Agricultural Systems, Vol. 51, No. 4, pp. 431–452, 1996

0308-521X/96 $15.00 + .00
ELSEVIER
0308-521X(95)00058-5

A Generic Model for Keeping Quality of Vegetable Produce During Storage and Distribution

L. M. M. Tijskens & J. J. Polderdijk

Agrotechnological Research Institute (ATO–DLO), P.O. Box 17, 6700 AA, Wageningen,
The Netherlands

(Received for publication 18 September 95)

ABSTRACT

A generic model on the keeping quality of perishable produce was formulated, based on the kinetics of the decrease of individual quality attributes. The model includes the effects of temperature, chilling injury and different levels of initial quality and of quality acceptance limits. Keeping quality of perishable produce was found to be inversely proportional to the sum of the rates of the separate reactions leading to quality decrease, irrespective of the kinetics of the decrease.

In its static form, the model is useful for statistical analysis and for predicting keeping quality at constant conditions. In its dynamic form, it predicts keeping quality as a function of temperature, initial quality and quality acceptance limits. These limits are defined by personal, regional or national preferences. Calculation of the dynamic model requires only one simple numerical integral, even for multiple limiting attributes. Due to the fast numerical integration of that one integral, optimization of distribution chains with respect to produce quality over a broad time and space region becomes economically feasible.

The model accounts for the behaviour of keeping quality of about 60 species of fruits and vegetables, including chilling-sensitive products, over a wide range of temperatures. Copyright © 1996 Elsevier Science Ltd

NOMENCLATURE

Variable	Dimension	Description
C	[–]	correction for biological age
Ea	[J/mol]	energy of activation

$f(\,)$	[–]	unspecified function
harvest time	[hr]	diurnal time of harvest
k	[ ][1]	quality reaction rate
KQ	[time]	keeping quality
N	[–]	number of processes
Q	[qua][2]	quality (amount, intensity, level etc.)
R	[J/mol/K]	gas constant = 8.314 J/mol/K
t	[time]	time
T	[K or °C]	temperature
α	[–]	diurnal time shift factor
β	[–]	translation factor
ω	[hr^{-1}]	daily frequency = $2*\pi/(24\ \mathrm{hr})$

Indices

abs	absolute (temperature)
b	a particular batch
ba	biological age
inf	at (minus) infinite time
l	limit
m	the measuring batch
max	maximal
ref	at reference temperature
st	at standard temperature
0	initial
1,2,3	process indication

INTRODUCTION

Whether or not a product is acceptable to the user depends on the product quality and on the level of the acceptance limit (Tijskens *et al.*, 1994*b*). The limit of acceptance is largely defined by the economical and psychosocial circumstances of the user; the quality of a product is largely defined by its intrinsic properties. As a consequence, product acceptability will partly depend on product behaviour and partly on consumer attitude. The

---

[1] The dimension of reaction rate depends on the mechanism of the reaction: time^{-1} for exponential and logistics mechanisms; $\mathrm{qua}*\mathrm{time}^{-1}$ for linear mechanism.

[2] Quality arbitrary unit: the dimension of quality is rather arbitrary, and depends on type of measurement and type of attribute measured. As long as one keeps the dimensions consistent, no problems arise.

concept of keeping quality combines both these aspects of product acceptance, that is, acceptance limit and intrinsic properties, into a generally applicable and simplified index of quality.

In order to describe, analyse and predict the response of quality to various constant and varying circumstances, the problem has to be decomposed. The underlying processes can be categorized as objective (e.g. chemical, physical, physiological processes) or as subjective (e.g. sensory perception, evaluation and acceptance). Much research concerning quality of foods is devoted to the search of those objective properties on which the subjective perception and evaluation of specific quality attributes are based (Watada *et al.*, 1984; Janse, 1989; Shewfelt, 1990; Kader, 1992; Reid, 1992; Polderdijk *et al.*, 1993).

The keeping quality of a product has frequently been used as a simple, attribute-unspecific identifier of overall quality (Sprenger, 1937; Hardenburg *et al.*, 1986; van Doorn & Tijskens, 1991; Polderdijk *et al.*, 1993). It has also been used to describe the relation of product quality with bacterial infection and growth (Labuza *et al.*, 1992; Fu & Labuza, 1993; Willcox *et al.*, 1993) and with the technical application of cooling (Meffert & van Vliet, 1974; Segurajaurgui Alvarez & Thorne, 1981; van Beek *et al.*, 1985).

With internal quality becoming increasingly important and an explicit part of supermarket policy (Monnot, 1990), application of a reliable model on internal quality has become necessary. To simplify the observed phenomena into an acceptable descriptive model, it is essential to break down the complexity of the various processes that affect quality, otherwise the simplification may be arbitrary, resulting in unreliable model formulations. The present paper relates overall keeping quality to the kinetics of the decrease of its individual quality attributes. The effect of temperature on keeping quality has been described independent of kinetic type. Information about the type of kinetic mechanism is only needed if the initial quality and the quality limit are different from the measuring conditions.

DEFINITION OF KEEPING QUALITY

A generally accepted definition of keeping quality is the time until a commodity becomes unacceptable (van Beek *et al.*, 1985; Fu & Labuza, 1993). The attribute limiting the product acceptance can be predefined (e.g. firmness, Polderdijk *et al.*, 1993) or may depend on circumstances (e.g. it can be firmness or colour, whichever attribute first becomes unacceptable). Keeping quality only provides information about the time the product can be kept prior to becoming unacceptable, but it does not provide information either about the actual state of the product's quality or about the processes occurring in the product. Without information, however, about the mechanisms involved in the decrease in quality or quality attributes, the dynamics of keeping quality cannot be described.

A new approach will be developed relying on the kinetics of the possible mechanisms involved, starting from the most simple situation of a single quality attribute in a constant environment, to several quality attributes in a constant environment, and finally towards complex quality attributes in a varying environment. Taoukis & Labuza (1989) have already described this approach for a single quality attribute only, solving the problem with a physical (diffusion) approach, without fully exploring the chemical approach.

