A System Dynamics Model of the Chicken Meat Supply Chain faced with Bird Flu

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Abstract

System dynamics methodology is widely applied in modelling and analyzing supply chain behaviour under uncertain environment. However, there are only few applications in food supply chain in a context of sanitary crises. In this paper, we are accordingly interested in studying the behaviour of the entire chicken meat supply chain coping with sanitary crises effects. A model is proposed to study the SC behaviour dealing with the shortages in upstream supply capacity and downstream unpredictable consumer behaviour disturbed by the crisis as well. This model will be simulated and analyzed to investigate the behaviour of the chicken meat SC under bird flu crisis during the period from October 2005 to March 2006 in France. We then use a sensitivity analysis to study the supply chain stability under different environment uncertainties. Our model should be helpful to decision-makers for other fresh food supply chains when they are facing such crises.

Keywords: Push-pull system, multi-echelon, buffer inventory, supply chain behaviour, sanitary crises, demand uncertainties, system dynamics.

1. Introduction

In our day, market systems are increasingly dynamic and volatile. In supply chain management (SCM), coping with uncertainty has become one of the most important issues for the deciders. In fact, one of the SCM problems is the changes in the supply chain behaviour due to internal or external factors. Petrovic et al. (1998) proposed that there are two sources of uncertainty inherent in the external environment in which the SC operates: customer demand and external supply of raw material. Sanitary crises caused by animal diseases threatening the development of food supply chain (SC) and the global economy is an example. During the past two decades, the food supply chains in Europe and France (Europe's largest producer and exporter of poultry products) have faced to non-stop food safety crises such as mad cow disease, the dioxin crisis, foot-

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and-mouth disease or recently, bird flu crisis. This menace seriously influences to human health and the economy of all countries in the world by its huge scope, hazard and soaring haste such as bird flu with its impact on poultry supply chain and the chicken meat supply chain in particular is extremely significant. The influence of these crises is not only on upstream production capacity resulted from disease infection between animal populations, but also on downstream consumption decrease.

In this context of highly uncertain environment, we are interested in studying the dynamic behaviour of the chicken meat supply chain under the bird flu crisis and their consequences in term of over costs for the industries. We have chosen the fresh meat standard chicken supply chain because its production represents 75% of the entire chicken meat supply chain and this is the most influenced sector of the chain by bird flu crisis. The finished fresh products of standard chickens include 60% of packaged entire chicken and 40% of processing chickens (including packaged carcasses and cooked products).

The chicken meat supply chain is a "classical" integrated push-pull supply chain with five echelons where initial rearing and slaughtering stages (rearing-slaughtering stage) are operated in a push-based manner while remaining processing, distribution, and consumption stages employ a pull-based scheme. In general, in SC management, the hybrid push-pull inventory control is based on buffer management (Golçalves, 2003). The specific characteristic of this chain is its small-size potential buffer between upstream push rearing-slaughtering stage with a fixed duration of 40 days and the downstream pull processing, distribution, and consumption stages which have to respond in less than 24 hours to consumer orders. In fact, the buffer size must be lower than five days due to the perishability of these products.

However, in this paper, we will not emphasize on the problems of buffer stock optimization but rather to propose a simulation approach focusing on the stability of the whole SC and its sensibility to the adjustment delays managed by the SC deciders. Firstly, we present a literature review focusing on general SC behaviour modelling, multi-echelon push-pull production-distribution, and food SC behaviour simulation modelling. And then, a more detail review focusing on dynamic supply chain modelling will substantiate our work of structuring a generic logistic flows model for the whole chicken meat supply chain. Finally, in order to analyse the stability of this supply chain, we propose a test with the real data of AI crisis influencing the French chicken supply chain and a what-if analysis.

2. Literature review

Many modelling approaches for analysing multi-echelon supply chain can be used like deterministic or stochastic analytical models, stochastic analytical models, econometric models or simulation models (Beamon, 1998). Among them, operations researchers had mostly used analytical approaches focusing mainly on how to improve the efficiency of the individual entities in a supply chain instead of improving the performance of the entire supply chain. Zazanis (1994) studies push and pull systems in a dynamic environment by examining push-pull production control system under a make-to-order policy with safety stock. Moreover, many researches were interested on optimization of buffer size on push-pull production systems or supply chains. For example, Salameh and Ghattas (2001) propose a model to calculate the just-in-time buffer inventory that minimizes the cost rate considering the sum of the buffer inventory holding costs and the cost due to shortage in a cycle. Giordano and Martinelli (2002) consider the optimization of the safety stock for a single-part type, single unreliable machine production system. However, they have a major drawback – the dramatic increase of the operational cost – so that their design should come from an economic analysis that balances the implementation cost (stored materials and occupied area) with the level of service provided to the consumers. In our case, we can not propose to optimize this buffer because of the perishability of the fresh products which need to be used within very short time delay (five days).

