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8 **Simulation modelling for food supply chain redesign;**
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10 **Integrated decision making on product quality, sustainability and logistics**
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Simulation modelling for food supply chain redesign; Integrated decision making on product quality, sustainability and logistics

Abstract

Food supply chains are confronted with increased consumer demands on food quality and sustainability. When redesigning these chains the analysis of food quality change and environmental load of new scenarios is as important as the analysis of efficiency and responsiveness requirements. Simulation tools are often used for supporting decision-making on supply chain (re)design when logistic uncertainties are in place, building on their inherent modelling flexibility. Mostly, the underlying assumption is that product quality is not influenced by or does not influence chain design. Clearly, this is not true for food supply chains, as quality change is intrinsic to the industry. We propose a new integrated approach towards logistics, sustainability and food quality analysis, and implement the approach by introducing a new simulation environment, ALADINTM. It embeds food quality change models and sustainability indicators in discrete event simulation models. A case example illustrates the benefits of its use relating to speed and quality of integrated decision making, but also to creativity in terms of alternative solutions.

Keywords: supply chain, food quality, logistics, sustainability, simulation.

1 Introduction

In recent years, Western-European consumers have become more demanding on food attributes such as quality, integrity, safety, sustainability, diversity, and associated information services. At the same time, companies in the food industry are acting more and more on a global scale. This is reflected by company size, increasing cross-border flows of livestock and food products, and international cooperation and partnerships. Global competition together with the advances in information technology have stimulated partners in food industry to pursue a coordinated approach to establish more effective and efficient supply chains, i.e., *supply chain management* (SCM).

In line with the Global Supply Chain Forum (Lambert and Cooper 1998), we define SCM as the integrated planning, coordination, and control of all logistic business processes and activities in the supply chain to deliver superior consumer value at less cost to the supply chain as a whole, while satisfying requirements of other stakeholders (e.g. the government or NGOs) in the wider context of the total supply chain network, cf. Van der Vorst and Beulens (2002). SCM should result in the choice of a *supply chain scenario*, i.e., an internally consistent view on how a supply chain should be configured in terms of the choice of partners from the total supply chain network, and the way their mutual activities on supply, production, and distribution of goods are coordinated. Clearly, this is not an easy task, because of a great variety of policies, conflicting objectives, and the inherent uncertainty of the business environment (Alfieri and Brandimarte 1997).

The design of Food Supply Chains (FSCs) is further complicated by an intrinsic focus on product quality (Van der Vorst and Beulens 2002, Luning and Marcelis 2006) and demand for environmental sustainability (Hagelaar *et al.* 2004, Srivastava 2007). The way in which food

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quality is controlled and guaranteed in the network, is of vital importance for chain performance. Also, apart from being a performance measure of its own, product quality is directly related to other food attributes like integrity and safety. Recently, more attention has been given to sustainability by introducing the notion of “green” SCM, i.e., “the set of SCM policies held, actions taken, and relationships formed in response to concerns related to the natural environment with regard to the design, acquisition, production, distribution, use, reuse, and disposal of the firm's goods and services” (Zsidisin and Siferd 2001). Within the context of Food Supply Chains (FSCs) the sustainability discussion focuses on the reduction of product waste, i.e., products that have to be thrown away because the quality is not suitable any more (e.g. van Donselaar *et al.* 2006), number of miles a product has travelled before it reaches the consumers’ plate (so-called “food miles”), and all greenhouse gas emissions related to the business processes in the supply chain network (so called “carbon footprint”), c.f. Edwards-Jones, G. *et al.* (2008). We conclude that investments in FSC design should not only be aimed at improving logistics performance, but also at the preservation of food quality and environmental sustainability.

Many types of models have been developed to support supply chain design (Min and Zhou 2002, Gunasekaran 2004, Meixell and Gargeya 2005, Kleijnen 2005). Kleijnen and Smits (2003) distinguish four simulation types for SCM: (i) spreadsheet simulation, (ii) system dynamics (SD), (iii) discrete event dynamic system simulation (DEDS), and (iv) business games. They conclude that the question to be answered determines the simulation type needed; SD provides qualitative insights, whereas DEDS simulation quantifies results and incorporates uncertainties. Games can educate and train users. In many cases, discrete event simulation is a natural approach for supporting supply chain network design, as their complexity obstructs analytic evaluation, see e.g. Ridall *et al.* (2000) and Huang *et al.* (2003). Discrete event

