OPTIMAL STORAGE TEMPERATURE DESIGN FOR FROZEN SEAFOOD INVENTORIES: APPLICATION TO PACIFIC WHITING SURIMI

Merrick Burden, Oregon State University, Merrick.Burden@noaa.gov
Gilbert Sylvia, Oregon State University, Gil.Sylvia@oregonstate.edu
Edward Kolbe, Oregon State University, Ed.Kolbe@oregonstate.edu

ABSTRACT

Frozen storage is an integral part of effective food distribution. In general, both food quality retention and storage costs will increase as storage temperatures decrease. In this paper, we develop a model for optimal temperature design for semi-perishable seafood inventory, and apply the model to Pacific Whiting surimi. General results demonstrate that managing optimal temperature is a dynamic concept dependent on the time-temperature tolerance of frozen inventory, the cost of frozen storage, and the rate of inventory dissipation. Specific results show that the optimal storage temperature of surimi varies with the rate of inventory dissipation.

Keywords: frozen seafood, cold storage, pacific whiting, surimi

INTRODUCTION

Frozen storage is an integral part of the food distribution process and is designed to preserve quality. In general, the colder the storage temperature, the higher the degree of quality preservation. This is particularly true for seafood, a product that tends to have a lower time-temperature tolerance than other forms of frozen food products.

Wessels and Wilen (1993) have described one process of decision-making for frozen fish inventories, focusing on dissipation of Japanese salmon. In their study, managing inventory dissipation rates is part of a profit maximization strategy similar to a model of non-renewable resource extraction. This is a short-run behavioral response on the part of the firm, where the inventory dissipation rate changes in response to expected fluctuations in market prices. Managing rates of inventory dissipation is one strategy to increase profits. Another is to lower the storage temperature to increase retention of quality and market value. However, lower temperatures also lead to higher costs.

The value of a marketed commodity is often estimated through hedonic prices which are estimates of the value of various characteristics. Implicit in the hedonic price method is the assumption that a commodity consists of various combinations, or bundles, of a smaller number of characteristics or attributes (Berndt, 1996). The marginal price effect of each characteristic is then calculated as the derivative of the hedonic price equation with respect to that characteristic. These are often called marginal implicit prices. As an example, prices of fish emerging from fish auctions can be viewed as hedonic prices which depend on the value of individual characteristics, such as species, fat content, type of handling, and size (McConnell and Strand, 2000). We can find extensive literature on the hedonic prices of agricultural commodities, including tomatoes, apples, wheat, cotton, milk, beef, and grapes. However, the hedonic study of fish prices is relatively underdeveloped, despite the growing awareness of the importance of quality to seafood markets (McConnell and Strand, 2000). One reason for this limitation is that the majority of seafood products are not standardized or measured by a set of agreed-upon or binding quality characteristics (Anderson and Anderson, 1991).

In spite of the lack of "hedonic price method" studies, there is evidence that quality characteristics influence the price received for seafood products. Hedonic and conjoint price studies have been conducted on several seafood products including Hawaiian Tuna (McConnell and Strand, 2000), Salmon (Anderson and Bettencourt, 1993), Pacific whiting fillets (Sylvia and Larkin 1995) and Pacific whiting surimi (Larkin and Sylvia, 1999). Surimi is of particular interest because it is the only seafood product with quality characteristics that are objectively measured and standardized.

Although lower temperatures may lead to higher quality and value, they lead also to increased cost. In an economic study of frozen food, Poulsen and Jensen (1978) used the concepts of supply and demand to describe the optimum frozen storage temperature. The supply curve, represented by the cost of energy to drive refrigeration machinery, increases with decreasing temperature. The demand curve, represented by losses of quality and value while in storage, decreases with decreasing temperature. The intersection of these curves represents the optimum temperature. While this approach provides some insight into the nature of the quality–cost question, temperature optimization in frozen food inventory is a more dynamic concept. It will depend also on length of time in storage.

Inventory levels of many frozen food products are highly seasonal. This is especially true for seafood products. Fisheries are typically characterized by a concentrated harvest period followed by a longer marketing period as stored product is sold out of inventory (Wessels and Wilen, 1993). Optimization in this case seeks to maximize the total profits of all initial inventory over the duration of inventory sales. Any setting of an optimal temperature will be a forward-looking concept that incorporates an expected rate of inventory dissipation. This expectation is critical in determining optimum temperature since quality is deteriorating over time, costs are accumulating over time, and the optimal temperature must balance these changes against the expected rate of inventory dissipation. Previous quality–cost tradeoffs have been analyzed only over the short run, where the rule for short-run profit maximization has been to set price equal to marginal cost (Frank, 1997). This means that if prices are sufficient to cover operating costs, a firm will continue to operate over the short-run. However, planning for a long-term strategy must also take into account capital, since a firm must cover the cost of that capital and differences in capital outlay could result in greater economic efficiency.

This study explores quality–cost tradeoff from a planning and investment perspective by developing a model of cold storage temperature optimization, then applying the model to a case study of Pacific Whiting surimi.

