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Optimisation of traceability and operations planning: an integrated model for perishable food production

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Abstract

The food industry has been under pressure of improving food safety, implementing efficient risk management, and managing quality 'from farm to fork'. Individual parties in a food supply chain must make appropriate strategic and operational adjustments, enhance product quality and increase operational efficiency and profits. In this paper, an optimisation model is developed integrating traceability initiatives with operation factors to achieve desired product quality and minimum impact of product recall in an economic manner. A case study with numerical example is provided to illustrate the theory. Sensitivity analyses are conducted. A comparison between the proposed model and the existing model operating in the case company is also presented.

Keyword: *Food traceability, optimisation modelling, optimal batch size, product recall, risk assessment, perishable food*

1. Introduction

The food industry has been under pressure of improving food safety, implementing efficient risk management and rapid response capabilities, and managing quality 'from farm to fork'. Since the regulation 178/2002 of the European Parliament and of the Council on general food law came into force in 2005, traceability has become an essential business

function for the food industry to consistently supply food products with quality and safety assurance. However, the efforts on building traceability systems have often been separated from profitable supply chain management strategies. This does not only hinder the enthusiasm of investment on efficient traceability systems, but also desert potentials to improve the supply chain efficiency through integration of traceability with operations management functions. This paper will address this issue and develop approaches to integrate traceability initiatives with operations management objectives. In this section, we will review concepts and existing research in relevant areas.

1.1 Traceability in food supply chains

Food traceability is defined as the ability to trace and follow food, feed, and ingredients through all stages of production, processing and distribution (European Commission, 2002). Studies on traceability systems and approaches for achieving different business objectives have been reported in the literature (Wilson and Clarke 1998, Mouseavi *et al.* 2002, Bertolini *et al.* 2006, Peres *et al.* 2007, and Pinto *et al.* 2007). The traceability systems reported in the research articles vary in complexity from simple paper-based recording systems to computer-based information technologies, including the most sophisticated systems with biological technologies. In most cases, the traceability systems have been developed without considering other supply chain activities. Some research (Viaene and Verbeke 1998, Golan *et* al.2004, and Schwagele 2005) argued that being able to track and locate products accurately in supply chains can lower inventory levels, quickly detect difficulties in manufacturing processes, and improve efficiency of logistics and distribution operations.

An integrated traceability system can improve process control and detect cause and effect when a product fails to conform to standards. It is also expected to improve operations planning so that raw material use is optimised (Regattieri *et al.* 2007). To achieve the values

of such integrated traceability systems for business, a key issue is how to seamlessly integrate traceability functions with supply chain management processes so that the traceability information can be used to manage and improve business processes (Wang and Li 2006). Among the studies on traceability issues, quantitative research that identifies benefits of such integration is still rarely found. In our research, relationships among traceability, production batch size, batch dispersion, inventory level, product shelf life, delivery patterns, and product recall impacts are quantitatively analysed.

1.2 Impact of supply chain operations on food traceability

Food products are often tracked and traced by manufacturing batches or logistic units, instead of individual product items (Jansen-Vullers *et al.* 2003). Batch numbers assigned at the start of the manufacturing processes accompany products as identifications throughout a supply chain. If a food safety problem comes from a raw material batch, all the finished products containing this raw material have to be identified and recalled. In the food industry, raw material batches from different suppliers with different prices and quality attributes are often mixed together. This is usually known as a batch dispersion problem which concerns relevant disassembling and assembling processes in the production (Dupuy *et al*. 2005). When raw material batches are mixed in finished product batches, it increases complexity for tracing back. Furthermore it increases the probability of food contamination which may cause potential product recalls. Dupuy *et al*. (2005) developed a traceability optimisation model to minimise the recall size by planning batch dispersions in supply chain operations. The research tried to minimise the impact of manufacturing and delivery processes on the size of possible product re-calls without considering impact of batch size and dispersion on operations performance.

Determining economic production batch size has been a major interest in both theory and practice. Various optimisation models have been developed (Goyal 1977, Sarker and Parija 1994, Sarker and Khan 1999, and Bogaschewsky *et al.* 2001). A large production batch size reduces the production setup cost, but increases stock level which leads to high inventory holding cost. Moreover, a large production batch size may require a mixture of raw material batches from different suppliers to fulfil a production order. Different raw material batches have different costs and risks in failure of meeting quality and safety requirements. Risk for food products is defined as a function of the probability of an adverse health effect and severity of that effect, consequential to a hazard (European Commission, 2002). Most food products contain a certain degree of risk. The magnitude of risk directly affects safety of the foods to public health and possibility of a food crisis that may require a product recall. However, food products can be placed on market as long as the risk is at an acceptable level.

1.3 Production and inventory control for perishable products

When studying perishable food, deterioration and shelf life have to be considered for determination of an economic production batch size. Shelf life is defined as the period between manufacture and retail purchase of a food product during which the product is of satisfactory quality (IFT 1974). It is the length of time that a given item can remain in a saleable condition on a retailer's shelf. Shelf life does not necessarily reflect the physical condition of a product (such as deterioration) since many foods deteriorate after a fixed period of time. However it may reflect the marketable life of a product (Nahmias 1975; Xu and Sarker 2003). Perishable food has a high deteriorating rate and a limited shelf life. It gets spoiled if they are stored beyond a certain period of time under given conditions. Dynamic pricing, planning and inventory control models for the perishable food have been reported extensively in the literature. Goyal and Giri (2001) presented a review of recent published

inventory literature for deteriorating inventory models. One type of the reviewed research is maximising business profits through pricing or allocating perishable products in an operational process according to their fixed shelf life (Bhattacharjee and Ramesh 2000, Zhao and Zheng 2000, Lin and Chen 2003). In such research, the product shelf life is a constraint to a pricing or delivery planning decision. Some research employs a concept, product value, to represent product quality and utility attributes based on which a decision on pricing or operational planning can be made. Li, *et al.* (2006a) proposed an automatic tracking enabled business model for food products. The model employs a dynamic planning approach to optimise retail chain profits. Inventory modelling incorporating the effect of a temporary price discount is another active area. Tersine (1994) developed an inventory model which incorporates the effect of a temporary discount in sale price. Shah *et al.* (2005) developed a mathematical model for an inventory system that considers a temporary price discount when commodities in an inventory system are subject to deterioration with respect to time.