METHODS

The equations in the mathematical description of the model have been developed and solved using MAPLE V (Waterloo Maple Software, Waterloo, Canada), a computer algebra program for manipulation of symbolic functions.

The data used in the statistical analysis have been read back from published graphs of keeping quality versus storage temperature for a number of products (Sprenger Institute, 1986; Paull, 1993). Data on the keeping quality of sweet basil in relation to diurnal harvest time have kindly been provided by Lange & Cameron (1994). The statistical analysis was carried out using non-linear regression (GENSTAT Statistical Package, Rothamstead, UK). To avoid the introduction of unnecessary errors by transformation of data (Ross, 1990; Tijskens, 1993) no transformation was applied.

The dynamic model is implemented in PROSIM (Sierenberg and de Gans, Waddinxveen, The Netherlands), a modelling language which combines the benefits of continuous, discrete, mixed and parallel modelling.

MATHEMATICAL DESCRIPTION OF THE MODEL

Single limiting quality attributes at constant temperatures

For simple situations in constant storage conditions the possibly complex behaviour of quality will reduce to a rather simple behaviour: by fixing the one storage temperature, inevitably, for a given value of initial quality and of quality limit, the attribute first to become unacceptable will always be the same. So, in a constant environment, the behaviour of only one quality attribute has to be considered in the deduction of the equations. What is not yet defined is the mechanism involved, or the (chemical) path along which the change of that particular quality attribute will take place. In practice the decrease of a single quality attribute can be approximated by one of the four following basic types of mechanism (Taoukis & Labuza, 1989):

- zero order reactions having linear kinetics;
- Michaelis Menten kinetics;
- first order reactions having exponential kinetics;
- autocatalytic reactions with logistic kinetics.

For each of these types a relation between keeping quality and the underlying reaction mechanism will be deduced. It has to be pointed out that the only assumptions made in the coming deduction of the equations is to be found in the mechanism chosen for a particular quality attribute. The deduction of the equations themselves is conducted entirely according to the fundamental laws of kinetics. Figure 1 gives a summary of the behaviour of quality attributes based on these four kinetic mechanisms. Keeping quality is the time until the quality crosses the acceptance limit. With the same initial quality and the same quality limit, Fig. 1 shows the effect of the kinetic mechanisms on keeping quality as depending on the level of the quality present and on the level of the acceptance limit.

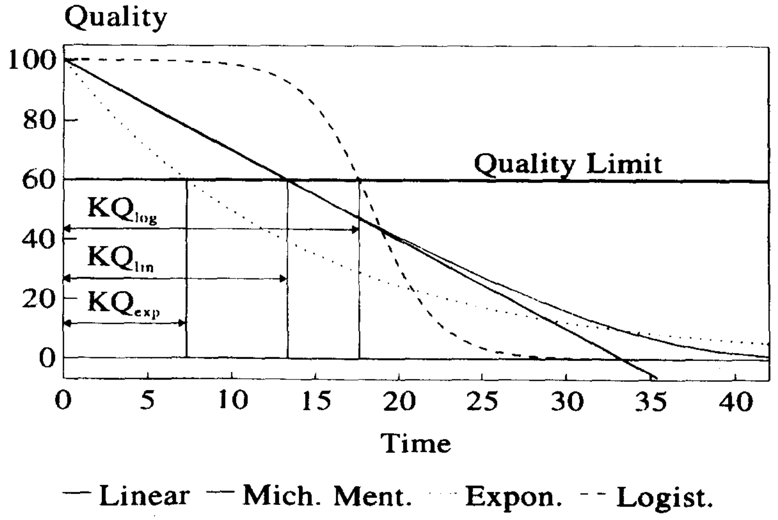

Fig. 1. Decrease in quality for several types of mechanisms (arbitrary units).

Linear and Michaelis Menten kinetics

Although linear kinetics or zero order reactions are relatively rare, Michaelis Menten kinetics are observed more frequently. This type of kinetics reduces to a linear one if the amount of substrate (here quality attribute) exceeds the specificity factor K_m, which is most probably the case in the initial region of decay. This initial part is the most important in quality assessment (see Fig. 1). If it should not be the case, Michaelis Menten kinetics reduce to the exponential type, covered in the next section.

For a quality decrease according to a zero order reaction, the following kinetics can be derived (variables are defined in Nomenclature):

$$\frac{dQ}{dt} = -k \tag{1}$$

Integration at constant temperature results in a linear relation:

$$Q = Q_0 - kt \tag{2}$$

where Q_0 is the initial value of Q.

When the quality Q exceeds the quality limit Q_l, the time elapsed is equal to the keeping quality, hence:

$$KQ = \frac{Q_0 - Q_l}{k} \tag{3}$$

The keeping quality KQ for zero order kinetics is proportional to the inverse of the reaction rate k of the decrease in quality.

Exponential kinetics

First order reactions leading to exponential responses are commonly encountered in natural processes. Based on fundamental kinetics, the relevant differential equation is:

$$\frac{dQ}{dt} = -kQ \tag{4}$$

Assuming constant temperatures, integration gives:

$$Q = Q_0 e^{-kt} \tag{5}$$

From this relation, the keeping quality can again be derived as the time at which the quality Q reaches the quality limit Q_l:

$$KQ = \frac{\log_e\left(\frac{Q_0}{Q_l}\right)}{k} \tag{6}$$

Again, as for linear decay, the keeping quality for exponential decay is proportional to the inverse of the rate k of quality decrease.