SURIMI

Surimi is a form of fish protein commonly used in the U.S. to manufacture seafood analog products such as imitation crab, shrimp, and lobster. Surimi is made from minced fish muscle protein subjected to repeated washing and dewatering to eliminate blood, myoglobin, fat, and sarcoplasmic proteins. To protect the remaining muscle proteins from denaturation and aggregation during frozen storage, the mince is mixed with cryoprotectants – primarily carbohydrates that will stabilize the biochemical properties during storage (Lanier, 2000). Under appropriate conditions of salt solubilization and heating, these fish proteins have the ability to form a highly cohesive unit, or gel; this property is what makes surimi valuable in the production of food products (Kim and Park, 2000). The ability of surimi to form a strong gel generally deteriorates during frozen storage, although the lower the temperature, the lower the rate of loss of deterioration. Thus, effective frozen storage is a vital part of surimi distribution.

The two most widely used tests to measure the strength of a given gel are the punch test and the torsion test. A punch test pushes a probe into the gel until it fails while recording both the force needed for the gel to fail, and the depth of the probe at failure. The torsion test measures stress and strain by twisting a cylindrical sample of surimi gel until it fails. Strain is an indicator of cohesiveness; stress indicates strength and hardness. Stress is strongly influenced by concentration of ingredients and processing, while strain is largely influenced by protein quality. Thus, strain is viewed as a better measure of quality and stability in frozen surimi.

MacDonald et al. (1992) incorporated the torsion test over the course of a 9-month study to assess the shelf life of frozen Pacific Whiting surimi. Results show a very rapid deterioration when held at +18°F; the retention of gel strength improved significantly as the temperature was lowered from –4° F to –22° F (Figure 1). Surimi gels stored at –58° F showed little or no improvement over those stored at –22° F. Therefore, as temperature is lowered, the retention of functional quality improves, but at a decreasing rate of improvement. Hoffman (2001) showed that the level of color characteristics for frozen surimi diminished at a diminishing rate at a constant temperature. These observations are consistent with past studies recording quality change with frozen storage temperature (Sikorski and Kolakowska, 1990, Kolbe and Kramer, 1993; Learson and Howgate, 1988; Moreno, 1984).

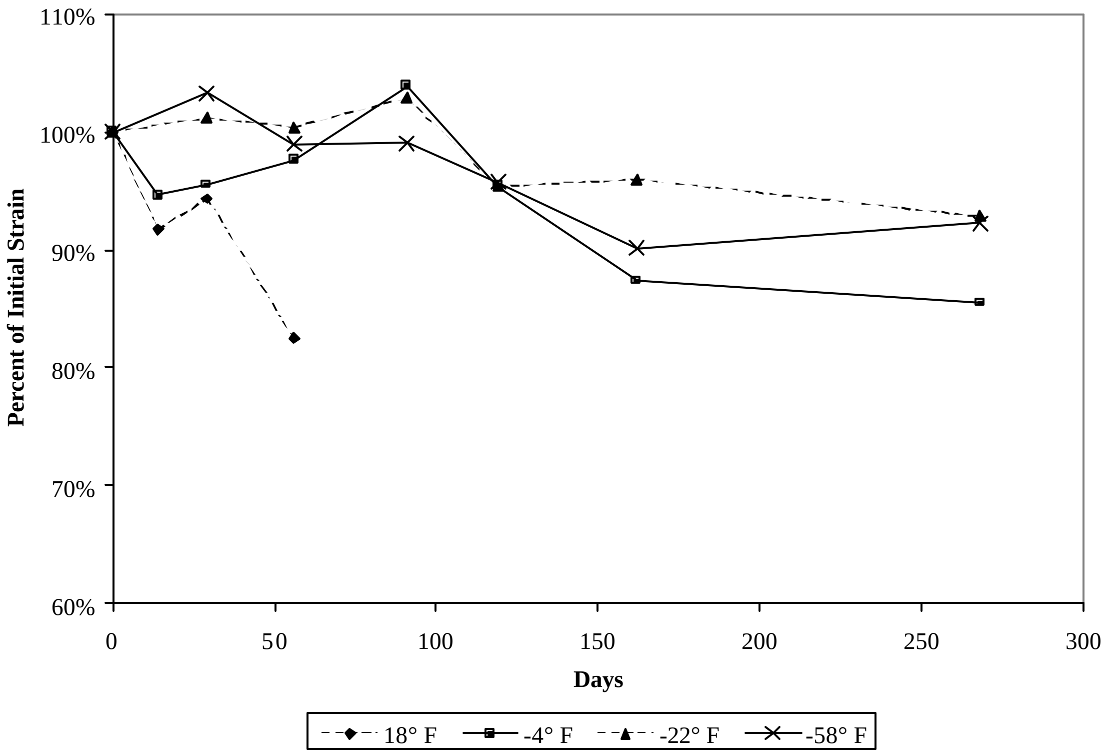

Figure 1. Deterioration of Torsion Strain in Frozen Pacific Whiting Surimi

A MODEL OF COLD STORAGE TEMPERATURE OPTIMIZATION

The economic benefits gained from holding inventory in cold storage are the result of a series of events. One of these is inventory dissipation, which we will assume to occur at a constant rate. That is, sales of frozen inventory occur continuously over a specified time interval. The revenue collected by the owner of the frozen inventory is dependent on quantity sold, the sum of revenues received at each sale, and the accumulated cost of holding frozen inventory in storage. When the inventory is placed into frozen storage, the owner of that inventory can either specify the holding temperature, or adjust the rate of inventory dissipation, to maximize the expected total revenues associated with that inventory. Each of these actions has its own set of variables that will affect the benefits gained from inventory management. Thus optimizing revenues associated with frozen inventory requires the consideration of such variables as the expected fluctuations in future prices, deterioration of quality, and costs of cold storage.

