Universitat de Lleida

Optimization models forimproving the decision-making in the pig production process under a Pig Supply Chain contex

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Universitat de Lleida

TESI DOCTORAL

OPTIMIZATION MODELS FOR IMPROVING THE DECISION-MAKING IN THE PIG PRODUCTION PROCESS UNDER A PIG SUPPLY CHAIN CONTEXT

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Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Enginyeria i Tecnologies de la Informació

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(2019)

ABSTRACT

This thesis focuses on the Pig Supply Chain structures raised during the latest years in the pig sector. Those structures appear as a consequence of an organizational change observed, where small companies and pig producers are vertically integrated, specialized and working together under the umbrella of big enterprises or cooperatives.

Pig Supply Chains structures have competitive advantages and allow to decrease risks, to create value and to deal with new challenges such as food quality and animal welfare. Despite this, new issues and concerns need to be considered by managers to plan the pig production efficiently. Decisions related to the production planning under the herd management perspective, such as to plan the flow of animals through housing facilities over time, scheduling transfers from farm to farm, when and how to sell the animals to the abattoir, the optimal batch management or farm's location and productive capacities improvements are key. Additionally, Pig Supply Chains motivates farm specialization and intensive farming. Therefore, there is an increment of transportation and farms' saturation in specific areas. Consequently, producers are more receptive in considering greener supply chains and production systems which are also motivated by the social and governmental attitude towards environmental issues.

Operations Research has been widely used for practical problems in various sectors such as business, economics, environmental and other disciplines. In the pig sector, a literature review reveals that most of the studies have focused on one specific problem or one phase in the pig production process. However, decisions impacting to the production planning under a herd management perspective impacts, and requires to have, the whole vision of the system.

Hence, the main objective of this thesis is to develop a set of decision models to help in the decision-making process for problems in the pig production process under a Pig Supply Chain structure which was stated above. The contribution of this work then, consists in 1) To balance the impact of emissions in the pig production system by developing a decision model under an economic perspective 2) To develop a multiperiod and multisite decision model for production planning taking into consideration the pig production process characteristics, and 3) to develop a decision model for planning tactical decisions in the pig production process for increasing the efficiency.

This thesis demonstrates that the use of models developed bring benefits in the decision-making process, emphasizes the computational complexity of modeling an integrated system, and opens new research opportunities in the pig sector.

RESUM

Aquesta tesi se centra en les estructures de la cadena de subministrament plantejades durant els últims anys en el sector porcí. Aquestes estructures apareixen com a conseqüència d'un canvi organitzatiu observat, on les petites empreses i els productors de porcs estan integrats verticalment, s'especialitzen i treballen junts sota el paraigua de grans empreses o cooperatives.

Les estructures de cadenes de subministrament en el porcí tenen avantatges competitius i permeten disminuir els riscos, crear valor i enfrontar nous reptes, com la qualitat dels aliments i el benestar animal. No obstant això, els gerents han de considerar els nous problemes i preocupacions per a planificar la producció porcina de manera eficient. Les decisions relacionades amb la planificació de la producció sota la perspectiva de la gestió del ramat, com la planificació del flux d'animals a través de les granges al llarg del temps, la programació de transferències de granja en granja, quan i com vendre animals a l'escorxador, la gestió òptima dels lots o les millores d'ubicació i capacitats productives són claus. A més, aquestes cadenes de subministrament motiven l'especialització i l'agricultura intensiva. Per tant, hi ha un increment en el transport i una saturació en les granges en àrees específiques. En conseqüència, els productors són més receptius a l'hora de considerar cadenes de subministrament i sistemes de producció més ecològics, que també estan motivats per l'actitud social i governamental cap als problemes ambientals.

La Investigació Operativa ha estat àmpliament utilitzada per a problemes pràctics en diversos sectors com negocis, economia, medi ambient i altres disciplines. En el sector porcí, una revisió de la literatura revela que la majoria dels estudis s'han centrat en un problema específic o una fase en el procés de producció porcina. No obstant això, les decisions que afecten la planificació de la producció sota una perspectiva de gestió del ramat impacten i requereixen tenir tota la visió del sistema.

Per tant, l'objectiu principal d'aquesta tesi és desenvolupar un conjunt de models de decisió per ajudar en el procés de presa de decisions per problemes en el procés de producció de porcs sota una estructura de cadena de subministrament esmentada anteriorment. La contribució d'aquest treball consisteix en 1) Balancejar l'impacte de les emissions en el sistema de producció porcina mitjançant el desenvolupament d'un model de decisió sota una perspectiva econòmica 2) Desenvolupar un model de decisió multiperíode i multigranja per a la planificació de la producció tenint en compte les característiques del procés de producció, i 3) desenvolupar un model de decisió per a planificar decisions tàctiques en el procés de producció de porcs per augmentar l'eficiència.

Aquesta tesi demostra que l'ús de models desenvolupats brinda beneficis en el procés de presa de decisions, emfatitza la complexitat computacional de modelar un sistema integrat i obre noves oportunitats de recerca en el sector porcí.

RESUMEN

Esta tesis se centra en la Cadena de Suministro de Cerdo surgida durante los últimos años en el sector porcino. Estas estructuras aparecen como consecuencia de un cambio organizativo observado, donde las pequeñas empresas y productores de cerdos están integrados verticalmente, se especializan y trabajan conjuntamete en grandes empresas o cooperativas.

Estas Cadenas de Suministro tienen ventajas competitivas y permiten disminuir los riesgos, crear valor y gestionar nuevos retos, como la calidad de los alimentos y el bienestar animal. A pesar de esto, los gerentes deben considerar los nuevos problemas para planificar la producción porcina de manera eficiente. Las decisiones relacionadas con la planificación de la producción bajo la perspectiva de la gestión del rebaño, como la planificación del flujo de animales a través de las granjas a lo largo del tiempo, la programación de transferencias de granja a granja, el cuándo y cómo vender los animales al matadero, la gestión óptima de los lotes o la granja, o la ubicación de granjas y capacidades productivas son claves. Además, estas Cadenas de Suministro motivan la especialización y la agricultura intensiva. Por lo tanto, hay un incremento en el transporte y una saturación de granjas en áreas específicas. En consecuencia, los productores son más receptivos a la hora de considerar cadenas de suministro y sistemas de producción más ecológicos, que también viene motivado por la actitud social y gubernamental hacia estos problemas ambientales.

La Investigación Operativa ha sido ampliamente utilizada para problemas prácticos en diversos sectores como negocios, economía, medioambiente y otras disciplinas. En el sector porcino, una revisión de la literatura revela que la mayoría de los estudios se han centrado en un problema específico o una fase en el proceso de producción del cerdo. Sin embargo, las decisiones que afectan a la planificación de la producción bajo una perspectiva de gestión del rebaño impactan y requieren tener la visión de todo el sistema.

Por lo tanto, el objetivo principal de esta tesis es desarrollar un conjunto de modelos de decisión para ayudar en el proceso de toma de decisiones para problemas en el proceso de producción de cerdos bajo una estructura de Cadena de Suministro que se mencionaron anteriormente. La contribución de este trabajo, entonces, consiste en 1) Balancear el impacto de las emisiones en el sistema de producción porcina mediante el desarrollo de un modelo de decisión bajo una perspectiva económica 2) Desarrollar un modelo de decisión multiperíodo y multisitio para la planificación de la producción teniendo en cuenta la producción porcina características del proceso, y 3) desarrollar un modelo de decisión para planificar decisiones tácticas en el proceso de producción de cerdos para aumentar su eficiencia.

Esta tesis demuestra que el uso de modelos desarrollados aporta beneficios en el proceso de toma de decisiones, enfatiza la complejidad computacional de modelar un sistema integrado y abre nuevas oportunidades de investigación en el sector porcino.

ACKNOWLEDGEMENTS

This PhD, aside from being a great experience, has been a huge challenge. This thesis would not have been possible without the help of a few people that has been present partially or completely throughout its development.

First, I would thank my supervisor Dr. Lluis Miquel Plà. This thesis would have not been possible without his understanding, patience and encouragement. In addition, I would like to acknowledge Dr. Adela Pagés, Prof. Victor M. Albornoz, and Prof. Antonio Alonso Ayuso and Jordi Mateo for the support and knowledge that they have provided during the realization of this PhD. In the operative side, I want to thank Josep Reixach from Batallé, S.A. for providing data and assistance.

I would also like to thank the BigDSSAgro group (CYTED). Through them, I was able to make new contacts and I got new opportunities for collaborations and ideas for the thesis.

Finally, I would like to thank my family for the support that they have provided me. First, to my wife Astra, for motivating and supporting me in this PhD. During the entire time, she made a big effort to help me make this thesis happen. To the rest of my family, who has been supportive in finishing this thesis: to my parents Rosa and Jaume; to my grandmother Maria; to my brother Marcel, Laura and Ruth; Julie, Ate Amanda and Ate Audrey.

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INTRODUCTION AND SCOPE OF THE RESEARCH

1.1 INTRODUCTION

Pork is one of the most produced meat in the world along with cattle, goat, chicken, and sheep. Pork meat's demand is increasing every year. According to the Food and Agriculture Organization of the United Nations (FAO), pork meat exceeded 110 million tons worldwide in 2017 [1]. China (46%), United States (10%), Germany (5%), Spain (4%) and Brazil (3%) were the main producers [2]. The European Union's (EU) aggregate was 21%. Additionally, the EU was the largest exporter in the world followed by the United States and Canada. Germany, Spain, and Denmark were the main EU's contributors.

In the case of Spain, those figures would not have been possible without the changes in the pig sector that have been produced in recent years.

Firstly, the industrialization of farms, abattoirs, feed mills, and meat plants by the inclusion of precision technology and information and communications technology (ICT), drives into a rapid evolution of the industry being more efficient and productive. The use of those technologies also allows gathering new data which is being useful for helping in the decision-making process. Secondly, there is an organizational change. Pig Supply Chains (PSC), structured in the form of big enterprises or cooperatives, integrates and coordinate their operations by using a tighter vertical coordination linkage. PSC has demonstrated to bring benefits by reducing the risk and uncertainty, creating value and dealing with new challenges and consumer concerns, such as environmental and sustainable vision; animal welfare; and food quality and safety [3, 4].

Supply chains represent all the organizations (also namely agents) involved and working together since the good is transformed until it arrives at the final client [5]. In the case of the PSC's, it includes the agents related to procurement (providers), pig production (farmers) and slaughtering (abattoirs) (Figure 1.1). The decisions, which previously were taken at an individual level, are now taken at the PSC level by the enterprise or cooperative (the so-called integrator) under a top-bottom flow.

In the case of the pig production process, the main organizational change lies in the three-site production system which is being fundamental for the

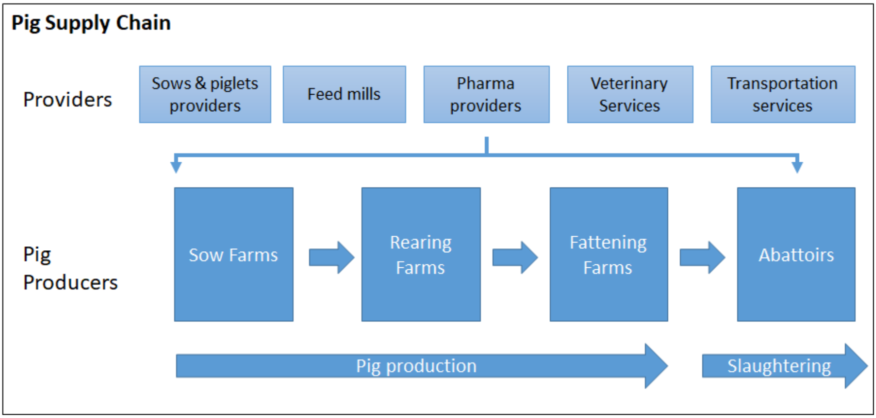

FIGURE 1.1: Pig Supply Chain structure and agents involved

specialization of the pig sector. This system divides the pig production process farming into three phases (namely maternity, rearing, and fattening). Farms which previously handled the entire production process (farrow-to-finish), are now evolved toward specialized farms in one of those phases being pig production more efficient and productive. Despite the advantages of this new organization, managers need to face new decisions (strategic, tactical and operational) non-existent to date and mainly related to the production planning and supply chain coordination under the herd management perspective. Those decisions are, for instance, the plan the flow of animals through housing facilities over time, scheduling transfers from farm to farm, when and how to sell the animals to the abattoir, the optimal batch management or farm's location and productive capacities improvement [6]. Furthermore, the three-site production system leads to multiplying the number of farms in a region and reinforcing the intensity of farming. As a result, saturated areas of farms with a significant amount of contamination, pollution or greenhouse gas (GHG) emissions provokes new environmental concerns. The GHG emissions also increased because of the additional transportation needs for transferring animals between farms while they are growing. As a consequence, the social attitude toward environmental issues and governmental regulations, make the pig producers companies more receptive to consider greener supply chains and production processes.

In Operations Research, researchers have been working with Optimization in the pig sector providing solutions for helping to the decision makers. Despite the research published until now, research opportunities in the pig production process still exist. For instance, (a) most of the studies take into consideration individual problems. However, the constant changes produced in the sector requires evolutionary change management by incorporating new capabilities and continuous research as previous authors agreed [6]. (b) because of its specific nature, existing literature focuses mainly in operational decisions rather than tactical or strategic decisions which the linkage of two or more agents or even the entire production process as a whole is more necessary [6].

Hence, this thesis presents a set of herd management optimization models focused in the three-site pig production system under the perspective of the PSC structure arise in Spain, for dealing and helping decision makers in operational and tactical decisions. More specifically, the impact of GHG emissions, production planning and the efficiency of the production process.

In this introductory chapter, some examples revise differences in PSC structures. In the following section, the three-site pig production system is described, including the decision challenges studied in this thesis. Later, the global objectives are presented together with the outline of the thesis.

1.2 THE PIG SUPPLY CHAIN MANAGEMENT

Through the literature, different PSC's structures and configurations could be found. Hence, issues / challenges, the decision-making process, and the stakeholders may vary depending on each one. Factors like the PSC structure, the vertical integration degree, the degree of cooperation / competitiveness between agents, or the influence that one agent exerts to the others, might lead to the need for different decision-making tools.

In China, pig production companies work independently between breeders, pig producers, and slaughterhouses [7]. The change to large pig production companies exist, although the predominance remains in the small size farms [8]. Therefore, there is an early stage of vertical integration in which decisions are taken at the agent level, for instance, farms [9].

In Canada, vertical integration exists between feed companies and pig producers. In that case, feed companies provide not only feed and ingredients but also a large variety of services (such as veterinarians, transportation companies) and also acts as the coordinator role in some cases with verbal agreements. Despite this, producers decide and use short time agreements with slaughtering which might avoid long-term relationship and cooperation [10].

In EU countries, the vertical integration in the pig sector might vary between countries. For instance, In Germany, the majority of slaughtered pigs are traded through cooperatives or private intermediaries, who negotiate overall yearly quantities with slaughterhouses and establish enduring relationships with farmers, but usually not under a contractual basis. [11]. Hungary, with a significant tradition in the pig production, faces with a lack of coordination of the agents in the PSC. Farmers distrust between them and the strong influence of processing companies impacts in the development of the sector [12].

On the other hand, Denmark presents a well vertical integrated system formed with small and domestic producers in a system in the form of independent farmers cooperatives [6]. In Spain, the main difference with Denmark is the existence of big integrators and the number of big players competing in the sector. This relationship falls under, most of the cases, a formal agreement [13]. Those enterprises not only own farms but also other agents are included in the PSC (i.e., abattoirs, feed mills, veterinary, and so) and control the different phases of the pig production process while farmers provide the physical structure and labor. Then, the decision-making process in production planning is made globally [4, 14].

Therefore, while in non-vertical integrated structures, the decisions tools might focus to specific problems and agents, in the case of integrated structures the need to make coordinated decisions globally, at an aggregate level and taking into consideration more than one agent in the process might be key for increasing the competitiveness.

1.3 THE PIG PRODUCTION PROCESS AND DECISIONAL CHALLENGES

1.3.1 *Introduction to the three-site production system*

The pig production process is divided into three phases (maternity, rearing, and fattening) encompassing different agents and/or farmers (Fig. 1.2). The aim is to produce pigs which will be sold to the abattoir. The lead time of the entire process takes between 24 and 30 weeks depending on different factors such as the genotype, animal feeding and selling price.

