An expert system for predicting orchard yield and fruit quality and its impact on the Persian lime supply chain

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A B S T R A C T

In recent years academics and industrials have shown an interest in agricultural systems and their complex and non-linear nature, aiming to improve production yield in the agricultural field. Innovative strategies and methodological frameworks are thus required to assist farmers in decision making for an efficient and effective resource management. In particular, this research concerns the structural problem of the Persian lime supply chain in Mexico, which still leads to low production yield over short time periods with heterogeneous fruit quality and also to the emergence of excessive middleman businesses arising from a fragmentation between orchard and exporting companies that constitute the first two links in the associated supply chain. Based on the Persian lime production cycle, an Expert System (ES) using Fuzzy Logic involving an inference engine with IF—THEN type rules is presented in this paper. A Mamdani model codifies the decision criteria related to agricultural practices for growing Persian lime in non-irrigated orchards. The ES allows the farmer to boost production in orchards by modeling application scenarios for agricultural practices. A case study based on an exporting company's fruit supply is discussed, in which the ES proves to be a useful tool to aid the decision making involved in the application of agricultural practices in the orchard. Results show an increase in production yield and fruit quality in the orchard, as well as a better synchronization between orchard and exporting companies, with a significant impact on inventory levels of fresh fruit in the link Persian lime exporting company.

1. Introduction

Mexican citrus fruit production is generally characterized by a low implementation of technology and good agricultural practices, which is partly related to low production yield and low fruit quality in non-irrigated orchards with an average yield of 14 t per hectare (t/ha), against 21 to 35 t/ha reported by the ten countries with highest productivity (FAO, 2009). The fresh fruit supply chain of Persian lime involves four stakeholders: (i) the growers of Persian lime; (ii) the companies that are dedicated either to fresh-fruit treatment or to juice-extracting for the post-harvest treatment of citrus fruit; (iii) the trading companies that put the product on the market and (iv) finally, the retailers who deliver the product to the final customer in a national or export market. A typical issue of this kind of supply chains in Mexican citrus fruit production concerns the exporting company's difficulty to supply Persian limes that meets market requirements both quantitatively and qualitatively; this explains the key role of farmers in the fresh fruit supply chain, since they are responsible for effectively managing the production process and fruit transport from the orchard to the fresh fruit exporting company.

The first link in the Persian lime supply chain is the citrus fruit cultivation area, consisting of several farmers who supply fresh fruit to the exporting companies. Two production systems can be distinguished either non-irrigated orchards (NIO) or irrigated orchards (IO). Farmers on NIOs basically apply agricultural practices and rely on mechanical equipment for their maintenance while IOs have irrigation systems, allowing higher production yield than on the same planting area in a non-irrigated orchard. In both production systems, chemical products are used and agricultural practices are implemented to increase production and improve fruit quality, which is classified according to two criteria for export, i.e. fruit size and color. Persian lime for export markets such as United States (USA), European Union (EU) and

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Japan (J) is packaged in boxes of 10, 20, and 40 lbs, all of which requiring the correct size and amount of limes per box. For this reason, suitable application of agricultural practices is significant considering how the producing orchard is the key supplier in the Persian lime supply chain, producing fruit with the right quality characteristics demanded by the exporting companies. In each production system, Persian lime production has three growth stages: Flowering, Fruit Set and Fruit growth. Flowering plays a critical role in the plant's reproductive cycle. Fruit Set refers to the process when a flower is set as a fruit. Finally, Fruit Growth is the phase when the fruit is harvested. The Flowering phase produces a production yield expressed in flower weight, which is significant in the next stage, Fruit Set, and is at the same time expected to produce fruit yield when eventually the ripened fruit is harvested. In every stage diverse agricultural practices and uncertain events determine yield for each growth stage, whether yield is maintained or reduced. Production dynamics emphasizes the importance of evaluating each development stage in the orchard as to estimate the production yield. The production yield and fruit quality of a production orchard can be uncertain, resulting in speculations about supply from the first to the second link of the Persian lime supply chain, which not only slows down the flow of fruit along the chain but also makes the chain more expensive due to factors beyond the orchard's production system such as middleman businesses or massive purchases of fruit, leading Persian lime exporters to stockpile fruit and generate high fresh-fruit inventories in the warehouse. The uncertainty of fruit supply has forced members of the first and second link of the supply chain to start looking for alternatives that increase productivity of producing orchards attempting to ensure a permanent supply and respond to customer's orders. Orchard production yield is closely related to the producer's economic profitability, so low productivity in the first link affects the supply chain in two ways: first, it has an impact on the producer as it reduces his harvesting profits, and second, it affects the second link, the exporting company, in a way that the company is now faced with the important challenge of ensuring supply and fruit quality demanded by the market.

In this context, this research is focused on Persian lime production in a non-irrigated orchard. The underlying idea is that the improvement of the orchard the management and of harvesting profits will allow for a better synchronization between the first two links of the supply chain, i.e. production in the orchard and citrus fruit exporting company. Improving this synchronization has the benefit that it reduces the economic consequences generated by the inventory of fresh fruit in the second link—exporting company. The article is organized as follows: Section 2 presents a literature review focused on the complex issue of agricultural supply chains. It presents various studies that have contributed to the concept of supply and to the improvement of the supply chain synchronization. Section 3 is a brief introduction to the Fuzzy Sets Theory and is dedicated to the Expert System design developed in this study with its validation process. In Section 4, a case study describes the effect on Persian lime supply chain synchronization between the first and the second link. Section 5 describes user perceptions concerning the expert system. Finally, Section 6 summarizes the main results of this study and suggests some perspectives.