On the other hand, simulation has mostly been used to study supply chain behaviour and performance since late 1980s. Recently, there emerge in the literature some works on food supply chain modelling using discrete-event or continuous simulations to study the global dynamics of the supply chain. The simulation approach was originally based on system dynamics. This was motivated by the fact that the structure of the SC and the flow control determine its performance. SC modelling and simulation were later investigated with discrete event simulation and continuous simulation. Van de Vorst et al. (2000) apply discrete-event simulation for modelling the dynamic behaviour of food supply chains and evaluating alternative designs of the supply chain. Chang and Makatsoris (2001) also study the requirements for supply chain discrete event simulation modelling. But dynamic simulations have proved its proficiency to analyse the supply chain because of its interactive and incorporates hierarchical feedback process (Pidd 1984). Furthermore, Rabelo et al. (2008) present a new methodology to predict behavioural changes in manufacturing supply chains due to endogenous and/or exogenous influences in the short and long term horizons by using system dynamics, neural nets, and eigenvalues. According to the authors, the methodology permits the identification of the causes that may induce a negative behaviour when predicted. Riddalls et al. (2000) conclude that global behaviour of a supply chain can only be assessed by using dynamic simulation.

Many supply chain models have today been built using system dynamics (SD) (Forrester 1961, Sterman 2000, Higuchi and Troutt, 2004, Kamath and Roy, 2007, Rabelo et al. 2008…). Created by Jay Forrester, system dynamics modelling has been used as a method of analysis, modelling and simulation for almost 50 years. The first production-distribution system identifies four supply chain echelons (Forrester, 1958). At each echelon, he takes into account the order and shipment delays and explains that the success of industrial enterprises depends on this interaction of these six flows and the capacity of understanding and controlling the system.

Moreover, SC behaviour is dynamic and controlled by nonlinear interrelationships and interactions among the system components (Shapiro, 2001). A particular behavioural problem with supply chains is known as demand amplification or Bullwhip effect in a supply chain occurring when slight to moderate demand uncertainties and variability become magnified when viewed through the eyes of management at each link in a supply chain (Lee et al., 1997). Besides, Sterman (2006) suggests that supply chain network is a complex dynamic system and generates multiple modes of behaviour including business cycles (oscillation in production and inventories), amplification of orders and production from consumption to raw materials (the Bullwhip Effect), and phase lag between the start of intervention and its effect (shifts in the timing of the cycles from consumption to materials). Additionally, recent studies on poultry supply chain modelling are focused on understanding the complex behaviour of poultry industry (Minegishi and Thiel, 2000). The authors emphasize on studying the operational problems of the production process and contributing some decision suggestions to managers but not on analysing the global behaviour of the entire supply chain. Our emphasis in this paper is on understanding the impact of uncertain environment upon the supply chain stability and the short-term reaction of the chain deciders facing inventory management and pilotage problems.

3. System dynamics model of the chicken meat supply chain

Generally, in food supply chain, farm is considered as primary food producers, various types of processing industry, trading companies, the food retail sector and final customer, each different step in the entire production process is viewed as link in the chain. Therefore, food supply chain management represents the management of the entire set of production, manufacturing/transformations, distribution and marketing activities by which a consumer is supplied with a desired product. In particular, the chicken meat supply chain studied includes five main stages: rearing, slaughtering, processing, distribution, and consumption (see Figure 1). In addition, there are always storing and transporting activities between the stages. An important characteristic of the poultry supply chain is its flexibility due to its short product life cycle: it could take approximately 70 days from hatching an egg to the stage when a customer consumes a poultry product. Therefore, it is relatively easy to introduce changes to the poultry supply chain in a short period of time. Moreover, some specificities of poultry production such as standardisation of poultry size and weight make the poultry supply chain very close to industrialised production, where poultry is highly manipulated in order to make production more efficient.