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3 simulation tools, however, tend to stress logistics analysis rather than product quality or
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5 sustainability.
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8 In food science literature, much attention has been paid to food quality change modelling
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10 and the development of Time Temperature Indicators (TTI) to individually monitor the
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12 temperature conditions of food products throughout distribution (Taoukis and Labuza 1999,
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14 Schouten *et al.* 2002ab, Tijskens, P. 2004). Typically, next to biological variations, food quality
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16 is determined by time and environmental conditions (such as temperature, humidity and the
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18 presence of contaminants), see Figure 1. Environmental conditions may be influenced by, for
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20 example, the type of packaging, way of loading and the availability of temperature conditioned
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22 transportation means and warehouses. Figure 1 shows an idealized pattern for product decay for
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24 a particular perishable product. Typically, realistic values – shown in the figure as individual
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26 measurements (+,x,o) - deviate from this pattern to some extent. This uncertainty follows from,
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28 among others, biological variations (see above) and non-homogeneous conditioning. For
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30 example, temperature distributions within a batch of food products tend to be non-uniform as it
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48 The use of time-dependent quality information in the design of perishable inventory
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50 management systems gets increasing attention of researchers (e.g. van Donselaar *et al.* 2006).
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52 However, using this information in the design of distribution systems is only scarcely addressed
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54 in literature. We only found one reference in literature; Giannakourou and Taoukis (2003)
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3 consider the potential of a TTI-based system for optimisation of frozen product distribution and
4 stock management using Monte Carlo simulation techniques. TTI-responses are translated to the
5 level of product deterioration, at any point in the distribution system, which enables the
6 classification of products according to keeping quality (shelf life) remaining. Their results
7 indicate that the amount of rejected products in the market can be minimized using a TTI-based
8 management system based on Least-Shelf-Life-First-Out (LSFO), in which products with the
9 closest expiration date are advanced first.
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20 Many publications can be found that discuss sustainability issues in supply chain
21 networks. Srivastava (2007) presents a state-of-the-art literature review on *Green SCM* with over
22 200 references. He concludes that Green SCM is gaining increasing interest among researchers
23 and practitioners of operations and SCM, and relates this interest to the escalating deterioration
24 of the environment, e.g. diminishing raw material resources, overflowing waste sites and
25 increasing levels of pollution. Linton *et al.* (2007) conclude that academic research on
26 sustainable development is still in its infancy. They suggest that supply chains must be explicitly
27 extended to include by-products (such as waste), to consider the entire life-cycle of the product,
28 and to optimise the chain from a total cost standpoint. More specifically, Quariguasi Frota Neto
29 *et al.* (2008) propose a framework for the design of sustainable logistics networks, in which
30 profitability and environmental impacts are balanced.
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46 The challenge, being addressed in this article, is to embed food quality models and
47 sustainability issues together with logistics processes in discrete event simulation models, in
48 order to facilitate an *integrated approach towards logistic, sustainability and product quality*
49 *analysis of FSCs*. We hypothesize that the integrated decision making will result in overall better
50 decisions compared to the disciplinary decision making taking only one of these aspects into
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3 account. Key contribution of discrete event simulation lies in its capability of modelling and
4 trading off elementary uncertainties underlying product quality, and chain logistics, as well as
5 their interaction. Our focus in this paper is on exploiting this flexibility by the development of a
6 simulation environment for FSC modelling, rather than specific models, like the aforementioned
7 model by Giannakourou and Taoukis (2003). Typically, such an environment allows for building
8 a variety of models for evaluating a wide range of FSC issues, such as the incorporation of new
9 chain actors, use of innovative and sustainable transport modes, consolidation practices and
10 concepts as Vendor Managed Inventory whilst taking relevant uncertainties into account.
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22 Foreseen advantages of the integrated approach would be in the speed and quality of
23 decision-making on FSC design. Decision speed may go up as many iterations may be avoided
24 following from the separate consideration of food quality and chain logistics. But, probably more
25 important, the quality of solutions may be improved as more and other innovative scenarios may
26 be tested – following from a total performance overview. One of those innovative scenarios is,
27 for example, using quality information to pro-actively direct distribution processes to profitable
28 markets, also called “Quality Controlled Logistics” (see Van der Vorst *et al.* 2007).
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39 Starting from the above observations on the needs, available means and opportunities for
40 FSC design, we propose a new simulation environment, named ALADINTM (Agro-Logistic
41 Analysis and Design INstrument). ALADINTM concerns a library of building blocks for
42 simulation modelling, and builds on the discrete event simulation tool Enterprise DynamicsTM.
43 Next to basic building blocks for modelling FSC infrastructures (producers, distributors etc.),
44 and flows of goods, information etc., its library embeds food quality models. To show the
45 potential of integrated decision making for FSC design we discuss a case study concerning the
46 import of pineapples from Ghana to the Netherlands.
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The remainder of the paper is organized as follows. First, in Section 2, we will characterize FSCNs in terms of parties involved, process- and product characteristics, and redesign strategies. In Section 3, we use this to highlight model capabilities essential for successful FSC simulation - as they underlie ALADINTM. Next, in section 4, we will introduce the main features of ALADINTM. In Section 5, we will present a case study to illustrate the applicability and potential of integrated decision making for FSC redesign. Finally, in Section 6, we will summarize our main conclusions, and highlight directions for future research.

2 Food Supply Chain Network

This section describes essential characteristics of a Food Supply Chain Network (FSCN), in terms of the parties involved, process and product characteristics and alternative redesign strategies.

2.1 Supply chain parties

The food industry is becoming an interconnected system with a large variety of relationships. This is reflected in the market place by the formation of (virtual) FSCs via alliances, horizontal and vertical cooperation, and forward and backward integration (Van der Vorst *et al.* 2005; see Figure 2). Lazzarini *et al.* (2001) refers to a “netchain” and defines it as ‘a directed network of actors who cooperate to bring a product to customers’. In a FSCN more than one supply chain and more than one business process can be identified, both parallel and sequential in time. As a result, organizations may play different roles in different chain settings and therefore collaborate with differing chain partners, who may be their competitors in other chain settings. We can

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3 conclude that supply chain networks are complex systems due to the presence of multiple
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5 (semi)autonomous organizations, functions, and people within a dynamic environment.
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20 A FSCN comprises organizations that are responsible for the production and distribution of
21 vegetable or animal-based products. From a general perspective, we distinguish two main types:
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24 1. FSCN for *fresh agricultural products* (such as fresh vegetables and fruit). In general, these
25 chains may concern growers, auctions, wholesalers, importers and exporters, retailers and
26 specialty shops and their logistics service suppliers. Main processes are the handling,
27 (conditioned) storing, packing, transportation, and trading of food products. Basically, all of
28 these stages leave the intrinsic characteristics of the product grown or produced in the
29 countryside unharmed, except for the product quality that depends on the environmental
30 conditions. Over time, the product quality can either increase (e.g. ripening of fruits) or decrease
31 - if harvested at a mature stage.
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34 2. FSCN for *processed food products* (such as portioned meats, snacks, desserts, canned food
35 products). In general, these chains comprise growers, importers, food industry (processors),
36 retailers and out-of-home segments and their logistics service suppliers. In these chains,
37 agricultural products are used as raw materials for producing consumer products with higher
38 added value. Sometimes the consumer products are hardly perishable due to conservation
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3 processes. This reduces the complexity of the FSC design significantly and largely eliminates
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5 the need for quality change models.
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10 This paper focuses especially on those food products, either fresh or processed, that are subject
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12 to notable quality changes over time.
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15 16 17 18 **2.2 Process and product characteristics** 19

20 Bourlakis and Weightman (2004) and Jongen and Meulenberg (2005) discuss a list of specific
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22 process and product characteristics of FSCNs that impact the redesign process, including the
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24 following:
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29 • Seasonality in production, requiring global sourcing.
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31 • Variable process yields in quantity and quality due to biological variations, seasonality,
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33 and random factors connected with weather, pests, and other biological hazards.
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35 • Keeping quality constraints for raw materials, intermediates and finished products, and
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37 quality decay while products pass through the supply chain. As a result there is a chance
38
39 of product shrinkage and stock-outs in retail outlets when product's best-before-dates
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41 have passed and/or product quality level has declined too much.
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43 • Requirement for conditioned transportation and storage means (e.g. cooling).
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45 • Necessity for lot traceability of work in process due to quality and environmental
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47 requirements and product responsibility.
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Due to these specific characteristics of food products, the partnership thoughts of SCM in FSCs have already received much attention over the past years. It is vital for industrial producers to contract suppliers to guarantee the supply of raw materials in terms of the right volume, quality, place, and time. Furthermore, they coordinate the timing of the supply of goods with suppliers, to match capacity availability. Actors in FSCNs understand that products are subject to quality decay as they traverse the supply chain, while the degree and speed of decay may be influenced by environmental conditions. For example, exposing a batch of fresh milk, fruit or meat to high temperatures for some time will significantly reduce product keeping quality (shelf life). Supply chain co-ordination is essential to make appropriate decisions on food conditioning.