The above research did not integrate batch size and shelf life management with traceability optimisation in manufacturing planning and inventory control. Our research has for the first time proposed an integrated operation-traceability planning model for perishable food management.

1.4 Methods used in the relevant research

Operations planning and design problems in food industry are often related to the choice of raw materials, number and size of batches, etc.. Mixed integer linear programming (MILP) or none linear programming (MINLP) approaches are frequently used for such problems with a clear quantitative objective function or quantitative multi-criteria objectives. Kallrath (2005) reviewed the current state of mixed integer optimisation in the process industry with a special focus on planning, design, global optimisation techniques and optimisation under uncertainty.

Mixed integer optimisation is able to deal with many detailed features such as tracing mode-changes, product origins and shelf life.

Efficient algorithms have been developed to solve these optimisation problems. Golhar and Sarker (1992) developed a simple algorithm with a one-directional search procedure to compute optimal manufacturing batch size and the associated total cost. Khan and Sarker (2002) proposed a heuristic method in which an initial solution for production batch quantity is determined by relaxing the integrity requirement. If the corresponding optimal value is not integer, then an integer in the neighbouring points was searched for the approximated optimal solution. Although this method is relaxed in the solution approach, it can be considered as a simple heuristic to solve the stated problem with less computational efforts and an acceptable level of accuracy.

In addition, simulation experiments have often been employed to numerically analyse model performance, particularly when the analytical solution cannot be obtained. Dupuy et al. (2005) used simulation experiment (LINGO 6.0 software) to solve a MILP problem. Microsoft Excel Solver has been also used to solve such problems (Sarker and Khan, 1999, Li *et al*. 2006b). It can solve linear and nonlinear mathematical programming models with continuous and/or integer variables. Linear and integer problems can be solved by the branch-and-bound method and the simplex method with bounds on the variables. Detailed implementation of the Solver tool can be found in Anderson et al. (1998).

2. Assumptions and notations in the research

The optimisation model is developed in a food manufacturing context with a cooked meat manufacturing case. It can however be applied to any batch production or manufacturing assembly and disassembly lines in perishable food production. According to possible

production patterns of using raw materials, two production scenarios are discussed in the optimisation model as shown in Fig. 1:

Scenario 1, two-level bill of materials (raw materials and finished products) involving multiple batches of different types of raw materials for one batch of finished products.

Scenario 2, three-level bill of materials (raw materials, components and finished products) involving multiple batches of different types of raw materials for multiple batches of components and one batch of finished products**.** This scenario can be extended to more generic situations for multiple-level bill of materials food production processes.

[Figure 1 is to be inserted here]

The model considers a manufacturing system that a production facility processes raw materials from suppliers into cooked meat. The finished products are delivered in a fixed quantity at a fixed time interval. The raw material ordering policy is not considered in this research. To simplify the analysis, following assumptions are made:

(a) Production rate is finite and is greater than demand rate;

(b) Stock shortage is not allowed;

(c) Demand rate is constant and known;

(d) Setup cost for an item is constant;

(e) The raw material is always available and one type of raw material batches could come from different suppliers;

(f) The size of same type raw material batch is constant;

(g) The size of a product batch is equal to the size of raw materials used in the production;

(h) Only the holding cost of finished product inventory is considered in the model;

(i) A fixed quantity of finished products is delivered at a fixed time interval;

(j) There is no constraint in space, capacity or capital;

Notations:

Parameters:

D: Demand rate of a product, units/period;

P: Production rate for a product, units/period (here $P > D$);

A: Unit set-up cost in production, £/set-up;

H: Inventory holding cost of finished products, £/unit/period;

x: Shipment quantity of products at a regular interval (units/shipment);

t: Time interval between successive shipments;

$B_{RF}(k)$: Proportion of the kth type of raw materials used in a finished product;

$B_{RC}(k)$: Proportion of the kth type of raw materials used in a component batch;

K: Type of raw materials;

$W_{i,k}$: Risk rating (weighting) of batch i of the kth type of raw materials;

d: Unit price discount in temporary price discount period, /shipment/time interval;

$P_{i,k}$: Unit price of batch i of the kth type of raw materials;

P_F : Unit transaction price of products;

T_L: Product life;

T_M : Customer acceptable shortest shelf life;

T_C : Contracted shelf life;

Q_k: Batch quantity of the kth type of raw materials;

M: Number of raw material batch types;

N: Number of component batch types;

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Variables

Q: Quantity of a finished product batch;

$Y_{RF}(k)$: Binary variable equal to 1 if the kth type of raw material batches are used in a finished product batch and 0 otherwise;

$Y_{RC}(k)$: Binary variable equal to 1 if the kth type of raw material batches are used in component batch j and 0 otherwise;

$Y_{CF}(j)$: Binary variable equal to 1 if component batch j is used in a finished product batch and 0 otherwise;

S: Integer variable which is the quantity of a type of raw material batches used in a product batch;

n: Integer variable which is the frequency of product shipments, number /period;

Y: Integer variable which is the number of shipments in a temporary price discount period.

This risk rating $W_{i,k}$ is influenced by various factors causing quality and safety problems such as storage condition, process environment and packaging, etc. It can be obtained through various risk assessment approaches. Approaches and models to measure and control the food risk have been available in the literature and authorities' documentation (CAC 2002 and Edler *et al.* 2002). With advanced tracking technologies and networked information systems in food supply chains, the information of risk assessment can be available to supply chain partners more readily nowadays (Li, *et al.*, 2006b). Therefore, in this research, we assume that the risk ratings for each individual raw material batch are available to food manufacturers. The given risk ratings are used to measure recall possibility and cost in the model.

3. Optimisation model

The proposed model is expected to integrate operational objectives with traceability targets in the perishable food production through incorporating risk and cost factors associated with operations management, traceability system, and shelf life management, so that the operational activities and the traceability initiatives can be coordinated towards an optimised system.

3.1 Operational factors

Typical economic production quantity (EPQ) models assume fixed costs for each production setup. The EPQ balances set up and inventory costs in order to minimize total costs. Here, the production setup cost in a planning period is described in equation 3.1.

$$C_{SET} = \frac{D}{Q} A \ . \qquad (3.1)$$

A larger manufacturing batch size reduces the setup cost component in the overall product cost. Food manufacturers often face the fact that retailers want products to be delivered in small quantities at fixed time intervals to minimise their inventory holding cost. This may result in the products produced in one batch being allocated in several deliveries.