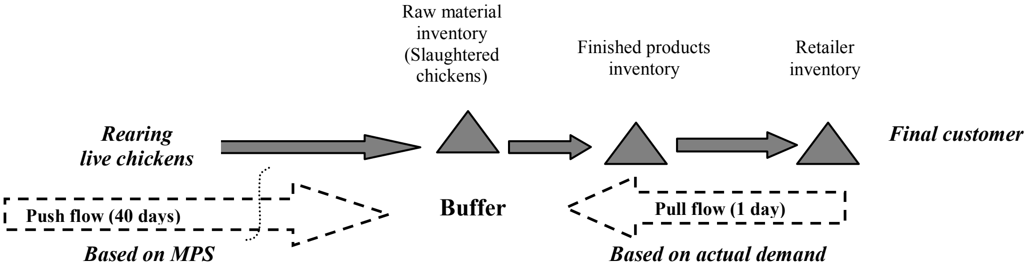

Figure 1. Logistic flow schema of the chicken meat supply chain

Our research interest is studying the evolution of total costs and the stability of this supply chain more particularly under sanitary crisis. This is not a problem of optimization because the customer demand varies in accordance with their reaction under bird flu crisis impact that cannot be represented by a usual probability function. Simulation approach will be used to study the stability of the whole SC and its sensibility to the adjustment delays managed by the SC deciders. The total costs will be measured in different scenarios of short term SC driving parameters without changing the model structuring.

The first step in identifying our modelling approach is to define the key system features and to create a high-level causal loop diagram that captures the key elements of the system in question including the major feedback loops. In this diagram (Figure. 2), there are a whole range of dependent variables and feedback dynamics that capture overall system behaviour and performance over time.

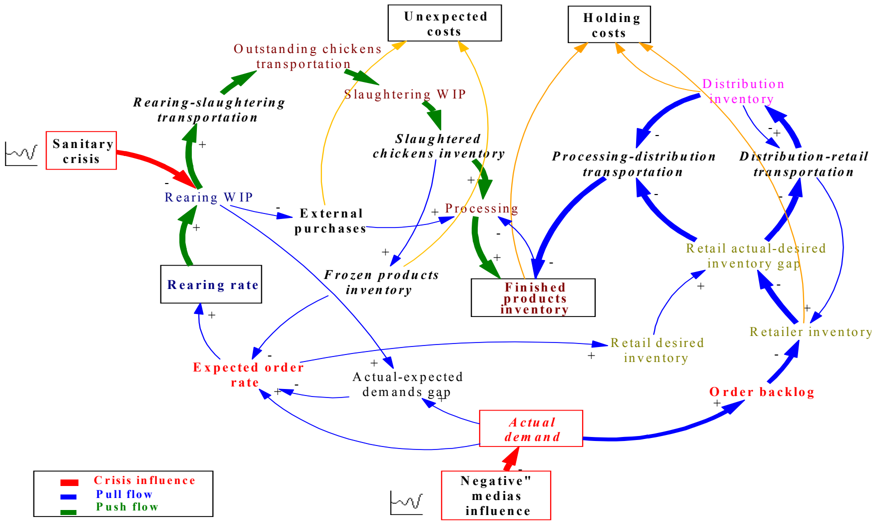

Figure 2. Causal loop diagram for Chicken supply chain model

The principal feedback loops included are described below:

<u>Loop 1:</u> Actual-expected demands gap – Expected order rate – Rearing rate – Rearing WIP.

<u>Loop 2:</u> Expected order rate – Rearing rate – Rearing WIP – Rearing-slaughtering transportation – Outstanding chickens transportation – Slaughtering WIP – Slaughtered chickens inventory – Frozen products inventory.

<u>Loop 3:</u> Processing – Finished products inventory.

<u>Loop 4:</u> Distribution inventory – Distribution-retail transportation.

<u>Loop 5:</u> Retail inventory – Retail actual-desired inventory gap – Distribution-retail transportation.

Our research is solely interested in the supply chain’s short-term actions concerning global pilotage of materials flows. Hence, five homeostatic loops described above are sufficient for representing logistic behaviours of the supply chain. However, it is well recognizable that other medium and long-term strategic regulation mechanisms equally work on supply chain in crisis in the field of prevention actions in sanitary level, communication, customer promotion policy, legislation modification and so on that we will not mention about for our case.

Basing on this causal diagram, the mathematical formulation of stocks and flows structures by a set of nonlinear differential level and rate equations will be defined. The level equations describe the accumulations within the system through the time integrals of the net flow rates, and the rate equations define the rate of change of the levels. Our SD model of the chicken supply chain is mainly based on the basic Forrester industrial model (1958) and the generic supply chain model of Sterman (2000). Base upon the causal loop diagram and the mathematical formulation of levels and flows diagram, the SD model of the chicken meat supply chain is modelled in *iThink®* software.