However, rather than using total costs during optimization, setting the optimum holding temperature is accomplished by examining the marginal benefits and costs associated with changes in the storage temperature. In a long-run perspective, these marginal conditions are reflected in some of the characteristics defining food quality, incremental changes in refrigeration energy, and changes in capital costs of cold store design. Assuming that temperature-specific characteristics can be separated into specific variables, one can develop a function describing the temperature-specific net value of frozen inventory. Using this approach, the optimum temperature is found by solving the following maximization problem.

$$\max_T NPV(TR) = NPV \sum_{i=0}^{m} \sum_{t=0}^{n} \{q_t * R[X(T,t), Y(T,\ t)]_t\}_i \qquad (1)$$

where
NPV(TR) is the sum of net present values of future temperature-dependent profits.
q_t is the quantity (in pounds) of product sold per day.
R_t is the profit per pound sold each day.

The product (q_t*R) is summed of time, t (days) through the inventory dissipation period, n (days). The problem assumes that inventory clears annually. The annual net revenue is then summed over the time, i (years) through the expected life of the facility, m (years).

Daily profit, R_t, is a direct function of two variables:
X is the value per pound of quality;
Y is the cost per pound of cold storage.
Each of these variables are in turn dependent upon time (t), and temperature (T).

It is assumed that the product value term, X behaves like a traditional demand curve over time, t; that it decreases at a decreasing rate over time. It is further assumed to be a convex function of temperature, T; that decreases in temperature will lead to ever-smaller improvements in value retention.

The shape of the cold storage cost function, *Y* is dependent on cold storage ownership. A vertically-integrated cold storage firm has a *Y* that decreases with increasing temperature, *T* and is nearly fixed over time, *t*. In this case, the only variable changing with time, *t* is the annual demand for refrigeration energy. If the cold store is not owned by the frozen inventory owner who now pays a periodic charge for storage, and if the operating and capital costs of relative temperature differences is reflected in storage charges, then *Y* increases with time, *t* and decreases with increasing temperature, *T*.

This maximization problem is a forward-looking and cumulative concept for which optimization is subject to the expected quantity sold each day, total quantity sold over all days, and the expected time needed to clear inventory. The model assumes that the inventory quantity and rate of inventory dissipation is repeating annually. This pattern can be viewed as an expectation of future inventory levels over the life of the facility. In addition, the model assumes that the dissipation period (over which inventory is cleared) is independent of holding temperature. Since this optimization is subject to a planning perspective, the formal optimization criterion is to maximize the total quantity of revenues over the life of the cold store facility.

Because the dissipation period and rate are assumed to be predetermined, equation (1) shows a relationship between cumulative profits and temperature, where temperature influences the value function, *X* and the cost function, *Y* over the dissipation period.

COST OF COLD STORAGE

The design temperature of a cold store would typically influence cost through differences in refrigeration machinery and building design, in addition to the rate of energy consumed. Building design for efficient low-temperature operation will require greater capital expense for such components as refrigeration machinery, insulation thickness, and alternative door designs. Cost estimates for well-designed and efficient cold storage facilities were derived from a series of estimates contracted from cold storage manufacturers and designers (Ristau, 2003; Stevens, 2003; Vallort, 2003). Costs are differentiated by total box cost (cost of building without refrigeration), costs of refrigeration machinery, cost of foundation, sprinklers, racking, and refrigeration energy demand. Other costs (e.g. labor) are independent of temperature, and therefore are not included in this analysis.

These costs were approximated with a log-linear model that uses size and temperature as explanatory variables (Table 1). Refrigeration costs generally increase as temperature decreases. Its cost is also dependent on scale, with cost per square foot decreasing as the size increases, given constant temperature.

As with refrigeration machinery, the unit cost (per cubic foot) of the cold storage box also decreases as size increases. Cost dependence on temperature for the box has an additional complexity. There is little variation in cost for temperatures between –10° and –20° F, but costs increase with temperatures lower than –20°. Thus, box costs were approximated with a log-linear spline regression which measures cost per cubic foot. This function has a "knot" that allows cost to increase more rapidly at temperatures below -20°.

The costs of foundation, racking, and a sprinkler system (titled "Miscellaneous" in Table 1) are estimated in terms of cost per cubic foot. This function is size - and temperature-dependent, decreasing as size increases; increasing as temperature decreases.

The last component of costs is the energy required to drive refrigeration machinery, expressed as dollars per cubic foot. In general, this component increases as temperature decreases; decreases as box-size increases.

