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KARPOGRAPHY: A GENERIC CONCEPT OF QUALITY FOR CHAIN ANALYSIS AND KNOWLEDGE TRANSFER IN SUPPLY CHAINS

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Abstract

As with other areas of science, supply chain analysis suffers from the fact that practitioners of its different component disciplines often find it exchange results and methods of analysis. For fresh produce supply chains a key issue is how to unite the elegant mathematical work on the physiology of quality change with the more qualitative methods of social science that are applied to the analysis supply chain management. This paper explores the possibility of utilising approaches which are widely used in demography to unify concepts of quality modelling and supply chain efficiency in the fresh produce sector. A key feature of demographic (or karpographic) models is that they use the average properties of individuals to model the behaviour of cohorts (or batches) and thus have a direct means of including biological variance within their scope. We illustrate the potential of matrix projection models to provide a simple way to unite mathematical analyses of keeping quality and subjective and qualitative analyses of supply chain efficiency. Among other results, the paper demonstrates a rational basis for the assumption, which has been adopted in recent policy changes to the EU food and agriculture policy, that short (or local) supply chains are, ceterus paribus, superior to longer ones. The analytical approach suggested spans the gap between theoretical modelling and knowledge transfer in a single step and requires no more to allow parameterisation than the elicitation of subjective probability estimates from supply chain participants on the transition of produce from one quality class to another.

Keywords: Quality, modelling, matrix model, variance, supply chain, probability

INTRODUCTION

"*A man coins not a new word without some peril and less fruit; for if it happen to be received, the praise is but moderate; if refused, the scorn is assured*" (Jonson, 1640).

The roots of the English word demography are the Greek words *demos* – the people – and *graphos* – from *graphein*, to write. Thus, demography, or demographic analysis is, literally, writing on, or the study of, people.

Demographic modelling exemplifies an approach to science which Turchin (2003) has referred to as *methodological individualism*. This approach, which owes much to Koestler's (1967) theories of hierarchical systems, assumes that the appropriate level at which to seek an explanation for the behaviour of a system is at the next scale down in the hierarchy of organisation. In demography the appropriate means to understand the behaviour of populations is considered to be through the study of the properties of individuals. By studying populations composed of individuals within categories, demographers are able to predict not only the size but also the structure of populations over time. We now highlight a long-standing goal of scientists researching quality in fresh produce to understand the behaviour of batches of produce (Tijskens & Polderdijk, 1996; Hertog, 2002; Schouten *et al*., 2002; Tijskens *et al*., 2003). There is a clear analogy between the wish of demographers to explain population behaviour in terms of individual vital rates, and the wish of post-harvest scientists to understand the behaviour of batches of produce in terms of the properties of individual items. This analogy in problem structure between the two disciplines is what prompts the suggestion of the term *karpography* (from the Greek *karpos* – fruit – and *graphos*) as a supply chain equivalent of demography. However, the intention here is not simply to make a play on words. Even if we reject the term *karpography*, the world of fresh produce supply chains can learn a great deal from the way different conceptual approaches are combined in the discipline of demography. The previous conference in this series (Tijskens & Vollebregt, 2003) highlighted the need for better knowledge transfer among the disciplines involved in supply chain analysis. The need was re-stated in the inaugural edition of the *International Journal of Postharvest Technology and Innovation* earlier this year (Tijskens & van Kooten, 2006). This paper attempts to show how some of the ideas used in demography might help to meet that need. In particular, the work reported here was stimulated by the question of how to provide a set of analytical tools which could span the gap between the approaches exemplified in the papers by Collins (2003) and Tijskens (2003) presented at the 2003 conference.

THE QUALITY CHAIN GRAPH (QCG) AND QUALITY PROJECTION MATRIX (QPM): CENTRAL ELEMENTS OF KARPOGRAPHY

The gap between those who approach a subject mathematically and those who take an empirical/observational approach is one which has divided ecology for many decades. Some success in bridging that gap has been achieved through an approach which combines the graphical depiction of the life history of individual organisms, with a formal system of mathematical analysis which utilises matrix algebra. Interested readers who are not familiar with these methods in a demographic context are referred to Caswell (2001) chapters 1 to 4.