The model includes ten sections: Demand and Master Production Schedule (MPS), rearing, slaughtering, processing and final manufacturing, transportation and distribution of both kind of finished products (entire chicken and processing chicken), retail sales, regulation sectors (retail adjustment and order backlog), supply chain performance (unexpected costs and holding costs) representing the feedback loops and system process of the entire supply chain. In addition, the model is built following some rules:

- Orders are always filled
- Live chickens are always available in external markets (non-integrated suppliers and importation)
- Chicken products are always delivered on time.

4. Simulation results

For simulating our model in French chicken supply chain, we only concentrate on the fresh standard chicken supply chain with 60% of packaged entire chicken (EC) and 40% of processing chickens (PC, including packaged carcasses and cooked products). Firstly, we will run the model in equilibrium with constant demand, no sanitary crisis, and the entire supply chain operates in the desired state. The equilibrium is reached when the available alive chicken's level for satisfying 2,083 tons/days including 1,250 tons/days of EC (60%) and 833 tons/day PC (40%) is stable at 2,083 tons/day. The supply chain fills all of its customer orders without extended costs due to external purchases or frozen products. And then, we apply our model for analysing the French chicken supply chain behaviour influenced by the Avian Influenza sanitary crisis during the period from the second week of Oct. 2005 until the end of Mar. 2006 (about 161 days). A test for stationary time series between the simulation result and the real data of standard chicken production evolution is conducted to valid our model. Comparing these two trends we obtain a ratio between the standard deviation and the average value of the production equal to 0.06 meaning a "relative" error rate of 6 %.

Using this real data for actual demand and rearing capacity, we will focus on analysing some main supply chain factors representing the entire supply chain behaviour in our simulation model:

- Actual and expected demands: *Total actual demand*, *Total Exp order rate*.
- Rearing capacity for filling orders: *Available alive chickens*

- Regulation factors: *Frozen chickens inventory*, *External purchases* and *unexpected costs*.
- *Inventory* management and *holding costs* of the entire supply chain.

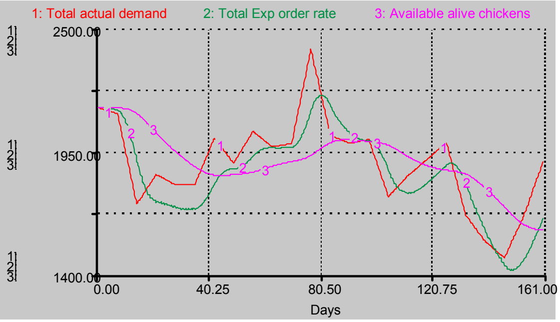

Figure 3. Effect on production capacity (tons)

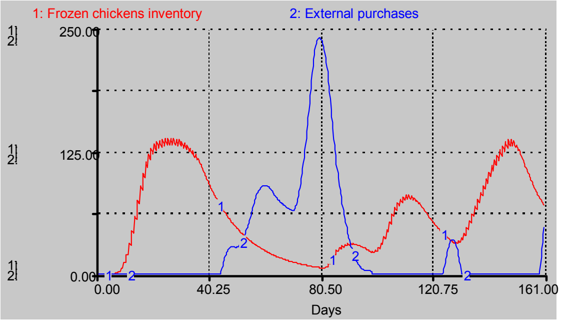

Figure 4. Effect on the level of frozen chickens inventory and external purchases (tons)

The figure 3 shows the *available alive chickens*' response to the fluctuation in the *actual demand* and to the impact of the bird flu crisis. In fact, the rearing capacity had not been concerned to the crisis until December 2005 while the *actual demand* is shrunk from October 2005 resulted from the influence of the Medias on consumer behaviour. As we can see in the figure, the quantity of *available alive chickens* has not the same fluctuation as the *total actual demand* (including EC and PC demands) because of the smoothing and adjustment rules in the chain with a *smoothing time* of 7 days and a time lag of 40 days *rearing cycle time*.