2.3 Redesign strategies for FSCs

Literature suggests several strategic, tactical, and operational redesign strategies to improve the efficiency and effectiveness of supply chain processes. An extensive literature review by Van der Vorst and Beulens (2002) identifies a generic list of *SCM redesign strategies* to facilitate the redesign process and attain joint supply chain objectives:

- Redesign the roles and processes performed in the supply chain (e.g., reduce the number of parties involved, reallocate roles such as inventory control, and eliminate non-value-adding activities such as stock keeping).
- Reduce lead times (e.g., implement information and communication technology (ICT) systems for information exchange and decision support, increase manufacturing flexibility or reallocate facilities).

- Create information transparency (e.g., establish an information exchange infrastructure in the supply chain and exchange information on demand/supply/inventory or work-in-process, standardize product coding).
- Synchronize logistical processes with consumer demand (e.g., increase frequencies of production and delivery processes, decrease lot sizes).
- Coordinate and simplify logistical decisions in the supply chain (e.g., coordinate lot sizes, consolidate goods flows, eliminate human interventions, introduce product standardization and modularization).

The above strategies address the general case of supply chain design. Specifically, for FSC we can add the redesign strategy to alter the time-dependent environmental conditions, under which products are (re)packed (e.g. using modified atmosphere packaging), stored and transported (e.g. using reefer containers), in order to improve on food quality. This will result in longer shelf lives, and therefore, provide room for the introduction of innovative logistics concepts. Furthermore, emphasis should be put on redesigning processes in order to reduce greenhouse gas emissions and energy consumption, see Linton *et al.* (2007) for an overview of this subject.

3 Modelling requirements for FSCs

In the previous section we characterized FSCNs in terms of parties involved, processes, products and alternative design strategies. Let us now relate these characteristics to requirements to be set on models for FSC simulation. Recall, that our choice for discrete event simulation is motivated by the type of problem studied, i.e. the design of FSCs, which are (1) characterized by uncertainties in product quality, and logistics as well as their interaction, and (2) evaluated for

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3 logistic costs and service, product quality, and sustainability. We distinguish between
4 requirements on simulation modelling that address the general case of SCM and requirements
5 that are specific for the food industry. As far as the general case is concerned, we build on earlier
6 work (Van der Zee and Van der Vorst 2005). An overview of these requirements is meant to (i)
7 support a review of current tools for supply chain simulation, and (ii) structure our discussion on
8 the new tool, see Section 4. We conclude this section by stating our research contributions.
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17 ***3.1 General requirements on supply chain modelling***

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21 As stated a typical supply chain involves multiple (semi)autonomous parties, who may have
22 several, possibly conflicting, objectives. Actions of one actor in the supply chain may influence
23 product and/or process characteristics for the next actor. SCM requires, among others, the
24 alignment of partner strategies and interests, high intensity of information sharing, collaborative
25 planning decisions and shared IT tools. These requirements often represent major hurdles
26 inhibiting the full integration of a logistics chain. Even when there is a strong partnership among
27 logistics nodes, in practice, there are potential conflict areas, such as local versus global interests,
28 and a strong reluctance of sharing common information on production planning and scheduling,
29 such as, for example, inventory and capacity levels (Terzi and Cavalieri 2004). SCM requires
30 trust and in-depth insight into each other's processes, which is difficult, since the widely
31 followed competitive model suggests that companies will lose bargaining power, and therefore
32 the ability to control profits, as suppliers or customers gain knowledge (Barratt and Oliveira
33 2001).
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53 The aforementioned characteristics make clear that an active participation and cooperation of
54 all parties are essential ingredients for the effective design of new supply chain network
55 scenarios. Even more since the complexity of the system and the solution space in terms of the
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3 number of alternative chain scenarios are significant. Involvement is therefore not only a
4 prerequisite for solution acceptance, but also fosters creative minds in finding alternative and
5 possibly better solutions – building on each others expertise on specific chain operations. In
6 order to facilitate an active involvement of decision makers in modelling and solution finding,
7 high demands are set on model transparency and completeness. Transparency refers to the
8 insight into model components and their workings, whereas completeness addresses a full
9 overview of design parameters. This leads us to the following requirements on simulation model
10 design, cf. Van der Zee and Van der Vorst (2005):
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- 25 1. *Model elements and relationships*: Supply chains assume an integrated approach to
26 physical transformation, data processing, and decision-making. Especially, the allocation
27 of control policies to specific chain members, and relationships, such as hierarchy and co-
28 ordination, deserve explicit attention as decision variables. This requires the explicit
29 notion of actors, roles, control policies, processes, and flows in the model.
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- 36 2. *Model dynamics*: The control of dynamic effects within the supply chain, as reflected in
37 e.g. stock levels and lead times, is an important issue given the many parties involved.
38 Therefore, the logistics of control, i.e. the timing and execution of decision activities,
39 should be explicit. This requires the ability to determine the dynamic system state,
40 calculate the values of multiple performance indicators at all times, and even more
41 important, allocate performance indicators to the relevant supply chain stages.
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- 50 3. *User interface*: The active and joint participation of the problem owners, i.e., the supply
51 chain partners, in the simulation study is required for two reasons (Hurrion 1991,
52 McHaney and Cronan 1998, Bell *et al.* 1999, Robinson 2002). First, as a means to create
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3 trust in the solution and among the parties involved, so there is a better chance of
4 acceptance of the outcomes of the study. Second, the quality of the solution may be
5 improved. This refers to model correctness as well as the performance of the chain
6 scenario. Clearly, it is almost impossible for the analyst to have all relevant information
7 on chain dynamics. Therefore, the domain related contribution of the problem owner in
8 terms of alternative solutions is vital to the success of the project. Given the foreseen role
9 of the problem owners, an explicit choice and representation of decision variables that
10 appeal to their imagination is important. This boils down to visibility and understanding
11 of all supply chain processes in the model, see “1. Model elements and relationships.”