The three phases in the production process involve different farms specialized of each type:

- **The maternity phase**: The first phase is held in the sow farms. Sows are inseminated with the aim to produce piglets. Sow farms have three housing facilities depending on the biological state of the sow:

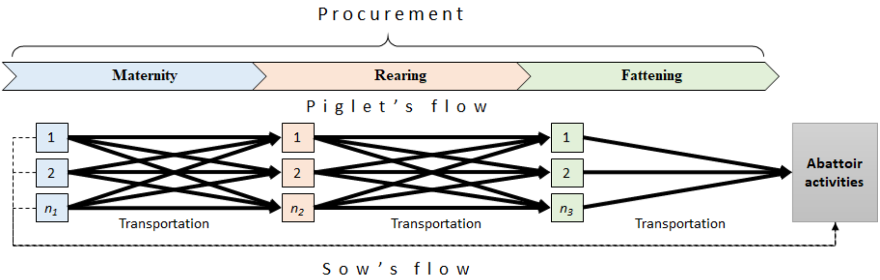

FIGURE 1.2: The pig production process

breeding-control, pregnancy and farrowing. In the breeding facility, the sows are inseminated and controlled to confirm the pregnancy. Once this pregnancy is confirmed, the sows are moved to the pregnancy facility. On the contrary, the sow will remain for additional insemination. When the productivity of a sow is considered below to the established parameters, it is sold to the abattoir and replaced by a new one. At this phase, causalities might affect to piglets and sows. The farrowing facility is where farrowing and weaning are done for a certain number of weeks (around four weeks). Once this is done, the piglets are weaned and transferred to the nursing facilities, which represents the second phase of the process.

- **The rearing phase**: In this phase, the piglets grow from weaning to the starting of the fattening process. Depending on the system configuration, this phase might take place 1) in the sow farm but as a separate facility, 2) in the fattening farms but also as a separate facility, or 3) located as a different farm as it is shown in Fig. 1.2. This phase takes between four and six weeks, and piglets here reach a weight between 15 to 35 kg.
- **The fattening phase:** This phase aims to fatten the pigs to reach the marketing weight before they are sent to the abattoir. Fattening farms might be divided into facilities, and each facility can be divided into pens. At this phase, facilities are filled and emptied in batches, also know as all-in-all-out management (AIAO). Under AIAO management, a facility cannot be filled with a new batch of pigs until the entire facility is emptied, cleaned and disinfected. AIAO is considered a good practice for preventing the spread of diseases [15]. At this phase, even

pigs are fed under the same regime, the individual growth is not equal, and the animals reach the marketing weight differently (i.e., from one to four weeks of delay). Marketing decisions can be considered at different levels: (a) individual, when decision makers use the visual inspection for selecting the pigs suitable to be delivered to the abattoir and (b) at a herd level, when decision makers decide whether an whole pen or section should be marketed [16]. This thesis uses individual marketing.

- **Slaughtering:** The end of the pig production process takes place when the pigs reach their marketable weight, and they are sold to the abattoir. Payment is a base price per kg of live weight which changes over time, but additionally, each abattoir applies bonuses and discounts to the base price depending on the quality of the carcass according to the SEUROP classification (Commission Regulation (EC) No.1249/2008). One of the characteristics of the modern pig production process is that it is a '*push*' system. In other words, the decision of the production is made without taking into consideration future demand, and it is more related to fulfill production capacity at maximum [14].

Farms in a three-site production system, have different locations; therefore, transportation is necessary for transferring animals from one farm to another or to the abattoir. Trucks which depend on its capacity makes transportation. The company might either own trucks or outsourced, which corresponds to another agent of the productive process.

Another group of agents which is present in all the production process are the providers of raw material necessary for the pigs' production. Procurement might include, for instance, feed mills, pharmaceutical & genetic companies which provides veterinary services, medicines, concentrates and semen through all the production process. Procurement can also be referred to as the purchase of animals. In this case, the acquisition of sows (to replace the old or unproductive ones or to increase the production of the entire system) or piglets (which is a practice for increasing the production rapidly).

1.3.2 *The environmental impact of PSC's*

Concerns on sustainability in supply chains are a key component and a new focus of research [17, 18]. The increment of the pig production highlighted the society's concerns about its environmental impact and future sustainability [19]. At a governmental level, different policies and regulations with the aim to decrease the emissions have been studied. For instance, in Australia, the Australian Emissions Reduction Fund (ERF) provides incentives to farmers for adopting new practices and technologies to reduce the emissions. EU also creates regulations with the aim to decrease those emissions [20]. The Spanish Government is preparing a regulation for reducing the emissions in the pig sector because the exceed by 30% of the quota assigned by EU [21].

Intensive farming as a consequence of the vertical integration in the PCS's reduces the number of farms but increases its capacities. The concentration of farms and therefore in the number of animals drives into saturated areas where GHG emissions are currently an issue. Diets and more specifically protein impacts considerably in those emissions [22]. In that case, frequently, farmers cannot make decisions about the diet which is given by feed mills. Additionally farms specialization in each phase of the production process requires transportation which is another emissions source [23].

The study of the GHG in the pig production process has been studied. For instance, in [24] argued the need for dedicated modeling approaches for food production systems like PSCs. In [25] investigated the potential fossil-fuel energy and GHG (greenhouse gas) savings in pig farming in Europe. In [26] optimized the fertilization of the crop-based, by utilizing more locally-produced feed ingredients, by adopting cereals like wheat rather than maize as base feeds, by reducing concentrations of certain metals, or by more efficient use of nitrogen. Also additional local studies in the emission field in pig production has been done locally in countries like France, Sweden, Portugal, Denmark, Spain, Italy and Korea, for instance [23, 27–38].

During the pig production process, the maternity and especially fattening phase is where more GHG emissions are generated (specially CO_2 and NH_4 among others) [23]. The emissions in fattening phase are produced because (1) the content in protein in the diet and (2) the phase is a growth process in which the pigs remains a large number of weeks to reach the optimal marketing weight (generally between 14 and 18). Therefore, to plan the deliveries of pigs from the fattening farms to the abattoir impacts in the GHG emissions.

The deliveries of pigs to the abattoir are phased for a single batch of animals. Additionally, in a vertically integrated system, AIAO management in which facilities in fattening farms cannot allocate new pigs until the facility is emptied and sanitized, adds complexity in the decisions.

In literature, researchers studied the problem under different structures of farms and abattoirs, taking into consideration the growth of the animals, marketing policies, the quality of the meat, and the price and reward system [15, 39–46].

Despite the rising concern in greener supply chains, studies focused on the optimization of deliveries of pigs' to the abattoir but taking into consideration its environmental impact has not been found.

1.3.3 *The coordination and production planning in a PSC*

In traditional farrow-to-finish pig production, the entire process is housed in the same farm. The piglets go through the different facilities in the farm corresponding to the growth phases until they are sold to the abattoir. Farmers make decisions within the scope of the farm. From a herd management perspective, decisions are mainly related to when to sell the pigs to the abattoir.

In a vertically integrated system, the farms are specialized in each phase for performing specific operations. The relationship with the integrator is under a contract which determines the minimal production or production goals. Farms have different capacities and locations. Therefore, transportation between farms is necessary. Transfers between farms are performed by trucks, which has different capacities depending on the weight of the animals.

For this reason, the coordination of the animals' flow in the production process is essential. Decisions like how many, when and where to transfer the animals create constraints in the availability of the farms. The result of the decisions impacts the production process during the entire pigs' product life-cycle. Therefore, the coordination between farms, phases, and linkages is necessary for efficient production planning. To which requires the vision of the entire production process instead single processes and decisions which were suitable to be operational might lead to being tactical.

Managers analyze the current situation of the system weekly. They decide the transfers of animals between the farms, by taking into consideration its occupancy and the trucks necessary. Those decisions increase in complexity because of the fluctuations in the piglets' production in the maternity phase, the survival factor of animals, the AIAO management or the marketing window in fattening farms. Managers use their own experience and rudimentary tools often without taking into consideration the whole system. They do not plan the production based on efficient transfers, farm's occupancy and future states of the system.

Literature review reveals, and other researchers agreed, that most of the papers in the pig production process are focused on individual problems rather in the whole system [6, 47]. Some examples are found in the sow's replacement problem [48–53]. and others are found with the problem of deliveries of pigs to the abattoir in fattening farms [15, 39–46, 54]. Papers involving two or more agents in the production process are also present in the literature [41, 55, 56], but papers involving a three-site production system are scarce despite its importance. In this sense, only [57] proposed a mixed-integer linear programming model to coordinate the flow of animals in a three-site system structure but without taking into consideration some of the key aspects of the production process like transportation, a finite time horizon, AIAO management, a marketing window or other welfare parameters.

1.3.4 *PSC response face to sales price uncertainty*

In a business environment, companies look for ways to increase their competitiveness and improving their efficiency. Some researchers agreed that the capability to be flexible is currently a competitive advantage [58] which is difficult for a '*push*' system. Others propose that companies need to be agile, adaptable and aligned to the market [59–61]. All of them agrees that the company's environment presents uncertainty and its management increase the efficiency of the organizations.

In the case of the pig production process, uncertainty is present in all its phases. For instance, in biologic and welfare parameters. The sales price, despite presenting seasonality, is also an uncertain parameter which impacts in the final result of the pigs sold to the abattoir in a product which life-cycle that it is between 24 and 30 weeks. External factors might influence the sales price, for instance, regulations, substitute products (i.e., beef, chicken or cattle), diseases and the production process itself. The decisions taken by managers 'here and now' concerning the piglets' production will impact the final results of the company in the following months caused by those variations in the prices. Therefore, the ability of managers to rapidly adapt the piglets' production to the needs, would increase the competitiveness of the company.

Flexibility would entail managers having different strategies for adapting the pigs' production according to the market perspectives. Those strategies are based mainly in 1) the readiness in which the production needs to be increased or decreased and 2) the risk and the return of the investment.

The first strategy involves the acquisition of new sows. It is the cheaper option in economic terms, and need more time to bring pigs to the abattoir because of breeding operations. Another strategy is by purchasing new piglets. This one decreases the lead time and allows companies to have more flexibility to face with sales price fluctuations. Purchasing piglets also reduce the risk of a mid-long term investment.

The flexibility in the production might also lead to farms' capacity constraints in the production process, and therefore bottle-necks might appear, in the rearing or fattening phases. Here, managers can or either to build/acquire a new farm or to rent. Renting farms also decrease the risk of a long-term investment, and it usually is done under a yearly contract.

1.4 SCOPE AND AIM (RESEARCH AND OBJECTIVES)

This thesis is developed under the three-site production system in a PSC context. The aim is to present a set of models helping in the decision-making process. Decisions challenges are selected as a result of the gaps detected in the literature. More specifically, the objectives of this thesis are:

1. To study the impact of CO_2 emissions in the fattening farms and the pigs' deliveries to the abattoir process, and to explore the conflict of both objectives under an economic perspective.

2. To develop a model based on the three-site production system structure for helping in the production planning and coordination, taking into consideration the process' particularities stated above.

3. To develop a model to increase the efficiency and flexibility of pig production under the uncertainty in sales price.

4. To detect new research opportunities in Operations Research as a consequence of the development of this thesis.

1.5 OUTLINE OF THE THESIS

This thesis is structured as follows:

- **Chapter 1**: Introduces the thesis and the three-site production system which this thesis is based. Also, the chapter includes the decision challenges studied. Finally, the thesis' aim and objectives are presented.

- **Chapter 2**: Presents the methodology used in this thesis in detail such as Linear and Integer programming, Stochastic programming and Multi-objective programming as well as forecasting and scenario generation. The chapter also introduces the production planning problem approach used in the subsequent chapters of this thesis.

- **Chapter 3**: Studies the deliveries of pigs from a fattening farm to the abattoir based on the revenue and CO_2 emissions by a bi-objective programming model. The model accounts the CO_2 emissions derived by feeding and transportation and reveals the impact and the relationship between those two objectives helping managers to find a commitment between them.

- **Chapter 4**: Presents a decision support tool under a Linear programming model to help decisions makers in production planning. The model aims to deal with transportation and pig's flow throughout the PSC under a finite time horizon.

- **Chapter 5**: The model in Chapter 4 is extended by a Mixed-integer linear programming model to take into consideration the AIAO management, the marketing window and survival factor. The model capabilities' also includes the ability to detect bottle-necks in rearing and fattening farms and their impact on the entire system.

- **Chapter 6**: The model in Chapter 4 is also extended in the first approach into a Two-stage stochastic model for studying the impact of the sales price as a stochastic parameter.

- **Chapter 7**: Extends the model presented in Chapter 5 and 6 into a Two-stage stochastic programming model with the sales prices as a stochastic parameter. The model aims to help decisions makers to balance the pig production and capacities of farms and to present alternatives for increasing the productivity of the entire system by purchasing piglets and by renting rearing and fattening farms.

- **Chapter 8**: Presents the global discussion of the results.

- **Chapter 9**: Presents the conclusions of the thesis, highlighting the importance of the tools for supporting the decision-making process in the pig production system, the results achieved and points out new opportunities of research.

2

METHODOLOGY USED IN THIS THESIS

2.1 OPTIMIZATION

In Operations Research, Optimization reaches the optimal solutions to complex and real problems through mathematical modeling [62]. In this thesis, Optimization has been used to address with the decision challenges detected in Chapter 1. In the following subsections, the Optimization techniques used in this thesis are described, although there are more sub-fields depending on the nature of the problem to solve.

2.1.1 *Linear programming & Integer linear programming*

Linear programming (LP) has become fundamental in practical problems applied in engineering, business, economics, environmental and other disciplines [63]. Basically, LP maximizes or minimizes a function subject to a set of constraints. A standard formulation of a linear program can be expressed like:

$$
\begin{aligned}
\min z &= c^T x \\
s.t. \qquad Ax &= b \\
x &\geq 0
\end{aligned}
\tag{2.1}
$$

where x is an $(n \times 1)$ vector of decisions and c,A, and b are known data of sizes $(n \times 1)$, $(m \times n)$, and $(m \times 1)$, respectively. The value $z = c^T x$ corresponds to the objective function, while $\{x | Ax = b, x \geq 0\}$ defines the set of feasible solutions. An optimum x^* is a feasible solution such that $c^T x \geq c^T x^*$ for any feasible x [64].

In a LP problem, all decision variables $x \in \mathbb{R}^n$ are continuous. In case the decision variables are integer the problem becomes an Integer Programming model (IP). The mixture between continuous and integer decision variables are the Mixed Integer Linear Programming models (MILP). Additionally, if there are no continuous variables and the components of vector x are restricted to be either 0 or 1, then the problem is called combinatorial or '*zero-one*' (or binary) Integer Programming Problem (ZOIP) [65]. IP or MILP programming models are computationally more complex than LP programming models basically because the feasible region is non-convex and of its combinatorial nature between its values.

In Chapter 4, LP has been used for modeling the three-site production system, which has been extended into a MILP model in Chapter 5 because of the inclusion, for instance, of AIAO management in which the use of binary variables is required.

2.1.2 *Multi-objective programming*

In many real problems, multi-objectives exist, in which generally those objectives are conflicting between them. Usually, improving one objective may deteriorate the other. For instance, minimize cost while maximizing performance or maximize profits while minimizing costs [66].

A Multi-objective linear programming (MOLP) model has k objectives in the objective function, m constraints on the objective functions, and n decision variables, where both, objective functions and decision variables, can be continuous or discrete [67].

The result is a set of solutions that define the best trade-off between competing objectives. Solutions need further processing to arrive at a single preferred solution [68].

In a single-objective optimization problem, the superiority of a solution over other solutions is easily determined by comparing their objective functional values. On the contrary, in a multi-objective optimization model, the goodness of a solution is determined by the dominance between solutions. A solution x_1 dominates solution x_2 when: (a) the solution x_1 is no worse than x_2 in all objectives and (b) the solution x_1 is strictly better than x_2 in at least one objective. Then the non-dominated set of solutions is called the Pareto-optimal frontier [68].