On the other hand, because of *MPS delay* (7 days), long *rearing WIP adjustment time* (55 days) and *rearing cycle time* (40), and all 40 days chickens must be slaughtered without delay, the rearing producers are not able to adjust the chicken output well enough to the change in the daily *actual demand*. That is also the reason why there are rise and fall in *frozen chickens inventory* and in *external purchases* when the demand goes up and down as shown in the figure 4. In this figure, the *total actual demand* varies continuously at low level from the simulation starting point but it starts to increase sharply from 1970 tons at 62nd day to the maximal level of 2,409 tons at 76th day. Accordingly, the *frozen chicken inventory* and the *external purchases* quantity move up and down. For example, the *frozen chicken inventory* reaches the maximum of 138 tons at 24th day while the *external purchases* are still equal to 0 and inversely, the *external purchases* starts increasing and reaches the height of 249.9 tons at 79th day whereas the *frozen chicken inventory* goes down by the lowest level of 6 tons. These fluctuations of *frozen chicken inventory* and *external purchases* cause the *unexpected costs* for the supply chain that reaches a peak of 192,943 Euros at 79th day when the *external purchasing level* is maximal.

In addition, we recognize that the variation in *retail inventory* level results in increasing and fluctuation in the *distribution and finished products inventory* levels since the retailer orders and purchases to its upstream supplier basing on the actual sale rate (pull-based scheme). According to the simulation results, a sudden augmentation at *retail inventory* level at 80th day of both PC and EC products followed by its rough drop leading to a significant increasing in *distribution and finished products inventories*.

These increases and fluctuations of inventory level at different stages of the supply chain lead to an increase of *holding costs* at each echelon of the chain. In fact, the *retail holding cost* is much bigger than the *holding costs at distribution and finished products* levels because of the higher safety stock for responding to final customers at retail level.

5. Sensitivity analysis

Effect of AI influencing fluctuation rate

In our case, for analysing the sensibility of the model, we now change the fluctuation degree of the exogenous factors in both upstream (crisis influence rate) and downstream (actual demand) of the supply chain (model input) to examine the change in some internal factors of the chain (model output).

In the following table, we will show the fluctuation ratios of these factors when the *crisis influence rate* and *actual demand fluctuation* rates are decreased or increased by 50% from their initial state with the observed fluctuation in reality.

Table 1. Effect of external environment influencing fluctuation on upstream and downstream factors

Fluctuation rate of crisis influence and actual demand rates	- 50%	+50%
Frozen chicken inventory	- 47%	- 11 %
External purchases	+ 52%	+ 35%
Unexpected costs	+ 41%	+ 30%
Rearing WIP	+ 2%	- 2%
EC inventory:		
at finished products inventory	- 10%	- 8%
at distribution inventory	- 26%	- 24%
at retail inventory	- 2%	- 3%
PC inventory:		
at finished products inventory	- 11%	+ 34%
at distribution inventory	- 16%	+ 21%
at retail inventory	+ 2%	- 2%

As we can see in the table, the *frozen chicken inventory* is considerably sensitive with the fluctuation of the *crisis influence rate* and *actual demand*. When the fluctuation rate is decreased 50% (small fluctuation) the suppliers can reduce nearly 50% of the freezing rate. However, when the fluctuation rate increases they have to keep more chickens in inventory but still smaller than the real situation (-11%) because there is a decrease in the rearing output resulted from increasing in the *crisis impact*. Additionally, in both cases, the *external purchases* level is always superior to those of real situation because of the production shortage that leads the *unexpected costs* also superior to the real situation. These results show that the internal supply chain stability is very sensitive to the changing in external environment.

On the other hand, we now focus on fluctuation effect all along downstream supply chain: inventory fluctuation at factory, distribution and retail levels. According to the results in the table, we identify that the level of *rearing work in process* is almost unchanged by daily external influence because of its long *demand adjustment time* (7 days) and rearing WIP adjustment time (55 days). However, the inventory levels at each echelon of the chain vary considerably, particularly at finished products inventory and distribution inventory because of their short lead time (1 day).

Effect of demand change time

Table 2. Effect of demand change time on internal factors

Demand change time (days)	*1*	*7*	*13*
Frozen chicken inventory (tons)	7,917	9,513	10,283
External purchases (tons)	5,988	4,679	3,985
Total unexpected costs (million Euros)	5.1	4.2	3.7
Total holding costs (million Euros)	93.2	87.6	82.9

We have found that by increasing the *demand change time* from 1 to 13 days, the amount of *frozen chicken inventory* lightly increases while the quantity of *external purchases*, the *unexpected costs* and the *total holding costs* of the entire supply chain (finished products inventory, distribution inventory, and retail inventory) considerably go down. It means that we can reduce the supply chain costs by increasing the *demand change time*.