2. Literature review and work position

Several studies have indicated that logistics systems ensure a continuous and uniform supply, and they can incur a high percentage of global production costs (Iannoni and Morabito, 2006), especially when perishable products are involved. In that case, the fresh products have to progress quickly through the supply chain and the time needed to use inventory as a buffer against demand variability is highly uncertain and short. Because of the need for an effective management of the agricultural supply chain, industrials and academics have become interested in collaborating even more closely with the stakeholders of the supply-chain. Taylor (2006) studies a series of agro-food chains, and concludes that demand variability of the final customer is found in all the analyzed chains. In some cases, the variability is the result of natural causes, such as seasonal consumption patterns or short-term fluctuation. In other cases, promotional activity is what creates significant uncertainty. The analysis of demand characteristics along the agro-food chains demonstrates a propensity for misalignment of demand and business activity rates due to issues such as demand amplification or production policies determined by factors other than demand, as for example lot size policy or variability in the supply of an agricultural product from its origin of production. In this respect, Bacarin et al. (2004) present a collaborative model for agricultural supply chains that supports negotiation, renegotiation, coordination and documentation mechanisms adapted to situations found in this kind of supply chain such as return flows. The model is supported by an architecture where chain elements are mapped to Web Services and their dynamics to service orchestration. Aiming to improve the coordination of the supply chain, Burer et al. (2008) and Carrillo et al. (2012), suggest optimization models based on negotiation, operating and operations strategies for each one of the agricultural supply-chain members. Canavari et al. (2010) examined how traceability is related to competitiveness in a fruit company. The authors support a hypothesis that states that traceability can be seen as a possible resource of the organization as a part of the information management in the supply chain. The article demonstrates that not only strategic, but also operative choices determine the way buyers and sellers along with chain members manage a single supply network. On the one hand, the authors highlight that traceability systems involve constraints of different kinds: economic, technological, available resources, legislation, laws and regulations – both external and internal – within the organization's area of competence. On the other hand, Coronado (2012) presents an association model for an agricultural products supply chain that describes different steps for implementing an association model between customer/supplier companies. The model seeks to establish an association level suitable for a relationship with suppliers, but not supplier selection. The model integrates fifteen companies' most valuable association experiences in customer/supplier relationships. It involves a process of aligning expectations and determines which level of cooperation is more productive. Ahumada et al. (2012) present a stochastic tactical planning model for the production and distribution of fresh agricultural products. The model incorporates the uncertainties encountered in the fresh product industry when developing growing and distribution plans due to the variability of weather and demand. The main motivation is to make tools available for producers to develop robust growing plans, while allowing flexibility to choose among different levels of exposure to risk. Catalá et al. (2013) present a strategic planning model for optimal restructuring of a pome (pears and apples) production farm concerning varieties and planting densities. The model decides the optimal investment policy for a given farm, maximizing the net present value of business while dynamically deciding its planting structure along a given time horizon under different financial scenarios. The model constraints impose restrictions on the activities to take into account risks and cultural practices. The mathematical model corresponds to a mixed integer linear programming problem, where integer decisions are related to the minimum reconversion land unit and funding requirements. As an approach towards coordinating the relationship between production and transformation, some investigations (González et al., 2008; Herrera and Osorio, 2006; Dongfeng et al., 2009; Erol and Ferrell, 2003; Amid et al., 2006) tackle this problem as a supplier development and/or supplier selection issue, a widely accepted view in different scenarios of the non-agrofood supply chain (González et al., 2008) highlights analytical approaches in fuzzy contexts, incorporating decision criteria based on performance, quality, service, costs, and risk, while other studies specifically deal with the nature of the evaluated supplier (Nilay Yüncenur et al., 2011; Kannan et al., 2013), or other criteria such as product innovation, a culture of quality, supplier image and environmental protection (Choya et al., 2003; Shen et al., 2013). Briefly, the bibliographical review emphasizes two approaches regarding supply and supplier selection. The former uses Artificial Intelligence (AI) techniques such as Fuzzy Logic (FL) (Kumar et al., 2013) and Artificial Neural Networks (ANNs) (Dilay and Bayraktar, 2008). The latter deals with designing and using mathematical models which allow for accurately modeling uncertainty with fuzzy logic and subsequently optimizing the decision-maker's multi-objective preferences (Paksoy et al., 2012). On the one hand, the application of ES in agriculture is reported in Shu-Hsien (2005) which presents a review of 166 articles from 1995 to 2004, finding ES applications for agricultural planning, crop management, investment analysis, and disease diagnosis …. On the other hand, Prasad and Vinaya (2006) compare the availability of several ES in agriculture with applications in irrigation and fertilization systems for increasing production. The large diversity in ES applications mainly addresses specific problems like for instance disease diagnosis and treatment (Tocatlidou et al., 2002; Mahaman et al., 2002; Yialouris and Sideridis, 1996; Gerevini et al., 1992), designing irrigation schedules and fertilization programs (Mostafa et al., 2006), and methods for decision making with insufficient knowledge in agriculture (Tocatlidou et al., 2002). All of these prove how ES are a useful tool in agricultural contexts, designed to maximize production yield and considerably enhance product quality in orchards, as in the case of Corona Sánchez et al. (2000), who present an ES for the nutritional diagnosis of orange trees, which uses expert information, bibliographical references, elaborated formulas and images of damage for the interpretation of foliar analysis. In the same way, Méndez and Villegas (2005) and Pichaya and Gumpanart (2005) also demonstrate the interest of ES. In the former study, fruit growing is modeled with FL for estimating citrus fruit yield based on hydro-climatic variables such as ambient temperature, evaporation, rainfall, sunshine, relative humidity, and a topographical variable used to describe the altitude of the orchard. In the latter research, an ANN is suggested to forecast tangerine yield taking into account some influential factors, especially weather conditions such as average monthly rainfall and temperature.

