Innovation-oriented Analysis of Critical Control Points (IACCP): Who Wishes to Solve Sweet Pepper Yield Oscillations?

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Abstract
A generic program for mathematical model-supported innovation profiling in fresh food supply chains is presented. Building on top of a crop growth model, strategies to address the problem of sweet pepper yield oscillations (flushes) are analysed quantitatively from both isolated or combined perspectives of the chain players: plant breeders, horticultural growers and traders. Yield oscillations in sweet pepper production, caused by crop physiology, and presumably synchronized by weather conditions, result in periodic oversupply at the market level. Growers try to desynchronise their own temporal yield pattern from that of the market, in order to target higher prices during low supply periods. A complication is that the quality of fruit products, in terms of size and colour/ripeness, may be affected when altering growing practices such as pruning, harvest timing, and climate control. Upstream, breeders can change physiological constants. Downstream, post harvest storage may produce value by better price targeting. The IACCP approach is presented, and is based on systematic decomposition of income, profits, cost and revenues with help of a simulation model. Especially the decomposition of revenues into isolated effects of production yield, price targeting, and various quality characteristics such as fruit size and fruit ripeness/colour shows how synergies between innovation strategies of collaborating (or competing!) players within a supply chain are created (or destroyed). Although the model is not yet fully validated in detail, such simulations may well support discussions on collaborative innovation strategies and on prioritisation of the research agenda.

INTRODUCTION
A major complication for growers of Sweet (bell) pepper (Capsicum annuum) is the periodic oversupply, and accompanying low prices, due to synchronous oscillations in crop yield with a period of about 6 to 8 weeks. These ‘yield flushes’ exist on plant level as a result of ‘abortion’ (spontaneous abscission) of young fruits in periods with heavy fruit loads and certain temperature and light conditions. The resulting ‘demographic gaps’ are difficult to prevent. To a lesser extent the growth of cucumber is characterised by the same phenomenon.

In agricultural chains, probably more than in other industrial supply chains, the large numbers of ‘primary producers’ (growers) presents a game-theoretical problem regarding innovation strategies as the pay-offs of innovations are not necessarily aligned for growers and breeders. Innovative growers that can succeed in (partly) suppress yield flushes will harvest fruits when other growers can not, and enjoy high prices. Growers will adopt an alternative (innovative) practice when the expected profit per square meter improves enough to recover their investment cost of the new growing practice. In contrast, breeders who develop a new cultivar, are interested in both the number of growers who can benefit, and by the profit difference while adopting the new cultivar variety. The complication is that the profit improvement for an individual grower depends on the fraction of growers who already choose to employ the new variety. A dilemma may
arise when individual growers proceed to adopt the new variety beyond the point at which profits for the breeder are maximal. Intricate pricing and exclusivity management is then necessary for the breeder to control the pay-off of its innovation program. In contrast, a national programme aimed at helping the entire sector of horticultural production will naturally adopt a different perspective.

We argue that the nature of this economic game depends on the biological details of the crop at hand, climate and weather conditions and historic micro-economic configurations and arrangements. This would show that in certain agricultural sectors there is no standard textbook optimal business economics approach to innovation management, and a specific multidisciplinary modelling exercise is called for to uncover the optimal innovation program.

**Modelling Approach**

Concerning the modelling approach, we pose the synthesis of simple model elements for the various processes along the whole chain together into a single multidisciplinary model above the development of ever more detailed models for each element in isolation. In turn, the construction of such an integrated model, is subservient to the usage of the resulting model. Understanding how a model helps to address strategic issues thus precedes the model refinement. Furthermore, if parts of a model barely influence the outcome of strategic decisions (in our case the agenda of the various chain players to speed up innovation), the model is simplified. However, two criteria for the model structure may prohibit model simplification: representation of logical (causal) relationships and interpretability. Especially in settings where several players seek ways to collaborate, it is important that they can explain and discuss their logic and assumptions in ordinary language. For example, telling a prospective innovation partner that a “marvellous neural network model” tells you to invest is not a sound basis to build trust. As we think that lack of familiarity and trust among chain partners are important barriers to innovation, we use models as discussion support tool for collaborative innovation strategies. Our approach thus combines mechanistic modelling in the life sciences with system dynamics modelling focused on business economics (Sterman, 2000).