Logistic kinetics

Logistic behaviour is also frequently encountered in natural processes (Thornley, 1976, p. 10; France & Thornley, 1984, p. 75; Tijskens & Evelo, 1994; Tijskens *et al.*, 1994*a*). Logistic behaviour can be regarded as the overall expression for autocatalytic processes, diffusion controlled processes, cascades of reactions and complex growth kinetics. The formulation of these types of reactions can be written in different forms. One is shown in equation (7):

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = -kQ\left(1 - \frac{Q}{Q_{\mathrm{inf}}}\right) \tag{7}$$

Again by integration assuming constant temperatures, one obtains:

$$Q = \frac{Q_{\mathrm{inf}}}{1 + C_{\mathrm{ba}}\mathrm{e}^{kt}} \tag{8}$$

with

$$C_{\mathrm{ba}} = \frac{Q_{\mathrm{inf}} - Q_0}{Q_0}$$

From this relation, the keeping quality can again be derived as the time at which the quality Q reaches the quality limit Q_1:

$$KQ = \frac{\log_{\mathrm{e}}\left(\frac{Q_{\mathrm{inf}} - Q_1}{Q_1 C_{\mathrm{ba}}}\right)}{k} \tag{9}$$

Q_{inf} represents the quality maximally possible at (minus) infinite time, whereas C_{ba} is a constant representing information about the biological age of the product (Tijskens & Evelo, 1994). Again the keeping quality is inversely proportional with the rate k of quality decrease.

Effect of temperature

From the above discussion it follows that keeping quality is proportional to the inverse of the reaction rate k of the decrease in quality, irrespective of the kinetic mechanism of the decrease. This gives the opportunity to describe the behaviour of keeping quality as a function of temperature.

Specific rates of chemical, biochemical and enzymatic reactions usually depend on temperature according to Arrhenius' law (Chang, 1981). Apparent rates, e.g. of enzymatic reactions can, at the relatively low storage temperatures encountered in practice, also be approximated by this law:

$$k = k_{ref} \mathrm{e}^{\frac{Ea}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{abs}}\right)} \tag{10}$$

The energy of activation Ea has a positive value, indicating an increase in reaction rate with increasing temperature. Due to the inverse relation with the reaction rate k the keeping quality will also depend on temperature according to Arrhenius' law. Application of the Arrhenius equation for the temperature dependence of the reaction rate k of quality decrease is in accordance with Taoukis & Labuza (1989). Segurajaurgui Alvarez & Thorne (1981) reported an empirical exponential relation between keeping quality and temperature.

Influence of initial quality and quality limits

The keeping quality in a constant environment can be represented as:

$$KQ = \frac{f(Q)}{k} \tag{11}$$

where $f(Q)$ is an expression comprising the initial quality Q_0 and the limiting quality Q_1. The exact formulation of $f(Q)$ depends on the reaction kinetics governing the decrease of the limiting quality attribute. In Table 1 an overview is given for the respective quality functions.

Taoukis & Labuza (1989) found the same relation with kinetic mechanism and called the factor $f(Q)$ the quality function. Within a situation constant for Q_0, Q_1, and for other quality references that depend on the mechanism (see Table 1), the quality function is constant.

TABLE 1
Overview respective quality functions

Kinetic mechanism	f(Q)
Linear	$Q_0 - Q_1$
Exponential	$\log_e\left(\frac{Q_0}{Q_1}\right)$
Logistic	$\log_e\left(\frac{Q_{\mathrm{inf}} - Q_1}{Q_1 C_{ba}}\right)$

Consequently, keeping quality does not depend on the type of reaction kinetics. In fact, equation (11) states a generic formulation for keeping quality, irrespective of the reaction mechanism involved.

The limit of acceptance is of major importance in the concept of keeping quality. It can be defined as the minimal quality necessary for a consumer to accept the product (Tijskens *et al.*, 1994*b*). When the initial quality is different from the initial quality of the measuring batch of products or when the quality limit changes during storage or distribution, the kinetic mechanism will, however, exert a strong effect on the observed behaviour of keeping quality by changing the value of the quality function $f(Q)$. Equation (11), combined with the quality functions shown in Table 1, points out how and when the initial quality and the setting of the quality limit will affect the keeping quality. The effect of both parameters can be visualized in Fig. 1 by imagining the quality limit to shift over the Y axis or the initial quality to change by a shift of the imaginary starting point of an experiment over the X axis. Keeping quality is then, by definition, the time at which the quality crosses the quality limit line. The change in keeping quality depends strongly on the kinetics of the quality decrease in time.

Multiple limiting quality attributes at constant temperatures

In many horticultural products, the quality attribute that limits the acceptance by the consumer shifts from one attribute at a certain temperature to another attribute at another temperature. This can for example be observed in chilling sensitive products. For the description of this more complex situation, let us assume that the storage temperature remains constant during the whole storage period, but the quality attribute that limits the keeping quality of the product changes from one attribute to another, depending on the level of the constant temperature. In tomatoes, for example, kept at constant temperatures below 8°C the limiting factor is usually the colour, above 13°C it is firmness. The extension to be made to the previous model is to determine which quality attribute is limiting at which temperature. Each separate quality attribute has to be described by its own kinetic mechanism. Next, all the quality attributes described have to be combined in some expression. The central issue in this problem is to deduce that expression for combining the effects of the separate quality attributes.

For theoretical and mathematical considerations, a clear distinction has to be made between attributes and processes. For applications in practice the process active in decreasing the quality and the quality attribute it is connected to, can be considered exchangeable, as they will be connected on a one-to-one basis in most cases.

In solving this problem a distinction has to be made between non-interfering and interfering quality processes. Non-interfering processes can be considered as additive at the level of differential equations, interfering ones as multiplicative.