MOLP has been used in Chapter 3 because of the study of the impact of two objectives. In this case, the profit and CO_2 emissions. The approach used is the weighted method, in which the objectives k are transformed into a single objective model by adding a weight w_k to determine the importance of each one. The weighted method provides a convex combination of the objectives, where:

$$\sum_{k \in K} w_k = 1$$

The weighted method ensures the optimal solution when the variables are continuous. In the case of MILP or IP, this method ensures an upper bound in maximization problems. Because of the use of binary variables in Chapter 3 the optimal solution is not guarateed.

2.1.3 *Stochastic programming*

In most of the problems, there is uncertainty in some of the parameters. Uncertainty may be caused by a lack of reliable data or future information. Dealing with uncertainty might lead to investigate its impact through sensitivity analysis, in which in many cases it is not an appropriate tool [69].

In Stochastic Programming (SP), the programming models are reformulated as an extension of the linear and/or non-linear problems where some of the parameters are probabilistic or through scenarios for managing this uncertainty. As a rule, stochastic programming models are more difficult to formulate and to solve than linear problems.

Stochastic programming has different methodologies and techniques [70]. In Two-stage stochastic programming models, decisions variables, which are implemented before an outcome of the random variable is observed, are known as first-stage decisions (or '*here and now*'). While decisions implemented after the outcome is observed, are the second-stage decisions. These second-stage decisions allows to model a response to the observed outcome, which constitutes the recourse [63]. A classical formulation for a Two-stage stochastic programming models can be writen as follows:

$$\begin{aligned} \min c^T x + E_\Omega[q(\omega)^T y(\omega)] \\ s.t. \qquad Ax = b, \\ T(\omega)x + Wy(\omega) = h(\omega), \\ x \geq 0, y(w) \geq 0 \end{aligned} \tag{2.2}$$

The first-stage decisions are represented by the $n_1 \times 1$ vector x. Corresponding to x are the first-stage vectors and matrices c,b, and A, of sizes $n_1 \times 1$, $m_1 \times 1$, and $m_1 \times n_1$, respectively. In the second stage, a number of random events $\omega \in \Omega$ may realize. For a given realization w, the second-stage problem data $q(w)$, $h(w)$ and $T(w)$ become known, where $q(w)$ is $n_2 \times 1, h(\omega)$ is $m_2 \times 1$, and $T(w)$ is $m_2 \times n_1$ [64].

When this '*observe and decide*' pattern is repeated, then the model is transformed into a Multi-stage stochastic programming model [69], which is not used in this thesis.

This thesis uses SP and more precisely Two-stage stochastic programming models for studying the impact of the uncertainty in the pigs' sales prices. SP has been used in Chapters 6 and 7.

2.2 SCENARIO GENERATION

2.2.1 *Forecasting under seasonability*

This thesis uses the historical information on the pig sales price in Chapter 7. Sales price in the pig sector presents seasonality in the pork prices which tends to decrease at the end of each year and increase in the middle of the year (Fig. 2.1).

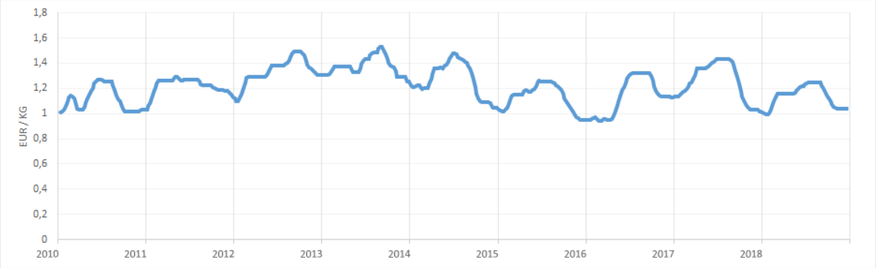

FIGURE 2.1: Pig sales prices in Lleida, Catalonia (Spain) according auction market Mercolleida from 2010 to 2018 [71].

Forecasting techniques have been used widely for generating future series based on historical information such as prices or demand. Two methods deals with seasonality: Holt-Winters [72] and ARIMA [73]. In [74], a comparison was done between those two methods, concluding that ARIMA is more effective with the presence of seasonal and consistent trend components. For this reason, the ARIMA method is used for creating a forecast of the sales price in Chapter 7 where, taking it as a basis, a scenario tree is generated.

2.2.2 *Scenario tree generation*

Any stochastic model might require to discretize the stochastic parameters in one or more values. This process is called scenario generation. A scenario tree (Fig. 2.2) consists of a set of nodes and branches. A scenario (s) is the path from root (the first node) to the leaf (the last node). The nodes can be associated with Group of Scenarios (G), such that two or more scenarios belong to the same group in a given stage provided that they have the same realizations of the uncertain parameters up to the stage [75]. In the end, each of the branches becomes a scenario (S). Each set of nodes, excluding the first one, have a single predecessor $\pi_{(g)}$ and a weight (w_g). Being $0 \leq w_g \leq 1$ and the sum of weights w_g in the same stage ($St_1, St_2, St_3, \ldots, St_n$) must also to be 1.

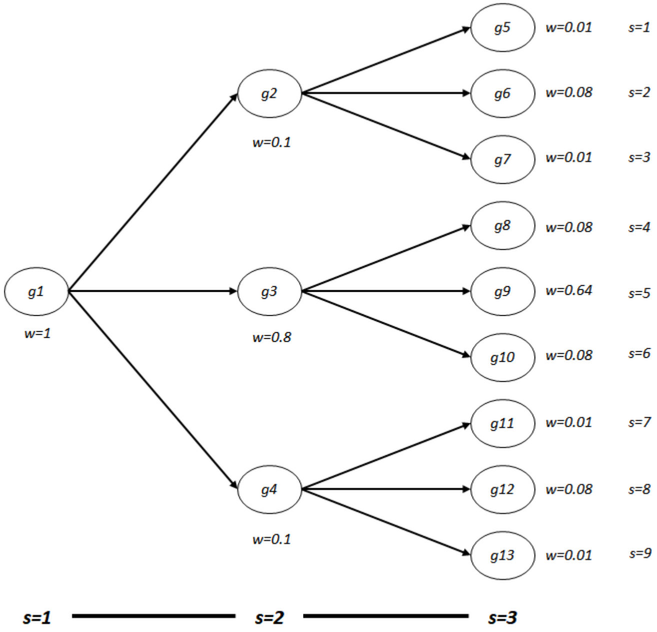

FIGURE 2.2: Scheme of a scenario tree

To date, there are several approaches to generate scenarios trees. For instance, [76] presented a survey of scenario generation methods in multistage stochastic programs concluding the difficulty to provide a general recipe for generating scenarios. In [77] techniques such as Montecarlo-based Schemes, moment-matching and path-based methods were evaluated and formulated the minimal requirements that should be imposed on a scenario generation method before it can be used for solving the stochastic programming model. Other methods that can be considered when generating scenarios are the tree reduction stages to simplify the complexity and to improve the performance of the models when trees tend to have a large number of possible scenarios. In this context, [78] developed heuristics for multistage models to generate scenario trees starting from a concrete scenario tree and using backward and forward techniques. Other authors reviewed these techniques and proposed heuristics to improve the performance from random data [79, 80].

Chapter 7 used Montecarlo simulation [81] for generating a scenario tree based in the pig sales price forecasted with ARIMA. Montecarlo asymptotically converges to the true distribution.

2.2.3 *The production planning problem*

The problems considered in this thesis corresponds to planning problems from a herd management perspective. In other words, with inventory and growing management. The approach of this thesis for solving the problems can be expressed in a problem for maximizing the benefit. A general LP notation of the problems can be expressed as follows:

$$\max z = \sum_{t \in T} (s_t - c_t) \tag{2.3}$$

The objective function z in (2.3) seeks the maximization of the profit. The profit at a period t is calculated by the aggregation of the income represented by s_t minus the total costs c_t associated over time. The problems studied in this thesis consider a finite time horizon $t \in T$ where each period t corresponds to a week of the whole time horizon T. The use of a finite time horizon permits the representation of the dynamics of the production process without assuming time-homogeneity of the parameters and herd size variations over time. In other words, the system conditions and decisions may vary over time, and therefore, they are not stationary. For this reason and infinite time horizon is not considered to represent the system.

On the other hand, for each week $t \in T$ each farm $h \in H$ might house stock of animals in different growing stages in the production process. Each growing stage $e \in E$ where E represents the productive cycle being $E = E_B \cup E_R \cup E_F$. Fig. 2.3 represents graphically the relation between the time horizon T and growing stages E.

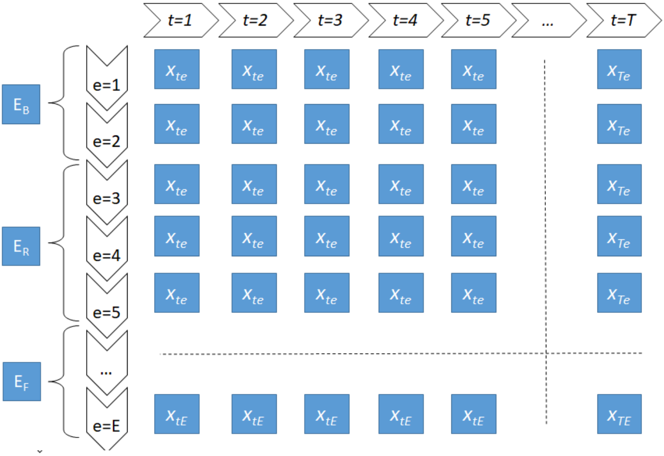

FIGURE 2.3: Relationship between the growing process states and the time horizon

The cost c_t corresponds to the cost associated to each farm in the t week. In other words, the cost of animals (for instance veterinary services, feeding or medicines), the cost of transportation from transferring the animals to the next phase and the cost of the emissions properly converted for each farm $h \in H$ as it is stated in (2.4).

$$c_t = \sum_{h \in H} \sum_{e \in E} c_{the} \tag{2.4}$$

Sales s_t corresponds to the aggregate of all the pigs from the farms allowed to send animals $h_1 \in H_1$ to the abattoir, being $H_1 \subset H$ and according to the structure of prices taken into consideration in each model as it is stated in (2.5).

$$s_t = \sum_{h_1 \in H_1} \sum_{e_1 \in E} s_{th_1e} \tag{2.5}$$

The approach stated before is adapted and / or adjusted to the particularities of each chapter and the OR technique used.

3

BI-OBJECTIVE OPTIMIZATION MODEL BASED ON PROFIT AND CO_2 EMISSIONS FOR PIG DELIVERIES TO THE ABATTOIR.

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Sustainability. *Volume 2018,10(6),1782*.
DOI: 10.3390/su10061782

Abstract: This paper presents a bi-objective model for optimizing pig deliveries to the abattoir accounting for total revenue and CO_2 emissions. Fattening farms house the most important stage in pig production and operations on farms must be coordinated with the rest of the pig supply chain when batch management is generally applied. The novelty of the model lies in the change of attitude in producers towards a greener production, which is becoming one of the major concerns in our society. In this context, we enrich the classical approach focused on revenue with the addition of the CO_2 emissions from the pigs on the fattening farms. Emissions derived from feeding and transportation are considered since they are the most important sources of CO_2. The model is tested using parameters representing a typical integrated Spanish fattening farm. Our findings reveal the impact and the relationship between revenues and emissions, highlight that the break-even is reached achieving a 459 kg of CO_2 per pig which corresponds to a reduction of 6.05%. On the other hand, the profit is slightly reduced by a 4.48% in favor of the environment.

Keywords: *CO_2 emissions; deliveries to abattoir; pig production planning; mixed integer programming; Pig SCM; Pig sustainability;*

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3.1 INTRODUCTION

The pig production industry has evolved greatly over recent years [82] to increase its efficiency financially and productively. At the same time, the increment of pig production worldwide has highlighted society's concerns about its environmental impact and future sustainability. For example, in Spain, production is concentrated in bigger firms acting as supply chains. They own the different agents covering the activity and operate under a vertical integration scheme [53, 83]. However, there are regions like Catalonia with areas saturated with farms and with manure pollution problems. The actual pig supply chain (PSC) organization of the sector represents benefits like farm specialization and disease control [82]. It is usual to find pig companies owning compound feed mills, farms of different kinds producing piglets or fattening pigs, abattoirs and meat packing plants, veterinary consultancies or even software business units. As a result, each production unit, like a farm, has to operate in coordination with the rest of the pig supply chain and the farmer has to obey the rules from the head office of the company, the so-called integrator [84]. However, this vertically integrated system leads to intensive farming, with bigger concentration of manure to manage in limited areas and additional transportation requirements to transfer and move piglets and pigs from one farm to another while they are growing (i.e. increasing total CO_2 emissions). Furthermore, society's attitude towards environmental issues is sensitive to greener and more respectful use of production means. This makes pig producers and pig companies more receptive to considering and evolving to greener supply chains, incorporating other criteria other than solely revenues into the traditional objective function.

In this context, this paper is concerned with fattening farms, these being the last stage in the pig production system and where most of the CO_2 emissions that affect the environment are generated. This is so, because as several authors have confirmed [23], feeding is the main source of CO_2 emissions with transportation being the second depending on fuel oil consumption. Fattening farms in a PSC receive piglets from rearing farms and operate under batch management [85]. Batch management, or all-in-all-out (AIAO) management, implies the entry of a batch of pigs into a farm, where they are fattened and sold when they reach a marketable weight (i.e. around 100 kg). This being achieved in around 16 weeks after arriving on the farm depending on the growth of pigs. Once all the pigs in a batch has been sent to the abattoir, the facility is cleaned and sanitized and made ready to receive a new batch of animals [15]. The fattening period depends on several factors like the feeding regime, growth curve, carcass and reward system [46]. Hence, marketing policies taking into account that partial sales produce better economic returns than selling the whole batch at a time. Visual inspection is the cheapest and most customary method of selecting pigs to be sent to the abattoir as innovative sensor technology solutions (based on individual records) are still too expensive [43]. In addition, carcass quality (i.e. aspects related to fat and lean content) is used by the abattoir to reward or penalize producers and makes delivery decision even more difficult. Thus the research questions addressed in this paper are:

> RQ1: Is the inclusion of CO2 emissions penalizing optimal decisions regarding the delivery of fattened pig to the abattoir?
>
> RQ2: What is a reasonable margin of profit reduction in favour of a greener production?
>
> RQ3: Are the policy of deliveries to the abattoir affected by the inclusion of CO2 emissions?
>
> RQ4: Is there room for additional gains in reducing CO_2 reduction preserving pig production efficiency?

Therefore, the aim of this paper is to explore conflicted objective like revenues and CO_2 emissions in fattening farms formulating and using a bi-objective mixed linear integer model to optimal balance the revenue for sending the pigs to the abattoir optimally and accounting for the CO_2 emissions during the fattening stage. The bi-objective model is based on the modelling approach presented by [46] and enriched with the information provided by the LCA of fattening farms presented by [23]. The response to global climate change has focused attention on the main sources of emissions with all significant sources coming under scrutiny, but neglecting many times the economic impact. This proposal represents a first approach to the consideration of CO_2 emissions besides relevant pig herd management decisions.

It is structured as follows: In Section 2, a literature review with relevant papers by previous researchers is carried out. In Section 3, the problem of deliveries to the abattoir and the mathematical model are presented. The results and discussion is analyzed in Section 4. Finally, Section 5 presents the conclusions.

3.2 LITERATURE REVIEW

Optimizing PSC and more precisely, the problem of optimizing the deliveries to the abattoir is not new in the literature [46]. For instance, [40] modelled a simple PSC with several farms and abattoirs all belonging to one cooperative while [86] formulated a model for the entire PSC that was then extended in [85] with more features like the inclusion of AIAO management in fattening farms. [15] considered an independent producer confronted with the optimal marketing of fattened pigs to multiple packers while [41] were concerned with the procurement plan of a PSC and provided a schedule for deliveries to an abattoir looking for homogeneous pig sizes. [42] and [44] proposed a model that took advantage of online live weight estimation telling the farmer, at a pen level, the number of pigs ready for marketing. Furthermore, [44] considered feeding decisions affecting animal growth and carcass composition made during the fattening process. [39] evaluated selected marketing policies under a limited number of scenarios and were able to identify the best one, but without solving the structured problem in general. Hence, [46] asserted that the problem of optimal marketing of fattening pigs has been addressed mainly from a theoretical point of view, without practical application for the real world. This is not a criticism as such, because new technologies have to be adapted and new methods developed for the future, as [42] and [44] recognized. Although those models took into consideration economic and financially related aspects like the marketing window, bonus and discounts policies for valuing carcasses, feed conversion, growth rate, no other sustainable criteria like CO_2 emissions were considered.