Even though there is a large body of work that use AI techniques (e.g. ANN and FL) to improve fruit production, the objective of this work involving an ES based on FL supported with its application to a real case study is twofold.

First, an efficient orchard production management model is presented that is based on an ES that uses FL to mimics the knowledge and expertise of the agricultural field dynamics for fruit production in its three basic stages (flowering, fruit set, fruit growth). At the same time we consider variables related with five agricultural practices that are common in any plantation (pruning, planting density, trees in production, control of pests, soil nutrition), and two uncertain events that are ever-present in agricultural setting i.e. wind and rain. The integration of agricultural practices in the ES as decision variables by considering two uncertain events for fruit production makes scenario modeling closer to reality (at agricultural field), with the simultaneous objectives of maximizing production output and improving the quality of fruit from the production cycle.

The second contribution of this work is the real application to validate the ES at a Mexican citric fruit packaging company, with the objective of effectively managing the agricultural practices that are offered to the farmer. It demonstrates the usefulness of the ES to solve the supply problem and the associated high levels of inventory of fresh fruit that are often involved by the Mexican exporting companies.

The state of the art reveals that there is a need to improve the common practices at agricultural field in two ways:

1. The use of agricultural practices in combination with uncertain parameters as decision variables in a management model must be considered to improve the yield performance and manage the quality of fruit (fruit calibre).
2. The orchard production must be modeled in a dynamic way by considering production scenarios considered involving the three basic events that are flowering, fruit set and growth.

Finally, the review of the state of the art has identified works that contribute to the application of methodologies and strategies to the agricultural field for irrigation systems and fertilization with the goal of improving production yield at field. Nevertheless, there is a gap in the application of Expert Systems that includes fruit production life cycle to evaluate the quality of the supplying orchard in the agro supply chain and also that helps synchronize the first and second links of the supply chain. In that sense, this study tends to contribute to bridge this gap.

3. Design and implementation of the expert system (ES)

3.1. Fuzzy Sets Theory (FST)

Nowadays, to obtain a better approach in the estimation of uncertain scenarios, works based on modeling studies require taking into consideration the largest possible obtainable information of the studied scenario. Computer intelligence and rule-based systems appear as possibilities within the activities of analyzing and modeling different environmental systems, offering paradigms of Artificial Intelligence, such as Fuzzy Logic, Expert Systems and systems based on Logic and Fuzzy Sets. Started in 1965 by Lotfi A. Zadeh, Fuzzy Logic appears as an important tool for control of complex industrial systems and processes. Contrary to traditional logic, FL allows working with not well-defined and imprecise information. FL can be used in processes when no mathematically precise models exist, and when knowledge is needed from an expert that uses ambiguous and imprecise concepts. An important contribution of the FST is its capacity of representing vague data matching the human brain in its use of approximate information and uncertainty to generate decisions, specifically to mathematically represent uncertainty and vagueness, and to supply formal tools to handle the intrinsic imprecision typical of many problems (Kahraman et al., 2003). In this regard, the necessity to work with fuzzy sets springs from the existence of concepts with no clear limits. In the same way as in sets used in classical logic, a fuzzy set is defined as a group of various elements that have a common feature. Yet contrary to the former, it does not require the absolute membership of an element, but recognizes that not all its elements possess the feature to the same extent. Nevertheless, an element may belong simultaneously to different sets to a different degree, as long as the sum of its degrees of membership is equal to the unit, so that a fuzzy set appears associated with a linguistic value or qualifier. The function that describes this degree of membership is called Membership Function and it can assume values within the [0,1] interval, the transition of the value between 0 and 1 being gradual and not changing instantaneously as happens in classical sets. A fuzzy set in a universe discourse can be defined as shown in Eq. (1).

$$A = \{(x, \mu_A(x)) | x \in U\} \quad (1)$$

where $\mu_A(x)$ is the membership function of the variable x, and U is the universe discourse. The closer the membership of set A to the value of 1, the higher the degree to which the variable x belongs to set A. Even though any function may be valid to define a fuzzy set, some functions are more commonly used because of their mathematical simplicity, such as the triangular type function and the trapezoidal type function, just to mention a few of them. In the same way as in classical sets, the basic operations in fuzzy sets are those of intersection, union and complement. For a review of related work in the fuzzy literature and/or experts systems, see Crina and Ajith (2011); Siler and Buckley (2005).

In this study, FL is used to generate a knowledge base in an Expert System for the estimation of production yield and of fruit quality in an orchard without irrigation. The diverging opinions of the experts are represented as blurred triangular and trapezoidal numbers, which describe the coded knowledge of the expertise of Persian lime growers. The ES models scenarios of the Persian lime production cycle in a non-irrigated orchard, and allows the producer to improve his decisions in the application of agricultural practices, so to estimate the production yield and the fruit quality. Similarly, the ES can be used by a fruit purchaser with the goal of evaluating fruit quality and yield in a non-irrigated orchard. In both cases, in order to improve decision-making, the ES starts from the information of agricultural practices employed by the farmer in his production orchard.

3.2. Design of the ES

The design of the ES involved four steps. The first step concerned the determination of the scope, type and goal of the ES. In the second step, knowledge and expertise from the farming experts related to agricultural practices and uncertain parameters that influence production yield and fruit quality were collected, and defined as variables in the ES knowledge database. In the third step, model variables were codified within the fuzzy logic model with Mamdani type inference.