Non-interfering processes

In non-interfering processes, the change of each quality attribute can be described by its own process without interference of other quality attributes. So, part of the overall quality decrease is connected to that specific process. The combination of each of these processes for each of the quality attributes then describes the decrease of overall quality. Unless explicitly asked for, consumers and expert panellists directly judge overall quality without first assessing the different attributes separately and then combining them into a final judgement. Assuming the same type of kinetics for each process (e.g. first order), this situation for three separate processes, acting on the same overall quality, is depicted in equation (12). For the three different processes, each potentially effective in decreasing quality, one could consider e.g. chilling injury (index 1), decrease of quality at intermediate temperature (index 2) and high temperature injury (index 3).

$$Q \xrightarrow{k_1} \text{decrease}$$

$$Q \xrightarrow{k_2} \text{decrease}$$

$$Q \xrightarrow{k_3} \text{decrease}$$

hence

$$\frac{dQ}{dt} = -(k_1 + k_2 + k_3)Q \tag{12}$$

Solving the differential equation for overall quality at constant temperatures generates a solution as shown in equation (13), which is very similar to the solution for a single limiting attribute (eqn (6)).

$$KQ = \frac{\log_e\left(\frac{Q_0}{Q_l}\right)}{k_1 + k_2 + k_3} \tag{13}$$

Each of the individual reaction rates, however, will exhibit its own Arrhenius type dependency on temperature (see eqn (10)). Consequently, the keeping quality will be inversely proportional to the sum of the three rate constants, each with its own temperature relation. The process or quality attribute that limits the acceptance of the product at a particular temperature will be the dominant factor in the denominator at that temperature, thereby effectively reducing the influence of the other two processes at that temperature. The level of constant temperature will determine which one of the three processes is limiting.

Of course, the formulation will be different for the other types of kinetics (linear or autocatalytic). That situation is not worked out in this paper. The solutions are, however, similar to the respective single attribute situation but again with a summation over all the reaction rates in the denominator. The situation will also be different and much more complicated if the type of kinetics is not the same for the three processes. One of the processes, however, will prevail at a certain temperature, thereby determining for the major part of the mechanism involved.

Interfering processes

When the processes or quality attributes do interfere with one another, the situation becomes very complex. Logical assumptions for obtaining a common or generic model can no longer be made. In that case, the different processes, including the interferences, have to be modelled separately. The formulation and implementation of interfering processes are well beyond the scope of this study. An example for this approach can be found in the chilling injury model derived by Tijskens *et al.* (1994*a*).

DYNAMIC MODEL

Until now, the model describes the keeping quality at fixed storage temperatures. The equations derived up to now, may consequently exclusively be applied at constant conditions of temperature, initial quality and quality acceptance limits. Temperatures, however, usually change dynamically during the lifetime of a commodity. Also, large differences in scenarios may be encountered for different storage and distribution situations. The fact that the proposed model fits well for a large number of products over a broad range of constant temperatures (see Results) indicates that in conditions occurring in practice, the basic assumptions are valid. If these assumptions are valid and if the quality attribute, that limits the keeping quality at a certain temperature, changes gradually from one attribute to another with changing temperature, then a dynamic approach is allowed.

As keeping quality is not a fundamental property like quality or a quality attribute, but a secondary one, predicting the time (to come) a product can endure, keeping quality itself can not be modelled dynamically. Based on the derivation of the proposed model, however, the necessary dynamics can be deduced from the kinetics for the overall quality (eqns (1) to (9)).

Constant boundary conditions

With a dynamically changing temperature acting on a decreasing quality, the remaining keeping quality at some standard temperature has to be calculated to compare different time temperature combinations and scenarios. This is the same technique as used by van Beek *et al.* (1985), Sprenger Institute (1986), Labuza *et al.* (1992) and Paull (1993). The remaining keeping quality is then called shelf-life. The standard temperature may be chosen as appropriate for a particular application or commodity. To compare various commodities, however, application of the same standard temperature is recommended.

The quality function $f(Q)$ for each type of kinetics is exactly the inverse function of the quality behaviour at constant temperature. Consequently, the keeping quality will change linearly during the (very small) time period during which the temperature can be considered constant. For each day of storage a certain fraction of keeping quality will vanish. The slope of the linear change will depend on the storage temperature as described by the complex rate constant (see the denominator of eqn (16)). Provided the quality limit remains the same throughout the storage period and provided the initial quality is the same as or comparable to the measuring situation, the dynamic model can be formulated as:

$$KQ_{\mathrm{st}} = KQ_{\mathrm{ref}} - \frac{\int_0^t k(T(t))\mathrm{d}t}{k(T_{\mathrm{st}})} \tag{14}$$

Although the type of kinetic mechanism of quality decrease is of major importance for the quality attribute itself, it completely disappears from the equation for keeping quality by the mere fact that the quality function $f(Q)$ is the inverse function of quality decay. If the model on keeping quality is solely applied on a local level (that is a constant limit of quality acceptance), or if one is only interested in keeping quality for reason of comparison (e.g. chain optimization) keeping quality can dynamically be estimated without any information about the type of mechanism involved.

Variable boundary conditions

The description and application of dynamic keeping quality becomes more complicated when the initial quality and/or the quality limit do not remain constant. The value of the quality attribute, determining the consumer acceptance, can no longer be represented by its analytical function but has to be expressed as the integral of the change in time with varying environmental temperatures. This dynamic change in quality applies the direct reaction rates instead of the relative ones with $k_{\mathrm{ref}}(1)$ equal to one as used in equation (16) and estimated in Tables 2 and 3. These direct reaction rates can be calculated if the initial quality (Q_{m0}) and quality limit (Q_{ml}) of the measured data set are known. The ratio between measuring conditions and actual conditions provides the necessary correction factor. The dynamic keeping quality with variable initial and limiting quality can be formulated as in equation (15). This equation not only corrects dynamically for varying initial quality, but also allows discrete changes in quality limit.

$$KQ_{\mathrm{dyn}} = \log_e \frac{\left(Q_{\mathrm{b0}} - \int\limits_{t=0}^{t} \frac{-\log_e\left(\frac{Q_{\mathrm{m0}}}{Q_{\mathrm{ml}}}\right) k(T(t)) Q_{\mathrm{b}}(t)\,\mathrm{d}t}{Q_{\mathrm{bl}}} \right) KQ_{\mathrm{ref}}}{\log_e\left(\frac{Q_{\mathrm{m0}}}{Q_{\mathrm{ml}}}\right) k(T_{\mathrm{st}})} \tag{15}$$