Conceptually, we differentiate the description of the **dynamics** of the core system (e.g. crop growth) from the model components that reflect **control** towards set-points (e.g. of climate variables, such as temperature), **design and operational** practices (e.g. production yield, harvest weight or ripeness, etc.) and **optimisation** of target functions, that may be stakeholder specific (profits, risk etc.). For each of these layers of model components, we very briefly describe our preferred modelling style.

For the description (modelling) of the dynamics of crop growth, we formulate differential equations for the core state variables. Variables have physical dimensions, are interpretable and notions such as time, development stage, carrying capacity or maximum organ size are avoided if possible, as we prefer to translate the ‘local’ biochemical or physiological mechanisms directly in mathematical form.

The effect of the input variables, such as light and temperature, are studied in three ways: as constant, as smooth, pre-defined function (e.g. sinusoidal light intensity pattern over the season, according to latitude), and as measured time series. Using constant or smooth input variables; we can relate certain system behaviours (e.g. endogenous period of oscillations) better to model constants. For empirical validation (not reported), we use actual time series for inputs.

Strategic and operational choices of the stakeholders have been modelled as algebraic functions of indicator variables in the system. For example, the harvest rate (the probability of fruits of being harvested per day) is modelled as an algebraic function of fruit weight and ripeness. Thus there is no single fruit weight or ripeness (e.g. colour) value at which fruits are harvested. In the example, effects of added personnel could follow from the calculation of the maximum harvest rate (e.g. (0.2 day⁻¹) from the number of times per week that grower personnel ‘comes by’ a particular location in the
Finally, regarding the optimisation of target functions, we take grower profits as main output variable instead of fruit harvest yield, precisely to study the effect of fruit quality (in terms of weight and ripeness/colour) and timing of the harvest relative to the fluctuating market prices. Figure 1 gives a graphical representation of the model.

THE INNOVATION ANALYSIS CRITICAL CONTROL POINT APPROACH

First of all four structural questions are addressed to define the problem:
A. Whose perspective is adopted? A single players’ performance or that of the chain? Note that we argue that a single player would still be required to analyse the incentives and pay offs for all other chain players in order to optimally leverage their investment capacities for its own good.
B. What is the goal: Is the target function financial only (e.g. yearly income), or is there more? If so, can these other factors be valued (customer loyalty), or are they a sine-qua-non condition (safety)?
C. What time horizon are we interested in? Is there a single point in time when a certain position must be attained (e.g. a target market share), or is the whole future innovation programme subject to conditions (e.g. grow without making a loss)?
D. What is the needed level of detail? More detail is needed for operational decision support for investments and daily practices than for sessions for strategic learning (e.g. on R&D, collaborations)?

In the present example, we adopt the perspective of innovative growers who wish to optimize their income over one season, in a rather ‘ideal’ computer simulation environment aimed at exploring various innovation strategies. In the future, we would like to address non-financial goals, such as energy use, and add more details in order to support short term operational management decisions.

In the IACCP approach, five steps are taken
1. Find or construct a mathematical model for the core biological processes and link its output variables to financial performance / the target function (of B)
2. Identify critical (sensitive, influential) control points (CCPs) for each player in the chain, both in terms of instantaneous and delayed effects (cf C). A control point is any parameter in the model that can be changed by a player, for example, a physiological constant (for the breeder), or fruit pruning practice (for the grower). A generic example of control points and the state they operate on are presented in Figure 2.
3. Determine the combination of parameter values (CCPs) that jointly maximize the target function. For daily practices, his can be done with time-varying values over the innovation period (in the example, one season), as an optimal strategy (pruning) may change parameters over the course of the season. Note that ‘routine’ reactions on input variables, such as weather conditions are already modelled as a practice with fixed parameters.
4. Construct the fastest or easiest way (“the transition path”) for all players to change their practices in order to approach the optimum from step 3.
5. Determine the smartest incentives for each player in order to minimally deviate from the optimal transition path and obtain acceptability by all players.