Food products require strict quality control. In many cases, for the quality assurance purpose, products cannot be delivered until the whole batch is produced. In our model, the accumulated inventory during the production uptime can not be used for delivery until the whole batch is completed. The next batch production resumes and completes at the time when the inventory from previous batch is exhausted and is ready for next delivery (see Fig.2). There is a staircase pattern in each batch production cycle, but there is no saw-tooth pattern during the production up-time. In the model, we only consider the holding cost of finished product inventory accumulated during the production uptime (the triangular area in

Fig.2) and the inventory ready for delivery (staircase area in Fig.2). The average product inventory level is given in equation 3.2.

$$I_{AVG} = \frac{Q^2}{2P \cdot nt} + \frac{(n-1)x}{2} . \quad (3.2)$$

[Figure 2 is to be inserted here]

Equation 3.2 can be obtained by calculating the relevant area of one batch production cycle in Fig. 2 and dividing it by the cycle time period *nt*. The area consists of one triangle area with the value of $Q^2/2P$, and $(n^2-n)/2$ rectangle areas with the value of *tx*. The integer variable *n* can be replaced by *Q/x*. The inventory holding cost equation can be therefore given as equation 3.3.

$$C_H = \frac{QxH}{2Pt} + \frac{QH}{2} - \frac{xH}{2} . \quad (3.3)$$

3.2 Incorporating traceability factors

Traceability systems would create additional costs for producers and for the food sector as a whole. The magnitude of these costs depends on the type of identification technology (e.g. barcode, wireless scanner and electronic transponders, etc.), the labour for the application and reading of the identification device, and the manner in which traceability data will be maintained (Disney *et al.* 2001). On the other hand, the performance of a food traceability system can be evaluated by its effectiveness in a food crisis: whether it enables to identify, isolate, and correct the problem quickly and efficiently, whether it reduces the scope of a food recall and the volume of products that must be withdrawn, and whether it helps to minimise possibility of the occurs of such crisis (Dupuy *et al.* 2005). For simplification, we consider the value of products that must be withdrawn in a product recall event with the

probability of the recall as a traceability related cost. Therefore, the recall cost for a demand period in Scenario 1 can be described in equation 3.4.

$$C_{REC} = D \cdot P_F \sum_{k=1}^{M} Y_{RF}(k) \sum_{i=1}^{S} w_{i,k} , \quad (3.4)$$

in which $S = Q \times B_{RF}(k) / Q_k$.

Here $w_{i,k}$ is a given risk rating for an individual raw material batch which affects the safety of finished products. It is associated with the probability of a potential product recall. The integer variable S denotes the number of batches of the kth type raw materials used in a finished product batch. The value of S depends on the production batch size. When the production batch size increases, the value of S will increase. It means more batches of the kth type raw materials are required to fulfil the production order. Intuitively, if more raw material batches are mixed in finished product batches, the possibility of food contamination increases.

$Y_{RF}(k)$ is a binary variable which equals to 1 when k type raw material batches are used in the finished product batch and 0 otherwise. In Scenario 1, if only one type of the raw material batches is converted to one batch of products, the quantity of finished product batch Q is equal to the quantity of that type of raw materials used in the finished product in which

$$Q = S \cdot Q_k , \text{ and } \sum_{k=1}^{M} Y_{RF}(k) = 1 . \quad (3.5)$$

When multiple types of raw material batches are used for one batch of finished products, we have:

$$\sum_{k=1}^{M} Y_{RF}(k) > 1 . \quad (3.6)$$

Individual raw material batches may have different price and risk attributes because of different types of raw materials which may come from different suppliers. These batches are often mixed together in bill of materials for balancing between cost and quality. The raw material cost is the sum of the costs of raw material batches used in the product batch

production. The cost of individual raw material batches can be calculated by multiplying the unit price ($P_{i,k}$) by the batch quantity (Q_k). Therefore, we have the raw material cost for a production cycle given in equation 3.7.

$$C_{RAW} = \frac{D}{Q}\sum_{k=1}^{M} Y_{RF}(k)\sum_{i=1}^{S} Q_k P_{i,k} . \quad (3.7)$$

In Scenario 2, a three-level bill of materials including raw materials, components and finished products (seen in Fig. 1) is considered. Raw materials used in a component batch only come from raw material batches. Based on the definition in equation 3.7, the raw material cost in the production of component batch *j* is therefore calculated as:

$$C_{comp(j)} = \sum_{k=1}^{M} Y_{RC}(k)\sum_{i=1}^{S} Q_k P_{i,k} \quad (3.8)$$

in which $S = Q \times B_{RC}(k) \big/ Q_k$

The raw materials used in a finished product batch come from component batches. The raw material cost in a production cycle for scenario 2 is therefore described as equation 3.9.

$$C_{RAW} = \frac{D}{Q}\sum_{j=1}^{N} Y_{CF}(j)\sum_{k=1}^{M} Y_{RC}(k)\sum_{i=1}^{S} Q_k P_{i,k} . \quad (3.9)$$

Based on equation 3.4 and 3.8, the recall cost for Scenario 2 is given as:

$$C_{REC} = D \cdot P_F \sum_{j=1}^{N} Y_{CF}(j)\sum_{k=1}^{M} Y_{RC}(k)\sum_{i=1}^{S} W_{i,k} \quad (3.10)$$

3.3 Incorporating shelf life factor

In practice, retailers expect a shelf life (T_C) against the expiration date (Display until or Sell by date) specified in a contract. In the case of our research, the shelf life for a product can be calculated by deducting its storage time at the manufacturer from the product life (T_L). Product life is measured in days counting from the day it is produced until the product becomes unacceptable for consumption. Therefore, the shelf life constraint can be written as:

$$T_L - (n-1)t \geq T_C \text{ , i.e. } n \leq \frac{T_L - T_C}{t} + 1 . \quad (3.11)$$

Here $(n\text{-}1)*t$ is the storage time (see Figure 2). When the shelf life of a perishable item is shorter than a contracted length of time at a retailer, it does not necessarily mean the quality attribute changes, but it certainly reduces its marketable life. The items have to be either disposed if it cannot be sold any longer or sold with a price discount to reduce the potential loss in sale. To take account of the product deterioration issue, we apply a temporary price discount policy (Shah *et al.*, 2005) to the model. The discount represents a cost incurred when the shelf life becomes shorter than the length of time required by a contract, but is within acceptable range which is given in equation 3.12.

$$T_M \leq T_L - (n-1)t < T_C ,$$

$$\text{i.e. } \frac{T_L - T_C}{t} + 1 < n \leq \frac{T_L - T_M}{t} + 1 \quad (3.12)$$

Here, T_M is the customer acceptable minimum shelf life. In practice, perishable products lose their utilities over certain period of time under given quality control conditions. In this case, a discount price policy is implemented by the suppliers of these products to promote sales (Shah *et al.* 2005). Retailers may also dynamically adjust the sales price of a perishable food product as its shelf life approaches the end and its inventory perishes (Wee and Yu 1997; Chun 2003). In this paper, we use the temporary price discount to quantify product deterioration cost. Therefore, the unit transaction price at which the product is actually sold is expressed as equation 3.13.

$$C'_{FP} = C_{FP}(1 - d \cdot Yt) . \quad (3.13)$$

In equation (3.13), d is the unit price discount in a temporary price discount period. Y is an integer variable which is the number of shipments during the temporary price discount period.