On the other hand, regarding the assessment of the environmental performance of the PSC, Life Cycle Assessment (LCA) is one of the most widely-applied methodologies. Several applications of LCA regarding pig-production systems can be found in literature [87] and in particular to fattening farms [23]. Notarnicola et al. [24] argued the need of dedicated modelling approaches for food production systems like PSCs. Several studies about the environmental profile of pig-meat production systems have revealed crucial factors like [25], who investigated the potential fossil-fuel energy and GHG (greenhouse gas) savings in pig farming in Europe. The analysis showed that pig farming in Europe presents a high potential for reducing fossil fuel use and GHG emissions. [26] conducted an LCA study concluding that the environmental burdens related to the production and delivery of pig feed can be decreased by: 1) optimizing the fertilization of the crop-based ingredients, 2) utilizing more locally-produced feed ingredients, 3) reducing concentrations of metals like Cu and Zn in the feed and 4) adopting cereals like wheat rather than maize as base feeds.

A review specifically about European LCA studies on pork production [88] mentioned that these assessments showed an average GWP (global warming potential) of 3.6 kg CO_2 per kg of pork. The carbon footprint was emphasized by [29] as an indicator of the environmental impact of meat production (including pork). The main reason was related to animal feeding since a more efficient use of nitrogen leads to less eutrophying and acidifying substances being released into the environment and lower GHG emissions in nitrous oxide form as well as increased productivity resulted in lower land requirements for feed production. Additional studies about the LCA of pig production are those by [27] in France; [28] in Sweden with an emphasis on feed choice; [30] regarding livestock protein feed production and the impact on land use and GHG emissions; [31] in Portugal concerning the LCA of pig-meat production; [32] in Denmark regarding an environmental assessment; [33] regarding the environmental impact of 15 pig farming systems in the European Union Q-PorkChains project; [34] in Spain concerning the water footprint of the pork industry; [35] in Italy concerning the environmental impact of the typical heavy pig production ; [36] in Spain regarding the carbon and water footprints of the pork supply chain; [37] in France about the environmental impact of extensive outdoor pig-production systems and [23] focusing on the LCA of Spanish fattening farms.

This literature review concludes that fattening farms are an important source of revenue and CO_2 emissions for the PSC and pig production in general. While optimal deliveries of pigs to the abattoir has been studied from an economic point of view, and also GHG emissions at this stage have been assessed, no studies have been found exploring together the managerial decision of delivering pig to the abattoir and derived CO_2 emissions during the fattening process. So, the analysis of greener practical proposals joining both perspectives (economic and environmental) are lacking.

3.3 MATHEMATICAL MODELING

3.3.1 *The optimal delivery problem*

The production process in a PSC is structured into three phases (maternity, rearing and fattening) encompassing different agents or farmers. This situation can correspond to a private company vertically integrated owning all or most of the farms, or a cooperative of associated producers who own one or several farms. In all cases, it is assumed the PSC operates under the general rules given by a PSC manager and followed by all farmers. In particular, fattening farms have to coordinate with the rest of the farms to free facilities from time to time to receive batches of pigs to be fattened under AIAO management. Decisions taken at the PSC level may include the feeding regime, supply of medicines, veterinary assistance, control of entries and exits of animals from facilities, deliveries and transport to the abattoir, etc. In each phase, there is a set of specialized farms, i.e. breeding, rearing and fattening farms. The second phase focuses on rearing piglets born in breeding farms. Piglets from different rearing farms move to compound fattening batches assigned to different fattening farms belonging to the PSC. Transfers between farms and/or to the abattoir are performed by different trucks, often contracted to a third party by the PSC Company. The capacity of the trucks depends on the type and the weight of animals and it is subject to EU regulations.

Fattening farms are the last and more important stage of pig production before pigs are sold to the abattoir. We assume pigs are incorporated onto a farm under AIAO management. The impact of selling prices, bonus and penalization, besides the need to free facilities to keep the system producing, affect delivery decisions to the abattoir directly. Even when a batch of pigs is eating the same feed, individual growth is not uniform and the animals reach marketing weight differently. This requires pigs to remain longer on the farm to gain the missing weight. This way, the emptying of a fattening farm occurs over a time window usually ranging for four weeks since the first delivery to the abattoir. A longer fattening period implies higher feeding cost and CO_2 emissions. In addition, truck CO_2 emissions depend on the size and capacity of each type of truck represented by its fuel consumption. However, the growth and carcass value can increase, thus making the delay beneficial. Each abattoir applies bonuses or discounts to the base price according to the live weight and quality of the carcass (percentage of lean meat). Carcasses are sorted using the SEUROP classification method (Commission Regulation (EC) No.1249/2008), which is mandatory in the European Union (EU), but also required in countries exporting to the EU. Transport and feeding have an impact in terms of CO_2 emissions throughout the PSC and the fattening farms are the most significant stage [23].

3.3.2 *The optimization model*

In this section, we present the formulation of the bi-objective optimization model for the deliveries to the abattoir.

Indices and sets

$t \in T,$ Index (in weeks) the fattening period is divided into, $t = 1, \ldots, T$.

$i \in P,$ Index of partitions to cluster pigs into growth categories $p = 1, \ldots, P$.

$k \in K,$ Index of types of truck $p = 1, \ldots, P$.

Parameters

$N,$ Batch size representing the number of pigs moved to the fattening farms.

$n_i,$ Cluster of growth category i, in which the initial batch was partitioned.

$\bar{w}_{it},$ Mean value of the live weight of pigs (kg) in the growth category i at week t. We assume the live weight of the batch follows a normal distribution, $w_t \sim N(\mu_t, \sigma_t)$.

$\omega,$ Selling price, € per kg of carcass weight.

$\bar{f}_{ti},$ Cumulative feed intake average (kg) by a pig in growth category i until week t.

$\beta_{it},$ Bonus given by the abattoir (€/kg of carcass weight) as a function of growth category i at week t.

$\delta,$ cost in euros per kg of feed intake.

$\lambda_k,$ Fixed cost in euros for trucks of type k sent to the abattoir.

$\alpha_i,$ cost in Euros for other expenses in the system for growth category i, such as vets and medicines.

$\xi,$ cost in Euros per young pig purchased.

$\psi_k,$ capacity of trucks of type k in number of animals.

$\tau_k,$ capacity of trucks of type k in kilograms of load.

$\varrho_{it},$ carcass weight per growth category i at week t.

κ, kg CO_2 -eq per kg of meat produced.

υ, Euros per kg of CO_2 .

γ_k emissions kg CO_2 per trip and k-truck type

φ, weight for bi-objective function ($0 \leq \varphi \leq 1$).

Decision variables

x_{it}, number of pigs from partition i to be sent to the abattoir in fattening week t.

y_{kt}, integer variable with the number of trucks of type k needed at week t to ship pigs.

z_{it}, inventory of pigs for partition i at the beginning of the fattening week t.

h_{it}, binary variable with value 1 when pigs from two consecutive partitions (i-1,i) are sent to the abattoir, 0 otherwise.

d_{it}, binary variable with value 1 when pigs from partition i at week t are sent to the abattoir, 0 otherwise.

w_{it}, Live weight when animals are sent to abattoir.

Objective function

The objective function (7.1) represents the profit from the pigs delivered to the abattoir and the CO_2 emissions from the pigs on the fattening farm and trucks during transport.

$$\max \varphi\Big(\sum_{i\in P}\sum_{t\in T}(\omega+\beta_{it})\bar{w}_{it}x_{it} - \sum_{i\in P}\sum_{t\in T}\delta\bar{f}_{ti}x_{it} - \sum_{t\in T}\sum_{k\in K}\lambda_k y_{kt} - \sum_{i\in P}(\xi+\alpha_i)n_i\Big)+ \\ +(\varphi-1)\Big(\sum_{i\in P}\sum_{t\in T}\kappa\upsilon w_{it} + \sum_{t\in T}\sum_{k\in K}\upsilon\gamma_k y_{kt}\Big)\Big) \tag{3.1}$$

The aim is to maximize the profits from the pigs delivered to the abattoir and minimize the CO_2 emissions. To do so, φ assigns a weight for each objective $\varphi = 1$ being the optimal maximization of the profit and $\varphi = 0$ the optimal minimization of the CO_2 emissions. Profit is calculated by the total of sales value minus the corresponding production cost. On the other hand, CO_2 emissions are calculated summarizing the total CO_2 emissions produced by the total kg of meat in week t per category i and by the trucks used for transport.

Constraints

$$z_{i1} = n_i \quad \forall i \in P \tag{3.2}$$

$$x_{it} \leq z_{it} \quad \forall i \in P, t \in T \tag{3.3}$$

$$x_{it} \geq z_{it} - N(1 - h_{it}) \quad \forall i \in P, t \in T \tag{3.4}$$

$$z_{it+1} = (z_{it} - x_{it}) \quad \forall i \in P, t \in T \setminus \{|T|\} \tag{3.5}$$

$$z_{i|T|} - x_{i|T|} = 0 \quad \forall i \in P \tag{3.6}$$

$$\sum_{i \in P} x_{it} \leq \sum_{k \in K} \psi_k y_{kt} \quad \forall t \in T \tag{3.7}$$

$$\sum_{i \in P} \bar{w}_{it} x_{it} \leq \sum_{k \in K} \tau_k y_{kt} \quad \forall t \in T \tag{3.8}$$

$$x_{it} \leq N d_{it} \quad \forall i \in P, t \in T \tag{3.9}$$

$$h_{it} \leq d_{it} \quad \forall i \in P, t \in T \tag{3.10}$$

$$d_{it} + d_{i+1t} \leq 1 + h_{i+1t} \quad \forall i \in P \setminus \{|P|\}, t \in T \tag{3.11}$$

$$w_{it} = \varrho_{it} x_{it} \quad \forall i \in P, t \in T \tag{3.12}$$

Constraint (3.2) fixes the initial inventory of pigs per growth category i in the first week. Constraint (3.3) establishes a limit for the deliveries no higher than the current inventory while constraint (3.4) determines the binary variable $h_{it} \in \{0, 1\}$ for ensuring all pigs in the i growth category at week t need to be sold before selling pigs from category $i - 1$ (lighter pigs). Constraint (3.5) updates the inventory for each category for the following week $t + 1$. Constraint (3.6) forces selling all the pigs in the current batch to be sold by the end of the marketing window (week $|T|$). This is necessary to meet the AIAO management requirements. Constraints (3.7, 3.8) determine the number of trucks of each type needed to deliver pigs to the abattoir, taking into account the capacity of the trucks in terms of number of animals and kilos of load. Constraint (3.9) determines whether a group of pigs in growth category i at time t must be sent to the abattoir or not. Constraints (3.10, 3.11) link the binary variables h_{it} and d_{it} to force the delivery of heavier pigs first. Constraint (3.12) controls the live weight for the animals to be sent to the abattoir in order to manage the CO_2 emissions.

3.4 RESULTS AND DISCUSSION

3.4.1 *Default parameters*

The parameters representing a vertically-integrated Spanish fattening farm operating under AIAO management with a batch N of 1000 pigs was considered. A marketing window of five weeks was also considered as the maximum. However, the model itself started to deliver pigs once they were profitable. Piglets are entered to the fattening farm at the age of 9 weeks, and stay on the fattening farm between 10 and 17 additional weeks. We divided the batch of pigs into ten growth partitions P representing different weight categories derived from a Normal distribution. Table 3.1 shows the mean and standard deviation of live weight and accumulated feed intake by week t.

Weekly pigs costs are considered from [89] with a cost per pig purchase ξ of 40,55€. The weekly feeding cost δ is established at 0.28€/kg. Other related costs α_i per pig are fixed to 21€per pig. The transport of finished pigs considered four different type of trucks with the characteristics detailed in Table 3.2. The emissions were estimated for an abattoir located at 100km from the farm and considering an interurban trip. Estimated CO_2 emissions per type of truck were taken from the official website [90].

The income is calculated by considering the base price of the abattoir referring usually to the price fixed in the auction market in Mercolleida (Spain), the most important in Spain. In this case, $\omega = 1{,}377$ €/kg. In practice, carcass information is detailed individually and given to the producer after each delivery has been slaughtered. Table 3.3 shows the distribution of bonuses and discounts in the SEUROP classification β to determine the final price value.

Finally, the price per CO_2 , v, is set at 0.01275 €/kg according to [91] with κ set at 5.5 kilos of CO_2 per kilo of meat produced, which is the worst case considered by [23]. This way, the bi-objective function is expressed in homogeneous units for both objectives.

The model was developed with the IBM ILOG CPLEX Optimization Studio that includes OPL, a modeling language and solved using CPLEX v12.8 in a Pentium 4 CPU at 2.1 GHz and 16Gb RAM. Microsoft Excel was used for data storage for both the input and output parameters due its user friendliness and flexibility when managing the data and the easy linkage to CPLEX.

In order to take an informed decision, the model was solved for different values of φ and considering a marketing time window of five weeks. De-

	Weight(kg)		**Intake(kg)**	
Age(Week)	**Mean**	**sd.**	**Mean**	**sd.**
1	29.7	3.9	5.1	5.5
2	33.4	4.6	12.1	8.5
3	37.8	5.4	20.5	12.1
4	42.6	6.3	30.2	15.9
5	47.9	7.4	41.3	19.7
6	53.5	8.4	53.4	23.6
7	59.3	9.5	66.4	27.5
8	65.3	10.6	80.3	31.4
9	71.3	11.8	94.9	35.3
10	77.4	12.9	110.1	39.2
11	83.4	14.0	125.7	43.2
12	89.2	15.2	141.6	47.1
13	94.8	16.3	157.6	51
14	100	17.5	173.7	54.9
15	104.8	18.7	189.6	58.9
16	109.1	19.8	205.3	62.8
17	112.8	21.0	220.6	66.7

TABLE 3.1: Mean and standard deviation of live weight and accumulated feed intake by week t

	T1	**T2**	**T3**	**T4**
Capacity (ψ_k)	50	220	440	550
Cost per trip (λ_k)	125	475	900	1000
Emissions kg CO_2 /trip (γ_k)	28.25	66.30	57.99	79.14

TABLE 3.2: Characteristic of the trucks available for transportation

pending on the relative importance given by the decision maker to the two objectives, a different marketing plan will be proposed. In this sense, the

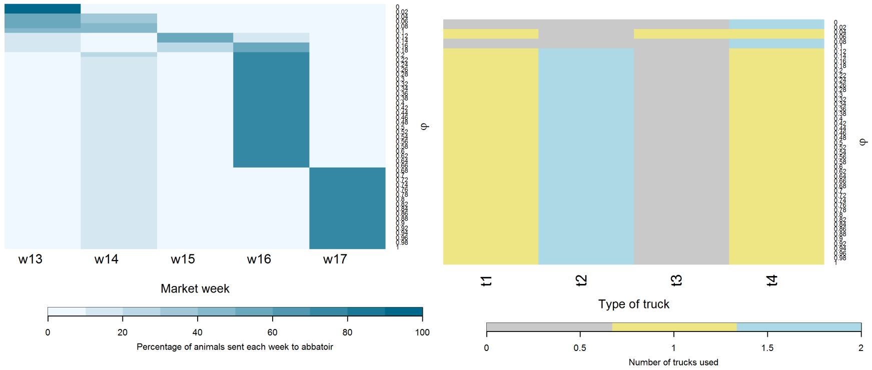
S	E	U	R	O	P	Live Weight (kg)	Carcass Weight (kg)
0.57	0.28	0.12	0.03	0.00	0.00	50	39.4
0.55	0.27	0.14	0.04	0.00	0.00	55	43.4
0.53	0.26	0.15	0.05	0.01	0.00	60	47.4
0.50	0.28	0.16	0.05	0.01	0.00	65	51.4
0.49	0.27	0.17	0.05	0.01	0.00	70	55.5
0.49	0.28	0.17	0.06	0.01	0.00	75	59.5
0.45	0.27	0.18	0.08	0.01	0.00	80	63.6
0.44	0.26	0.19	0.09	0.03	0.01	85	67.6
0.43	0.25	0.18	0.09	0.03	0.01	90	71.7
0.41	0.24	0.19	0.10	0.04	0.01	95	75.8
0.40	0.23	0.19	0.11	0.05	0.02	100	79.9
0.39	0.23	0.19	0.12	0.05	0.02	105	84.0
0.38	0.22	0.19	0.12	0.06	0.03	110	88.1
0.38	0.21	0.19	0.13	0.07	0.04	115	92.3
0.37	0.2	0.18	0.13	0.07	0.04	120	96.4

TABLE 3.3: Bonuses based on the SEUROP class distribution and weight (live and carcass)

fleet of trucks available may give flexibility in pig transport if capacities are different. To summarize the information given by the model, we present two type of graphics in Figure 3.1: a) the distribution of the number of animals (in percentage) sent to the abattoir each week, and b) the number of trucks of each type employed.