Finally, the fourth step was dedicated to the ES validation. The validation and reliability process was carried out by consultation with experts in citrus fruit production in order to collect production yield and quality values that have been historically observed in a Persian lime producing orchard. In addition, the ES design the ES involves the dynamics modeling of the citrus fruit production system, as well as the identification of the relationship between farming practices, production yield and fruit quality in the orchard. For the production cycle of Persian lime in a non-irrigated orchard, an ES is proposed in this work that integrates four fuzzy models (FMs) that help the producer to improve his decisions for orchard management through adequate agricultural practices. Three of them are designed according to each of the Persian lime growth stages: Flowering (FM-1), Fruit set (FM-2), Fruit growth (FM-3), in order to estimate the production yield in tons per hectare harvested (t/ha), and one (FM-4) to estimate the percentage of fruit quality for export. Fig. 1 describes the integration of the FMs and the ES simulation program. Table 1 describes the variables related to agricultural practices, and uncertain events defined in the knowledge database for the FMs expert systems as Input elements (I), and the operations variables defined as Output elements (O). Appendix A describes the variables and fuzzy sets, as well as the operating values for the fuzzy sets of the FMs of Flowering (FM-1), Fruit set (FM-2), Fruit growth (FM-3) and Quality (FM-4). The knowledge base for Flowering yield (flY) in FM-1 is composed of 864 inference rules, the Fruit set yield (fsY) of

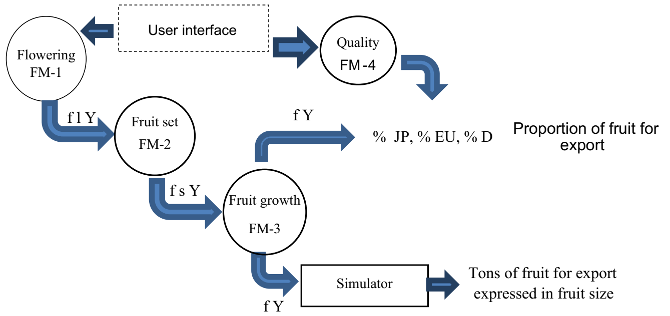

Fig. 1. Expert System based on Fuzzy Logic for estimating production yield and Persian lime quality in a non-irrigated orchard.

MD-2 and the Fruit Growth yield (fY) for FM-3 are composed of 60 rules and finally, FM-4 involves 54 inference rules.

On the one hand, based on the production cycle, the ES is initiated by estimating Flowering volume (flY) using FM-1. The flY value estimated by FM-1 is fed, along with other values of agricultural practices, into FM-2 to estimate the volume of Fruit Set (fsY), which is successively fed into FM-3 to finally estimate the Fruit Growth yield (fY) of the orchard. On the other hand, the fourth FM (FM-4) uses the fY value estimated by FM-3 to determine the total amount of fruit in accordance with its quality. FM-4 estimates the percentage of fruit expressed in terms of percent (%) of Japan quality (J), European Union quality (EU), and Persian lime with damage (*D*). The USA quality (USA) is deduced by subtracting the output estimations for Japan, EU and Persian lime with damage from 100%. Once the proportion of exportable fruit is estimated, the total amount of fruit is determined (fY) according to the output of FM-3. To estimate the fruit size, the ES is embedded in a simulation program developed by PROMODEL®, which models the fruit classification process of a citrus fruit exporting company and measures the volume of fruit in relation to the lime size and the quality of the export market. In a practical sense, the FM-4 is designed to obtain global estimates of fruit quality in the orchard based on values for agricultural practices, while the simulation program leads to the estimation of the total amount of fruit classified according to size, based on the value estimated by FM-3. This kind of information is useful for the exporting company because it will improve its decision when selecting a supplying orchard.

In this study, a Mamdani type model (implemented within MATLAB® 7.0.1, Matrix Laboratory), is used to develop the ES: this system with multiple inputs and outputs represents information using fuzzy logic. Each input and output variable is represented in the system through a Linguistic variable. The rule base is developed according to the IF-THEN type, that constitutes the inference method based on the knowledge base and consequent inference engine. The defuzzification process uses the centroid calculation method. An example of how an operating rule is triggered in this study can be expressed as follows: If the planting density is high, and if the number of trees in production is high, and if the pruning and cleaning is intense, and if the soil nutrition is appropriate, and if there is heavy rainfall, and if there is little or no control of pests, and if the wind is weak, then the production yield is little or null. Appendix B is an example of the set of rules activated in a production scenario when FM-3 is used to evaluate the fruit Yield corresponding to the third stage of the lime production life cycle at orchard.

Let us recall that the objective is to improve the synchronization between the two first links through an increase in orchard yield and quality classification represented by fruit size. For this purpose, historical data were collected regarding production yield and fruit quality (based on size) historically observed in a non-

Table 1
Variable codification in the knowledge base of the FMs in the expert system.
Source: Own design based on work sessions with panel of experts.

Variables	Definition	Measurement units	Status in the FM: input (I)/output (O)
Pruning (*P*)	Agricultural practice that influences flowering. This Practice is used to induce flowering	t/ha	I
Soil nutrition (*S*)	Agricultural practice transferring nutrients to the plant, soil applied or foliar applied, with the aim of maximizing production yield and fruit quality	Number of applications	I
Wind (*W*)	Uncertain event that directly affects production yield and quality of the fruit	km/h	I
Rainfall (*R*)	Uncertain event that supplies water to the orchard	mm/month	I
Control of pests (*C*)	Agricultural practice that controls pests that affect yield and quality of the fruit	Number of applications	I
Planting density (*PD*)	Operational variable related to the amount of planted trees in the orchard	t/ha	I
Trees in production (*T*)	Operational variable related to the amount of trees producing Persian lime in the orchard	t/ha	I
Flowering yield (flY)	Linguistic expression that represents the flowering obtained at the orchard	t/ha	**O**
Fruit set yield (fsY)	Linguistic expression that represents the fruit set obtained at the orchard	t/ha	**O**
Fruit growth yield (fY)	Linguistic expression that represents the fruit growth yield obtained at the orchard	t/ha	O
Japan quality (JP)	Linguistic expression representing the percentage of fruit produced in the orchard corresponding to Japanese quality	% Of production	O
European Union quality (EU)	Linguistic expression representing the percentage of fruit produced in the orchard corresponding to European Union quality	% Of production	O
Damaged (*D*)	Linguistic expression representing the percentage of fruit produced in the orchard that is damaged	% Of production	O