Y equals to the number of total shipments in a batch production cycle deducting the number of shipments in the none-price-discount period, which is given in equation 3.14 (see Fig.2).

$$Y = n - 1 - \frac{T_L - T_C}{t} \tag{3.14}$$

Subject to: $0 < Y \le \frac{T_C - T_M}{t}$.

Now, the cost associated with perishable product inventory can be obtained by aggregating the price differences between the real transaction price and the contracted trade price of each shipment during the price discount period (see equation 3.15).

$$C_{PERISH} = \begin{cases} \frac{D}{Q} x P_F \sum_{y=1}^{Y} d \cdot y \cdot t, & when \ \frac{T_L - T_C}{t} + 1 < n \le \frac{T_L - T_M}{t} + 1; \\ 0 & when \ 0 < n \le \frac{T_L - T_C}{t} + 1. \end{cases}$$

Where, $Y = n - 1 - \frac{T_L - T_C}{t}$;

Subject to: $n \le \frac{T_L - T_m}{t} + 1$ and $0 < Y \le \frac{T_C - T_M}{t}$ (3.15)

As discussed in section 3.1, the integer variable n can be replaced by Q/x. By incorporating the product shelf life factor, operational factors, and traceability factors, we have the integrated optimisation model as equation 3.16:

Objective:

$$\text{Min } TC = \begin{cases} C_{SETUP} + C_{RAW} + C_{REC} + C_H + C_{PERISH}, & when \ \left(\frac{T_L - T_C}{t} + 1\right) \cdot x < Q \le \left(\frac{T_L - T_M}{t} + 1\right) \cdot x; \\ C_{SETUP} + C_{RAW} + C_{REC} + C_H, & when \ 0 < Q \le \left(\frac{T_L - T_C}{t} + 1\right) \cdot x. \end{cases}$$

Where $C_{SET} = \frac{D}{Q} A$ (see equation 3.1); $C_H = \frac{QxH}{2Pt} + \frac{QH}{2} - \frac{xH}{2}$ (see equation 3.3);

$$C_{RAW} = \begin{cases} \frac{D}{Q}\sum_{k=1}^{M} Y_{RF}(k)\sum_{i=1}^{S} Q_k P_{i,k}, & With\ \ Scenario\ \ 1\ (see\ equation\ \ 3.7) \\ \frac{D}{Q}\sum_{j=1}^{N} Y_{CF}(j)\sum_{k=1}^{M} Y_{RC}(k)\sum_{i=1}^{S} Q_k P_{i,k}, & With\ \ Scenario\ \ 2\ (see\ equation\ \ 3.9) \end{cases};$$

$$C_{REC} = \begin{cases} D \cdot P_F \sum_{k=1}^{M} Y_{RF}(k)\sum_{i=1}^{S} w_{i,k}, & With\ \ Scenario\ \ 1\ (see\ equation\ \ 3.4) \\ D \cdot P_F \sum_{j=1}^{N} Y_{CF}(j)\sum_{k=1}^{M} Y_{RC}(k)\sum_{i=1}^{S} W_{i,k}, & With\ \ Scenario\ \ 2\ (see\ equation\ \ 3.10) \end{cases};$$

$$C_{PERISH} = \frac{D}{Q} x P_F \sum_{y=1}^{Y} d \cdot y \cdot t \quad \text{(see equation 3.15)}$$

$$S = Q \times B_{RF}(k) \Big/ Q_k \ ; \ Y = \frac{Q}{x} - 1 - \frac{T_L - T_C}{t};$$

Subject to:

$$0 < Q \le \left(\frac{T_L - T_M}{t} + 1\right) \cdot x \ ; \ 0 < Y \le \frac{T_C - T_M}{t} \ ; \ S{>}0; \ Q \ge Q_k \ ; \ T_L > T_C > T_M > 0 . \qquad (3.16)$$

4. Case study and numerical analysis

In this section, a case study and numerical analyses are presented. As the integrated model contains binary and integer variables, the total cost function is non-differentiable with respect to production batch quantity. Therefore we use simulation experiments to numerically analyse the model performance. In Section 4.4, when ignoring traceability factor, analytical optimal solution is produced. The numerical simulation is implemented by a Microsoft Excel spreadsheet. Sensitivity analysis is also performed.

4.1 Case study and numerical simulation results.

The case is based on a UK food manufacturer supplying ready to eat cooked meats of beef, pork, lamb, chicken and turkey to major UK supermarkets. Products are produced and traced

at batch level. Orders from main customers arrive daily including more than 20 different products and the delivery has to be made within the same day. As a cooking process takes long lead time, make-to-order becomes impossible. To smooth the production and meet customer demand, a large production batch size is used. This results in a large amount of cooked products being held in the inventory. Products produced in one batch are usually allocated into several deliveries. Furthermore, with the large production batch size, several raw material or component batches which may come from different suppliers are likely required to fulfil a production order. The mixture of different types of raw materials or components leads to a batch dispersion problem that increases the complexity of traceability. Although the company deploys a strict HACCP scheme to ensure compliance with all relevant legislations and industry codes, product recalls do happen occasionally due to various reasons.