3.4.2 *Maximizing revenues and minimizing CO_2 emissions*

To analyze the impact and relationship between profit and the CO_2 emissions, we generated a total of 51 different instances s by increasing φ by 0.02. Each instance represents a linear convex combination of the two objective functions. As a result, the different combinations ranged from $\varphi = 0$ (giving the most environmental optimum) to $\varphi = 1$ (giving the most profitable optimum). Figure 3.1 shows this outcome, particularly the distribution of the number of animals sent each week (Figure3.1a), and we can appreciate how under minimization of emissions, all pigs were sent to the abattoir as soon as possible. Otherwise, if only revenues are maximized, then most of the pigs are sent to the abattoir in week #17 according to the base parameters considered. This scheduling involves different means of transport ranging from the less polluting to the cheapest ones (Figure3.1b).



(a) Distribution of the number of animals sent each week

(b) Type of truck used

FIGURE 3.1: Summary of the solution obtained for different values of φ

Regarding the observed outcomes for both objective functions, Figure 3.2 shows the relationship between profit and CO_2 costs for each φ. In case of only taking the CO_2 emissions into consideration, i.e. $\varphi = 0$, the model presented less profits. This was produced because the model sent all the pigs to the abattoir in the first week to reduce CO_2 emissions in feeding as much as possible (see Figure 3.1a). Profits, then were reduced by a 26.68%. On the contrary when $\varphi = 1$ (maximizing the profit) the CO_2 emissions were not taken into consideration and therefore, the model maximized only the profit allocating trucks only regarding cost and no other considerations.

On the other hand, Table 3.4 shows the relationship between maximizing the profit and minimizing CO_2 emissions depending on φ. The table shows that φ did not affect the profit or CO_2 emissions for $\varphi \geq 0.68$. Also, it was noted that for small φ the reduction of the cost of CO_2 emissions is higher than the reduction of the profit. This relationship changed when $\varphi \geq 0.10$. In

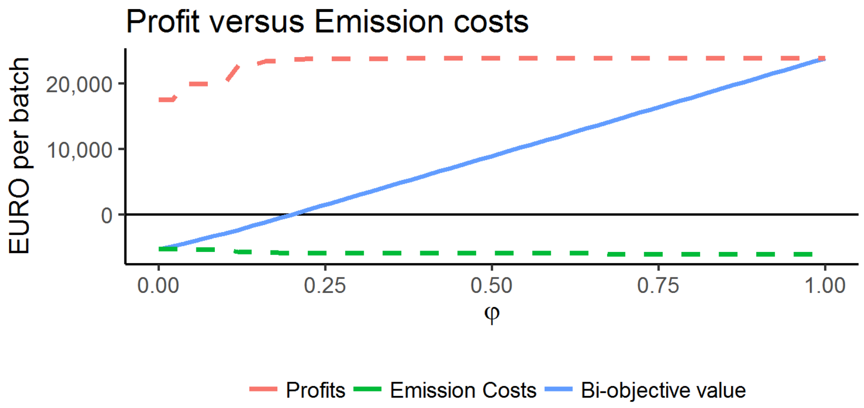


FIGURE 3.2: Expected profit versus Emission costs and weighted bi-objective function value for different values of φ

other words, the effort to decrease the cost of CO$_2$ was relatively higher in terms of profit. Hence, the $\varphi = 0.12$ with a profit of 22,821 Euros and a cost of 5,685 Euros in CO$_2$ emissions was used as a reference. These results confirmed that the level of CO$_2$ emissions does not increase to the same extent as profit can do. Note that additional reductions in CO$_2$ emissions would be feasible considering different diets and manure management systems not considered in this paper.

In terms of deliveries to the abattoir, Table 3.5 shows the schedule for different φ and how CO$_2$ emissions may affect the scheduling and selection of means of transport. As seen when $\varphi = 0$ all the animals must be sent to the abattoir as soon as possible to minimize emissions. This is in the first week of the marketing window because the model does not take the profits into consideration. Meanwhile, φ increases with the deliveries becoming later as profit has priority over the CO$_2$ emissions, being reached the maximum profit and maximum cost of the CO$_2$ emission with $\varphi = 0.68$ in contrast with $\varphi = 0.12$, that was the better profit vs. CO$_2$ emissions balance found.

Figure 3.3 shows the expected profit earned on average per week considering different time horizons associated to different marketing windows. The initial optimal solution allowed fattening pigs for a maximum of 17 weeks with no extra revenues for additional weeks. This maximum, and corresponding time window, was reduced week by week to shorter time horizons of up to 14 weeks. We investigated the Euro per day reward for each time

φ	**% Profit decrease**	**% CO_2 emission decrease**	**Profit (€)**	**CO_2 cost (€)**
1			23,891	6,051
0.68	0.00	0.00	23,891	6,051
0.38	0.33	2.65	23,812	5,891
0.22	0.50	3.44	23,684	5,843
0.20	0.87	3.44	23,684	5,843
0.16	1.189	4.35	23,440	5,788
0.12	4.48	6.05	22,821	5,685
0.10	15.30	11.36	20,237	5,364
0.08	15.88	11.59	20,098	5,350
0.04	16.63	11.82	19,919	5,336
0	26.68	13.31	17,516	5,246

TABLE 3.4: Behaviour of each objective function depending on φ value

φ	**13**	**14**	**15**	**16**	**17**
0	1,000	0	0	0	0
0.04	600	400	0	0	0
0.08	550	450	0	0	0
0.1	500	500	0	0	0
0.12	200	0	600	200	0
0.16	180	0	220	600	0
0.20	50	220	0	730	0
0.22	50	180	0	770	0
0.38	0	200	50	750	0
0.68	0	200	0	0	800
1	0	200	0	0	800

TABLE 3.5: Schedule of deliveries of pigs to the abattoir depending on φ value and considering a marketing window of five weeks (13-17)

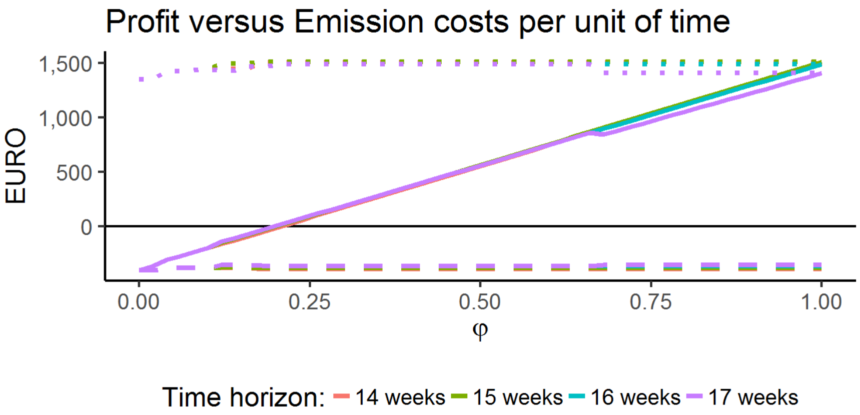
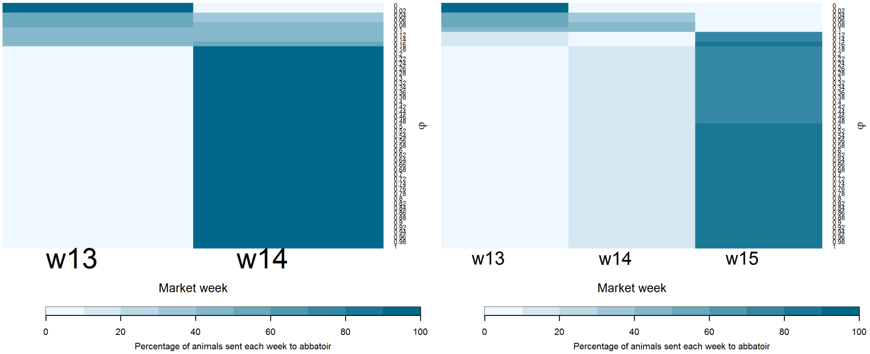


FIGURE 3.3: Expected profit versus emission costs and weighted bi-objective function value per week for different values of φ and different time horizons

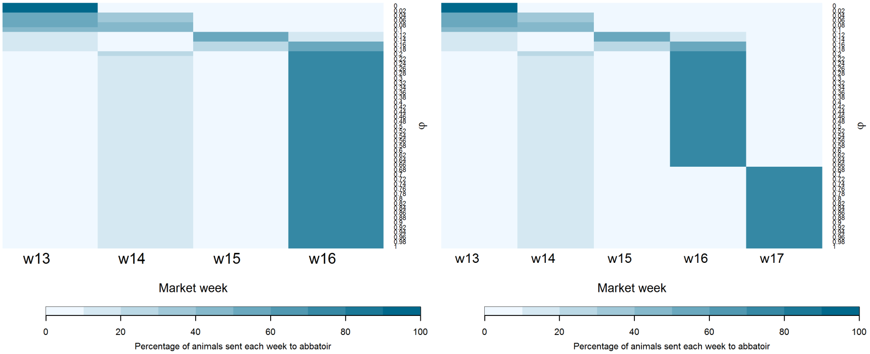
horizon. This way we look for the optimal fattening duration, not just for a single batch of pigs, but rather in the optimal value per unit of time. Then, while we observed that the maximum profit per batch is obtained when 17 weeks is the maximum time a pig can stay on the farm, looking at the profit per week generated by the batch, the maximum is obtained at 15 weeks. With regards to the CO$_2$ emissions, these are minimized with shorter time horizons due to the linearity of the function. This result is explained by the fact that shorter time horizons produce less meat in total and consequently there is a lower footprint.

With regard to different time horizons analyzed, Figure 3.4 shows the patterns observed in the solutions obtained for different values of φ. We can appreciate how the effect of including the emission costs suggests a range of diverse solutions depending on the weight given to each goal. The range of solutions observed is enlarged with the time horizon allowed. For the shortest horizon (14 weeks) the solutions are mostly either to sell everything in week 13 (when the goal is to minimize emissions) or to sell the whole batch in week 14 (when the weight of the profit is above $\varphi > 0.16$). On the other hand, when the time horizon is 17 weeks, the marketing plan of selling the whole batch in week 14 happens only when the goal is to focus on minimizing emissions. When the time horizon is 17 weeks, the set of



(a) Horizon 14 weeks

(b) Horizon 15 weeks



(c) Horizon 16 weeks

(d) Horizon 17 weeks

FIGURE 3.4: Distribution of the number of animals sent each week for different values of φ and different market windows

solution changes gradually up to the point of selling around 20% of the animals in the batch in week 14 and the rest, in week 17.

3.5 CONCLUSIONS

Deliveries of fattened pigs to the abattoir is one of the most important activities in the PSC and has received attention from the managerial point of view. This paper highlights their importance according to previous research works and states the environmental concern, which is increasing in the pig sector mainly because of environmental awareness among producers and the social attitude of consumers. No studies were found that combined economic and environmental assessment approaches together for fattening farms. Our contribution relies on a bi-objective mixed integer programming model able to optimize the deliveries of the pigs to the abattoir taking the CO_2 emissions into consideration. In agreement with the literature, feeding and transport by trucks are the main sources of emissions considered. The bi-objective model maximizes profits and minimizes CO_2 emissions, thus helping managers to find a compromise between these two conflicting objectives.

We only emphasize profit as economic driving tends to involve higher CO_2 emissions that are not proportional to the final revenue achieved. That is, the level of CO_2 emissions does not increase to the same extent as profit can do. We demonstrated that for a single farm and a single batch, it is possible to decrease the CO_2 emissions by 6.05% which represents a penalty of 4.48% of the total revenue. Therefore, the multiplicative effect over the entire PSC represented by a cooperative or a large integrator would have a bigger impact. Note that additional reductions in CO_2 emissions would be feasible considering different diets and manure management systems not considered in this paper.

4

MULTIPERIOD PLANNING TOOL FOR MULTISITE PIG PRODUCTION SYSTEM.

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Journal of Animals Science. *Volume 2014,92(9),4154-4160*.
DOI: 10.2527/jas.2014-7784

Abstract: This paper presents a multiperiod planning tool for multisite pig production systems based on Linear Programming (LP). The aim of the model is to help pig managers of multisite systems in making short-term decisions (mainly related to pig transfers between farms and batch management in fattening units) and mid-term or long-term decisions (according to company targets and expansion strategy). The model skeleton follows the structure of a three-site system that can be adapted to any multisite system present in the modern pig industry. There are three basic phases, namely, piglet production, rearing pigs, and fattening. Each phase involves a different set of farms; therefore, transportation between farms and delivering of pigs to the abattoir are under consideration. The model maximizes the total gross margin calculated from the income of sales to the abattoir and the production costs over the time horizon considered. Production cost depends on each type of farm involved in the process. Parameters like number of farms per phase and distance, farm capacity, reproduction management policies, feeding and veterinary expenses, and transportation costs are taken into account. The model also provides a schedule of transfers between farms in terms of animals to be transported and number of trucks involved. The use of the model is illustrated with a case study based on a real instance of a company located in Catalonia (Spain).

Keywords: *Decision support system; herd transport; linear programming; sow herd management*

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4.1 INTRODUCTION

During the last decades, a transformation from the traditional single-site system of pig production based on small family farrowing-to-finish farms to larger, more industrialized, controlled, and efficient farms has been observed [3], [92]. Nowadays, multisite systems concerned with housing production phases like breeding, rearing, or fattening at different sites are more common. For each of these phases, a set of specialized farms have their own characteristics, facilities, and location, and therefore transportation is necessary. Private companies and cooperatives tend to integrate and coordinate their operations into pork supply chains by using tighter vertical coordination linkages [53]. Supply chains have competitive advantages and are becoming important for the sector [4] because they help reduce risk and uncertainty and creates value [3]. In this context, aggregate planning provides a unified production plan to chain and production managers at the lowest cost [93]. Aggregation allows pig chain managers to make decisions at strategic, operational, and tactical levels [94]. That is, to coordinate and control the stock of animals and their flow along the chain, scheduling transfers among farms over a time horizon. A survey of literature on pig production reveals most papers are devoted to operations on individual farms like the replacement of sows [56], sow herd models management [95], or deliveries to the abattoir [15, 54] . So far, only a few models had been proposed [57].

Thus, this paper presents a multiperiod planning tool for multisite pig production systems based on linear programming (LP). The aim of the model is to help pig managers of multisite systems in the decisions cited above.

4.2 MATHERIALS AND METHODS

The procedures involving animals and animal care conditions were approved by the Ethical Committee of Animal and Human Experimentation of the Universitat de Lleida, Spain.

4.2.1 *Modeling the Pig Production System*

The research is motivated by a case study of a Spanish pig production company located in the northeastern region of Spain (specifically in Catalonia). The company's support is essential for the development of the model and during the validation of the preliminary results presented here. The model has two purposes, each with a different scope. The first one aims to support and help to produce the week-by-week schedule of transports. This schedule is related to the decision making process regarding where, when, and how many piglets or pigs will be transported weekly and the number of trips needed. The second purpose is strategic, emphasizing the analysis of the production capacity by farm, phase, and whole system in the mid-term or long-term. Decisions involved include buying or selling farms to balance production and capacity, enlarging or shrinking the size of the company, and establishing a reward policy for employees in charge of specific individual farms or phases. For instance, at present, the company's management team conducts a growth strategy based on the acquisition of new sow farms to increase production without taking into account the farm's location. The model should permit the exploration of the impact of the addition or removal of farms from the system, adjusting their supplies for future demand. Therefore, the company can also consider grant subsidies and penalties for farmers depending on their contribution to the total revenue of the system.