RESULTS AND STATISTICAL ANALYSIS

Both systems, a single limiting attribute for a range of constant temperatures, and multiple limiting attributes shifting gradually over the temperature range, can be described in one function relating keeping quality with temperature. In equations (3), (6), (9) and (10) no algebraic simplifications were applied, nor was it verified whether each parameter could be statistically estimated. From the four parameters in equation (13) (one on the numerator and three in the denominator) only three can be estimated: the equation is over-parametrized. In equation (16), the system is fully developed towards a formulation more useful for practical application and statistics.

$$KQ = \frac{KQ_{\mathrm{ref}}}{\sum_{i=1}^{N} k_{\mathrm{ref}}(i)\, e^{\frac{Ea(i)}{R}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T_{\mathrm{abs}}}\right)}} \tag{16}$$

TABLE 2

Estimated parameters for a single limiting attribute, based on equation (16). Data from the Sprenger Institute (1986)

			Estimated parameters			*Standard error*	
Product	R^2_{adj}	*N*	KQ_{ref}	$k_{ref}(1)$	$Ea(1)/R$	KQ_{ref}	$Ea(1)/R$
Asparagus spears	98·4	1	2·876	1	13 018·0	0·359	1185·0
Bean broad	95·3	1	3·701	1	12 520·0	0·575	1420·0
Blackberry	99·4	1	2·768	1	6669·0	0·0728	277·0
Brussel sprouts	94·1	1	1·552	1	17 147·0	0·408	2067·0
Cabbage, Chinese	99·8	1	6·814	1	9817·0	0·223	295·0
Cabbage, Savoy green	95·4	1	0·657	1	33 144·0	0·385	3915·0
Cabbage, Savoy red	92·4	1	12·250	1	20 270·0	4·71	3256·0
Cabbage, Savoy yellow	92·4	1	12·250	1	20 270·0	4·71	3256·0
Cabbage, white	92·9	1	20·150	1	18 565·0	6·38	2714·0
Carrot, winter	93·4	1	25·190	1	14 233·0	6·18	2184·0
Carrot, unwashed	97·6	1	8·401	1	24 076·0	1·80	1830·0
Carrot, washed	95·0	1	1·983	1	19 855·0	0·465	2066·0
Cauliflower	99·4	1	6·074	1	14 944·0	0·461	667·0
Celeriac	99·3	1	35·460	1	11 852·0	1·62	427·0
Celery	99·5	1	4·920	1	13 518·0	0·297	482·0
Celery, blanched	93·9	1	0·622	1	28 877·0	0·343	4548·0
Cherry	99·7	1	4·913	1	8797·0	0·0925	205·0
Chicory	99·4	1	5·347	1	11 283·0	0·221	382·0
Currant, black	98·4	1	3·096	1	10 304·0	0·232	623·0
Currant, red	98·8	1	5·001	1	10 426·0	0·291	554·0
Endive	97·5	1	2·914	1	11 917·0	0·381	1170·0
Gherkin	94·7	1	6·602	1	10 947·0	0·548	1348·0
Gooseberry, ripe	98·8	1	5·001	1	10 426·0	0·291	554·0
Gooseberry, unripe	98·8	1	7·869	1	9544·0	0·403	496·0
Grape	99·9	1	33·500	1	13 699·0	1·23	340·0
Kale	97·2	1	3·892	1	14 684·0	0·601	1401·0
Kohlrabi + leaf	100·0	1	12·680	1	6892·8	0·0919	70·2
Leek	98·4	1	5·311	1	14 021·0	0·865	1264·0
Lettuce	98·7	1	2·762	1	11 015·0	0·233	765·0
Lettuce, iceberg	99·7	1	4·885	1	8192·0	0·135	260·0
Mushroom	99·8	1	2·410	1	6194·0	0·0309	140·0
Onion	98·7	1	99·570	1	6696·0	5·14	403·0
Onion, cut	99·4	1	1·825	1	4202·0	0·0439	229·0
Onion, hand peeled	94·2	1	4·499	1	8826·0	0·600	1228·0
Onion, machine dry peeled	100·0	1	3·374	1	5992·0	0·0209	61·6
Parsley	99·5	1	5·099	1	12 125·0	0·242	397·0
Pea green	98·9	1	2·194	1	8703·0	0·084	391·0
Peach	88·0	1	2·105	1	13 301·0	0·503	2176·0
Plum Victoria	98·5	1	6·393	1	8634·0	0·412	590·0
Purslane	97·2	1	2·586	1	5708·0	0·119	494·0
Radish, black + leaf	98·3	1	2·276	1	9313·0	0·109	474·0
Radish, black − leaf	99·5	1	24·730	1	12 272·0	1·09	410·0
Raspberry	96·9	1	2·528	1	5996·0	0·133	558·0
Rhubarb + leaf	98·4	1	2·144	1	9770·0	0·107	486·0
Rhubarb − leaf	100·0	1	6·221	1	9099·7	0·0514	81·9
Spinach	99·7	1	2·523	1	8766·0	0·071	267·0
Strawberry	99·9	1	2·226	1	4492·1	0·0104	48·9
Turnip	99·3	1	62·910	1	8285·0	2·69	404·0

TABLE 3

Estimated parameters for two limiting attributes, based on equation (16). Data from the Sprenger Institute (1986)

Product	R^2_{adj}	*N*	*Estimated parameters*					*Standard error*			
			KQ_{ref}	$k_{ref}(1)$	$Ea(1)/R$	$Ea(2)/R$	$k_{ref}(2)$	KQ_{ref}	$Ea(1)/R$	$Ea(2)/R$	$k_{ref}(2)$
Bean, French	80·0	2	5·985	1	9712·0	−32 694·0	0·0549	0·858	3185·0	12 064·0	0·0734
Bean, runner	92·5	2	5·731	1	11 173·0	−57 151·0	0·0015	0·604	2473·0	17 662·0	0·0029
Bean, slicing	85·1	2	5·029	1	8712·0	−34 147·0	0·0374	0·425	2488·0	9852·0	0·0410
Beetroot	99·1	2	75·740	1	21 126·0	−18 987·0	0·0473	7·030	3425·0	11 788·0	0·0622
Bell pepper	98·6	2	11·800	1	15 458·0	−40 449·0	0·0648	0·476	1127·0	3492·0	0·0202
Cucumber	97·6	2	15·040	1	4343·0	−19 206·0	0·6800	2·160	960·0	3073·0	0·2800
Kohlrabi – leaf	98·9	2	40·930	1	13 023·0	-44 540·0	0·0005	2·120	1952·0	77 013·0	0·0050
Papaya (data Paull, 1993)	95·5	2	30·040	1	6387·0	-21 390·0	0·5330	4·670	777·0	2850·0	0·1860
Tomato	98·6	2	26·510	1	9369·0	−50 697·0	3·1500	4·020	1594·0	7104·0	0·7260