Table 1. Log-Linear Regression Results for Cold Storage Costs

(Coefficients are in units of 2003 US dollars)

	Model Specification			
Variables	Box	Refrigeration	Miscellaneous	Energy
Intercept	3.386 (0.543)	4.1482 (0.243)	1.927 (0.498)	6.78 (0.412)
LN(square feet)		0.4770 (0.023)		
LN(cubic feet)	-0.225 (0.029)		-0.202 (0.04)	-0.615 (0.028)
LN(Fahrenheit*-1)	0.032 (0.159)	-0.288 (0.056)	0.143 (0.103)	0.518 (0.091)
LN(((Fahrenheit*-1)-20)*D)	0.0532 (0.274)			
R-square	0.746	0.928	0.606	0.972
Observations	25	21	20	18
F value	20.539	115.595	13.078	256.879

Values in parentheses are standard errors. D represents a dummy variable for temperatures below minus 20°

QUALITY DETERIORATION

Assigning an objective level of quality to seafood products is difficult. This study focuses on surimi, an exception because it is objectively graded based on the measurement of several characteristics: color, gel strength, water content, pH, and impurities. Despite the fact that the level of these characteristics largely influences surimi price, there is surprisingly little information available showing the change in these characteristics while in frozen storage. The effort by MacDonald et al. (1992) shown in Figure 1, identified the strength of surimi gels held at various storage temperatures over time. As expected, the retention of surimi gel strength is higher at lower temperatures.

From the standpoint of quality deterioration in the frozen inventory, it is appropriate to examine only those surimi characteristics that are temperature-dependent: color, gel strength, and pH. These variables are interconnected. Ice crystal formation in frozen surimi concentrates salt, increases dehydration or drip-loss, and decreases pH. These changes in turn lead to undesirable protein denaturation and lipid oxidation. Protein denaturation and pH changes significantly affect gel strength; lipid oxidation may lead to a change in color (Hoffman, 2001). Because the temperature-dependent characteristics while in frozen storage relate directly or indirectly to the same chemical changes, it is reasonable to assume a strong correlation between changes in the levels of pH, color, and gel strength while in frozen storage. Thus we will use the gel strength data of MacDonald et al. (1992) to show changes in the aggregate level of quality. Such changes are generally consistent with past studies describing the quality of frozen food.

Data of Figure 1 show that for storage temperatures below 18° F, some increase in strain values was observed for up to 100 days. This increase is not observed for other quality variables (such as color), and it is unlikely that the market would bear an increasing price for surimi after it has been held in storage. Thus, we will assume a functional form that is concave in time, *t* using only those strain values that decrease over time to predict the aggregate level of quality.

There is a lower bound of quality, not equal to zero, below which the product is no longer marketable. This quality threshold is reached when a surimi gel will no longer pass a "double fold test", i.e. when a sheet of gel shows no cracks after it is literally double-folded (MacDonald et al, 1992). Given our units and scale of quality retention, this threshold occurs near the level of 76% of remaining quality. In fact, value deterioration (as a function of quality) is continuous and worth significantly more than zero provided quality is above the minimum threshold value. The model developed in this study assumes that value deteriorates in a continuous manner so long as quality is above the minimum threshold.

It should be noted that surimi companies assign grades based on the level of color, gel strength, water content, and impurities. This would imply a value function that is not continuous over time, but deteriorates in a step-wise manner. However, evidence and experience suggest this is not the case. One reason is that the level of characteristics used in determining surimi grade are not binding, meaning that a firm may allow less-than-ideal levels of certain characteristics into a specific surimi grade. Furthermore, an empirical model developed by Larkin and Sylvia (1999) using production location and surimi grade as explanatory variables showed a very low ability to predict surimi price. This could be because there is no common grading schedule for surimi, implying that each firm decides which characteristics to include, how they are measured, and the levels and nomenclature that define each grade.

Several functional forms were evaluated to model quality deterioration. The model that resulted in the best fit and that was most consistent with our assumptions regarding the properties of quality deterioration is best described as a non-linear regression function with time (in days) and temperature (in Degrees Fahrenheit) as explanatory variables. Using assumptions previously described regarding use of data from MacDonald et al. (1992), the resulting model is given below.