To verify and demonstrate expected benefits of the proposed model, we compare total cost generated by the existing production system in the case with the optimal solution from the proposed model. The company has sufficient production capacity to meet customer demands. Fixed shipment quantities for simulation are derived from the average quantity in delivery records of chosen products. The risk rating (weighting) $W_{i,k}$ is obtained using current HACCP approach (CAC 2002) applied in the company, where likelihood, severity, and numbers of products exposed to safety hazard are assessed. First In First Out policy (FIFO) is applied to raw material batches in production. Finished products have certain range of product life and are only allowed to be in stock for a limited period. Products that are suitable for two scenarios are chosen to carry out the numerical analysis. The Macro tool in Excel is used to simulate the model performance by changing values of the model parameters. Tables 1 to 3 display examples of sample data used in the model and the results generated in the numerical simulation. A month is used as a planning period.

[Table 1 is to be inserted here]

[Table 2 is to be inserted here]

[Table 3 is to be inserted here]

4.2 Analysis of the batch dispersion differences

To investigate how individual cost factors affect the performance of integrated optimisation model, three different cases are simulated to illustrate the batch dispersion differences. Both case one and case two are under the condition of Scenario 1. In case one, only one type of raw material batch is used for a finished product batch. Case two considers the situation involving multiple types of raw material batches in a finished product batch. Case three is under the condition of Scenario 2. The simulation experiments have used the same model parameters for different cases: D = 6,000units/month, P = 9,000units/month, A = £300/set-up, H = £1 unit/month, x = 300units/shipment, T_L = 12 days, T_C = 7 days, and T_M = 5 days. Same average raw material costs and product selling price are used in the simulation. The total cost against production batch quantity is plotted in Fig. 3.

[Figure 3 is to be inserted here]

Here, the production batch quantity Q equals to $n*300$. n is the scale value on x axis which represents product shipment frequency. 300 is the shipment quantity of the sample. The different total cost curves indicate that the total cost is more sensitive to production batch quantity changes in Scenario 2 than that in Scenario 1. This may be explained by the fact that

a larger batch quantity in Scenario 2 is more likely to have higher traceability cost due to the batch dispersion problem. It increases the probability of potential product recall which is directly reflected in the recall cost of the objective function (see equation 3.16).

As the probability of product recall is affected by the risk rating of raw material batches used in finished products, we investigate the performance (the total cost) of the proposed model when different values of risk rating are applied. The analysis results are illustrated in Fig. 4. It indicates that, when the risk rating is low to a certain range (close to $W = 0.0001$, which means the probability of product recall is close to zero), the total cost curves against production batch quantity come to a trend with which the recall cost can almost be ignored. In contrast, when the risk rating is high, the total cost is more sensitive to the production batch quantity.

[Figure 4 is to be inserted here]

Based on the above analyses, the integrated model can be used at both the operational level and strategic level. At the operational level, the model can be used to determine the best way to constitute raw material and components batches with a minimum dispersion. At the strategic level, a new product recipe may be tested in a traceability point of view to improve the product quality and safety management.

4.3 Analysis with the raw material batch Price-Risk ratio

A finished product batch could be produced from a number of heterogeneous raw material batches with different price or risk features. Decision making on whether a particular raw material batch should be replaced by another batch with different price and risk rating is critical to improve the overall performance of the food manufacturing. To have a deeper and

dynamic insight into the joint impact of price and risk feature on the overall performance of the proposed approach, Price-Risk ratio is defined in the numerical analysis (see equation 4.1).

$$\lambda = \left| \frac{\Delta P_i}{\Delta W_i} \right| \tag{4.1}$$

ΔP_i and ΔW_i are variations of raw material cost and risk rating respectively. We expect that, with different values of Price-Risk ratio λ, the optimisation model will deliver different performance. Considering the variation of the two factors, the objective function for Scenario 1, where one type of raw material batches is used in a product batch, can be expressed in equation 4.2.

$$TC' = \begin{cases} C_{SETUP} + \frac{D}{Q}\sum_{i=1}^{S} Q_k P_i + \frac{D}{Q} Q_k \Delta P_i + DP_F\left(\Delta W_i + \sum_{i=1}^{S} w_i\right) + C_H + C_{PERISH} \\ when \ \left(\frac{T_L - T_C}{t} + 1\right)\cdot x < Q \le \left(\frac{T_L - T_M}{t} + 1\right)\cdot x; \\ C_{SETUP} + \frac{D}{Q}\sum_{i=1}^{S} Q_k P_i + \frac{D}{Q} Q_k \Delta P_i + DP_F\left(\Delta W_i + \sum_{i=1}^{S} w_i\right) + C_H, \\ when \ Q \le \left(\frac{T_L - T_C}{t} + 1\right)\cdot x. \end{cases} \tag{4.2}$$

When $TC - TC' > 0$, the manufacturing system delivers a lower total cost by replacing a new raw material batch with a different price and risk rating. If $\Delta P_i < 0$ and $\Delta W_i < 0$ (or $\Delta P_i > 0$ and $\Delta W_i > 0$), it is obvious that the total cost will decrease (or increase). Therefore, we only discuss the other two situations:

$$\Delta P_i > 0 \quad and \quad \Delta W_i < 0 \quad , \Delta P_i < 0 \quad and \quad \Delta W_i > 0 \tag{4.3}$$

Through deducting equation 4.2 from equations 3.16, we have equation 4.4.

$$TC - TC' = D\left(\frac{\Delta P_i}{S} + P_F \Delta W_i\right) \tag{4.4}$$

As D is assumed as a positive constant, if $\Delta P_i/S + P_F \Delta W_i > 0$, the manufacturing system delivers a lower total cost by replacing a new raw material batch. In both of the situations in

equation 4.3 $\Delta P_i/\Delta W_i<0$. The analytical results indicate that in both situations, the replacement with another raw material batch at a different price and risk rating reduces the total cost if $\Delta P_i/\Delta W_i<-S\cdot P_F$. In contrast, the total cost increases if $\Delta P_i/\Delta W_i>-S\cdot P_F$. In addition, there is no difference in the total cost by such a replacement if $\Delta P_i/\Delta W_i=-S\cdot P_F$.

To validate the above analysis, simulation experiments are implemented for both situations. The experiments use the same model parameters (D = 6,000 units/month, P = 12,000 units/month, A = £300/set-up, H = £1 unit/month, x = 200 units/shipment, Q_k = 200 units, and P_F = £20). Different values of Price-Risk ratio λ are simulated. The simulation results shown in Fig. 5 and Fig. 6 confirm the above analysis. It also illustrates that if $\lambda > S\cdot P_F$, the total cost is more sensitive to the price of raw material batches than that to the risk rating. If $\lambda < S\cdot P_F$, the total cost is more sensitive to the risk rating of raw material batches than that to the price.