Table 2
Observed values in Persian lime production in a non-irrigated orchard during the year 2010.
Source: Records of orchard management in an exporting company, 2010 (production period: January–October).

Planted ha/ha in production	Growth stage	*P*	*S*	*C*	*R*	*W* (km/h)	*PD* (high)	*T*	Harvested tons	*Y* (t/ha)	Quality (%)			
											J	EU	USA	Damaged
11.0/10.9	Flowering	2	3	3	6.6	12	25[a]	95%	47.84	5.80	16.00	13.90	53.12	16.98
	Fruit set	–	2	–	4.13	14	–	–						
	Fruit growth	–	2	3	11	16	–	–						

Hectares (ha); planting density (*PD*); pruning (*P*); trees in production (*T*); soil nutrition (*S*); rainfall (*R*); control of pests (*C*); wind (*W*); yield (*Y*).

[a] Expected yield.

irrigated orchard and then fed into the FMs. The impact of the ES on the first and second links is measured by the amount of fruit that does not meet the customer's packaging requirements in a citrus fruit exporting company (second link). For this purpose, a simulation model in PROMODEL® uses the output value of the FM-3 production yield to classify the fruit according to the customer's needs. An inventory indicator of fresh fruit on the plant measures the amount of Persian lime without packaging.

In order to determine the reliability of the ES, the values observed in the production orchard of the studied case are compared with the estimated values of the ES. Table 2 describes historical values observed in the Persian lime production in a case study in a non-irrigated orchard for Flowering, Fruit set and Fruit growth stages, respectively. Data indicate that in an orchard of 11 planted hectares, and with 10.9 ha in production, pruning was performed two times, soil nutrition three times, and pests control three times with 6.6 mm of rainfall and an average wind of 12 km/h, along with high-density planting and 95% of the trees in production. In the period, 47.84 t were harvested, resulting in 5.8 t/ha of export quality corresponding to 16.00% Japan quality, 13.90% EU quality, 53.12% USA quality and 16.98% of the product was damaged or did fit with export quality.

The values *P*, *S*, *C*, *R*, *W*, *PD* and *T* of Table 2 are introduced into the Flowering, Fruit Set and Fruit Growth FMs, as well as into the FM-4 of fruit quality of the ES. It can be observed how the estimation of 5.31 t/ha measured by the ES and accordingly by FM-3, is remarkably close to 5.80 t/h, the value that was historically registered by the exporting company. Table 3 shows the estimations provided by the ES and their comparison with the historical values registered by the exporting company. A very good agreement between the predicted and experimental values is observed.

The simulation program implements a fruit classification process that interprets historical data from 2005 to 2007 regarding Persian lime arrival from orchards to an exporting company. It involves the different stages of the Persian lime packaging process with three parameters, i.e. average fruit classification process time per lime, average amount of export quality per hour, and capacity utilization percentage. To validate the simulation model and to check if it is an adequate representation of the real system, a paired *t*-test was applied according to Law Averill and Kelton (2000), which is used to compare the results from the simulation model to historical data of the real system. This test produced a confidence interval that includes zero, which shows there is no significant difference between the simulation results and real data, so it can be concluded that the model is valid.

The optimal number of replications was also determined according to Law Averill and Kelton (2000); since the model analyzes more than one performance measure, the largest value of $n^* \beta$ is used at a 96% confidence level. It was found that the optimal number of production runs was 12 replications, each of these represents a working day at the packing plant. The simulator results allow an analysis of the amount of fruit according to size and color. The estimation of Fruit Growth Yield (f Y) of FM-3 is fed

Table 3
Observed – historical – values for 2010, compared with estimated values (related to orchard yield and fruit quality) by the FMs in the ES for a non-irrigated orchard.

t/ha (Harvested)		Quality (% of the estimated production)							
Observed[a]	FM-3	Japan		Europe		USA		Damaged	
		Observed[a]	FM-4	Observed[a]	FM-4	Observed[a]	Difference	Observed[a]	FM-4
5.80	**5.31**	16.00%	**14.30%**	13.90%	**12.20%**	46.88%	**53.70%**	16.98%	**19.80%**

[a] Historical data provided by the company.

Table 4
Estimated fruit quality obtained by FM-4, and the PROMODEL® simulator.

fY[a]	Exportable fruit (t/ha) estimated by FM-4				Estimated exportable fruit (t/ha): FM-4 – vs – simulator	
	Japan	Europe	Damaged	USA–Canada	FM-4	Simulator
5.31	0.7593	0.6478	1.0513	2.85	**4.26**	**4.73**

[a] Estimated value by FM-3 of the ES for Production yield.

into the simulation model to estimate the size and amount of exportable fruit. The results of Table 4 show that there is a very close agreement between the historical values registered in the citrus fruit exporting company and the values estimated by the simulation model and by FM-4.