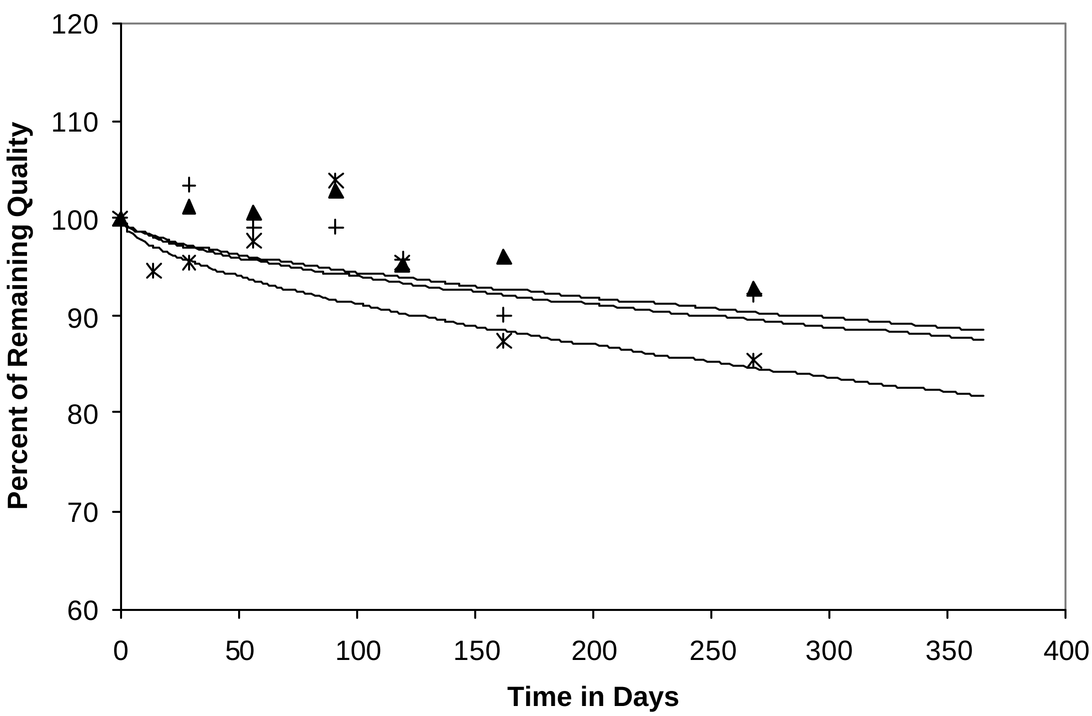

Figure 2 shows a graphical form for three storage temperatures plotted with the source data.

$$Quality = 100 - (time)^{0.56}(temperature* - 1)^{-0.29}$$

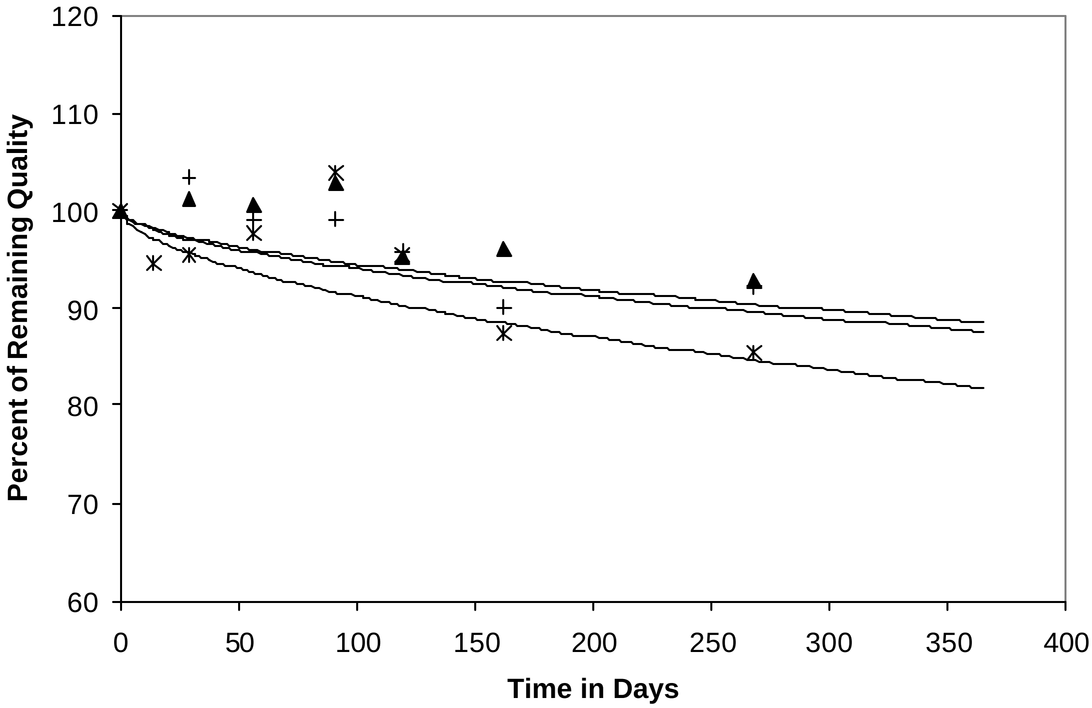

Figure 2. Predicted Quality Deterioration in Frozen Surimi
Data points are from MacDonald et al, 1992.
* -4°F ? -22°F + -58°F

MODEL APPLICATION

Time-temperature quality information is combined with economic analysis to estimate optimal temperatures for storing frozen Pacific Whiting surimi. Note that, while this application is for surimi, the process can be applied to other types of frozen foods for which quality/value attributes can be quantified.

Information used to estimate the value of frozen surimi comes primarily from the work of Larkin and Sylvia (1999) and MacDonald et al. (1992). In a hedonic model of Pacific Whiting surimi, Larkin and Sylvia (1999) estimated the marginal implicit prices of water, pH, impurities, color (both whiteness and lightness), and gel strength from the punch test, expressed as force, depth, and energy. Water content, in percent by weight, will influence acceptance, undesirable if too high. The pH level can be influenced by storage conditions, where levels exceeding neutral values are more desirable. Impurities are the remaining skin and bone fragments, measured in millimeters and assigned specific levels based on size. Whiteness and lightness represent the color; whiteness is calculated as Z, a value in the CIE (Commission Internationale de l'Eclairage) Lab standard color test, and represents the blue region of the spectrum; lightness is represented by a value, L which measures blackness and whiteness. Force, depth, and gel strength were described previously. These characteristics, their temperature dependence, and their marginal implicit prices are further defined in Table 2.