[Figure 5 is to be inserted here]

[Figure 6 is to be inserted here]

4.4 Analysis of model performance when ignoring recall factor

As recalls are low probability events, further analysis is performed by ignoring the traceability factor. We investigate how other cost factors (C_{SETUP}, C_H, *and* C_{PERISH}) influence the model performance. Then, the objective function (see equation 3.16) is simplified as:

$$TC = \begin{cases} \dfrac{DA}{Q} + \dfrac{QxH}{2Pt} + \dfrac{QH}{2} - \dfrac{xH}{2}, & when\ 0 < Q \le \left(\dfrac{T_L - T_C}{t} + 1\right)\cdot x; \\ \dfrac{DA}{Q} + \dfrac{QxH}{2Pt} + \dfrac{QH}{2} - \dfrac{xH}{2} + \dfrac{D}{Q} xP_F \sum_{y=1}^{Y} d\cdot y\cdot t, & when\ \left(\dfrac{T_L - T_C}{t} + 1\right)\cdot x < Q \le \left(\dfrac{T_L - T_M}{t} + 1\right)\cdot x. \end{cases} \quad (4.5)$$

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4.4.1 Case one

When $0 < Q \le [(T_L - T_C)/t + 1] \cdot x$, the total cost function is given as

$$TC = \frac{DA}{Q} + \frac{QxH}{2Pt} + \frac{QH}{2} - \frac{xH}{2}. \quad (4.6)$$

To optimise the total cost, we have:

$$\frac{\partial TC}{\partial Q} = -\frac{DA}{Q^2} + \frac{xH}{2Pt} + \frac{H}{2}; \quad \frac{\partial^2 TC}{\partial^2 Q} = \frac{2DA}{Q^3} > 0 \quad (4.7)$$

The derivative above confirms that the total cost is a convex function. By differentiating *TC* with respect to *Q*, we have the optimal batch quantity solution *Q** in equation (4.8).

$$Q^* = \sqrt{\frac{2DAPt}{(x + Pt)H}} \quad (4.8)$$

Subject to: $0 < Q \le [(T_L - T_C)/t + 1] \cdot x$

The calculated *n (=Q*/x)* may not be an integer as we replace *n* by a continuous variable in equations 3.3 and 4.6. In the case of non-integer *n*, we take the neighbouring integer value which produces an approximate minimum cost as the solution. Details of the method to find optimal solution can be found in Khan and Sarker's (2002) research where an algorithm to solve such a batch sizing problem was developed. We perform a simulation experiment to validate the analysis result. The total cost with production batch size *Q* is plotted in Fig. 7. The total cost is computed for each paired *n* (integer) and the batch size *Q*. The data used to generate the results are D = 6,000 units/month, P = 9,000 units/month, A = £300/set-up, H = £1 unit/month, x = 200 units/shipment, T_L = 18 days, T_C = 7 days, and T_M = 5 days. The behaviour of the cost function in Fig. 7 reflects a smooth and convex pattern in the range $0 < Q \le 2200$.

[Figure 7 is to be inserted here]

4.4.2 Case two

When $[(T_L - T_C)/t + 1] \cdot x < Q \le [(T_L - T_M)/t + 1] \cdot x$, the total cost function is given as:

$$TC = \frac{DA}{Q} + \frac{QxH}{2Pt} + \frac{QH}{2} - \frac{xH}{2} + \frac{D}{Q} xP_F \sum_{y=1}^{Y} d \cdot y \cdot t \qquad (4.9)$$

By substituting $Y = n - 1 - \frac{T_L - T_C}{t}$ (see equation 3.14) and $n=Q/x$, equation 4.9 is transformed into equation 4.10.

$$TC = \frac{DA}{Q} + \frac{QxH}{2Pt} + \frac{QH}{2} - \frac{xH}{2} + \frac{D}{2Q} xP_F d \cdot t \cdot \left(\frac{Q}{x} - \frac{T_L - T_C}{t} \right) \cdot \left(\frac{Q}{x} - 1 - \frac{T_L - T_C}{t} \right) \qquad (4.10)$$

To optimise the total cost, we have equation 4.11:

$$\frac{\partial TC}{\partial Q} = -\frac{DA}{Q^2} - \frac{DxP_F d \cdot (T_L - T_C)^2}{2Q^2 t} - \frac{DxP_F d \cdot (T_L - T_C)}{2Q^2} + \frac{DP_F dt}{2x} + \frac{xH}{2Pt} + \frac{H}{2};$$

$$\frac{\partial^2 TC}{\partial^2 Q} = \frac{2DA}{Q^3} + \frac{DxP_F d \cdot (T_L - T_C)^2}{Q^3 t} + \frac{DxP_F d \cdot (T_L - T_C)}{Q^3} > 0 \qquad (4.11)$$

The equations above confirm that the total cost is a convex function. Through equation 4.11, we have the optimal batch quantity solution Q^*:

$$Q^* = \sqrt{\frac{xDP\left[2At + xP_F d(T_L - T_C)^2 + xP_F dt(T_L - T_C)\right]}{DP_F dt^2 P + xH + tHP}} \qquad (4.12)$$

Subject to: $[(T_L - T_C)/t + 1] \cdot x < Q \le [(T_L - T_M)/t + 1] \cdot x$

Similar to case 1, as n is changed to a continuous variable, we take the neighbouring integer value which produces an approximate minimum cost as the solution. A simulation experiment is implemented to validate the analysis result. The total cost functions with production batch size Q are plotted in Fig. 8. The data used to generate the results are D =

6,000 units/month, P = 9,000 units/month, A = £500/set-up, H = £1 unit/month, x = 200 units/shipment, T_L = 15 days, T_C = 13 days, and T_M = 5 days. The behaviour of the cost function in Fig. 8 reflects a smooth and convex pattern in the range $600 < Q \leq 2200$.

[Figure 8 is to be inserted here]

The advantage of the proposed integrated model lies in incorporating the traceability factors with the operational aspects. However, the analysis in Section 4.4 provides a useful support to find optimal manufacturing performance under the circumstance that companies do not have significant product safety issues and recalls can almost be ignored.