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25 4. *Ease of modelling scenarios*: The execution of “what if” analysis should be transparent,
26 given the complexity of the supply chain, the large number of conceivable scenarios, and
27 the wishes and requirements of the problem owners. This concerns both the choice of
28 building blocks and the time required for tailoring, and adapting them to the right format
29 for model adoption. Another demand is model reuse, because of the combination of
30 volatile business environments and the major modelling efforts required. Reusable
31 models may help to increase the speed of modelling and analyzing alternative scenarios,
32 while reducing costs of decision support.
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44 **3.2 Specific requirements on modelling FSC**

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47 Next to the general requirements on modelling, additional, more specific, requirements for
48 modelling FSCs should be mentioned. Here we will address the issue of modelling food quality
49 and environmental sustainability, being prime performance indicators for FSCs.
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1. *Model elements and relationships*: Modelling food quality assumes the presence of attributes of model elements that, next to logistics cost and service aspects, express the actual product status on quality. Also methods are to be defined for modelling quality decay due to progress in time and environmental conditions. In turn attribute values of food and their foreseen behaviour may be an input to dedicated (pro-active) control policies for operating the supply chain, being responsive to, for example, the (estimated) best-before-date. Clearly, quality preservation is a major issue in FSCN, which can be improved via the use of sophisticated environmental conditioning techniques (in transport and warehousing) and the reduction of lead times. Of course these new techniques and supply chain processes should be evaluated on energy use and environmental load to guarantee sustainability. Model elements should incorporate these specific characteristics of FSCN, especially the keeping quality constraints for products and the occurrence of quality decay while progressing through the supply chain under specific environmental conditions.
2. *Model dynamics*: Food quality tends to be a continuous variable. Here we consider the process of its decay at discrete moments in time. This assumes an event related “inspection” of relevant food attributes. Finally, the model should be able to deal with the aspect of *uncertainty*. FSCN deal with biological products that are not homogeneous in product quality and yield (see section 2). Control policies in the model should be able to distinguish between batches with different characteristics and make (logistical) decisions based on this information. This will allow for “Quality Controlled Logistics” (Van der Vorst et al., 2007).

3.3 Review of simulation tools for FSC design

In the past, many simulation tools for supply chain analysis have been developed. Van der Zee and Van der Vorst (2005) present a literature review in which they assess the modelling characteristics of these packages given the previous requirements on FSC modelling. They conclude that current simulation approaches cannot fully cope with the demands on model and tool design for supply chain analysis. They mention an important shortcoming of available tools concerning the modelling of supply chain decision making. In line with earlier findings for the field of manufacturing, see for example, Mize Bhuskute *et al.* (1992) and Karacal and Mize (1996), they conclude that decision makers, control rules and their interactions are mostly “hidden”. A reason for this may be the analyst’s choice of building blocks, which does not appeal to supply chain partners. Further, control elements may be dispersed throughout the model – being associated with various building blocks or with the time-indexed scheduling of events. Also, they may simply not be visualized. The “hiding” of control is surprising as control structures are intrinsic to supply chains. This implicit modelling harms realism, next to modelling flexibility and modularity. Essentially, the implicit modelling of decision-making in simulation analysis can be traced back to the (implicit) reference models underlying simulation tool libraries and the analyst’s activities in model building. As far as the embedding of food quality models in discrete event simulation models is concerned we could find no examples in literature.

3.4 Research contribution

In this article we propose a new integrated approach towards modelling FSCs that foresees in food quality models and sustainability issues being embedded in simulation models. Moreover, we implement the approach by introducing a simulation environment, ALADINTM.

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3 The environment is meant as a basis for models allowing for effective and efficient decision
4 support on FSC design. “Efficient” as the assessment of logistics, sustainability and food quality
5 considerations is realized using a single tool. “Effective” as more and possibly better solutions
6 can now easily be studied. Tool effectiveness is further strengthened by its conformance to the
7 modelling framework for supply chain simulation, proposed by Van der Zee and Van der Vorst
8 (2005). It sets demands on the explicit modelling and visualization of key decision variables, like
9 control structures, and product quality decay. In this way model transparency is enhanced -
10 aiming to stimulate an active involvement of decision makers in a joint search for better and
11 mutually accepted solutions.
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24 25 26 27 28 **4 Simulation environment**

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31 In this section we introduce the simulation environment ALADINTM. After a general
32 characterization of the tool, we discuss it in some detail being guided by the classification of
33 demands on simulation modelling for FSCs, see Section 3.
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39 40 **4.1 General description**

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42 ALADINTM is a visual interactive simulation environment building on the Logistics Suite of the
43 object oriented simulation package Enterprise DynamicsTM (ED). It concerns a library of generic
44 building blocks for modelling FSCs and its behavior. Choice of underlying concepts is largely
45 based on the modelling framework proposed in our earlier work (Van der Zee and Van der Vorst
46 2005, Van der Zee 2006). Food quality models for a range of fresh products are embedded in this
47 library. They relate food quality to food logistics in terms of time and choice of resources for
48 food production, transportation and storage.
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4.2 Model elements and relationships

ALADINTM is based on three key concepts: agents, jobs, and flows. *Agents* represent supply chain network entities (such as planners, retail outlets, producers, and distribution systems) as autonomous objects that are assigned decision-making intelligence. All chain activities are defined as *jobs*, including activities related to decision-making. Where physical jobs result in goods, control jobs result in job definitions for agents in the controllers' domain of control. *Flow items* (also called *business entities*) constitute the movable objects within a supply chain. We include four types of flow items in the modelling framework: product flows, information flows, resources that facilitate the transformation processes (assignment of capacity), and job definitions. *Job definitions* specify a job in terms of e.g. its input, processing conditions and the agents to whom the resulting output should be sent. By introducing a demand controller in ALADINTM, physical and information and control layers can be separated (Figure 3). In this way, model transparency is increased, as discussed in Section 3

INSERT FIGURE 3 HERE

In ALADINTM, specific agents have been developed, see Table 1. Supply chain network models are composed of a reusable set of software components (building blocks, called 'atoms' in ED) that represent agents (with multiple inputs and outputs), their control policies (e.g. inventory policies, routing policies), and their interaction protocols, i.e., message types that regulate the flow of information, goods, and cash. Besides these supply chain building blocks,

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3 ALADINTM's core consists of quality change models. These models describe quality behaviour,
4 for example botrytis in strawberries or weight loss of bell peppers, under specified conditions
5 (temperature, relative humidity, modified atmosphere, etc.). They incorporate parameters that
6 reflect stochastic biological variations in product quality change and are developed by experts in
7 lab-experiments under controlled conditions (see Schouten et al., 2002ab).
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28 Alternative designs of perishable product supply chains (see the redesign strategies in
29 section 2.3) can be simulated, visualized, and analyzed. ALADINTM adds the indicators product
30 quality or product freshness (remaining keeping quality and product waste) and energy use and
31 CO₂ emissions to classical performance indicators such as transportation costs, stock levels, and
32 delivery reliability (e.g. Gunasekaran *et al.* 2000). In this way, ALADINTM helps the decision
33 maker, to trade off logistics costs and service (product quality, sustainability and availability),
34 when assessing specific (re)designs of the FSC.
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45 **4.3 Model dynamics**