4. Case study: Impact on the first and second link in the Persian lime supply chain

In order to evaluate the impact on the synchronization between the first and second link in the Persian lime supply chain, a simulation model in PROMODEL® is designed and integrated into the ES. The model represents the fruit classification process in an exporting company and evaluates fruit volume considering fruit size and color quality of the export market. The different stages of the Persian lime packaging process involve fruit receiving and feeding, mechanical selection, manual selection, fruit washing, fruit drying, fruit waxing, wax drying and fruit sorting.

A case study is presented here in order to prove how ES can be useful in the Persian lime supply chain. This study selects the supplying orchard that generates the smallest inventory of fresh fruit in the company warehouse. Five orchards were considered in this case study, involving historically Persian lime growers of a Persian lime exporting company: O-1, O-2, O-3, O-4, O-5. All orchards are located in a different geographical area, which results in a difference in the application of agricultural practices and in the conditions of the citrus fruit production.

In this case study, a typical fictitious demand is considered for a Persian lime exporting company in a scenario of peak season of fruit supply, on a typical working day in a citrus fruit packing plant. Table 5 offers a packaging program and packaging priority typical for a working week in the peak season of Persian lime supply. The exporting company's work scenario operates as follows:

a. Average daily fruit arrival ranges from 90 to 160 t.
b. All required resources are available for packaging, labor, energy, transport and other services required in the product selection–classification–packaging system.
c. Fruit packaging programs are designed at weekends to be put into practice on Mondays (day 1).
d. Packaging programs are bound by rules of priority and orders have to be integrated within 72 h.

Table 5
Fruit packaging program.

Market	Size[a]	Caliber[b]	Package (lbs)	Priority	Kg of required fruit
Japan (J)	54	230	10	3	1,905.12
Japan (J)	60	250	10	3	2,857.68
Japan (J)	42	175	10	1	21,555.07
Europe (EU)	48	200	10	1	64,665.21
Europe (EU)	54	230	10	1	21,555.07
USA	42	175	10	2	28,576.8
USA	40	150	40	2	54,432
USA	60	250	40	2	21,772.8
USA	54	230	10	2	38,102.4

[a] Size: refers to the diameter of the lime (equatorial axe).
[b] Caliber: refers to the number of limes that fit into a box meant for export.

Table 6
Values estimated by the ES for yield and fruit quality in a non-irrigated orchard.

Supplying orchard	Yield estimated by FM-3	Quality estimated by FM-4		
	Orchard production (t)	J (t)	EU (t)	USA (t)
O-1	142.42	29.05	24.21	58.82
O-2	103.66	16.79	14.20	51.21
O-3	140.88	29.12	34.3	38.11
O-4	117.75	16.59	14.82	56.71
O-5	130.38	31.14	37.66	34.43

e. Packaged fruit must not remain more than eight days in cold-storage rooms before shipment.
f. USA orders can be supplemented with EU and J qualities while the reciprocal practice turns out to an undesired alternative, because of potential customer complaints.
g. Each operating day, the fruit packaged is that which has been delivered during the same day.
h. Each orchard will be managed as a single delivery for a particular day, Monday to Friday (i.e. numbered day 1 to 5).

Two scenarios are studied to define the fruit arrival at the exporting company. The former occurs randomly while in the latter, the ES is used to decide fruit intake. Table 6 presents the results estimated by the ES for five supplying orchards.

The arrival scenarios of the supplying orchards are described in Table 7, where scenarios A–D correspond to random scenarios, whereas scenario E corresponds to a fruit intake program supported by an ES decision: fruit intake from O-5 takes place on Monday (respectively from O-2 on Tuesday, from O-1 on Wednesday, from O-3 on Thursday and finally intake from O-4 on Friday). Table 8 shows the intake order of orchards at the company based on the ES decision and the export market that is targeted on each day in compliance with the packaging program.

To measure the impact of that decision, the ES is supported by a simulation program that classifies fruit according to the packaging program established in this case study. The analysis of these values formed the basis for evaluating the inventory status of unpackaged fruit that failed to meet the required quality of the packaging program at the end of each operating day.

Table 9 shows the inventory status for each scenario. Fig. 2 demonstrates this inventory status, and shows how on day one (Monday) a uniform fruit inventory is presented for all fruit intake scenarios, while on days two (Tuesday) and three (Wednesday), the fruit intake decision based on the ES proves to maintain the fruit inventory levels below the remaining scenarios.

Besides the advantage of a low inventory policy, minimizing inventories of fresh fruit that will not be packaged at its arrival and will demand storage and handling in the company is a strategy that offers another advantage to the company. This case study shows – based on inventories of fruit without packaging on days two and three – a significant disparity in inventory on those days of 12,354.5 and of 31,029.43 kg for day two (Tuesday) and day three (Wednesday), respectively. When these quantities are translated into investment at $ 19.00 Mexican pesos per kilogram in orchards, they amount to $ 234,735.00, and $ 589,559.00 Mexican pesos. On a weekly basis, they represent $ 824,294.00 Mexican pesos. In addition to this benefit, using this ES has also the advantage to estimate fruit quality by the end of the week. The company can thus manage its planning at the beginning of the week and focus on each market, thus creating a competitive organizational advantage as it increases customer responsiveness.

Table 7
Arrival of orchard product to exporting company.

Scenario	Arrival of Persian lime to the company					Intake process
	Monday	Tuesday	Wednesday	Thursday	Friday	
A	O-3	O-5	O-1	O-2	O-4	Random
B	O-5	O-3	O-1	O-4	O-2	Random
C	O-3	O-5	O-1	O-4	O-2	Random
D	O-5	O-4	O-3	O-1	O-2	Random
E	O-5	O-2	O-1	O-3	O-4	Decision made by ES

Table 8
Fruit arrival based on ES suggestion (Scenario E).