In the following we illustrate and report on our progress with this program for the case of sweet pepper yield oscillations. For lack of space we do not present the details of the mathematical models here; for the recently developed crop growth model, we refer to Schepers et al. (2006). The financial model that underlies the innovation game in a supply chain setting, involves formulations describing price forming mechanisms and the valuation of product quality characteristics. The same model is applied to keep track of the harvested yield of the segment of non-innovating growers, as their production volume determines price formation as well. In addition we can see whether the harvested yield, average price, quality level, cost levels and income of the whole production area increases or decreases. This is relevant for the perspective of sector-wide and governmental organizations wishing to assess public innovation programmes. Finally, the difference in
The willingness of individual growers to innovate.

The Financial Situation: Market Price and Quality Effects

Four indicators for the harvested fruits determine daily revenues: 1) daily yield (kg fresh weight per square meter), 2) the market price that each daily batch of produce was sold for, the intrinsic product quality characteristics of 3) average fruit size and 4) average ripeness. When (‘speculative’) storage of fruits is taken into account, the daily harvested yield should be replaced by the volume of ‘fruits brought to the market’. After subtracting costs, both fixed and variable (for capital, labour, energy and storage) income is computed as cumulative daily profits.

The market price was computed endogenously, as its movements over the season are caused by the synchronized harvest pattern of the growers. Price depends on the supply/demand ratio where imports and demand are price-sensitive while the local supply is inflexible unless innovative measures are taken by growers or ‘speculative storage’ is present.

Regarding fruit quality, the price a grower receives is modulated as a function of both average fruit weight (size) of the daily batch, and average ripeness. For fruit size, we assume an expected fresh weight of 200 grams, while for ripeness (in practice colour) a temperature-sum of 50 days at 20ºC was expected. Rough inspection of real life data showed that relative negative deviations of the average fresh weight or ripeness are linearly translated into price effects, while above-expected performance is not rewarded with a price premium.

Some Tentative Results

If the breeder could manipulate the value of the fruit sink strength, it would seem logical to expect that increasing it would benefit fruit yields and thus grower’s income. However, at much increased values of the fruit sink strength, the vegetative parts can not develop as strongly, yielding to less assimilate supply. Thus the model presents a bell shaped profile with an optimum for this parameter (Figure 3, dashed line). However, there is also an effect on the temporal profile of the harvest: stronger fruit sink strength brings about somewhat earlier harvest and with a shorter period of oscillation. Thus, the growers that would use a new variety with an increased fruit sink strength, could desynchronize their harvest pattern from that of their non-innovating colleagues. More interesting still, lowering the fruit sink strength would equally lead to desynchronization of the harvest pattern and equally yield to higher revenues (solid line with two optima). Obviously, this extra profits can only obtained if not all growers in the production area adopt the new crop variety. The upper line in the graph actually shows the profit effect for an infinitely small segment of innovative growers, whose production does not influence price formation. The lower line shows the case where all growers adopt the crop variety with the indicated fruit sink strength. The arrows point to the dilemma: only a small fraction can benefit from the desynchronization strategy, (arrow pointing slightly upward), whereas the whole population would decrease profits if all growers would switch (downsloping arrow).