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48 Model dynamics is realized by job execution. We capture the dynamic behaviour of the chain
49 processes by modelling the FSC as a network of agents, jobs, and flows with precedence
50 relationships; the jobs can be triggered by multiple causes and have outcomes and processing
51 times that depend on the entities processed and available resources. This includes the calculation
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3 of (variations in) product quality aspects (such as weight, colour and firmness) related to the
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5 specific conditions to which the products have been exposed and sustainability indicators.
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8 9 **4.4 User interface and ease of modelling**

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12 In our choice of concepts we tried to adopt basic logistic terminology and developed a library of
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14 recognizable building blocks, starting from experiences of several industrial projects. This
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16 includes an explicit representation of supply chain coordination in terms of decision makers,
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18 their activities, and their mutual tuning of activities, also see 4.2.
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22 23 **4.5 Applications**

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26 ALADINTM has been successfully applied in several case studies in which new supply chain
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28 scenarios have been evaluated. For example, we compared alternative distribution systems (e.g.
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30 warehousing, cross docking and different transport modes at different environmental conditions)
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32 for the export of fresh products such as peppers and tomatoes. Furthermore, new ordering
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34 policies for fresh products have been evaluated, in which a balance is sought between stock-outs
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36 and product waste (shrinkage) in retail outlets. ALADINTM visualizes and quantifies the
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38 consequences of design choices for the remaining shelf life of the product and the level of
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40 environmental load. In order to illustrate the advantages of integral decision making and the
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42 capabilities of ALADINTM in somewhat more detail, we discuss one of the case studies in the
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44 next section.
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5 Case study: pineapple supply chain

To illustrate the added value of an integrated analysis of alternative FSC designs we consider a case study concerning the import of pineapples from Ghana to the Netherlands. In this case two import supply chain scenarios have been compared on logistics costs, product quality decay, energy use and CO₂ emissions. First we will consider the background of the case and the scenarios that were chosen for further analysis. Next we consider the data collection and modelling process. We conclude with a discussion of the simulation results and a brief evaluation of the contributions made by ALADINTM in modelling and analyzing alternative supply chain scenarios.

5.1 Background

The market for fresh pineapple in Europe is increasing; European consumers demand ready-to-eat products with a sweet taste and golden colour. The import of fresh pineapples to the Netherlands from predominantly Ghana, Costa Rica, Ivory Coast and South Africa amounts to about 35 tons on a yearly basis, although almost 75% of that is redistributed to mainly Germany and Russia. Pineapples intended for shipping are harvested when green, while those intended for immediate eating are harvested in the semi-ripe state and those intended for canning in the ripe state. Only sound fruit may be approved for transport; pineapples require particular temperature, humidity/moisture and ventilation conditions. Intact pineapples can be kept for a several weeks, whereas cut pineapple has a much more restricted shelf life. Based on discussions with two product experts (that have performed studies on the keepability of cut pineapples under specific laboratory conditions, c.f. Tijskens 2004) and participating chain partners, a generic quality decay model was developed in order to estimate the quality decay of cut pineapple (see figure 4).

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3 This model uses the yeast concentration as limiting quality attribute, starting after cutting the
4 whole pineapple.
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20 It can be seen that the keepability of cut pineapple varies from 6 to 9 days at a fixed temperature
21 of 4°C. This is a result of biological variation in the initial quality of the product. Biological
22 variation within the same batch cause differences in initial quality of cut pineapple, such that
23 different packages of cut pineapple may have a different pattern of quality decay at the same
24 temperature. Each package of cut pineapple is provided with a guaranteed Best-Before-Date
25 (BBD) at a storage temperature of max. 4°C, which is equal to “the current date + 6 days”.
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34 Much of the fresh pineapples reach the Netherlands by costly air transport. This is
35 motivated by the fact that so far alternative ways of transportation, like over sea, resulted in
36 significant quality decay and product shrinkage, due to lengthy transportation times. Major
37 developments in quality preservation via the use of modified atmosphere packaging and
38 sophisticated chilling techniques, however, challenge Dutch importers and retailers to reconsider
39 their means for transportation. Could transport by sea now be an option – to reduce overall chain
40 costs? The project group including all supply chain members identified several alternative FSC
41 designs of which we will discuss two for illustrative purposes. These scenarios are (see figure 5):
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- 53 1. Producing pineapples in Ghana, cutting in Ghana, and air transport of cut pineapple to the
54 Netherlands and distributing the cut pineapples to retail outlets (*‘the air chain’*).
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2. Producing pineapples in Ghana, sea transport of intact pineapples, cutting in the Netherlands and distributing the cut pineapples to retail outlets (*'the sea chain'*);

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To measure the effectiveness and efficiency of alternative designs, the project team formulated three *key performance indicators* for this FSC: the distribution costs along the supply chain (we only focus on transport and warehousing and leave out the costs of the cutting process), the energy and emissions during distribution (regarding emissions only CO₂ emissions are considered, where 73 g CO₂ is calculated per MJ direct energy use), and the product quality when arriving at the retail store. This last factor is measured by three sub-indicators;

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- The remaining number of days until the predetermined BBD. In other words, the *remaining selling time* at the retail outlet.
 - The remaining keepability of the product at a storage temperature of 4 degrees according to the expert model out of Figure 4. In other words, for how long will the yeast concentration still be acceptable?
 - The percentage of products for which the BBD is not reached yet, but has a yeast concentration which is not acceptable anymore.

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Note that the definition of performance indicators is case dependent, and relates to the business strategies of participating companies, product and process characteristics.

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INSERT FIGURE 5 HERE

5.2 Collecting data

In order to be able to model the scenarios, chain data was collected using document analyses and experts interviews (see tables 2,3). Table 2 shows all distribution activities (transport and storage) from harvest to retail outlet for the air chain. For each activity data are collected about: duration, temperature, cost, direct energy use, and emissions. Each supplied batch triggers the activities as represented in the following tables. Table 3 presents data for the sea chain as far as they are different from those for the air chain.

INSERT TABLE 2 HERE

INSERT TABLE 3 HERE

At the time of the research there were six flights per week from Ghana, each distributing 160 kg's of cut pineapples. By sea transport, only two shipments per week were taken place, each distributing 1200 kg's intact pineapples. Note that 2.5 kg intact pineapple result in about 1 kg cut pineapple. Therefore, both scenarios are comparable in volume, because in each scenario 960 kg cut pineapple is supplied to the retailer.