Table 2. A Hedonic Model of Quality Characteristics

Marginal Implicit Price	Characteristic	Temperature Dependence	Definition
-2.972	Intercept	No	
-0.007	Water	No	Water content (percent by weight)
0.003	Impurity	No	Impurities (greater than 2mm = 1point, < 2mm = 0.5 point)
-0.238	PH	Yes	pH level
-0.039	White	Yes	Whiteness (Z value in CIE X, Y, Z; blue region of spectrum)
0.073	Light	Yes	Lightness (L value in L, a, b; 0 = black, 100 = white)
0.005	Depth	Yes	Indentation depth at failure, indicates cohesiveness (cm)
2.237	Force	Yes	Force at failure, indicates firmness (g)
-0.003	Gel	Yes	Force*Depth = gel strength, represents energy required to penetrate the sample

Source: Larkin and Sylvia (1999)

The marginal prices of each characteristic shown in Table 2, when combined with temperature-dependent levels of these characteristics while in frozen storage will give a price (and value) of the surimi over time. An estimate of the level of each characteristic at time zero is presented in Table 3. These are average values based on multiple lots of surimi.

Table 3. Value of Quality Characteristics at Time Zero

Attribute	Level	Price	Value
Intercept		-$2.972	-$2.972
Water	74.7	-$0.007	-$0.549
PH	7.3	-$0.238	-$1.737
Impurity	2.6	$0.003	$0.008
White	53	-$0.039	-$2.059
Light	78.4	$0.073	$5.722
Depth	763.3	$0.005	$3.534
Force	1.4	$2.237	$3.132
Gel	1091.8	-$0.003	-$3.357
TOTAL			**$1.723**

Source: Larkin and Sylvia (1999)

Table 3 shows the estimated value of surimi to be $1.72 per pound at time zero and assumed 100% quality retention. As previously stated, the analysis is concerned with those characteristics that change with temperature and time: pH, whiteness, lightness, force, depth, and gel strength (Park, 2003; Hoffman et al., 2001; Kim and Park, 2000; MacDonald et al., 2000; Larkin and Sylvia, 1999; MacDonald et al., 1992). Thus, the estimate of value while in storage is accomplished by holding temperature-independent characteristics constant and allowing temperature-dependent characteristics to change according to the quality deterioration function.

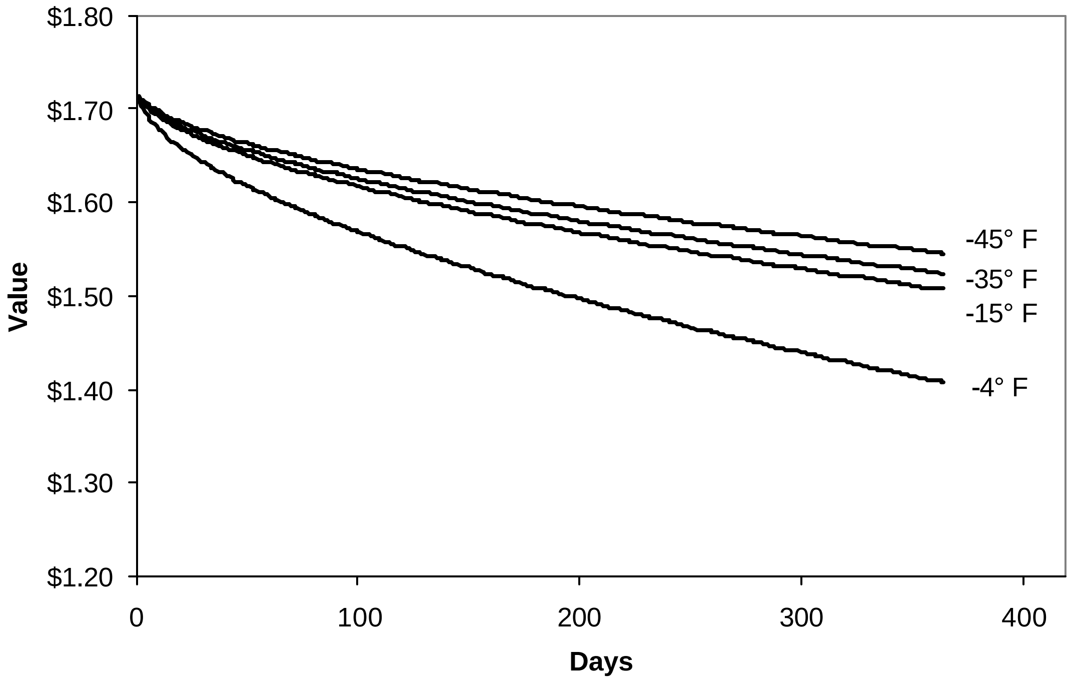

Figure *3* gives the graphic results. When these values are reduced by the time-dependent marginal cost of storage, the result will be the net revenue per pound of surimi.