Effect of rearing WIP adjustment time

Table 3. Effect of rearing WIP adjustment time on internal factors

Rearing WIP adjustment time (days)	*55*	*70*	*85*
Frozen chicken inventory (tons)	9,513	9,706	9,843
External purchases (tons)	4,679	4,668	4,645
Total unexpected costs (million Euros)	4.219	4.22	4.208
Total holding costs (million Euros)	87.6	87.3	87

The value of all the factors in this table is lightly changed showing that changing in *rearing WIP adjustment time* has little impact on the supply chain behaviour in short-term.

Effect of freezing adjustment time

In this case, the *frozen adjustment time* is varied from1 to 9 days:

Table 4. Effect of freezing adjustment time on internal factors

Freezing adjustment time (days)	*1*	*5*	*9*
Frozen chicken inventory (tons)	28,146	9,513	5,775
External purchases (tons)	7,980	4,679	4,113
Total unexpected costs (million Euros)	7.8	4.2	3.5
Total holding costs (million Euros)	108	87,6	84,1

The simulation results show that by increasing the *freezing adjustment time* we can reduce the level of *frozen chicken inventory*, *external purchases*, *unexpected costs* and the *total holding costs*. However, in reality, we can not hold fresh slaughtered chickens more than 5 days because of their perishability.

Effect of retail inventory adjustment time

Table 5. Effect of retail inventory adjustment time on downstream inventories

Retail inventory adjustment time (days)	*1*	*4*	*7*
Holding costs at finished product inventory (million Euros)	17.3	18.4	19.5
Holding costs at distribution inventory (million Euros)	18	19.4	20.6
Holding costs at retail inventory (million Euros)	52.3	49.8	47.5

The results show that if the retailer extends its *inventory adjustment time*, they can reduce their *holding costs* but the producers and the distributors will bear an increase in their *holding costs*.

6. Remarks and discussions

The simulation results reveal some essential behavioural features of this supply chain:

- In our model, the change in *expected order rate* and the *available live chickens* (upstream sectors) depend on the variations of both customer demand (downstream external impact) and *sanitary crises rate* (upstream external impact) while the *inventory levels* at each supply chain echelon (downstream sectors) are oscillated mainly according to the variation of *customer demand* and the supply chain adjustment policies. Therefore, an emerging problem is how to maintain a significant buffer size to response to supply line coping with both changing in *customers demand* and instability in production capacity. Additionally, because of the complexity (lots of time delays along the multi-echelon SC) and the specific characteristic (short-term perishable products) of the chicken meat SC, optimizing this push-pull SC is really complicated. Nevertheless, this is important issue requiring much further research that we would like to continue in our upcoming studies.

- When the variation of sanitary crises influencing rate is minor, the level of the *available live chicken* decrease or the rearing production is always inferior to the *actual demand* and the *expected order* rate because it is impossible to adjust immediately the rearing level and with the same quantity. The customer demand is daily varied but the rearing production is adjustable every 55 days, including 40 days for *rearing cycle time* and minimum 15 days for ensuring sanitary conditions. Therefore, the supplier has to keep the non-delivered chickens in freezing inventory.

- In contrast, when the variation of *sanitary crises influence* rate is more significant than the *demand* variation, the level of *available live chicken* considerably decreases and the supplier has to purchase live chickens from external markets. Consequently, they have to suffer from some problems of raw material availability and *unexpected cost* concerning about external market price and transportation cost. This result suggests that the supply chain performance is affected not only by *customer demand* changes but also by the fluctuation in raw material supply resulted from external environment impact.

- The results of sensitivity analysis show that the supply chain behaviour is quite sensitive not only to the variation of external environment but also the deviation in internal control factors of the supply chain. By adjusting these internal factors (time delays), we can reduce the external effects and enhance the performance of the system.

7. Conclusion

This paper has explained why our work has focused on simulation modelling for studying the behaviour of the entire chicken meat supply chain threatened by high uncertainties in the supply capacity (the impact of sanitary crises influence on rearing farms) as well as in the customer demand (unpredictable consumer behaviour effecting the sales rate). A systems dynamics model basing on Forrester methodology has been developed to analyse the stability of the supply chain within this context of exogenous perturbations in both the upstream and downstream of the supply chain. The simulation of the system dynamics model has been carried out in the programmable continuous simulation environment of *Ithink®* software that makes it possible to simulate internal dynamics of each SC stage and also the entire chicken supply chain in sanitary crises situation as well. The simulation results show that fluctuations in customer demand and production are progressively amplified by each supply chain stage and affect the stability of the whole chain. The complexity and particularity of this supply chain behaviour have been studied and discussed. The findings in this paper substantiate the previous observations and put forward some important issues that require further researches on this kind of supply chain.

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