The production process considered in this paper involves different kinds of farms: 9 sow farms, 22 rearing farms, and 131 fattening farms plus 1 abattoir. Figure 5.1 shows the production process and the relationship between the different farms involved. For all the farms, parameters such as farm capacity, initial inventory, and transfers between farms and to the abattoir are considered. In `https://cv.udl.cat/x/3YD0x3`, the complete list of parameters are given in detail.

According to the phases in the pig production process, the first phase takes place in sow farms. The aim of sow farms is to wean the maximum number of piglets to be transferred to rearing farms. Each sow is inseminated and is expected to become pregnant. If not, there are possible additional attempts until a successful conception happens, leading to a farrowing and subsequent lactation period. For simplicity, the herd size of sow farms is taken as a constant representing the steady state of the herd structure and, accordingly, the associated piglet production. That is, each sow can produce 0.518 piglets per week (i.e., 26.95 piglets per sow per year on average). After giving birth 9 times, the sow is sent to the abattoir for infertility reasons. Piglets stay in the sow farms for 4 wk before being sent to rearing farms. The cost per piglet and sow each week is 1.874€ and 4.85€, respectively. The second phase involves piglets that are sent to rearing farms to be fed for a 6 wk period. Here, the cost per piglet and week is 2.66€. Finally, in the third phase, piglets are transferred to the fattening farms with the aim of selling them to the abattoir once they have reached a

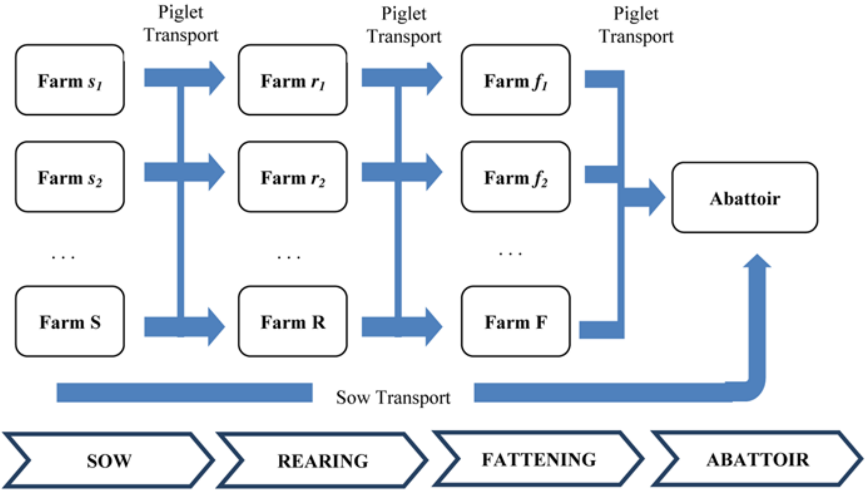

FIGURE 4.1: Pig production system: phases (sow, rearing, fattening, and abattoir) and transfers between farms.

marketable weight. Pigs are sent to the abattoir after 18 wk and cost 4.382€ per week. The costs presented include all the associated costs corresponding to each phase of the production process (feeding, doses of insemination, labor, transportation, and veterinary expenses).

Transportation is outsourced to a single and specialized subcontractor. Thus, the company reduces fixed costs, such as the management of a truck fleet, additional facilities, and associated personnel. Hence, the number of trucks is not taken into consideration explicitly; instead, the number of trips required for transportation is needed. The company sends the trip schedule, and the subcontractor creates a transportation plan according to their constraints. Transportation cost depends on the distance between farms or to the abattoir, having a price per kilometer, from the source farm to its destination. The distance between the truck's origin to the source farm is not taken into consideration as that cost is assumed by the subcontractor. Transportation cost is set to 1€ per km and truck.

Capacity of trucks, weight, and cost are taken into account depending on the type of animals transported. One truck can transport up to 700 piglets from sow farms to rearing farms and from rearing farms to fattening farms but only 240 pigs from fattening farms to the abattoir. The capacity of trucks for the sow farms that are culled is also 240 per truck.

The model also takes into account the selling price based on the average of recent historical market series and remains constant through the time horizon defined. Two different values are considered based on the quality of the animal sold, namely, whether they come from the fattening farms or from sow farms, that is, commercial pigs or culled sows. The experiment takes 126€ in both cases, representing a lower value per kilogram of meat in sows with respect to fattened pigs. A time horizon of 156 wk (3 yr) has been considered realistic for the experiment.

In Table 4.1, a list of all the activities and constraints, which were taken into consideration by the model, is shown. The constraints are discussed in detail in the next section.

Activities	Constraints
Sow Farms	Initial inventory
Sow Management	Capacity of facilities
Capacity Control	Sow herd dynamics
Reproduction	Abattoir
Transfers to the abattoir	Growth of animals
Piglet's	Transfers between farms
Sow herd control	Transportation capacity
Piglet's weaning	Piglets' birth
Transfers to rearing farms	Demand
Rearing farms	
Capacity control	
Growth control	
Transfers to fattening farms	
Fattening farms	
Capacity control	
Growth control	
Transfers to the abattoir	

TABLE 4.1: Activities and constraints in the multi-period linear programming model

4.2.2 *Formulation of the model*

The objective of this model is to get the maximum gross margin achieved by optimizing the production from sow farms to the abattoir (for a complete definition of the model, see [96]. This benefit is represented by the gross margin calculated by the addition of incomes from pigs sold to the abattoir minus the total amount of pigs' expenses and the transportation cost incurred for each farm. The model is formulated on a weekly basis given most of the activities on the farm and transportation between phases and to the abattoir occur regularly at this time frame. Therefore, the objective function is the total gross margin. It is calculated as the summation of weekly income minus cost over the time horizon for all farms. The general specification of the objective function is as follows:

$$\max \sum_{t \in T} \sum_{h \in H} (v_{t,h} - c_{t,h}), \tag{4.1}$$

where $v_{t,h}$ corresponds to the total weekly income of farm h in the t week, in particular, sales to the abattoir of culled and fattened pigs. The incomes only include sow farms and fattening farms, whereas $c_{t,h}$, corresponding to the total weekly cost of farm h in the t week, includes all the farms in the production process.

Different groups of constraints representing scarcity in some resources or limiting capacities have to be added to the model to achieve the objectives.

Capacity of facilities.

All facilities have a limited capacity. The capacity in sow farms depends on the number of sows that can be housed, whereas in rearing and fattening farms it depends on the maximum number of pigs that can be fed at a time. The capacity of each farm must be considered each week.

Initial inventory.

All farms which are part of the production process must have an initial inventory at the beginning of the planning horizon. This initial inventory affects the flow of animals along the chain in the succeeding weeks and over the time horizon period that is being considered.

Sow herd dynamics.

It is assumed that sow farms are operating under a steady state derived from the herd structure at equilibrium. This is because sow herd dynamics are modelled as a Markov decision process [48]. For this reason, the steady state in each sow farm has to be considered.

Abattoir.

The abattoir is big enough to accept all pigs produced weekly, so there is no need to consider abattoir capacity or limit production, although it would be also possible to do it depending on the case study or if the company enlarged its own production much more.

Growth of animals.

Pigs that are fed on farms grow from one stage to the next. We assume that all pigs are fed under the same regime and grow in proportion to their age. Therefore, the inventory has to be updated over the time horizon considered. For simplicity, casualties of growing pigs are taken into account at the moment the animals are transferred to the following phase in the chain. This way the system tends to overestimate costs, but not the income, as casualties are not sent to the abattoir.

Transfers between farms.

Piglets that are transferred to the rearing or fattening farms are assumed to be done at the beginning of a week. Later on, after completing the number of weeks expected to grow for the current phase, all of them exit at the end of the last week. For this reason, the weekly flow of piglets sent to rearing farms cannot exceed the total number of piglets weaned the same week. The number of pigs starting the fattening phase cannot exceed the number of pigs finishing in the rearing phase in the same week.

Transportation capacity.

Constraints affecting transportation are related to the capacity of each truck. Animals sent to the abattoir are heavier than those transferred between farms, so different capacities or trucks may apply depending on what is to be transported. Hence, the number of trucks used to transport culled sows to the abattoir will depend on the replacement rate in each sow farm and the trucks capacity. Accordingly, the capacity of the trucks to transport piglets will vary depending the phase.

Litter size.

The number of piglets born alive will depend on the parity number and the number of sows per parity, and it is stated by an average litter size [48].

Abattoir's quota

The company requires the farmers to meet a minimum production quota. The aggregate of this quota must satisfy a minimum quantity of animals sent to the abattoir. This is a strategic decision of the company to ensure a minimum production based on the overall production capacity.

To develop the model, the modeling language ILOG OPL has been used. The solver CPLEX v12.2 solved the model in a laptop computer (Pentium Dual-Core CPU at 2.1 GHz and 4 GB RAM).

The database has been developed with Microsoft Excel. It contains different sheets where users are allowed to register and maintain all input parameters for the model. The enterprise resource planning (ERP) of the company generates a Microsoft Excel file with an updated inventory of animals for each farm as well as the rest of parameters as prices and unitary costs considered by the model. After the model is executed, model outputs are retrieved, and reports and statistics are generated. The automation of this process is enough to allow an easy adoption of the model by the company.

4.3 RESULTS

The model, according to the parameters used, has 948,792 constraints and 1,397,374 variables. The execution time is 4.5 h, having a GAP of 0.47% (because of the complexity of the model, a tolerance between the approximated solution given and the upper bound solution is defined). The optimization model shows a profit of 0.35€ per kilo of meat sent to the abattoir and a profit of 992.25€ per sow per year. As some of the direct cost incurred in the whole supply chain are taken approximately (such as labor, farms maintenance, electricity, water, etc.), this amount can be used as a reference but not as an exact value.

In addition, the production capacity of each farm, phase, and the entire production process over time can be evaluated. In this sense, the outcome indicates that the capacity of all facilities involved in the production process are enough to host all produced pigs. In particular, rearing and fattening farms are capable of rearing and fattening all piglets produced in the sow farms. The steady state inventory of sows is of 12,705 animals. They are weaning a steady production of 6,585 piglets per week. Moreover, all the culled sows are sent to the abattoir and replaced by new ones.

The global capacity of rearing farms is never overflowed. This means that the set of farms can accommodate all the piglets produced by the sow's farms. Although all rearing farms are used, their average occupancy varies depending on the week. Rearing farms tend to be occupied between 65% and 85% of their maximum capacity. At this phase, transfers between sows and rearing farms tend to locate near the piglets to the slaughterhouse or where the fattening farm's population is higher. This is because a truck can transport more pigs at this stage than when the pigs become heavier. Figure 4.2 shows the abattoir in coordinates (0,0), the location of sow farms and the preferred rearing farms used.

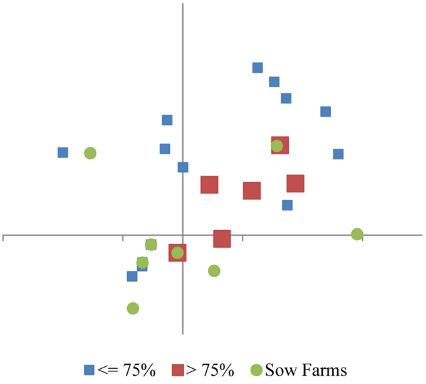

FIGURE 4.2: Location of the sow farms (circles) and rearing farms (squares) from the abattoir (coordinates (0,0)), where most occupied rearing farms are the ones nearest to the abattoir.

The fattening farm's capacity is higher than the rest of the farms because the pigs stay in this phase longer (18 wk). The location of farms used at this stage do not have a pattern, as shown in Fig. 4.3. The occupancy varies from one to another. For instance, Fig. 4.4 shows a farm with a high occupancy that has been only emptied twice in the entire time horizon. On the contrary, Fig. 4.5 shows a farm occupancy used only in certain weeks when the other farms are full.

To help with the operational decisions, the model can provide a weekly transportation schedule of the transfers to be done between farms and between farms and the abattoir. Tables 4.2 and 4.3 show examples of the transfers from sow farms to rearing farms and from rearing farms to fattening farms during the third week. These examples show the source and the destination farms as well as the quantity of piglets and the number or trips needed to transport them.

4.3.1 *Sensitivity to Parameter Changes*

As the model aims to be a useful tool for the company and other companies or researchers, some others experiments have been done to study the model's behavior. A lot of experiments can be done this way, but to simplify and give a clear example of model behavior, Table 4.4 only shows the most relevant behaviors and the variance between them: increasing the sales

FIGURE 4.3: Location of the fattening farms from the abattoir (coordinates (0,0)), where the most used farms are near rearing farms.

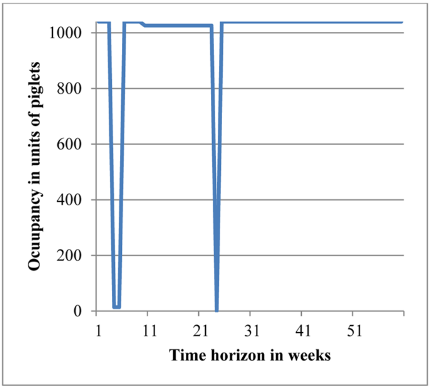

FIGURE 4.4: Example of Farm #270, with a capacity of 1,040 piglets and located 27 km from the abattoir where the occupancy is high.

price, decreasing transportation cost, and increasing or decreasing the litter size. The experiments show that increasing the sales prices at the proposed range does not affect the production, having a minimal effect on transfers between farms as the cost of transportation does not change. Therefore, the sales price affects the final benefit but not at the operations level in the production process. On the other hand, the transportation cost affects both the cost of transport and the number of trips needed. According to Table 4.4, in case this cost is eliminated or reduced drastically, the model would not take

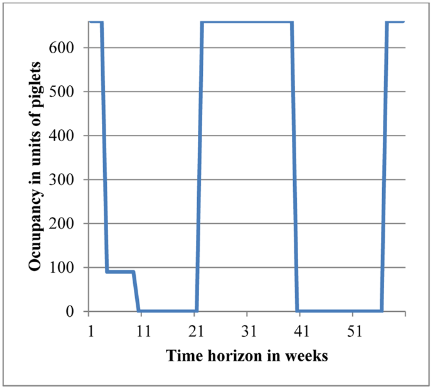

FIGURE 4.5: Example of Farm #154, with a capacity of 660 piglets and located 49 km from the abattoir where the occupancy is not high.

into consideration the distance between farms when scheduling transports. Finally, the decrease in the number of litter per sow affects the entire production process only in terms of quantity to be produced, and consequently, the benefit decreases. On the other hand, an increase of the litter size per sow can generate an overproduction, making the farms overloaded. In this case, the model could not transfer all the piglets produced in the sow farms to the rearing farms due to the capacity restrictions, and the model would not have solution.

4.4 DISCUSSION

The model has been considered useful by the company at this stage. Benefits come mainly through the week-by-week schedule to support and help make decisions regarding where, when, and how many piglets will be transported for a certain period of time; evaluation of the production capacity of each farm, phase, and the entire supply chain over time; and in the planning and scheduling of the trucks needed weekly, which means saving oil and time.

Moreover, the execution of the model can be useful for the company in making midterm or long-term decisions. It is also worth mentioning that before the project started, the company's department of production was assisted only by an Excel spreadsheet as well as by conducting weekly meetings that decided the flow of animals to be transported, that is, origin

From sow farm	Piglets' quantity	Number of trucks	To rearing farm
4	300	1	1
4	244	1	128
5	232	1	15
8	624	1	15
9	1,039	2	128
14	126	1	140
14	421	1	294
15	105	1	15
15	562	1	23
15	556	1	199
17	686	1	15
17	540	1	137
18	575	1	290
132	504	1	176
132	71	1	128
Totals	6,585	16	

TABLE 4.2: Weekly example of piglets' transfers from sow farms to rearing farms

and destination, but without considering the transportation costs or the need for buying new fattening farms to allocate for unforeseen number of piglets.

The model can be adapted to different multifarm production systems as a result of its flexibility when setting up their parameters. The structure of the model described is focused on a three-site system, but a two-site system or a mixture of both can be also modeled this way.