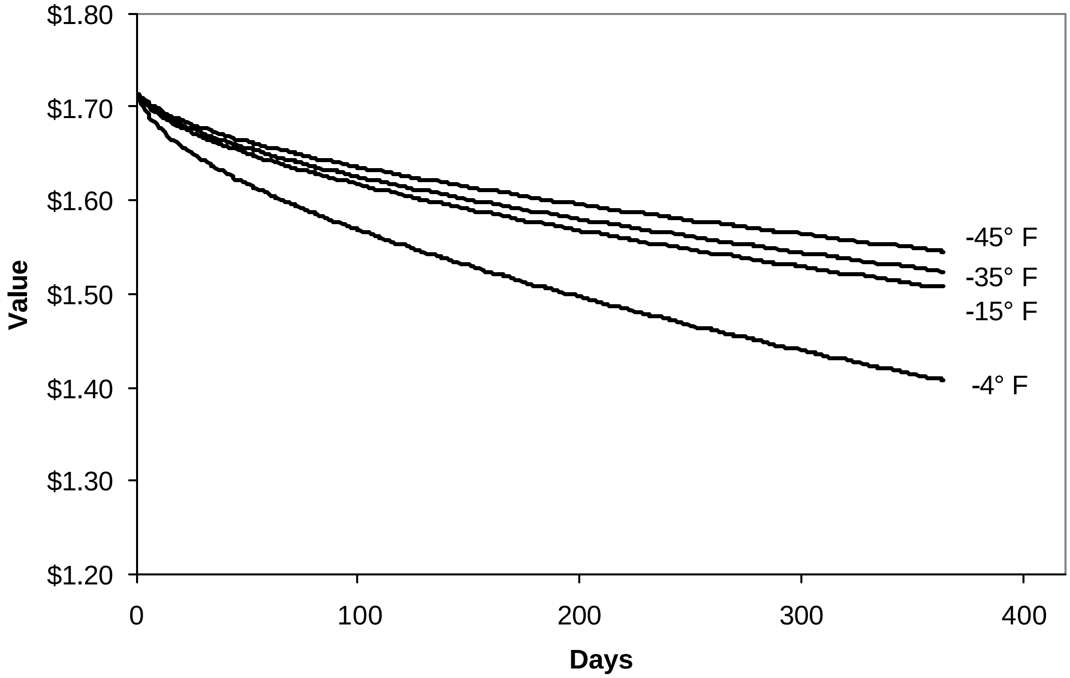

Figure 3. Predicted Value Deterioration of Frozen Surimi (value per pound)

The outcome of these analyses and demonstration of planning issues can best be shown by an example application. We assume a facility having 5,328 square feet of floor space, a height of 25 feet, and designed to hold 1 million pounds of product. Estimates of capital and energy costs result from the regressions given in Table 1. Converting these temperature-dependent costs to marginal costs per pound is accomplished with a set of assumptions:
1) the cost of a box designed for a temperature equal to ambient temperature is $250,000; so marginal box cost with respect to temperature will be the estimated box cost minus $250,000.
2) the cost of sprinklers, foundation, and racking designed for a temperature equal to ambient temperature is calculated to be $90,000; so marginal cost with respect to temperature will be the estimated cost minus $90,000.
3) capital costs are the result of a loan at 8% over 20 years
4) the price per kWh is $0.10.
5) the discount rate is 6%.
Total refrigeration cost will be a marginal cost, since a cold store designed for ambient temperature would not need refrigeration. The optimization assumes that the cold store is privately owned by the owner of inventory, and used only for surimi storage. Capital costs are annual fixed costs and energy usage is determined by the number of months surimi is held in storage (which will also be the number of months of operation).

We combine this information to generate an optimum temperature setting for two rates of inventory dissipation. For simplicity, these dissipation rates are assumed constant and dictated by the selected dissipation period, or total time of inventory sales.