5. Conclusion

In this paper, an integrated model is presented for simultaneously optimising the production batch size and batch dispersion policy in a food manufacturing context. The model incorporates operational costs (production setup cost, inventory holding cost, raw material cost and product perish cost) with the cost related to safety and quality assurance (recall cost). As the total cost function is non-differentiable with respect to production batch quantity, simulation experiments are used to numerically analyse the model performance. The analysis result shows performance of the proposed approach under different options of operational parameters. Considering that recalls are low probability events, analytical optimal solution is produced in the condition that traceability factor is ignored. The major contribution of the research is the proposed innovation in food manufacturing supply chain management. The research demonstrates benefits from seamless integration of operational planning with strategic considerations in food quality and safety issues. Such innovation has significant potential to justify the investment on food traceability in food supply chains. The

integrated optimisation model provides enterprises with a practical approach to quantitatively evaluate supply chain performance from both traceability and operations management initiatives. Our research would help the industry to understand potential values of traceability systems in food supply chain operations.

Although the proposed model is developed in a perishable food manufacturing context, the integrated optimisation approach would be applied to a broader area in which products go through batch production and assembly processes. Nowadays, besides the food sector, the traceability issue has become strategically important in many other industries, such as paper, steel, pharmaceutical and electronic industries. In pharmaceutical industry, tracking and tracing become more urgent than ever to provide safety assurance to customers (Lachance, 2004; Grant, 2006). In the textile market, the increasing counterfeit production of clothes reveals the lack of adequate techniques to assure both the brand authentication and the trustworthy of textiles involved in the intermediate manufacturing stages (Corbellini et al. 2006). In other industries such as electronic equipment and automobile manufacturing, traceability is crucial to quality assurance and recycling processes where efficient tracking and tracing enable quick identification of defect components and efficient selection of disposal methods for discarded products.

In the above industries, the production batch size, relevant operational and traceability cost features are not only major elements of the overall operational cost, but also crucial factors which affect safety and quality of end products as discussed in previous sections. The proposed approach in our research provides a new way to strategically and operationally integrate traceability considerations with operations and supply chain management functions. It would potentially support the industries to build cost effective solutions for implementation of traceability systems.

In the proposed model, the risk rating $W_{i,k}$ for each raw material batch imposes considerable impact on the overall system performance. However, many companies have difficulties in implementation of continuous risk assessment applications due to lack of expertise, training, time, motivation, and money. Therefore, current technology advancement in IT to support networked cost-effective risk monitoring solutions would be a prerequisite for the proposed operations-traceability integration. Further research is being conducted on practical approaches which enable structured analysis of food risk in food supply chains.

In our research, a temporary price discount is used to calculate the product deterioration cost in the optimisation model. However, for perishable food with a high deterioration rate, operational parameters in manufacturing and logistics processes such as delivery frequency, packing size, and sales price, etc. often significantly affect the product shelf life. Therefore, future research may be given to modelling more accurate product value lost features to extend the integrated operations-traceability optimisation model to a whole supply chain view, so that more benefits from the operations-traceability integration approach can be added.

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Figures

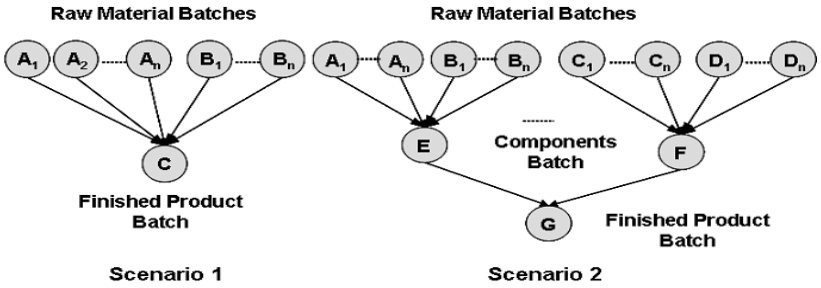

Figure 1. Two production scenarios.

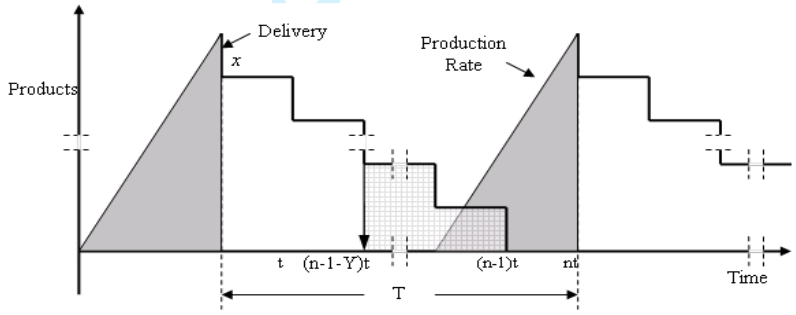

Figure 2. Product inventory level against time.

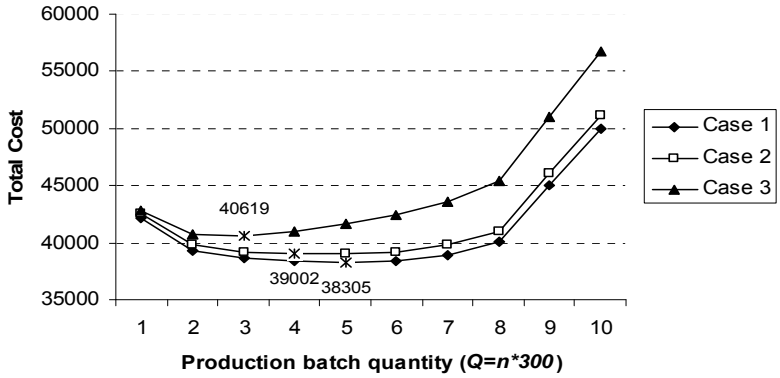

Figure 3. Total cost curves in three scenarios under same model parameters (the simulated optimal points are indicated with *).

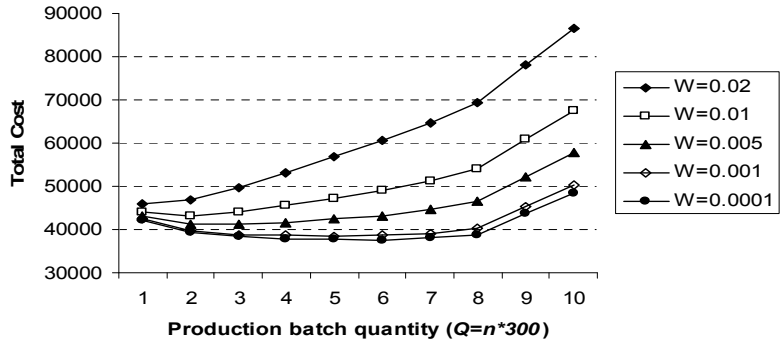

Figure 4. Variations of the total cost against the production batch quantity with different risk rating.