5.3 Modelling and analysis - ALADINTM

Evaluating the two scenarios on the defined performance indicators required modelling and analysis of several supply chain scenarios. We did so using ALADINTM. Note that in the project much more complex scenarios were evaluated; the two presented here are just for illustration purposes.

We modelled the supply chain applying some of the reusable building blocks and designed scenarios by setting the model elements, for example, applying air transport versus transport by ship. Alternative designs of the product supply chains were simulated, visualized, and analyzed. By changing the environmental conditions to which the pineapples are exposed (e.g. by using new packaging materials or conditioned reefer containers) we could simulate the impact of changes in the distribution system on keeping quality and sustainability indicators. Applying new logistical concepts changes the control and product flows which impacts costs and, via a change in the duration or processes, changes the keeping quality of the pineapples and the environmental load.

5.4 Simulation results

Table 4 presents an overview of the main model outcomes based on the data and assumptions described before. It shows that from a cost and sustainability perspective the sea chain provides the best results, when looking at product quality the air chain performs slightly better. Remark how the interpretation and weighting of the outcomes of the study is left to the decision makers. Simulation will not provide this answer. Further decision support may come from alternative techniques, like multi criteria analysis (see, for example, Quariguasi Frota Neto *et al.* 2008). We do not discuss those techniques here.

INSERT TABLE 4 HERE

When we look closer at the simulation results of the air chain the following issues come to the front. Air transport is responsible for over 70% of all logistic cost. Energy use happens mostly during air transport (85%), but also the open truck from harvest to producer uses a lot of energy (10%). Looking at remaining keepability (according to the expert model) at the moment the products arrive at the retail outlet, the average is below 5 days, with a variation from less than 3.5 days to more than 5.5 days. The average remaining selling time (according to the BBD) at the time of arrival at the retail outlet is equal to 3.9 days. The 6 days after cutting BBD seems to be realistic for this chain. A rather small percentage of all products -5.9% on average, according to the expert model – has a keepability that is less than the remaining selling time - according to the BBD. Typically, they reflect the products with a bad initial quality.

Results for the sea chain indicate that sea transport is responsible for almost 60% of all logistic cost. Energy use happens mostly during transport from grower to sea port (over 50%). At the moment the products arrive at the retail outlet, the average remaining keepability at 4°C (according to the expert model) is about 4 days, with a variation from less than 3.5 days to more than 4.5 days. Setting the BBD 6 days after cutting is not realistic in this case. Five days after cutting 10.6% of all products has a keepability which is less than the BBD-code indicates (based on six days).

5.5 Evaluation

Let us now address ALADINTM role for FSC design – building on the experiences in doing the case study. Firstly, the integration of facilities for modelling product quality, sustainability and product logistics provides an improved means for analyzing FSCs. Instead of studying effects of alternative scenarios on product quality, sustainability and logistics using separate tools, a single tool suffices. More effective solutions may result from this approach, as interaction effects for logistics and product quality may be studied. Speed and quality of decision making clearly benefited from the integrated approach. Furthermore, the definition of model building blocks and relationships in line with the modelling framework proposed by Van der Zee and Van der Vorst (2005), and Van der Zee (2006), resulted in transparent models. In this way they contributed to the communicative value of visual simulation models. A final remark concerns the need for a screening of candidate solutions. Typically, an FSC allows for configuring a multitude of alternative supply chain configurations. Using simulation for modelling all configurations may simply be too time-consuming. We therefore advocate the use of a screening procedure for pre-selecting alternative configurations. This may include, for example, deterministic models, or expert consultation.

6 Conclusions and directions for future research

The challenge addressed in this article, is to embed food quality models and sustainability indicators in discrete event simulation models, in order to facilitate an integrated approach towards logistic, sustainability and product quality analysis of FSCs. By introducing a new discrete event simulation tool ALADINTM that answers to this challenge, we aim to provide a new and improved means for analysing and redesigning FSCs. Its core consists of the

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3 combination of reusable process building blocks and quality decay models that facilitate the
4 modelling of FSCs. As such, it contributes to improved decision-making with respect to FSC
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6 design. Specific strengths of the tool relate to:
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12 • The integration of logistics, quality decay and sustainability modelling. The presence of
13 these models makes it possible to use simulation in workshop settings as transparent tool
14 for trading off FSC performance with respect to all respective elements.
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- 18 • The explicit modelling of control structures, building on an explicit modelling
19 framework. Rather than relying on the implicit mental reference models of the analyst
20 and the availability of standard building blocks in the library of Enterprise Dynamics™,
21 new building blocks were developed in ALADIN™ to offer the analyst guidance in
22 modelling specific FSCs. This provides communication means via an explicit and well-
23 defined notion of concepts, and helps in reducing the modelling efforts of the analyst,
24 because of the possibilities for reuse of model classes, i.e., agents, flow items and jobs.
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- 28 • The capabilities for more effective and efficient decision support on FSC design. The
29 case example concerning a pineapple supply chain showed that the tool provides an
30 integrated means for participants to generate transparency in the supply chain network
31 and jointly develop and evaluate innovative supply chain scenarios.
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49 Future research will focus on the further development of ALADIN™ extending the
50 complexity of quality decay models and quality interaction effects of multiple products
51 distributed together. Furthermore, in line with Van der Zee and Slomp (2008), and Van der Zee
52 (2007) we are researching a promising possibility to use ALADIN™ as a basis for a simulation
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gaming and training tool. A suchlike tool should enable managers to jointly evaluate alternative decision making scenarios in FSCs on multiple performance indicators, such as costs, product quality and sustainability.

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Table 1: Specific agents in ALADIN™

<i>Agents</i>	<i>Representation</i>
Production unit	Food factory or a grower, who produces products with biological variation in quality and quantity (seasonality).
Transportation unit	Climate controlled truck or vessel with specific temperature and modified atmosphere settings and related energy use and CO ₂ emission per unit.
Storing and distribution unit	Warehouse or retail outlet with specific climate control characteristics and related energy use and CO ₂ emission per unit.
Demand unit	Market place with demand for products with specific shelf lives, colours, etc.
Food product	Specific food product (e.g. pepper, cut vegetable) with its specific quality decay model, related to the settings of environmental conditions in time.
Demand controller	Explicit modelling of information flow and decision-making activity that activate the goods flow.