In the next simulation experiment, we let growers vary the ripeness at which they harvest fruits. One of the options for growers to escape harvesting during periods of market oversupply (when everyone else harvests) is to harvest peppers in a green stage, when the crop was in fact meant to produce yellow or red peppers. Although they receive
a lower price per kg product for green peppers, the oscillatory pattern of fruit bearing of
the crop is changed, resulting in a shifted pattern of harvest relative to growers that let the
fruit completely turn red. The effects of harvesting at a green stage thus are shown by the
decomposition of revenues into effects of yield, price and quality. We can separate the
effects of yield and price by computing the revenues that would have been obtained with
a constant price, reflecting the weighted average market price. As we have made explicit
assumptions on how average fruit size and fruit ripeness affects price, we can compute the
revenues that would have been obtained while setting aside the effects of these quality
properties. Figure 4a show this decomposition of revenues. Clearly the effect of timing
compensates the loss of revenues due to the green colour (lower ripeness) and smaller
fruit size. Figure 4b shows the income per m² for the growers that harvest at the green
stage (dashed line) and at the red stage (solid line), as function of the fraction of growers
that harvest at the green stage (we assume they do so all season long). The point where it
has no further improving effect on income is at about 60%. It is interesting to see how this
figure depends on other parameters in the system. Multiplying these incomes per m² by
the area that adopts either harvest strategy, we see that for the whole population (solid line
on top in figure 4c), the income decreases, as more growers adopt green harvesting,
illustrating the game theoretical aspects of this example.

DISCUSSION AND FUTURE RESEARCH

As the model is based on theoretical considerations, and with only sparse inclusion
of heuristics for sweet pepper growth, we should stress that further validation is necessary
to attach any practical meaning to these ‘thought experiments’. However, as argued
above, we think that exploring the possibilities to translate highly strategic issues into a
simulation environment can be helpful in uncovering relative sensitivities of improved
income towards various innovation interventions at the various control points. Many more
applications, or again, thought experiments can be envisioned: with the mathematical
model at hand, it is possible to compute the effects of altered grower practices, crops with
altered physiological constants (that the breeder may develop), but also to compute the
synergy when both actions are taken at the same time. In this manner, the value of
cooperation can be values quantitatively! Regarding the effect of timing of bringing
agricultural produce to the market, the effect of post-harvest storage is of utmost
importance. Apart from the usual complexity of speculative storage of goods, fresh
produce is perishable. We hope to use the model in order to study the effects of pre-
harvest grower practices to post-harvest keeping quality.

Other quality traits, such as disease proneness of fruits (e.g. blossom-end-rot)
might be modelled by a similar approach as for the temperature sum dynamics, for the
accumulation and distribution of Ca²⁺. Likewise secondary metabolites determining taste,
such as organic acids may be modelled, allowing to optimize harvest timing according
market prices, colour and taste profiles. This would allow to optimise breeder and grower
innovation strategies focused on optimising yield, harvest timing, disease proneness (e.g.
during post-harvest transportation and storage) and a wider range of quality traits than
colour and size, such as taste.

Many drawbacks exist for any model of reality. A ubiquitous simplification in
models is the omission of biological variation among plants, and batches, although this is
an important issue (Tijskens et al., 2003). Monte Carlo simulations may be used to
explore the influence of biological variance between plants or among horticultural
growers. Alternatively the full probability density function could possibly be incorporated
into the model, as was done by Schepers and van Kooten (2006) for a simpler model
describing the effects of variation in fruit ripeness on consumer liking and chain
innovation. In general, we think that in strongly non-linear models, the difference
between inclusion and omission of biological variance, of either initial conditions of state
variables or fixed model constants, increases. Furthermore it should be expected that new
dynamic crop behaviours or economic dilemmas arise because of variance.
Literature Cited

Figures

Fig. 1. A graphical outline of the mathematical model that represents plant and fruit physiology, grower practices, and storage strategies.
Fig. 2. The strategic action that the various chain players can employ to control fruit vegetable production and product quality in order to stimulate consumption.

Fig. 3. Growers’ income per square meter for a small innovative group of growers as a function of a fruit sink strength.
Fig. 4. Revenue decomposition (a) and innovation exclusivity diagrams (b and c).