Despite the advantages shown in the previous section, the results of the model itself indicate opportunities for improvements. First, the current model can be extended in a stochastic optimization model to deal with the uncertainty of some parameters such as sale prices and demand. Second, the explicit inclusion of batches of animals in fattening farms may extend the model's functionality for those companies which work with it. That is, the so-called all-in-all-out management system that has been demonstrated as useful for disease prevention and control of the animals. Third, adding flex-

From rearing farm	Piglets' quantity	Number of trucks	To fattening farm
15	664	1	281
15	699	1	306
15	406	1	145
20	789	2	289
20	684	1	291
20	240	1	204
137	406	1	221
176	518	1	145
190	1,199	2	103
199	99	1	112
199	203	1	267
256	678	1	203
15	664	1	281
15	699	1	306
Totals	6,585	14	

TABLE 4.3: Weekly example of piglets' transfers from rearing farms to fattening farms

ibility in the duration of phases to create a marketing window for deliveries to the abattoir and therefore to account for uncertainties in the growth of animals allow to better the capture of opportunity costs from the market.

Finally, the huge number of farms involved and the relationship between them demand a large amount of computational time. The extension of the model having more functionalities as requested by the company will make the model more complex. Hence, the parallelization of the model with the aim to improve the execution time is an interesting approach that we are exploring.

At present, other Spanish companies, as well as consultancies, have already shown interest in the proposed model.

	Farm occupancy[1]			Number of trips[2]			
Experiment	S	R	F	SA	SR	RF	FA
Base[3]	26,342	39,513	118,540	1,705	2,278	2,036	4,432
SP[4] +20%	0%	0%	0%	0%	0.1%	0.01%	0%
SP[4] +30%	0%	0%	0%	0%	0%	0.01%	0%
TC[5] = 0%	0%	0%	0%	0%	60%	117%	40%
LS[6] =-20%	-20%	-20%	-20%	0%	-9%	-10%	-17%
LS[6] =+20%[7]	-	-	-	-	-	-	-

TABLE 4.4: Percent of variance of farm occupancy and trips per experiment.

[1] Farm occupancy in number of piglets in sow farms, rearing farms and fattening farms.

[2] Number of trips: SA = From sow farms to the abattoir; SR = From sow farms to rearing farms; RF = From rearing farms to fattening farms; FA = From fattening farms to the abattoir.

[3] The experiment described in this paper.

[4] SP = Sales price

[5] TC = Transportation cost

[6] LS = Litter size

[7] Shows no result due the fattening farms exceeds the occupancy.

4.5 CONCLUSIONS

Our contribution emphasizes the importance and complexity of decision making tasks in the modern organization of the pork sector. Therefore, models and tools that help in this decision making context are needed. Although the model presented open areas for improvement, such as schedule transports, planning the flow of animals, and analysis capacities as described previously, it can be used as it is, and it makes it possible to envision and explore new business opportunities for a single pork supply chain. Finally, the capability of the model of being integrated into the ERP of pig companies allows the model to be easily adopted by them.

5

PRODUCTION PLANNING OF SUPPLY CHAINS IN THE PIG INDUSTRY.

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Computers and Electronics in Agriculture. *Article in press*.
DOI: 10.1016/j.compag.2018.08.042

Abstract: This paper presents a production planning model for managing the pig herd production system operating as a Pig Supply Chain (PSC). The model is formulated as a multiperiod mixed-integer linear programming (MILP). The production system may represent a large farmer, a private company or a cooperative managing several farms operating according to the so-called three site system (sow, rearing and fattening farms; the latter under all-in-all-out management). The model is intended for practical use and illustrated with a case study based on a real instance in Catalonia (Spain). The model helps PSC managers when making decisions by providing an overall view for planning production over time. The objective is to maximize the total revenue calculated by the total amount of sales to the abattoir minus production costs. The latter depend on the feeding system, veterinary and medical care, labor and transportation. Practical results include a schedule of animal transfers between farms, batch management and deliveries to the abattoir from fattening farms, number of trips and the occupancy rate of all facilities. Bottlenecks in the production process regarding flow of animals, throughput and capacities along the PSC were detected beforehand allowing the company to react accordingly. Then, as three fattening farms were found to be redundant, farm occupation rate could be improved by 22% purchasing additional piglets. We estimated a maximum purchase price of 70.15 Euros per piglet beneficial for the company.

Keywords: *Production planning; Pig SCM; MILP; Pig production*

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5.1 INTRODUCTION

Over recent decades, the pig industry has greatly evolved in western countries, especially in Europe [6]. Concerns about the environment, food quality and animal welfare are the new challenges for this sector. As a result, the profile of the typical farm is changing from a family-based, small-scale, and independent firm, to one in which larger firms are more tightly aligned with the pig production and distribution processes. Modern firms integrate their operations into a Pig Supply Chain (PSC) structure by using tighter vertical coordination linkages [53, 83]. In addition, PSC structure, in conjunction with the three-site production system (i.e. systems involving three phases represented by sow, rearing and fattening farms), has competitive and health control advantages because of the specialization and coordination of agents within the chain. This organization helps to diversify the number of specialized farms, makes integration easier in bigger companies, reduces the risk of disease and uncertainty and creates value [3, 4]. However, these PSC structures generate new issues. New decisions need therefore to be taken into account by managers at a PSC level instead of at farm level to coordinate and improve the global PSC performance [3, 14]. In this context, decisions like planning the flow of animals through housing facilities over time, scheduling transfers from farm to farm, when and how to sell the animals to the abattoir, optimal batch management of fattening pigs and type of farms and location now deserve the attention of pig supply chain companies. PSC companies have to allocate resources and time to solve these questions properly. Because of the relative novelty of those structures, most companies perform these tasks based on managers' experience or by holding regular meetings where decisions are reached by consensus. The approach to scheduling transfers is mostly by hand or with a rudimentary support of spreadsheets, not capable of representing the whole PSC dynamics, and even less the possibility of improving or forecasting the overall efficiency of the systems. This situation represents a challenge for new applications of operational research proposals to solve real problems in the pig industry [47] and which this paper is aimed.

The literature about modeling decision making in the pig industry reveals that most studies have only considered specific problems in individual farm operations [95] or related to just one single agent of the PSC [6]. For instance, [95] revised sow herd management models and observed that the replacement problem of sows is the most common problem that was dealt with. Relevant papers on optimizing sow replacement have been published making use of a variety of modeling techniques, such as linear programming, dynamic programming and hierarchic Markov models [48–52]. Proposed models stated before consider an infinite time horizon and homogeneous parameters over time. Short-medium term decisions are commonly taken by managers and require a flexibility to cope with changes over time represented better into a finite time horizon framework.

Studies concerning other individual installations like fattening farms, are scarce but present in the literature [15, 54]. Something similar happens with papers taking into consideration farms belonging to two or three phases. For instance, [55] presented one of the first PSC model, but only for epidemic purposes: the analysis of the spread of Salmonella along the chain while [41] presented a PSC model for Thailand but emphasizing the collection and transportation of fattened pigs to the abattoir and responding to the particular needs of that national sector. The paper of [56] focused on a single sow farm but considering some constraints aimed at coordinating the sow farm into a pig supply chain. Proposals with the integration of models adopting the overall vision of the production process are appearing little by little. In this context, [57] proposed a first mixed-integer linear programming model to control the flow of animals in a three-site system structure but without taking transportation constraints into consideration. The model proposed by these authors was later reformulated by [86] to take into account transportation and the flow of the animals through different facilities. However, the new model neglected some important operational aspects for practical decision making: a marketing time window to deliver fattened pigs to the abattoir (according to fluctuations in the sales price); the commercial value of carcasses by a grid reward system based on leanness, back-fat thickness and weight; batch management instead of continuous production; and finally, facility location and occupation.

Thus, the aim of this work is to extend the scope of the preliminary model in [86] rendering it useful in practice. The new realistic model proposed was tested with a Spanish pig production company which is a part of the official BD-Porc Spanish pig databank and located in Catalonia (north-east Spain). Therefore, the main objectives of this paper are 1) to consider a PSC model with new production planning capabilities based on the marketing time window, sales prices, facilities and batch management 2) to highlighting the complexity of the resulting mathematical model and propose pathways to achieve reasonable computational solving times.

The remainder of the paper is organized as follows: in section 2 a detailed description of the pig production process considered in this paper

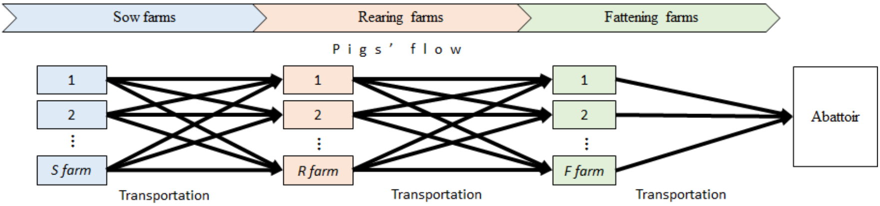

FIGURE 5.1: Pig production process structure

is presented. Section 3 presents the formulation of the PSC model, while the analysis of the model performance and results are drawn in section 4. Finally, the main conclusions and future work are outlined in section 5.

5.2 THE PIG PRODUCTION SYSTEM AS A PSC

Pig production as a PSC is structured into three phases (maternity, rearing and fattening), encompassing different agents or farms, mainly sow, rearing and fattening farms (Fig. 5.1). This situation corresponds mainly to a vertically-integrated private companies owning all or most of the farms or to cooperatives of associated producers, owners of one or several farms. In all cases, it is assumed that the PSC operates under general rules given by a sole pig supply chain manager and followed by all farmers. For example, decisions taken at the PSC level may include the feeding regime, supply of medicines, assistance by veterinaries or animal scientists, control of the entry and exit of animals from the facilities, deliveries and transportation to the abattoir, etc. In each phase, a set of specialized farms with their own characteristics, facilities and location are considered. The first phase focuses on producing piglets in sow farms, the second phase focuses on rearing piglets in rearing farms, while the third and last phase focuses on fattening farms, preparing pigs for delivery to the abattoir. The pigs remain for a certain number of weeks in all of these farms (phases) in order to ensure correct growth, reaching a minimum weight by the end of each phase, with health and welfare conditions. Transportation between the farms for the different phases is necessary and makes production planning and coordination more complex. There are three types of origin for collecting the animals (sow, rearing and fattening farms) and three types of natural destinations for delivering the animals (e.g. from sow to rearing farms, from rearing to fattening farms and from fattening farms to the abattoir). Transfers between farms are performed by truck, often contracted to a third party by the PSC company. The capacity of the trucks depends on the weight of the animals and it is subject to EU animal welfare regulations.

Four-weeks-old piglets, weaned and over seven kg of live weight, are sent from sow farms to rearing farms for a specific number of weeks ranging from four to eight. The reared pigs weighing from 20 to 30 kg of live weight are transferred to fattening farms. The last phase ends up with pigs sent to the abattoir once they have reached a marketable weight (around 100 kg), which is expected to happen from 15 to 18 weeks after starting the fattening phase. Traditional sow and fattening farms operated with a continuous flow of animals occupying facilities all the time. However, the pig industry nowadays operates under batch management. Batch management in sow farms consist of ensuring a number of farrows per week per sow by grouping sows into batches. Sows of the same batch are synchronized at the same reproductive stage. Batch management in fattening farms, also known as the all-in-all-out (AIAO) system, operates differently than in sow farms. Under AIAO management, a fattening unit is filled and emptied by batches of pigs. In between batches, the facility is empty and available for cleaning and disinfection. Batch management is one of the best practices in preventing the spread of illness and disease [15]. PSC is characterized by the product pushing along the chain instead of being pulled by demand and so, the abattoir appears as a bottleneck when the market cannot absorb all the production. For this reason, many pig companies tend to own abattoirs or establish formal agreements to mitigate a lack of demand (i.e. excess production). The selling price for the fattened pigs is often based on a reference price agreed weekly by buyers/sellers (producers/abattoirs) in auction markets, like Mercolleida in Spain. Additional discounts or premiums for leanness or backfat thickness and carcass weight that represent market preferences are also implemented by abattoirs within the EU. Carcass classification is mandatory in EU abattoirs according to the Regulation (EEC) No. 1208. It is the so called SEUROP classification system used to fix the reward system by each abattoir.

5.3 MATHEMATICAL FORMULATION OF A GENERAL PSC

In this section we present the mixed-integer linear programming model representing a vertically-integrated PSC to determine the optimal planning of pig transfers through the PSC over a finite time period.

Indexes and sets

$t \in \mathcal{T}$, time horizon (in weeks), $t = 1, \ldots, T$.

$h \in \mathcal{H}$, farms belonging the PSC, $h = 1, \ldots, H$. $\mathcal{H} = \mathcal{H}_B \cup \mathcal{H}_R \cup \mathcal{H}_F$: Disjoint partition of farms in three phases (sites), $\mathcal{H}_B$ being the set of sow farms, $\mathcal{H}_R$ the set of rearing farms and $\mathcal{H}_F$ the set of fattening farms.

$e \in \mathcal{E}$, Growing period in weeks, $e = 1, \ldots, \mathcal{E}$. Set $\mathcal{E}$ represents the productive cycle in weeks of a commercial pig from farrowing to the slaughtering. $\mathcal{E} = \mathcal{E}_B \cup \mathcal{E}_R \cup \mathcal{E}_F$: Disjoint partition of the productive cycle in each phase, i.e. weeks spent by pigs in different facilities, being $\mathcal{E}_B = \{1, \ldots, \mathcal{E}_B\}$ the set of weeks corresponding to the lactation period (from birth to the weaning of piglets), $\mathcal{E}_R = \{\mathcal{E}_B + 1, \ldots, \mathcal{E}_R\}$ set of weeks corresponding to the rearing period (from weaning to the beginning of the fattening) and $\mathcal{E}_F = \{\mathcal{E}_R + 1, \ldots, \mathcal{E}_F\}$ set of weeks corresponding to the fattening period.

$e \in \mathcal{E}_F^W$, Marketing time window weeks, $e = W, \ldots, \mathcal{E}_F$, at the end of the fattening period where the pigs can be delivered to the abattoir ($\mathcal{E}_F^W \subseteq \mathcal{E}_F$).

$s \in S$, physiological state of a sow, $s = 1, \ldots ..., S$.

Parameters

$IN_{h,e}$, initial inventory of pigs of age $e \in \mathcal{E}$ in the farm $h \in \mathcal{H}$.

K_h, housing capacity of farm $h \in \mathcal{H}$.

$LS_{h,t}$, litter size at farrowing in sow farm $h \in \mathcal{H}_B$ per week $t \in \mathcal{T}$.

$CP_{t,e}$, unitary cost per week $t \in \mathcal{T}$ and age $e \in \mathcal{E}$ per piglet including feeding, medicines, medical care, amortization of sows and associated and indirect costs.

CT, unit transport cost per kilometre and per truck.

$D_{h,h'}$, distance from farm $h \in \mathcal{H}$ to farm $h' \in \mathcal{H}$.

D_h^A, distance from farm $h \in \mathcal{H}$ to the abattoir.

KN_h, capacity, given in terms of number of animals transported, for trucks departing from farm $h \in \mathcal{H}_B \cup \mathcal{H}_R$ to another farm.

KP_h, capacity, given in terms of number of animals transported, for trucks departing from farm $h \in \mathcal{H}_F$ to the abattoir.

$P_{t,e}$ expected value of a pig of age $e \in \mathcal{E}$ at period $t \in \mathcal{T}$. This price is estimated taking into account a distribution of weight and lean percentage for pigs produced in [43] and different carcass qualities (lean content and carcass weight) for the pigs sent to the abattoir.

SV_t, salvage value of culled sows at week $t \in \mathcal{T}$, at the last reproductive state $S \in \mathcal{S}$.

$p^h_{s',s}$, transition probabilities of sows from s' to s in sow farm $h \in \mathcal{H}_B$, with $s', s \in \mathcal{S}$.

$SF_{h,e}$, survival factor for pigs of age $e \in \mathcal{E}$, estimated as the average proportion of pigs surviving at farm $h \in \mathcal{H}$ from one week to the next. Note: this factor depends on h to incorporate different elements, such as the type of farm, location, etc.

λ_t, discount factor at week $t \in \mathcal{T}$ to account for the time value of money.

Decision variables

$z_{t,h,s}$, integer variable used for the inventory of sows at the physiological state $s \in \mathcal{S}$ and farm $h \in \mathcal{H}_B$ at week $t \in \mathcal{T}$.