The quality chain graph (QCG)

As an illustrative example, consider a perishable fruit commodity which can be graded into one of three mutually exclusive quality classes, q_1, q_2, and q_3 where the quality declines as the class index increases. We assume that, as a result of the usual biological processes, other things being equal, an individual fruits will undergo a non-reversible set of transitions from q_1 to q_2 to q_3. In the period between a batch entering the chain and leaving it, individual fruits are assumed to have finite probabilities of either staying in the quality class they are in, or undergoing one or more transitions to lower quality classes. Figure 1 represents these possibilities graphically, with their (so-called) state transition probabilities p_{ij} (where $i = 1,2\ldots j$ are the indices of one or more quality classes shown by the nodes of the graph). We can see from the graph that, for example, fruit in class q_1 have probability p_{11} of staying in class 1, probability p_{12} to degrading to class 2, and p_{13} of apparently degrading directly from class 1 to class 3. Furthermore, since these three probabilities capture all possible fates for class 1 fruit they must sum to 1 (*i.e.* $p_{11} + p_{12} + p_{13} = 1$).

The quality projection matrix

In Figure 1 the transition probabilities from the QCG have been translated into the corresponding quality projection matrix (QPM). Note that the QPM is a square matrix with one row and one column corresponding to each of the possible quality states. Each of the columns of the QPM contains the transition probabilities for corresponding quality class to undergo a transition to the quality classes corresponding to the rows. So, for example, the diagonal elements of the QPM running from the top, left to bottom right corners contain the probabilities that fruit will remain in the same class during the period between observations as the class to which they belong at the first observation. The lower, off-diagonal elements of the QPM contain the probabilities for degradation of quality between one observation period and the next.

Using the QCG/QPM to analyse supply chain performance

It should be apparent that where quality can be described in a set of discrete categories, it is quite straightforward to draw the generic QCG and translate this into a QPM. Of course, to be of use in a numerical analysis of chain performance we must obtain values for the transition probabilities. These values are a function of the processes operating in each specific chain. From what has just been said we can see that the QCG, in its generic form, deals with the logical possibilities for the quality fate of individual fruit, independent of the type of supply chain which handles it, but constrained by the way in which quality is defined in categories. The definition of quality categories fixes the number of states in the QCG and the number of transition probabilities among the states. Different supply chains result in different specific parameterisations of the generic QCG and QPM by supplying the numerical values for the transition probabilities.

To demonstrate these points we imagine a supply chain comprising four elements: A producer (P); a grader/packer (G); a distributor (D); and a retailer (R). The chain operates in a linear manner, so that batches of fruit move in the order P→G→D→R. Consider a batch of fruit, N in total say, comprising n_1, n_2 and n_3 fruit, of quality classes q_1 ,q_2 and q_3 respectively, entering the supply chain. The quality profile of the batch is fully described by the 3×1 vector $\mathbf{q}_t$. Note that proportions of fruit in each class (*i.e.* n_1/N, n_2/N and n_3/N) can be used instead of the absolute numbers of fruit to describe the quality profile. We will define the start of chain operation as time point, t, and the time point when the chain has processed the batch as t+1. Now, writing $\mathbf{Q}$ for the QPM of the chain, the relationship between the quality profiles of the batches at the start and end of the chain can be written as $\mathbf{q}_{t+1} = \mathbf{Q} \cdot \mathbf{q}_t$; *i.e.* as the result of multiplying the QPM, $\mathbf{Q}$, to the vector $\mathbf{q}_t$ Figure 2 shows an example for the QCG shown in Figure 1 in which the probabilities of fruit remaining in classes q_1 and q_2 have been set to 0.95, while the probability of degrading to a lower class is 0.05. Inspection of Figure 2 shows that batch profiles at the start and end of the chain are, $q_{1,t}$ = 0.99, $q_{2,t}$ = 0.01, $q_{3,t}$ = 0 and $q_{1,t+1}$ = 0.0.94, $q_{2,t+1}$ = 0.049, $q_{3,t+1}$ = 0.001 respectively. In other words, a batch starting with 99% class 1 fruit and 1% class 2 fruit, comprises 94% class 1 fruit, 4.9% class 2 fruit and 0.1% class 3 fruit at the end of the chain.

We note, in passing, that treating quality as a vector of states explicitly leads to an acceptance of inherent biological variance. Vectors describing the **proportion** of a batch in each of the quality classes can be thought of as empirical estimates of the expected frequencies for individuals drawn from a multinomial distribution. Accepting this definition allows access to a well-researched distributional basis for defining and modelling quality statistically (Agresti, 1990).