N stands for the number processes contributing to the keeping quality. This number is usually not greater than two. The value of the first reaction rate at reference temperature $k_{ref}(1)$ is put to one. So, the numerator in equation (16), KQ_{ref} in equation (16) stands for the quality function divided by the reaction rate of the first component $f(Q)/k_{ref}(1)$. $f(Q)$ is called the quality function by Taoukis & Labuza (1989) and is defined by the type of kinetics involved (see eqns (3), (6), (9) and Table 1). All reference reaction rates in the denominator stand for the ratio of the reference reaction rates $k_{ref}(i)/k_{ref}(1)$. They each represent the relative importance of the Nth quality process at the reference temperature.

In the single process system ($N = 1$) KQ_{ref} represents the keeping quality at the reference temperature. At the same reference temperature, KQ_{ref} can be directly used to compare the keeping quality of various products. In a multiple process system ($N > 1$), KQ_{ref} represents the keeping quality at reference temperature for the first process only, without an effect of the other processes. By putting the first reference reaction rate $k_{ref}(1)$ to one, not only statistical analysis becomes possible without information of the level of the quality function $f(Q)$ (only information about the ratio to $k_{ref}(1)$ is needed), but the remaining reference reaction rates as well as the expression for keeping quality become virtually independent of the kinetic mechanism involved.

The hypothesis that keeping quality is inversely proportional to the sum of the reaction rates of the decrease in quality, irrespective of the mechanism and the number of limiting attributes involved, has been tested on data for a number of products (Sprenger Institute, 1986; Paull, 1993). The reference temperature is arbitrarily chosen to be 10°C. First the data were analysed with N equal to 1. When the percentage variance accounted for (R^2_{adj}) was smaller than 80%, for example for chilling sensitive products, N was put to 2 and the data were re-analysed also estimating the second reaction rate. In Table 2 the results and standard errors for about 50 products with only a single limiting attribute are shown. Table 3 shows the results for products with two limiting attributes.

The possibilities and benefits of application of the dynamic model (eqn (15)) in international transport have already been presented (Tijskens & Polderdijk, 1994). The dynamic keeping quality formulated in equation (14) has successfully been used in visualizing differences in temperature profiles over different types of packages. In a simulated transport two designs of storage crates generated for the same sequence in external temperature, shown in Table 4, a slightly different sequence of product temperature. Based on this product temperature sequence, the keeping quality of stored french beans was calculated according to equation (14). In Fig. 4 the calculated keeping quality is shown for french beans in the two dynamically changing product temperature scenarios.

TABLE 4
Temperature sequence in simulated transport

Action	*Temp (°C)*	*Time (hr)*
From auction to export firm		
Transport	8	1
Packing	16	1
Storage	8	4
From export firm to distribution centre		
Transport	8	4
Storage	8	2
From distribution centre to retail		
Transport	19	2
Sales	19	48

FURTHER DEVELOPMENT AND VALIDATION

In the formulation of the model (eqn (16)) the effects of initial (Q_0) and boundary conditions (Q_1) are separated from the dynamic processes ($k(i)$). As a consequence, all terms and parameters have a distinct physical or chemical meaning. The external storage conditions like temperature, controlled atmosphere, modified atmosphere and relative humidity, will only have an effect on the rate of the occurring reactions. Preharvest or growth conditions will only have an effect on the potential keeping quality (KQ_{ref}) and will act upon the level of initial quality. Based on the data of Lange & Cameron (1994) on the keeping quality of sweet basil as affected by the diurnal harvest time, this aspect of the formulation for keeping quality was investigated. It was found that for each of the harvest times (from 2 a.m. to 10 p.m.) the reaction rates and their temperature dependency were almost the same. Only the potential keeping quality (KQ_{ref}) was affected by the diurnal harvest time, showing a sinusoidal behaviour with harvest time. The applied formulation for keeping quality was altered to include this phenomenon:

$$KQ = \frac{KQ_{\max}(\beta + \sin(\omega \text{ Harvest time} + \alpha))}{\sum_{i=1}^{N} k(i)} \tag{17}$$

Non-linear regression on the complete set of keeping quality data with diurnal harvest time, time and temperature of subsequent storage as explaining variables gave a percentage variance accounted for (R^2_{adj}) of about 90%. The estimated parameters and their standard error are shown in Table 5. The difference between measured and calculated keeping quality was well within the range of observed variation.

TABLE 5
Estimated parameters for sweet basil according to equation (17). Data from Lange & Cameron (1994)

Product	R^2_{adj}	KQ_{max}	$k_{ref}(1)$	$E(1)/R$	$k_{ref}(2)$	$E(2)/R$	α	β
Parameter	89·3	6·99	1	9550	2·89	−14 980	3·344	5·22
Standard error		2·57		1947	1·34	2400	0·194	1·02

DISCUSSION

The model was found to be generic and applicable to all products analysed, from moderate as well as from tropical areas. The percentage variance accounted for (R^2_{adj}) is high and all standard errors are relatively small, irrespective of the number of attributes involved, irrespective of the absolute magnitude of the keeping quality and irrespective of the origin of the commodities (from tropical or moderate areas). In the analysis of 60 commodities only three products showed a percentage variance accounted for (R^2_{adj}) below 90%. Increasing the number of attributes to three or more was never required. Statistical validation for each commodity separately (R^2_{adj}) combined with generic validation (number of products) indicates the model to be quite reliable and powerful. In Fig. 2 the measured and calculated keeping quality for a single ($N=1$, lettuce) and a double ($N=2$, tomato) attribute system is shown.