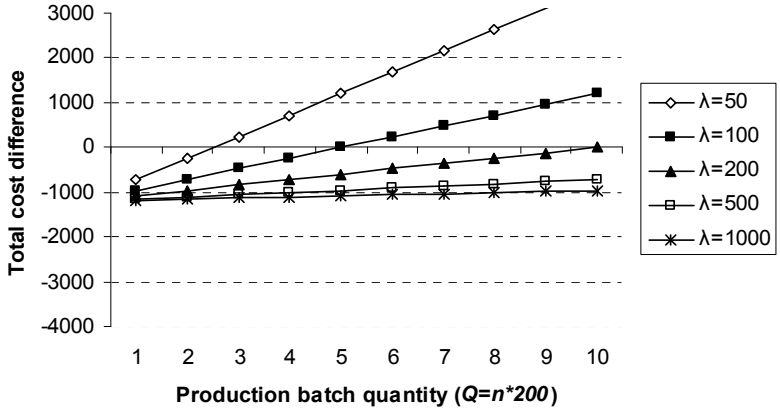

Figure 5. Variations of the total cost saving against Price-Risk ratio λ when $\Delta P_i>0$, $\Delta W_i<0$.

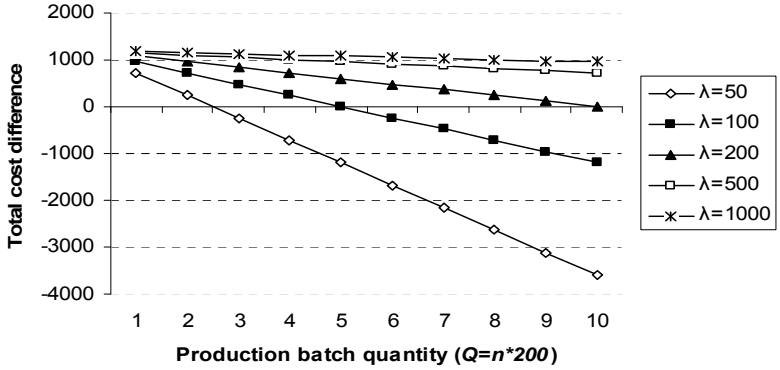

Figure 6. Variations of the total cost saving against the Price-Risk ratio λ when $\Delta P_i<0$, and $\Delta W_i>0$.

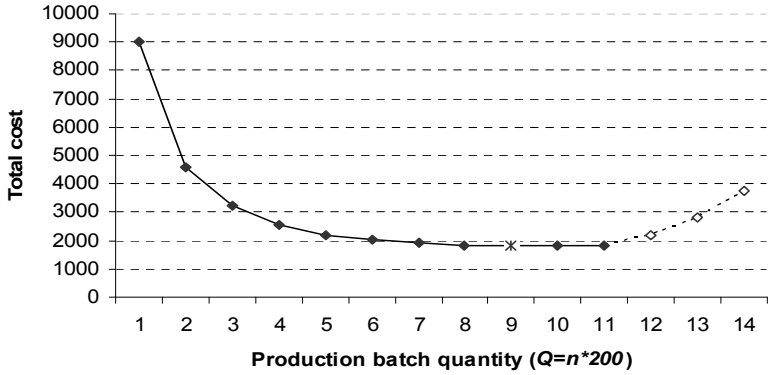

Figure 7. Total cost curve in case 1 when ignoring traceability cost factor (* indicates the optimal point).

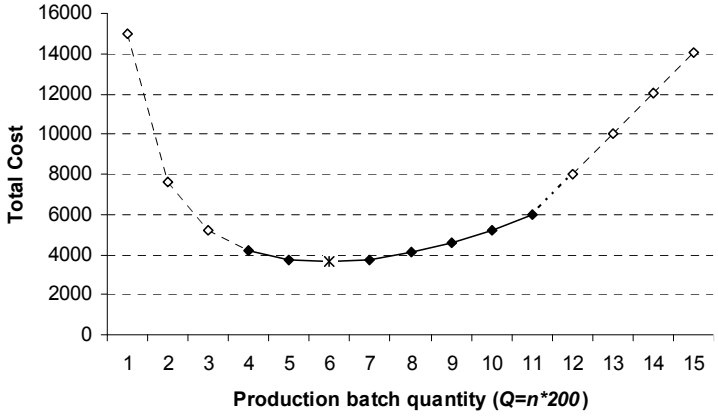

Figure 8. Total cost curve in case 2 when ignoring traceability cost factor (* indicates the optimal point).

Tables

Table 1. Sample data and results in scenario I when one type of raw materials is used

Product	Input information									Current practice		Optimal results	
	D	P	A	H	x	Q_k	T_L	T_C	T_M	Q	TC	Q^*	TC^*
Roast Pork	4,800	9,000	300	1	160	200	12	7	5	800	25,743	**1,000**	**25,688**
Pastrami	9,000	12,000	300	1	300	200	12	10	7	1,200	54,627	**1,000**	**54,452**
Roast Beef	12,000	15,000	500	1	400	200	12	10	7	1,200	73,912	**1,400**	**73,876**

Table 2. Sample data and results in scenario I when multi types of raw materials are used

Product	Input information											Current practice		Optimal results	
	D	P	A	H	x	Q_1	Q_2	Q_3	T_L	T_C	T_M	Q	TC	Q^*	TC^*
Sage&Onion Chicken	4,500	9,000	300	1	150	100	50	0	10	7	5	600	29,265	**750**	**29,212**
Curry Beef	6,000	9,000	300	1	200	200	50	0	12	7	5	1,000	35,931	**1,000**	**35,931**
British Meat Platter	6,000	9,000	400	1	200	100	50	100	12	7	5	1,000	41,571	**750**	**41,503**

Table 3. Sample data and analytical results in scenario II.

Product	Input information								Current practice		Optimal results	
	D	P	A	H	x	T_L	T_C	T_M	Q	TC	Q^*	TC^*
Easy Meals 1	6,000	9,000	300	1	200	12	7	5	1,000	40,161	**800**	**39,968**
Easy Meals 2	6,000	9,000	300	1	300	12	7	5	1,200	34,158	**900**	**33,831**

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