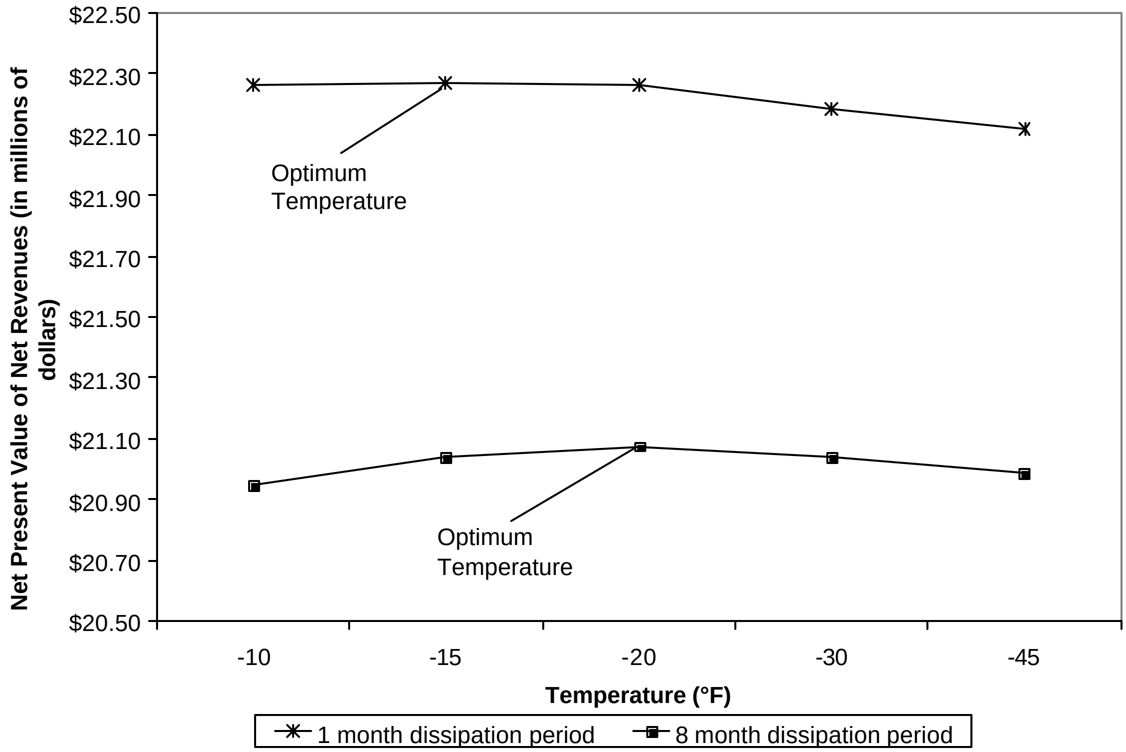

Figure *4* shows the results. The total net revenue is lower for the longer dissipation period, because inventory sold at later dates will have lower quality and value and higher cumulative costs. Note that ongoing increases in surimi market value could strongly influence these results. Optimum storage temperature also varies with the inventory dissipation rate, as expected, due to the tradeoffs between quality preservation and the cost as a function of temperature. For the example of an 8-month dissipation period, additional quality preservation at –20° F outpaces the cost of maintaining the lower temperature. Thus for our example of a million pound capacity, it is most profitable, by about $100,000, to hold at -20°F (vs -18°F) when the inventory dissipation period is 8 months.

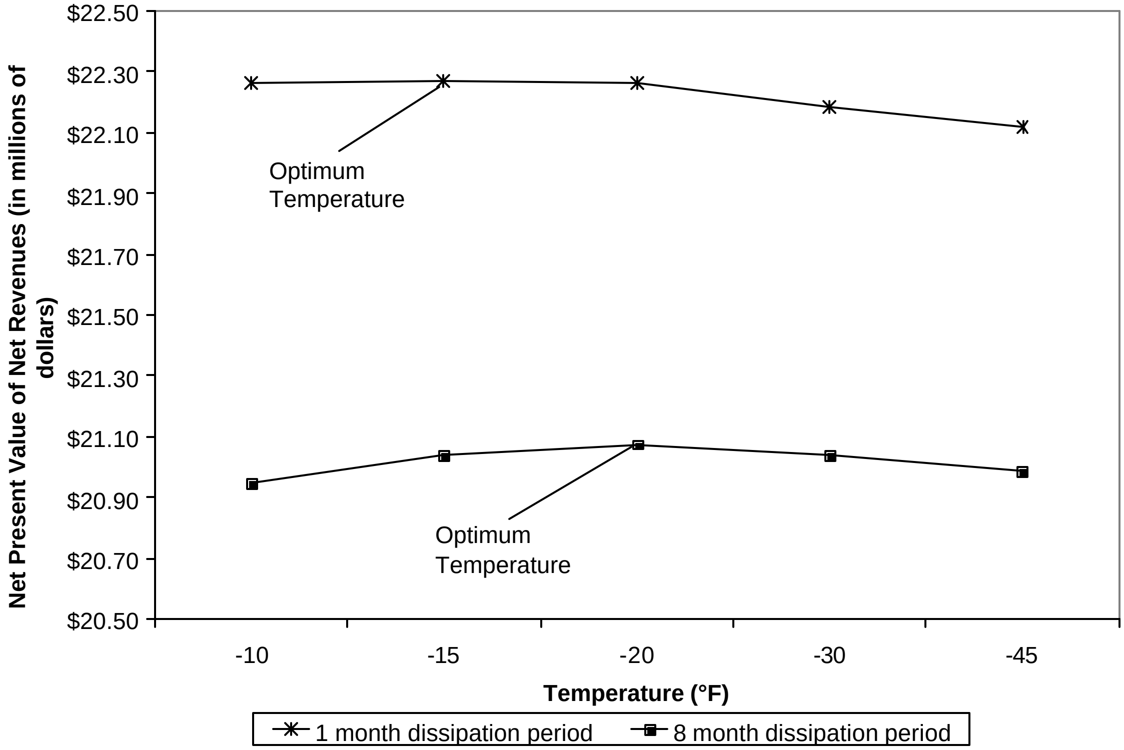

Figure 4. Net Present Value as a Function of Temperature for Two Rates of Inventory Dissipation

Conclusion

Storing seafood as frozen inventory is an integral part of the seafood distribution process. In general, colder holding temperatures have a higher degree of quality preservation, and evidence suggests that higher quality will command higher market prices. Assuming the goal of seafood distributors and marketers is to gain maximum profit, then one variable affecting that goal is the holding temperature for a given product. This paper demonstrates one approach for determining the optimum storage temperature. Using the properties of frozen food quality and cold storage cost and planning, this paper has shown that optimization is more than a two dimensional concept, and that managing temperature is also dictated by the dissipation period and rate of inventory sales. This empirical example using Pacific Whiting surimi shows that the optimum storage temperature is a dynamic process dependent on quality retention, storage cost, and inventory dissipation, and that the optimal storage temperature will vary depending on different strategies of inventory sales.

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