USING KARPOGRAPHY IN INCLUSIVE ANALYSES OF SUPPLY CHAINS

Collins (2003) highlighted the importance of inclusive processes to the development of successful chains. These involve chain participants actively in research on how to improve the supply chains within which they work,. Key elements identified by Collins (2003) are: **strategic intervention**, by supply chain participants collectively in the analysis and improvement of the chain; **action learning**, involving data collection, reflection and abstraction of general concepts based on specific experiences; and **empowerment** of the participants by encouraging them to take individual and collective responsibility for the actions required in response to the intervention and learning. The following section gives an outline of how karpographic analysis might be used in inclusive processes, to build better chains.

Comparing expectation and reality

Let us assume that the QPM, **Q**, defined above, gives the expected performance for the chain in our example. Furthermore, we will assume that the chain is required, as a minimum standard, to deliver batches with at least 90% class 1 fruit. The results presented in Figure 2 suggest that the chain should meet this standard. Now, the QCG/QPMs deal with events and collapse dynamic temporal processes into probabilities of those events, the transition probabilities changing if the time interval between events is changed. Thus, while we have defined **Q** as the QPM for the whole chain, a separate QPM for each link in the chain ($\mathbf{Q_P}$, $\mathbf{Q_G}$, $\mathbf{Q_D}$ and $\mathbf{Q_R}$, say) could be defined. The action of the chain, overall, on a batch of fruit $\mathbf{q}_t$ is then found by the matrix product $(\mathbf{Q_P}{\cdot}\mathbf{Q_G}{\cdot}\mathbf{Q_D}{\cdot}\mathbf{Q_R})\cdot\mathbf{q}_t$. Letting $\mathbf{Q'} = (\mathbf{Q_P}{\cdot}\mathbf{Q_G}{\cdot}\mathbf{Q_D}{\cdot}\mathbf{Q_R})$, we can write the expected performance of the chain from this analysis as $\mathbf{q}'_{t+1} = \mathbf{Q}'{\cdot}\mathbf{q}'_t$. Now, following an action learning approach, imagine that we give the responsibility for supplying the numerical values in $\mathbf{Q_P}$, $\mathbf{Q_G}$, $\mathbf{Q_D}$ and $\mathbf{Q_R}$ to the supply chain participants in a workshop setting. The number of ways in which we could do this is almost limitless and allows the possibility to very thoroughly explore preconceptions among the participants about chain performance. For example, we could ask each participant to write down their own QPM and construct **Q'** from the results. Alternatively we could ask the participants to role-play and take on the role of the previous link in the chain and write down the corresponding QPM, constructing **Q'** from these values. Or, we could shuffle the assignment of roles at random, or ask each participant to write down a QPM for every link in the chain including their own, resulting in a set of **Q'** matrices each of which can be analysed.

Recalling that the desired minimum performance of our hypothetical chain is to deliver 90% class 1 fruit, imagine that the individual participants assess their own performance as shown in Figure 3. Each of the participants appears to exceed the desired standard by some margin, but the net result, because the performance of the chain overall is the product of the individual links, is a performance below the desired level.

The results this *gedankenexperiment* illustrate why, other things being equal, short supply chains should out-perform long ones. If each component in the chain has only a finite probability of maintaining quality, and if these probabilities are independent of one another, then the overall probability of maintaining quality is the product of the individual probabilities. If these probabilities of maintaining quality are approximately equal in magnitude and = p then the overall probability for a chain with n components is $p_c = p^n$. With p<1 as n increases, p_c decreases.

Figure 3 focuses only on the initial and final quality profiles of the chain. Confronting any discrepancy between expectation and reality in the final quality might, in itself, be a useful experience in chain analysis for participants, but the method can also be used to look at the change in the quality profile at each successive link in the chain. This kind of link-by-link analysis can be backed up with empirical studies based on sampling along the chain (see Nunes *et al.*, 2003). What such an analysis makes obvious, either when based on sampling data or on elicited transition probabilities, is the obvious but important result that the best that any chain participant can do is to pass on the batch to the next link in the chain in the same state that they receive it.

CONCLUSION

The methods presented here appear to offer a lot to the analysis of quality in chains. Most importantly, they link individual and batch characteristics and deal explicitly with within-batch variance while also providing a formal means to connect mathematical and descriptive approaches to the analysis of quality in chains. What is needed now, in addition to a more extensive account of their potential applications, is an empirical examination of their usefulness in the analysis some real supply chains.