Table 2: Data of the air chain from Ghana

<i>Activity</i>	<i>Time (hrs)</i>	<i>Temperature. (°C)</i>	<i>Logistic cost (Euro cents)</i>	<i>Energy (MJ)</i>	<i>Remarks</i>
1. Transport Grower-Producer	4	25	2 per kg	16.5 per tonkm	Open truck
2. Storage Producer (whole)	44	7	52 per pallet (780 kg) per day	0.001677 per second	Cold storage
3. Storage Producer (cut)	5	4	52 per pallet (320 kg) per day	0.001677 per second	Cold storage
4. Transport Producer-Airport	0.5	4	4 per kg	2.27 per tonkm	Climate controlled
5. Storage and handling Airport	4.5	5	100 per pallet (320 kg) per day + 2.5 per kg	0.0049 per second	Stored in reefer container
6. Air transport	7	8	80 per kg + 22 per kg	9.76 per tonkm	
7. Storage Airport Schiphol	6	7	15 per kg	0.001677 per second	
8. Transport Schiphol-LVC	1	5	5 per kg	2.27 per tonkm	
9. Storage LVC	20	4	52 per pallet (320 kg) per day	0.001677 per second	
10. Transport LVC-retail DC	1	4	5 per kg	2.27 per tonkm	
11. Cross docking retail DC	4	4	52 per pallet (320 kg) per day	0.001677 per second	
12. Transport retail DC-retail outlet	1	4	5 per kg	2.27 per tonkm	

Table 3: Data of the sea chain from Ghana

<i>Activity</i>	<i>Time (hrs)</i>	<i>Product temp. (°C)</i>	<i>Logistic cost (Euro cents)</i>	<i>Energy (MJ)</i>	<i>Remarks</i>
2. Storage Seaport	6	25	0	0	Wooden barn
3. Sea transport	288	8	19 per kg	0.1 per tonkm	
4. Storage Antwerp	24	7	52 per pallet (780 kg) per day	0.001677 per second	Cold storage
6. Storage Producer (whole)	9, 33 or 57 [†]	7	52 per pallet (780 kg) per day	0.001677 per second	
7. Storage Producer (cut)	4	4	52 per pallet (320 kg) per day	0.001677 per second	
8. Transport Producer-LVC	1	4	5 per kg	2.27 per tonkm	
9. Storage LVC	19	4	52 per pallet (320 kg) per day	0.001677 per second	

Table 4: Comparing overall results of the two scenarios

<i>Scenario</i>	<i>Average quality</i>	<i>Logistics costs</i>	<i>Energy and emission</i>
Air chain Ghana	+ (BBD 3,9 days; bad before BBD 5,9%)	- (1192 Euro/wk)	-- (77227 MJ/wk 5638 kg CO ₂)
Sea chain Ghana	+/- (BBD 3,7 days; bad before BBD 10,6%)	+ (793 Euro/wk)	+ (14508 MJ/wk 1059 kg CO ₂)

[†] Retail outlets are ordering every day, while produce is supplied only once per three days. This implies that some pineapples are stored for a longer time than others

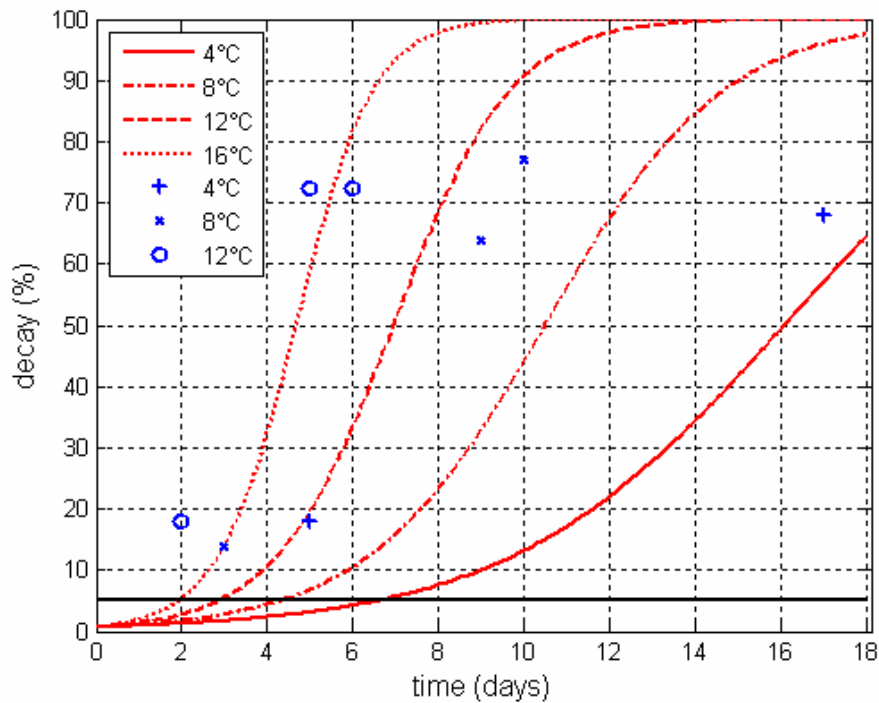


Figure 1: Example of idealized food quality decay as a function of time for alternative temperature conditions for a specific product (+, x and o show significant outliers measured in laboratory test) (Schouten *et al.*, 2002a).

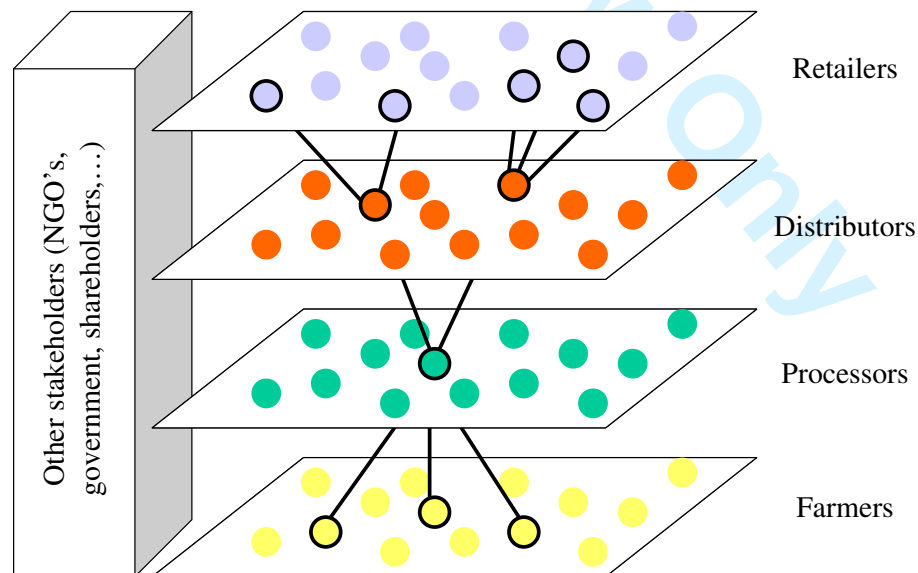


Figure 2: Schematic Diagram of a Food Supply Chain Network (Van der Vorst *et al.*, 2005).