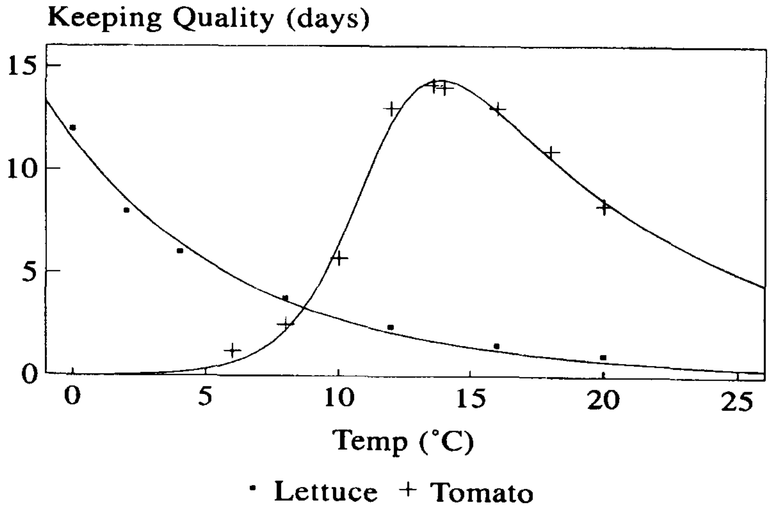

Fig. 2. Measured (points) and calculated (solid line) keeping quality for lettuce and tomato.

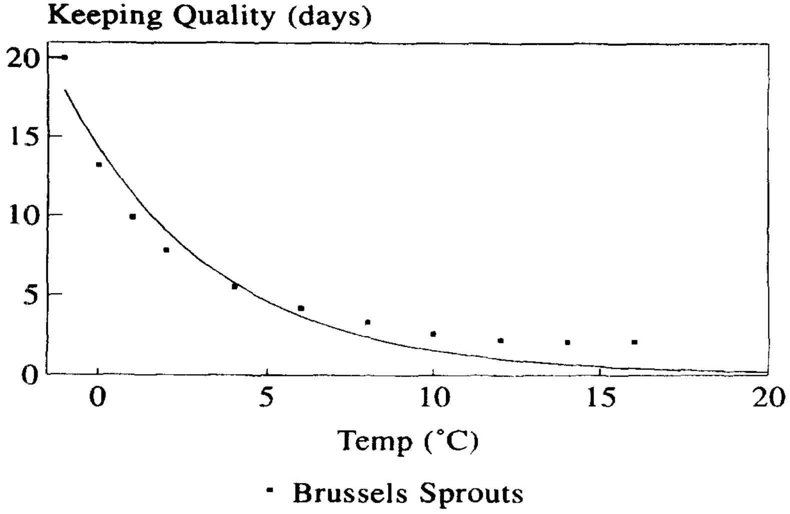

Fig. 3. Measured (points) and calculated (solid line) keeping quality for Brussel sprouts, showing abberration at high temperatures

Some products exhibit a value for keeping quality at higher temperatures, somewhat higher than predicted by the model (see Fig. 3 for brussel sprouts). This deviation could not be fixed by introducing of another term ($N > 1$). Apparently, some threshold in keeping quality is present for these

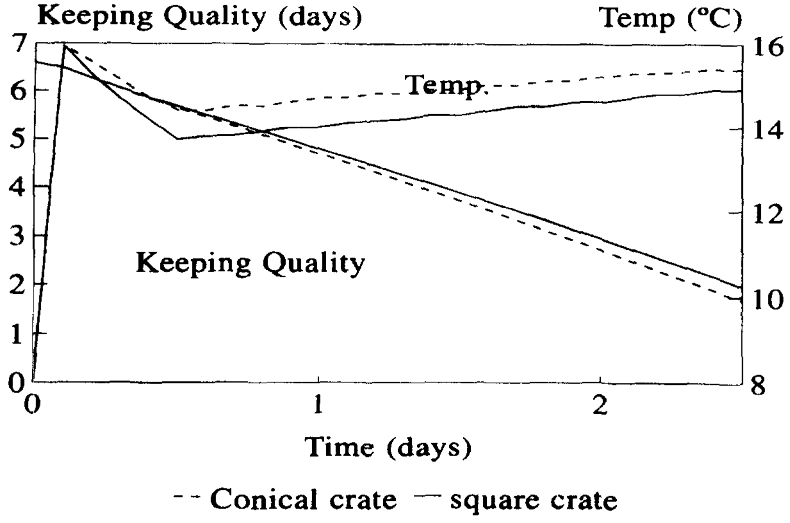

Fig. 4. Dynamic keeping quality of French beans at different histories.

types of products. This may be due to a mix of types of mechanisms in equation (12), e.g. one exponential with one linear mechanism (see section on non-interfering processes). This mathematical system with mixed mechanisms has been solved using MAPLE V. The solution, however, was not suitable for a generic approach, and was excluded from further investigation.

External factors (like temperature and harvest time) behave indeed as postulated in the deduction of the formulation. As a consequence, the applied decomposition of the problem and the resulting model can be considered to be valid. What causes the sinusoidal effect of the diurnal harvest time cannot be discovered with the available data. A link to the intensity (α) and the quality (β) of the sunlight seems to be likely.

CONCLUSIONS

Keeping quality can be modelled by one generic model suitable for static applications and for statistical analysis. More than 60 different horticultural products comply in storage at constant temperature to the proposed model with a high degree of reliability.

Dynamic modelling of keeping quality is possible provided the dynamic changes in temperature are not too excessive over the storage and distribution period.

The mechanism of quality decrease, most often neither recorded nor reported, provides the necessary information to allow description of the influence of initial and limiting quality. Based on this knowledge and on the derived relations, changes in keeping quality by differences between international and local acceptance (for example fashion and preferences) can be described and predicted. Consequently, information based on local acceptance can be translated to regions with different accepting customs.