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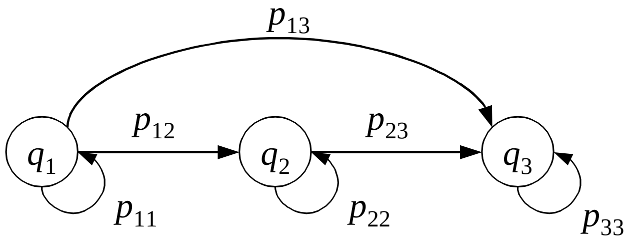
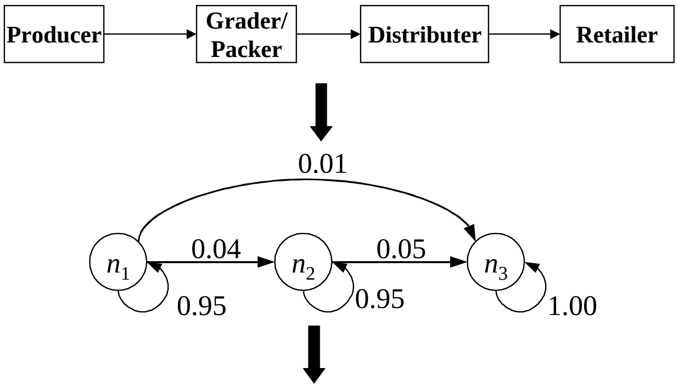


$$\mathbf{Q} = \begin{pmatrix} p_{11} & 0 & 0 \\ p_{12} & p_{22} & 0 \\ p_{13} & p_{23} & p_{33} \end{pmatrix}$$

Figure 1. A generic quality chain graph (QCG) and corresponding quality projection matrix (QPM) for an hypothetical commodity for which three quality categories are distinguished. Quality declines from q_1 to q_3.



$$\begin{bmatrix} 0.94 \\ 0.049 \\ 0.01 \end{bmatrix} = \begin{bmatrix} 0.95 & 0 & 0 \\ 0.04 & 0.95 & 0 \\ 0.01 & 0.05 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.99 \\ 0.01 \\ 0 \end{bmatrix}$$

Figure 2. An illustration of how a particular supply chain leads to the parameterisation of a generic quality chain graph into a particular quality projection matrix.

$$\mathbf{Q_P} = \begin{bmatrix} 0.97 & 0 & 0 \\ 0.02 & 0.90 & 0 \\ 0.01 & 0.10 & 1 \end{bmatrix} \quad \mathbf{Q_G} = \begin{bmatrix} 0.98 & 0 & 0 \\ 0.02 & 0.99 & 0 \\ 0 & 0.01 & 1 \end{bmatrix} \quad \mathbf{Q_D} = \begin{bmatrix} 0.95 & 0 & 0 \\ 0.05 & 0.90 & 0 \\ 0 & 0.10 & 1 \end{bmatrix} \quad \mathbf{Q_R} = \begin{bmatrix} 0.95 & 0 & 0 \\ 0.04 & 0.95 & 0 \\ 0.01 & 0.05 & 1 \end{bmatrix}$$

$$\mathbf{Q} = \begin{bmatrix} 0.95 & 0 & 0 \\ 0.04 & 0.95 & 0 \\ 0.01 & 0.05 & 1 \end{bmatrix} \qquad \mathbf{Q'} = \begin{bmatrix} 0.858 & 0 & 0 \\ 0.113 & 0.804 & 0 \\ 0.0.29 & 0.196 & 1 \end{bmatrix}$$

$$\mathbf{q_t} = \begin{bmatrix} 0.99 \\ 0.01 \\ 0 \end{bmatrix} \quad \mathbf{q_{t+1}} = \begin{bmatrix} 0.9405 \\ 0.0490 \\ 0.0105 \end{bmatrix} \qquad \mathbf{q_t} = \begin{bmatrix} 0.99 \\ 0.01 \\ 0 \end{bmatrix} \quad \mathbf{q'_{t+1}} = \begin{bmatrix} 0.815 \\ 0.145 \\ 0.040 \end{bmatrix}$$

expected delivered

Figure 3. An hypothetical example of using quality projection matrices to examine supply chain performance. Each participant in a four-link chain has reported their own performance. The chain is expected to deliver the performance shown in matrix Q. The actual performance is captured in **Q'**, the matrix product ($\mathbf{Q_P}\cdot\mathbf{Q_G}\cdot\mathbf{Q_D}\cdot\mathbf{Q_R}$). The chain fails to deliver its target performance of 90% class 1 fruit despite each participant exceeding this standard for their own link.