Orchard	Day	Tons of fruit	Packaging program implemented
O-5	Monday	130.38	EU
O-2	Tuesday	103.66	EU–USA
O-1	Wednesday	142.42	USA
O-3	Thursday	140.88	USA–J
O-4	Friday	117.75	J

5. User perceptions of the expert system for production yield and fruit quality

In an expert system, nothing is obvious, and its domain should therefore be specified. Since the ES suggested here is built with a knowledge base of experts in a specific domain, it is expected that it can incorporate knowledge that will make it more "robust" as to include additional variables related to the cultivation system. Here are a number of perceptions of experts about the functionality of the ES.

1. The ES demonstrates response *speed* in its results, *accuracy of judgment* in agreement with that of the expert, *flexibility to adapt* to scenarios reflecting the general context of citrus fruit production.
2. The development setting of the ES and technological infrastructure is *accessible*, it does not require specialized knowledge, and it proves to be *practical* to be handled in orchards.

On the basis of these results, the developed tool can be particularly useful to the Persian lime grower (first link) for decision making in the application of agricultural practices reflecting production interests at the orchard. Furthermore, the exporting company (second link) will be able to use the ES to improve decision-making in fruit purchasing.

6. Conclusions

The ES based on FL has proven to be a useful tool for synchronizing the first two links of the Persian lime supply chain in three ways. First, it helps identifying behavioral patterns of variables in the Persian lime production system in orchards. Second, it is particularly useful for modeling production scenarios through system variables in agricultural practices, which can lead

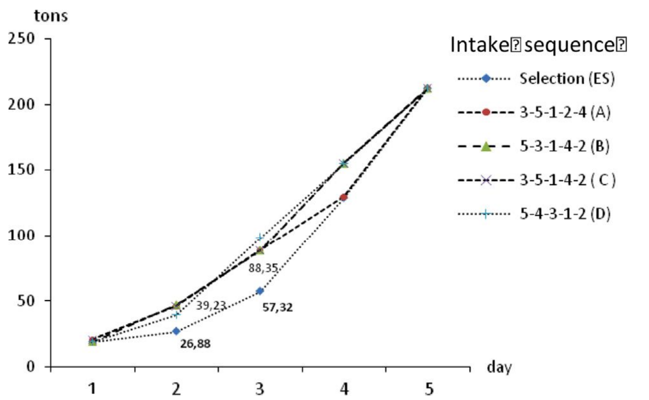

Fig. 2. Scenario for inventory generated by fruit intake. Reference: Table 9.

Table 9
Persian lime inventory (kg) generated by fruit intake to the packaging plant for five scenarios.

Sequence of intake according to number of orchard	Scenarios Unpackaged fruit inventory (kg)				
Day	3-5-1-2-4 (A)	5-3-1-4-2 (B)	3-5-1-4-2 (C)	5-4-3-1-2 (D)	Decision by ES 5-2-1-3-4 (**E**)
Monday	20,461.07	18,890.07	20,461.07	18,890.07	**18,890.07**
Tuesday	45,665.41	46,935.34	45,665.41	39,231.52	**26,877.02**
Wednesday	88,350.75	88,350.75	88,350.75	98,330.80	**57,321.32**
Thursday	129,409.38	154,937.36	154,937.36	154,895.79	**128,795.84**
Friday	212,271.03	212,271.02	211,892.83	211,892.82	**211,892.82**

to significant economic benefits when the estimations are compared with the company historical records; and third, the approach can easily model a scenario for selecting supplying orchards, e.g. choice of the most convenient time of product intake from every orchard to the company, synchronization between supply links.

Since the knowledge base of the ES contains information related to agricultural practices such as pests control, tree pruning, fertilizer application, planting density and trees in production, it has provided insight in their interaction with uncertain events such as rainfall and wind, directly affecting yield and fruit quality, and also in the way water management and fertilization – combined with agricultural practices modeled in the ES – can be viewed as beneficial.

The advantage of modeling production scenarios from the producing orchard creates the opportunity to control fruit inventory in the exporting company (second link), which favorably decreases inventories of fresh fruit in the exporting company and distribution warehouses. This can help reducing the Bullwhip Effect of the Persian lime supply chain. It must be highlighted that the design of the ES required integrating research from an area to which little attention has yet been paid, i.e. the Persian lime supply chain. As a result, results from this research contribute to relevant topics such as characterizing the Persian lime supply chain in Mexico or also setting criteria for efficient Persian lime production in a non-irrigated orchard based on agricultural practices and uncertain events in citrus fruit production in orchards. Topics for future investigation on the basis of these results include applying optimization methods for supplier selection or optimizing classification, packaging and eco-design packaging processes.

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Appendix A

Tables A1–A4 describe the operating values for the fuzzy sets of the FMs of Flowering, Fruit set, Fruit growth and Quality.

Table A1
Fuzzy model for flowering yield in a NIO: fuzzy sets and operating intervals.

Flowering (FM-1)						
Input			Knowledge base	Output		
Variable	Fuzzy set			Variable	Fuzzy set	
	Definition	Interval			Definition	Interval
Planting density (*PD*)	Low High	[0 5 15 20] [15 20 32 32]	864 Inference rules	Flowering yield (flY)	Null-little	[0 0 1 2]
Trees in production (*T*)	Very low Low Medium High	[0 10 40 60] [40 60 80] [60 80 100] [80 100 100]			Very low	[1 2 8 10]
Pruning (*P*)	Not performed Aesthetic Intense	[0 0 3 6] [3 6 15 20] [15 20 32 32]			Low	[8 10 13 15]
Soil nutrition (*S*)	Low Corrective Appropriate	[0 0 1 2] [1 2 3 4] [3 4 5 6]				
Rainfall (*R*)	Low High	[0 5 10 50] [10 50 170 170]			Medium	[13 15 20 25]
Control of pests (*C*)	Null-minimum Protection	[0 0 1] [0 1 3 3]				
Wind (*W*)	Weak Strong Rough	[0 0 40 50] [40 50 60] [50 60 100 100]			High	[20 25 32 32]

Table A2
Fuzzy model for fruit set yield in a NIO: fuzzy sets and operating intervals.