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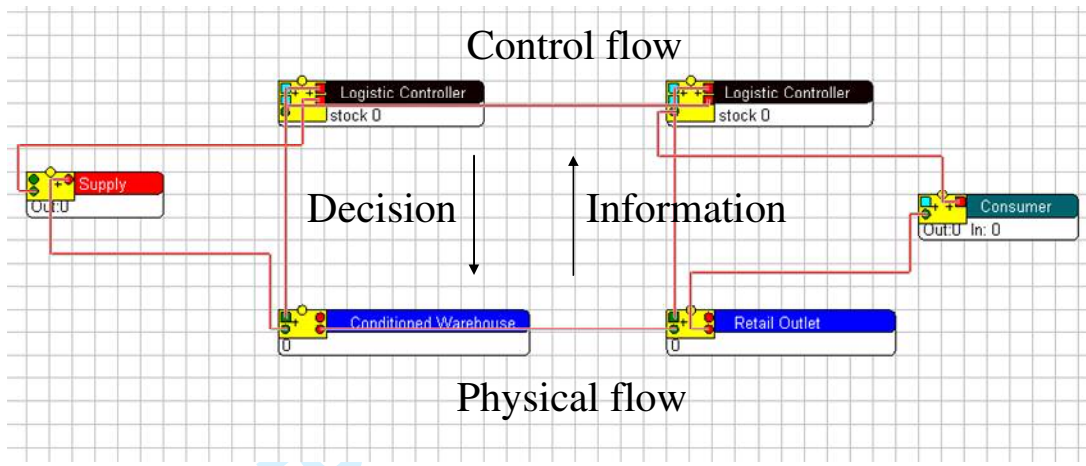


Figure 3: ALADIN™ improves modelling transparency by making a distinction between the goods flow (Physical flow) and its planning and control (Control flow).

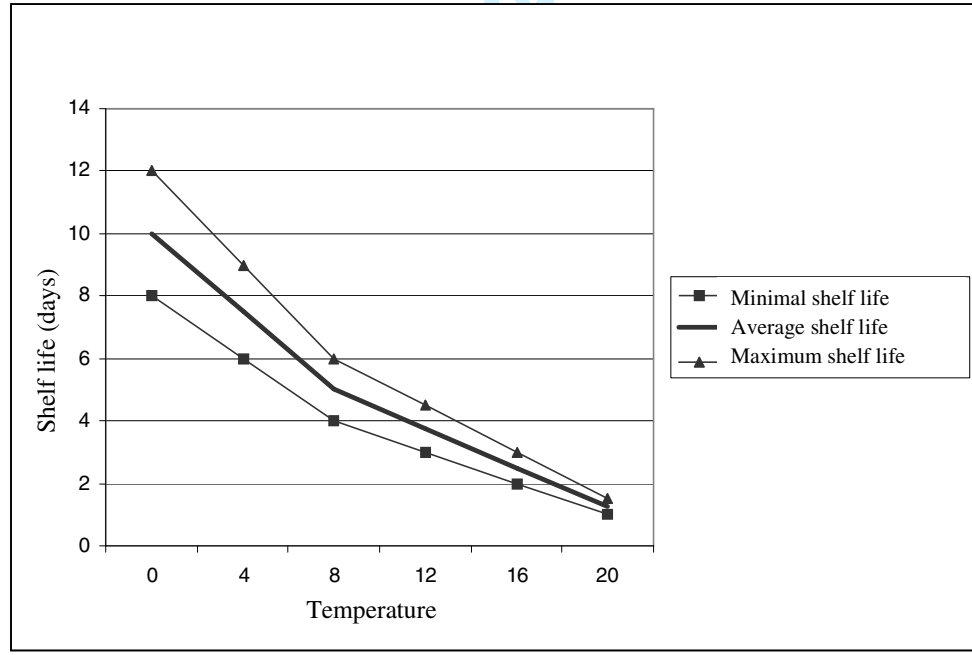


Figure 4: Average and variability in shelf life of cut pineapple depending on the temperature.

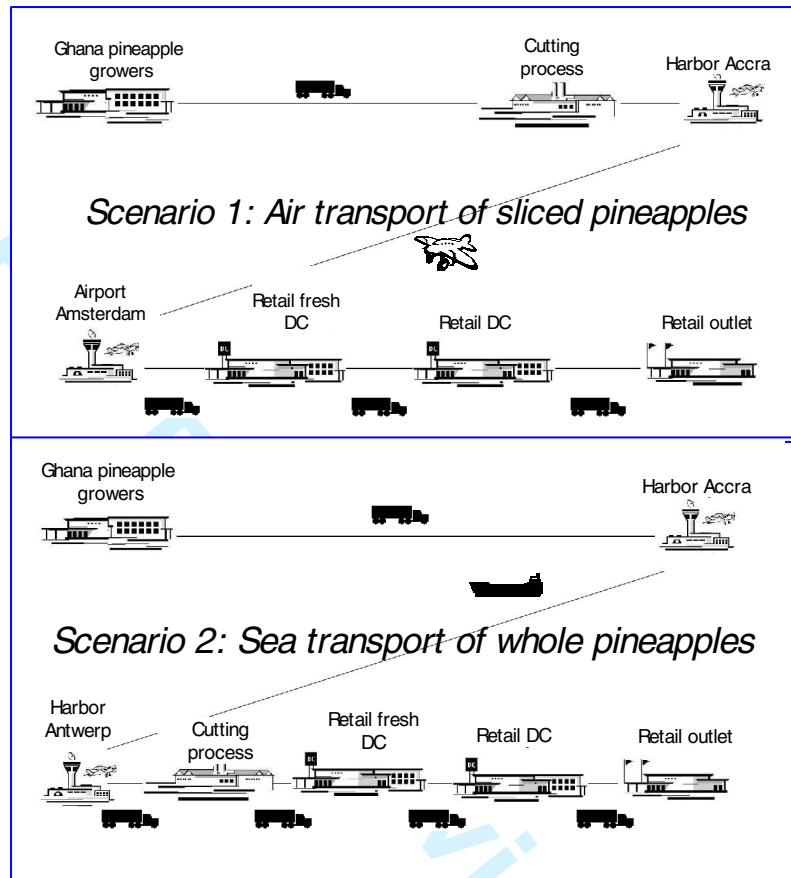


Figure 5: Two supply chain scenarios for importing pineapples from Ghana