The applied decomposition of the problem allows one to link the effects of external factors, preharvest and postharvest, to those model parameters that, based on the common rules of kinetics, are most likely to be involved.

Optimization, with respect to quality, of complete storage and distribution chains now comes into perspective.

Both fundamental as well as applied research can use the same concept of keeping quality, based on the simplified description of quality decay. This will greatly enhance the exchange of information between fundamental research and practical application.

ACKNOWLEDGEMENTS

This study was conducted in the framework of a research programme on fruits and vegetables, partly financed by the Dutch Commodity Board for Vegetables and Fruits. The valuable discussions with Dr W. G. van Doorn and Prof. Dr J. de Baerdemaeker are gratefully acknowledged.

REFERENCES

Chang, R. (1981). *Physical Chemistry With Applications to Biological Systems.* Macmillan Publishing Co., New York.

France, J. & Thornley, J. H. M. (1984). *Mathematical Models in Agriculture.* Butterworths, London.

Fu, B. & Labuza, T. P. (1993). Shelf-life prediction: theory and application. *Food Control,* **4,** 125–133.

Hardenburg, R. E., Watada, A. E. & Wang, C. I. (1986). *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stock.* U.S. Dept. of Agriculture, Agriculture Handbook, No. 66, revised edition.

Janse, J. (1989). Effects of humidity, temperature and concentration of the nutrient solution on firmness, shelf life and flavour of sweet pepper fruits (*Capsicum annuum* L.). *Acta Horticulturae,* **244,** 123–132.

Kader, A. A. (1992). Postharvest biology and technology: an overview. In *Postharvest Technology of Horticultural Crops,* ed. A. A. Kader. University of California, Publication No. 3311.

Labuza, T. P., Fu, B. & Taoukis, P. S. (1992). Prediction for shelf life and safety of minimally processed CAP/MAP chilled foods: a review. *Journal of Food Protection,* **55,** 741–750.

Lange, D. D. & Cameron, A. C. (1994). Postharvest shelf life of sweet basil (*Ocimum basilicum*). *HortScience,* **29,** 102–103.

Meffert, H. F. Th. & van Vliet, P. (1974). Wärmeschutz, -grad und Wärmeschutzkosten bei Kühltransporten. *Klima-Kälte-Technik,* **9,** 126–130.

Monnot, P. (1990). Internal quality as marketing instrument. *Acta Horticulturae,* **259,** 25–30.

Paull, R. E. (1993). Tropical fruit physiology and storage potential. In *Proceedings of an International Conference on Postharvest Handling of Tropical Fruits,* 19–23 July, Chiang Mai, Thailand, pp. 198–204.

Polderdijk, J. J., Tijskens, L. M. M., Robbers, J. E. & van der Valk, H. C. P. M. (1993). Predictive model of keeping quality of tomatoes. *Postharvest Biology and Technology,* **2,** 179–185.

Reid, M. S. (1992). Maturation and maturity indices. In *Postharvest Technology of Horticultural Crops,* ed. A. A. Kader. University of California, Publication No. 3311.

Ross, G. J. S. (1990). *Nonlinear Estimation.* Springer Verlag, New York.

Segurajaurgui Alvarez, J. & Thorne, S., The effect of temperature on the deterioration of stored agricultural produce. In *Developments in Food Preservation, Part 1,* ed. S. Thorne. Applied Science Publishers, London.

Shewfelt, R. L. (1990). Quality of fruits and vegetables. *Food Technology,* **44,** 99–106.

Sprenger, A. M. (1937). *Het Leerboek van de Fruitteelt* (The Handbook of Fruit Growing). Elsevier, Amsterdam.

Sprenger Institute (1986). *Produktgegevens Groente en Fruit.* Mededeling No. 30.

Taoukis, P. S. & Labuza, T. P. (1989). Applicability of time–temperature indicators as shelf-life monitors of food products. *Journal of Food Science*, **54**, 783–788.

Thornley, J. H. M. (1976). *Mathematical Models in Plant Physiology.* Academic Press, London.

Tijskens, L. M. M. (1993). Modelling colour of tomatoes. Advantage of multiple nonlinear regression. In *Proceedings COST94 Workshop*, September, Leuven, Belgium.

Tijskens, L. M. M. & Evelo, R. G. (1994). Modelling colour of tomatoes during postharvest storage. *Postharvest Biology and Technology*, **4**, 85–98.

Tijskens, L. M. M. & Polderdijk, J. J. (1994). Keeping quality and temperature, quality limits and initial quality. In *Proceedings COST94 Seminar on Quality Criteria*, 19–21 April, Bled, Slovenia.

Tijskens, L. M. M., van Kooten, O. & Otma, E. C. (1994*a*). Photosystem 2 quantum yield as a measure of radical scavengers in chilling injury in cucumber fruits and bell peppers. *Planta*, **194**, 478–486.

Tijskens, L. M. M., Sloof, M. & Wilkinson, E. C. (1994*b*). Quality of perishable produce. A philosophical approach. In *Proceedings COST94 Workshop*, October, Wageningen, The Netherlands.

van Beek G., Boerrigter, H. A. M. & Nereng, B. (1985). *The Use of a Storability Diagram for Mushrooms*, Report No. 2299 Sprenger Institute, Wageningen, The Netherlands.

van Doorn, W. G. & Tijskens, L. M. M. (1991). FLORES: a model on the keeping quality of cut flowers. *Agricultural Systems*, **35**, 111–127.

Watada, A. E., Herner, R. C., Kader, A. A., Romani, R. J. & Staby, G. L. (1984). Terminology for the description of developmental stages of horticultural crops. *HortScience*, **19**, 20–21.

Willcox, F., Hendrickx, M. & Tobback, P. (1993). Evaluation of safety and quality of 'grade 4' products. In *Proceedings COST94 Workshop*, September, Leuven, Belgium.