Fruit set (FM-2)						
Input			Knowledge base	Output		
Variable	Fuzzy set			Variable	Fuzzy set	
	Definition	Interval			Definition	Interval
Flowering yield (flY)	Null-little Very Low Low	[0 0 1 2] [1 2 8 10] [8 10 13 15]	60 Inference rules	Fruit set yield (fsY)	Null-little	[0 0 1 2]

Table A2 (*continued*)

Fruit set (FM-2)						
Input			**Knowledge base**	**Output**		
Variable	**Fuzzy set**			**Variable**	**Fuzzy set**	
	Definition	**Interval**			**Definition**	**Interval**
	Medium High	[13 15 20 25] [20 25 32 32]			Very Low	[1 2 8 10]
Soil nutrition (*S*)	Low Appropriate	[0 1 2] [1 2 2 6]			Low	[8 10 13 15]
Rainfall (*R*)	Low High	[0 0 10 50] [0 50 170 170]			Medium	[13 15 20 25]
Wind (*W*)	Weak Strong Rough	[0 0 40 50] [40 50 60] [50 60 100 100]			High	[20 25 32 32]

Table A3
Fuzzy model for fruit growth yield in a NIO: fuzzy sets and operating intervals.

Fruit growth (FM-3)						
Input			**Knowledge base**	**Output**		
Variable	**Fuzzy sets**			**Variable**	**Fuzzy sets**	
	Definition	**Interval**			**Definition**	**Interval**
Fruit set yield (fsY)	Null-little Very Low Low Medium High	[0 0 1 2] [1 2 8 10] [8 10 13 15] [13 15 20 25] [20 25 32 32]	60 Inference rules	Fruit growth yield (fY)	Null-little Very Low	[0 0 1 2] [1 2 8 10]
Soil nutrition (*S*)	Low Appropriate	[0 1 2] [1 2 6 6]			Low	[8 10 13 15]
Rainfall (*R*)	Low High	[0 0 10 50] [10 50 170 170]			Medium	[13 15 20 25]
Wind (*W*)	Weak Strong Rough	[0 0 40 50] [40 50 60] [50 60 100 100]			High	[20 25 32 32]

Table A4
Fuzzy model for quality in a NIO: fuzzy sets and operating intervals.

Quality (FM-4)						
Input			**Knowledge base**	**Output**		
Variable	**Fuzzy set**			**Variable**	**Fuzzy set**	
	Definition	**Interval**			**Definition**	**Interval**
Control of pests (*C*)	Null-minimum Low Basic	[0 0 1] [0 1 2] [1 2 3 3]	54 Inference rules	Japan quality (J)	Minimum Low High	[0 0 1 2] [1 2 10 20] [10 15 30 30]
Soil nutrition (*S*)	Low Corrective Appropriate	[0 0 1 2] [1 2 3 4] [3 4 6 6]		European Union quality (EU)	Minimum Low High	[0 0 1 2] [1 2 10 20] [10 20 25 25]
Rain fall (*P*)	Low High	[0 0 10 50] [10 50 170 170]		Damaged (*D*)	Low	[0 0 6 10]
Wind (*W*)	Weak Strong Rough	[0 0 40 50] [40 50 60] [50 60 100 100]			High Damaged	[6 20 30] [20 40 100 100]

Table A5
Set of activated rules in FM-3 for a production scenario example derived from the Fruit set stage to determine the fruit growth yield (fY).

Fruit growth (FM-3)			
Input (I)		**Activated rules**	**Output (O)**
Variables	**Scenario**	• IF (fruit set yield is medium) and (soil nutrition is low) and (rain fall is low) and (wind is weak) then (fruit yield is very low)	Fruit growth yield (fY) **14.6 t**
Fruit set yield (fsY)	22 t	• IF (fruit set yield is medium) and (soil nutrition is low) and (rain fall is high) and (wind is weak) then (fruit yield is low)	
Soil nutrition (*S*)	2 Applications	• IF (fruit set yield is medium) and (soil nutrition is appropriate) and (rain fall is low) and (wind is weak) then (fruit yield is low)	
Rainfall (*R*)	45 mm	• IF (fruit set yield is medium) and (soil nutrition is appropriate) and (rain fall is high) and (wind is weak) then (fruit yield is medium)	
Wind (*W*)	40 km/h	• IF (fruit set yield is high) and (soil nutrition is low) and (rain fall is low) and (wind is weak) then (fruit yield is low)	
		• IF (fruit set yield is high) and (soil nutrition is low) and (rain fall is high) and (wind is weak) then (fruit yield is medium)	
		• IF (fruit set yield is high) and (soil nutrition is appropriate) and (rain fall is low) and (wind is weak) then (fruit yield is medium)	
		• IF (fruit set yield is high) and (soil nutrition is appropriate) and (rain fall is high) and (wind is weak) then (fruit yield is high)	

Appendix B

Table A5 shows the set of rules that are activated in the production scenario example that assumes a Fruit set yield (fsY) of 22 t/ha, in which there where 2 applications of nutrients to the soil (*S*), with an average rain fall (*P*) of 45 mm, and average wind of 40 km/h.

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