC above the monthly mean. Here, it may be seen that even pasteurised milk is affected in the state of Rajasthan and that the amount is large (6929 tonnes). It is probable that this effect is the result of the long standard duration of power outages (the current mean is 3.8 hours, in July) being multiplied in the scenario enough to cause the milk spoilage. In view of the average duration of power interruptions, it seems odd that refrigerator ownership is not lower than its current level of 12% and 47% in rural and urban households, respectively.

Table 1, below, shows the value in 2012 US$, of the food at risk in the D2 scenario and D2 + C4 scenario, for illustration. These values have been calculated based on the tonnage of losses as calculated previously, which are then multiplied by the values of purchases recorded in [9]. States where insufficient data availability, or where there are no calculated losses, are omitted.

Table 1: Value of food at risk, per Indian state region, for scenarios D2 and D2 + 4C (thousands of US$, at 2012 values)

Scenario	**D2**				**D2 + 4C**			
Location	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**
State	**Chicken Fillet**	**Chicken Fillet**	**Fish Fillet**	**Fish Fillet**	**Chicken Fillet**	**Chicken Fillet**	**Fish Fillet**	**Fish Fillet**
Andhra Pradesh			92	198	432	1182	92	198
Arunachal Pradesh			13				13	16
Assam			137	334			137	334
Bihar							40	87
Chhattisgarh			17	42			17	42
Gujarat			47	127			47	127
Haryana			3	33			3	33
Karnataka			41	198			41	198
Kerala			2156	2943	522	862	2156	2943
Madhya Pradesh	46	208	19	66	46	208	19	66
Maharashtra			113				113	1282
Manipur			27	44			27	44
Meghalaya							14	
Nagaland							10	19
Punjab	168	195	4	9	168	195	4	9
Rajasthan	41	91	14	10	41	91	14	10
Tamil Nadu			185	852	333	1397	185	852
Tripura			34	147			34	147
Uttar Pradesh	87	384	76	129	87	384	76	129
Uttarakhand			14	30	32	62	14	30
West Bengal			370				370	3131

4. Discussion

According to the FAO [13] the total supply in tonnes for 2012 of the three foodstuffs modelled are: whole milk, 66,359,604; chicken, 66,359,604; fish (freshwater, pelagic, demersal and other marine fish), 5,891,140. Combining these data with estimates of pre-consumer losses derived from Jha et al [14], gives the results in Table 2, below. The indications here are that the potential losses in domestic refrigerators, when power supplies are interrupted for long enough, are large when compared to losses that might be expected in previous stages of the food supply chain.

These modelled losses are sensitive to the caveats given above and add to the question, "How much food would actually be at risk?" A potentially significant effect that cannot currently be quantified is the question of how much food would be cooked, or consumed, immediately the household becomes aware of the power failure. For example, if there were a power failure in the early afternoon, could some households cook and/or consume the vulnerable food, immediately, thereby avoiding the loss? To which households would this apply and can the situation be quantified realistically? Similarly, data is lacking for how much of the supply is consumed without entering the chill chain, the level of informal sales that are not recorded and the amount of food that could be consumed before deterioration would occur. For example, in Kerala, there is a high level of consumption of fish, but as this is a coastal state, the level of loss may be lower, due to fish passing very quickly from net to plate. These are questions beyond the scope of this case study.

Table 2: State-level potential losses, in tonnes, and expressed as percentages of available tonnage and mean national rates of loss prior to reaching the consumer. Scenario D2 + 4C; doubled interruption duration and heatwave 4ºC above average in week 28.

	combined rural and urban losses (tonnes)		**loss expressed as percentage of national total available to consumer**		**loss expressed as percentage of national pre-consumer losses**	
State	**Chicken**	**Fish**	**Chicken**	**Fish**	**Chicken**	**Fish**
Andhra Pradesh	726	191	0.034	0.012	0.467	0.353
Arunachal Pradesh	0	11	0	0	0	0.021
Assam	0	197	0	0	0	0.364
Bihar	0	70	0	0	0	0.128
Chhattisgarh	0	34	0	0	0	0.063
Gujarat	0	104	0	0	0	0.191
Haryana	0	14	0	0	0	0.025
Karnataka	0	158	0	0	0	0.291
Kerala	743	4114	0.035	0.013	0.478	7.590
Madhya Pradesh	106	51	0.005	0.002	0.068	0.093
Maharashtra	0	569	0	0	0	1.050
Manipur	0	26	0	0	0	0.047
Meghalaya	0	5	0	0	0	0.009
Nagaland	0	14	0	0	0	0.026
Punjab	137	5	0.006	0.002	0.088	0.009
Rajasthan	52	12	0.002	0.001	0.034	0.022
Tamil Nadu	752	565	0.035	0.013	0.484	1.043
Tripura	0	72	0	0	0	0.133
Uttar Pradesh	210	123	0.010	0.004	0.135	0.227
Uttarakhand	34	25	0.002	0.001	0.022	0.045
West Bengal	0	1525	0	0	0	2.814

There are also the effects of technical adaptation to unstable power supplies to consider. In addition to methods of providing an uninterruptible power supply, such as standby generators and batteries, technologies incorporated into the construction of refrigerators are becoming increasingly common in countries such as India. One such technology is the use of phase change materials that may keep refrigerators at a safe temperature for several hours, following a loss of electricity supply [15]. Without robust data on the degree of market penetration of such technologies, their potential effects have been ignored in the model. That said, if the power supply is interrupted for long enough and food remained unconsumed, it would still be at risk and the model gives some indication of this outcome.

In terms of the utility of the model, it presents an early phase attempt to estimate the potential losses of food in terms of the FWL Protocol's requirement to quantify losses as the weight of food lost. However, the methods employed here may not be perfectly aligned with the protocol's requirements, but might be modified to be so. The current weight estimation may then be converted to a nutritional value, where adequate data exist. Additionally, through a simplistic conversion of the weight of losses into a monetary value, one financial cost of food loss can also be estimated. In terms of the reliability of electricity supply grids, the model could provide a basic input to cost benefit analyses of reliability improvement programs. Also, with more data that can be linked to the types and weights of foods modelled, it may be possible to attempt an estimation of the environmental consequences of unreliable power supplies on refrigerated foods.

5. Conclusions

The model described here provides an estimation of the amount of three foodstuffs that may be made unfit for human consumption, due to power supply interruptions. The present iteration of the model relies upon a number of assumptions that overcome some of the shortfalls in data accessibility. Principal among these shortfalls are the lack of: good grid reliability data; information on patterns of food purchasing among consumers; data on how consumers store their food; seasonal availability and purchasing patterns; how consumers react to power interruptions; the effects of refrigerator types.

For the future, an expanded database of foodstuffs, within the source FRISBEE model or something similar, would increase the applicability of the overall model to include more foods that are eaten around the world. However, the foodstuffs modelled here can generally be considered to be high value, making the model potentially useful for cost benefit analysis of the avoidance of power interruptions and more importantly the reduction of their duration.

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