$y_{t,h,e}$, integer variable used for the inventory of pigs of age $e \in \mathcal{E}_h$ at (the end of) week $t \in \mathcal{T}$ on the farm $h \in \mathcal{H}$.

$u^B_{t,h,h'}$, integer variable used for the inventory of piglets at week $t \in \mathcal{T}$ transferred from farm $h \in \mathcal{H}_B$ to farm $h' \in \mathcal{H}_R$.

$u^R_{t,h,h'}$, integer variable used for the inventory of reared pigs at week $t \in \mathcal{T}$ transferred from farm $h \in \mathcal{H}_R$ to farm $h' \in \mathcal{H}_F$.

$u^F_{t,h,e}$, integer variable used for the inventory of pigs at age $e \in \mathcal{E}^W_F \subseteq \mathcal{E}_F$ transferred from farm $h \in \mathcal{H}_F$ to the abattoir at week $t \in \mathcal{T}$.

$n^A_{t,h}$, integer variable to control the number of trips at week $t \in \mathcal{T}$ to transport animals leaving the farm $h \in \mathcal{H}_F$ to the abattoir.

$n_{t,h,h'}$, integer variable to control the number of trips at week $t \in \mathcal{T}$ to transport piglets from phase to phase being $h \in \mathcal{H}_B$ and $h' \in \mathcal{H}_R$, or $h \in \mathcal{H}_R$ and $h' \in \mathcal{H}_F$.

$\lambda^1_{t,h}$, binary variable used for batch control, being $\lambda^1_{t,h} = 1$ when farm $h \in \mathcal{H}_F$ has pigs of age $e = \mathcal{E}_r + 1$, and $\lambda^1_{t,h} = 0$ otherwise.

$\lambda^2_{t,h}$, binary variable used for batch control, being $\lambda^2_{t,h} = 1$ when farm $h \in \mathcal{H}_F$ has pigs of age $e \in \mathcal{E}_F \setminus \{\mathcal{E}_R + 1\}$, and $\lambda^2_{t,h} = 0$ otherwise.

Objective function

The objective function (5.1) represents the total discounted benefit in Euros over the time horizon $t \in \mathcal{T}$ to be maximized.

$$\begin{aligned}\max \sum_{t\in\mathcal{T}} \lambda_t \Bigg[\sum_{h\in\mathcal{H}_B} SV_t z_{t,h,S} + \sum_{h\in\mathcal{H}_F} \sum_{e\in\mathcal{E}^W_F} P_{t,e} u^F_{t,h,e} - \Bigg(\sum_{h\in\mathcal{H}} \sum_{e\in\mathcal{E}} \mathit{CP}_{t,e}\, y_{t,h,e} + \\ \mathit{CT} \Big(\sum_{h\in\mathcal{H}_B} \sum_{h'\in\mathcal{H}_R} D_{h,h'} n_{t,h,h'} + \sum_{h\in\mathcal{H}_R} \sum_{h'\in\mathcal{H}_F} D_{h,h'} n_{t,h,h'} + \\ \sum_{h\in\mathcal{H}_F} D_{h,a} n^A_{t,h} \Big) \Bigg) \Bigg] + \lambda_T \sum_{h\in\mathcal{H}} \sum_{e\in\mathcal{E}} P_{T,e} y_{T,h,e}\end{aligned} \tag{5.1}$$

The income is calculated from two sources: unproductive sows (at physiological state S) from sow farms and pigs from the fattening farms, which are both transferred weekly to the abattoir. It should be noted that fattening farms are only allowed to deliver pigs to the abattoir during a marketing window, once enough pigs on the farm have reached marketable weight. The marketing window allows the manager to be flexible with the timing of the delivery of the animals to the abattoir. The cost takes into account two terms: stocking and transportation. The stocking cost is calculated taking into consideration the number of pigs on each farm and their age. The transportation cost is calculated per phase with the unitary cost of transportation, CT, in Euros per km, the number of trips needed to transport the animals (between farms or to the abattoir) and the distance between origin and destination. Finally, to depict the activity of the system beyond the end of the time horizon considered, the inventory on the farms at the end of the time horizon is valued economically.

Constraints

$$\sum_{s\in\mathcal{S}} z_{t,h,s} \le K_h \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T} \tag{5.2}$$

$$z_{t,h,s} = \sum_{s' \in \mathcal{S}} p^h_{s',s} z_{t,h,s'} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T}, s \in \mathcal{S} \tag{5.3}$$

$$y_{t,h,1} = \sum_{s \in \mathcal{S}} \mathbb{LS}_{h,t}\, z_{t,h,s} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T} \tag{5.4}$$

$$\sum_{e \in \mathcal{E}_R} y_{t,h,e} \leq K_h \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T} \tag{5.5}$$

$$y_{t,h,E_R+1} \leq K_h \lambda^1_{t,h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} \tag{5.6}$$

$$\sum_{e \in \mathcal{E}_F : e > E_R+1} y_{t,h,e} \leq K_h \lambda^2_{t,h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} \tag{5.7}$$

$$\lambda^1_{t,h} + \lambda^2_{t,h} \leq 1 \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} \tag{5.8}$$

$$y_{0,h,e} = \mathbb{IN}_{h,e} \quad \forall h \in \mathcal{H}, e \in \mathcal{E} \tag{5.9}$$

$$y_{t,h,e+1} = \mathbb{SF}_{h,e}\, y_{t-1,h,e} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T}, e \in \mathcal{E}_B : e < E_B \tag{5.10}$$

$$y_{t,h,e+1} = \mathbb{SF}_{h,e}\, y_{t-1,h,e} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T}, e \in \mathcal{E}_R : e < E_R \tag{5.11}$$

$$y_{t,h,e+1} = \mathbb{SF}_{h,e}\, y_{t-1,h,e} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T}, e \in \mathcal{E}_F \setminus \mathcal{E}^W_F \tag{5.12}$$

$$y_{t,h,e+1} + u^F_{t,h,e} = \mathbb{SF}_{h,e}\, y_{t-1,h,e} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T}, e \in \mathcal{E}^W_F : e < E_F \tag{5.13}$$

$$\sum_{h' \in \mathcal{H}_R} u^B_{t,h,h'} = y_{t,h,E_B} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T} \tag{5.14}$$

$$\sum_{h' \in \mathcal{H}_F} u^R_{t,h,h'} = y_{t,h,E_R} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T} \tag{5.15}$$

$$y_{t,h,E_B+1} = \sum_{h' \in \mathcal{H}_B} u^B_{t-1,h',h} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T} : t > 1 \tag{5.16}$$

$$y_{t,h,E_R+1} = \sum_{h' \in \mathcal{H}_R} u^R_{t-1,h',h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} : t > 1 \tag{5.17}$$

$$u^B_{t,h,h'} \leq \mathbb{KN}_h\, n_{t,h,h'} \quad \forall h \in \mathcal{H}_B, h' \in \mathcal{H}_R, t \in \mathcal{T} \tag{5.18}$$

$$u^R_{t,h,h'} \leq \mathbb{KN}_h\, n_{t,h,h'} \quad \forall h \in \mathcal{H}_R, h' \in \mathcal{H}_F, t \in \mathcal{T} \tag{5.19}$$

$$\sum_{e \in \mathcal{E}_F} u^F_{t,h,e} \leq \mathbb{KP}_h\, n^A_{t,h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} \tag{5.20}$$

The capacity of the sow farms is taken as the number of sows instead that of piglets in constraint (5.2), since piglets are fed by the sow until they are weaned. This capacity is known in advance and constant for the whole time horizon. Constraint (5.3) represent the sow herd dynamics modelled as a Markov Decision Process as described in [48]. Constraint (5.4) models the relationship between the number of piglets born alive, the stock of sows and the average litter size. Constraints (5.5) imposes a limited capacity K_h for the rearing farms, while constraints (5.6)-(5.8) limit the capacity in in fattening farms, taking into consideration the AIAO management. Constraints (5.9) fixes the initial inventory $\mathbb{N}_{h,e}$ at the beginning of the planning horizon.

Pigs which are fed on farms grow from one stage to the next week by week. We assume that all pigs are fed under the same regime and grow accordingly for their age. Therefore, the inventory reflects this changing situation over the time horizon considered and has to be updated weekly. Inventory constraints (5.10)-(5.13) are stated for each farm and phase of the supply chain. The number of weeks in each phase (sow, rearing and fattening) is defined by $\mathcal{E}_B$, $\mathcal{E}_R$ and $\mathcal{E}_F$ respectively. The number of piglets to be transferred to the rearing or fattening farms has to be entered the same week. Later on, after completing the expected growth for the phase, they are all taken out at the same time. For this reason, constraint (5.14) states that piglets sent to rearing farms cannot exceed the total number of piglets weaned (i.e. of age E_B) and constraint (5.15) states that the pigs starting the fattening phase cannot exceed the number of pigs finishing the rearing phase. Piglets transferred between farms continue the growing process in a new phase, on a new farm according to constraints (5.16)-(5.17).

Constraints (5.18)-(5.20) compute the number of trips necessary to transport the animals, taking into account the capacity of each truck. Constraints (5.18)-(5.19) compute the number of trips needed to transport the piglets between the farms. The animals sent to the abattoir are heavier than those transferred between farms and so, different capacities of trucks may be required. The number of trips from fattening farms to the abattoir is computed in constraint (5.20).

5.4 COMPUTATIONAL EXPERIMENTS

5.4.1 *Case study*

The model (5.1)–(5.20) was applied to a real case, corresponding to a typical medium-sized company in the Spanish pig sector. The company managed in 2015 nine sow farms, 22 rearing farms and 131 fattening farms. In this experiment a constant discount factor λ_t=1 was considered over the whole time horizon. The list of farms and their main characteristics (initial inventory, capacity, etc.) is available at `https://cv.udl.cat/x/tv3LMk`. In this case, the pigs stay on the sow farms for four weeks, six weeks in rearing farms and a maximum of 18 weeks on fattening farms to complete the fattening process. The marketing time window on the fattening farms ranges from week 15 to 18 of the fattening period. The model assumes that the sow farms operate under a steady state in which the herd structure is in equilibrium. Accordingly, piglet production is derived from the number of weekly farrowing. The productivity of the sows is between 24 and 28 piglets per sow per year depending on each farm. The sows are culled after 9 parities and sold to the abattoir. Culled sows are replaced by newly-purchasing gilts. The weekly cost per sow is set to 4.85 Euros and includes feeding, insemination, medicines, medical care, purchase amortization and other related cost. This cost is incurred per pig as a variable and productive cost in the first stage of the production process where the sow farms are involved. The weekly cost of growing animals, i.e. piglets, rearing and fattening pigs was 2.061, 2.926 and 4.820 Euros respectively. One single truck transferred 700 piglets from the sow farms to the rearing farms and from latter to the fattening farms, but a maximum of only 240 from the fattening farms to the abattoir as maximum. The unitary transportation cost was fixed at 1 Euro/km for all the production process. A 52-week time horizon (one year) was considered. Prices are taken from the historical data for 2015 published by Mercolleida, the main Spanish pig auction market located in Lleida (Figure 5.2). In preliminary runs, no slaughtering penalties or bonuses for lean content and carcass weight were considered.

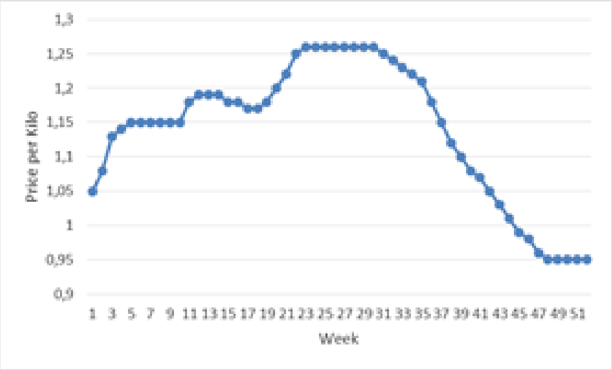

FIGURE 5.2: Price in Euro per live-weight kilo paid by the abattoir

The model was implemented with the IBM ILOG OPL modeling language and solved using CPLEX v12.7 in a Pentium 4 CPU's at 2.1 GHz and 16Gb RAM. Microsoft Excel was used for data storage for both the input and output parameters due its user friendliness and flexibility when managing the data and the easy linkage to CPLEX offered by IBM ILOG.

5.4.2 *Results and discussion*

The size of the proposed model (5.1)–(5.20) is shown in Table 5.1. The integer nature of inventory variables was ignored because of the little information they brought and the benefits regarding computational times solving the model. The model was solved in 2.3 hours with a 0.5 GAP (standing GAP for the difference between the best integer objective and the best solution found).

Variables	#
Binary	13,624
Continuous	581,182
Constraints	444,222
Non-zero coefficients	1,452,267

TABLE 5.1: Size of the MILP model (5.1)–(5.20)

The model represented a production of 6,585 piglets per week. The production cost reported in the sow farms (including sows' and piglets' cost) was 17.35 Euros per piglet and the total averaged cost per pig sent to the abattoir was 75.19 Euros. The benefit was 52.8 Euros per pig sold to the abattoir. Decisions concerning pig transportation used to be made by the company with the aim of transferring pigs to any available farm without taking the transportation cost nor any coordination of transport into account. Those decisions used to be taken in regular meetings based on actual inventories with the goal of allocating all the pigs to all the available farms. Usually, farm location or another strategy for filling farms to make the productive process more efficient had not considered. In contrast with this practice, the model has demonstrated that the global capacity of the farms was never overflowed and the respective average occupancy was 74% and 73% for rearing and fattening farms respectively (75% and 74% for rearing and fattening farms respectively when continuous management was considered, i.e. without batch management in fattening farms). Figure 5.3 shows the global occupancy per week for the rearing and fattening farms. In the rearing farms, the occupancy remained constant after transferring the initial stock of piglets to the fattening farms. On the contrary, in the fattening farms the stock varied significantly, mainly because of the effect of the marketing window. This is a common practice in the industry. For instance, in week 16, the price per pig increased significantly. Fattening farms tend to increase their stock the previous weeks and send as many pigs as possible when the price per pig is higher.

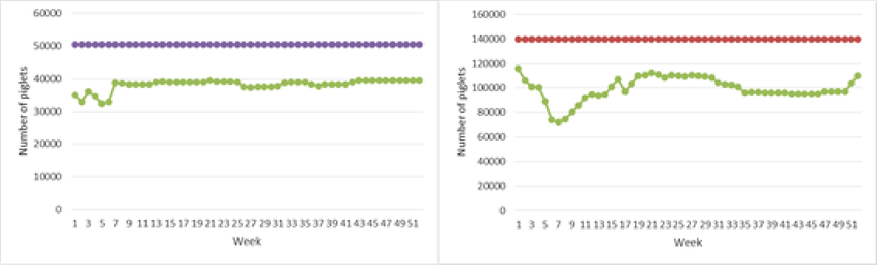

FIGURE 5.3: Global farm occupancy (in green) vs. global capacity in a) rearing farms b) fattening farms.

Rearing and fattening farms with a global occupation below 70% were considered non-strategic farms. Those farms were used when other farms were not big enough to accommodate the available number of pigs. Other farms were not reused during the given time horizon after cleaning out the initial stock. The model showed 27% and 33% of the rearing and fattening farms respectively in this situation. For instance, farm #11 was considered strategic by the company because of its location, occupancy (97%) and the batches created which are 800 pigs (the full farm capacity). Three farms in total (one rearing farm and two fattening farms) were not used again after releasing their initial inventory and therefore could be considered inactive.

The occupancy rate of the fattening farms was also observed and depended on the batches created under the batch management policy. The model behaviour tended to adjust the size of batches to the farms′ capacity, and so, reducing transportation costs. At the fattening phase, the number of batches created by the model represented a 90% of the farm capacity. 9% of the fattening farms reported an utilization below 90%. Therefore, those farms were considered non-strategic. Table 5.2 shows a sample of 10 fattening farms comparing the initial inventory corresponding to existing batches at the beginning of the time horizon with the batches proposed by the model and their averaged size during the finite time horizon considered. The divergences between the batches created by the model and the initial batch showed several inefficiencies of the company when filling the fattening farms (e.g. batches created in farms 14, 15 and 296, among others, prove that the profitability in batch management can be increased). On the other hand, there are other fattening farms the model does not use at full capacity, e.g. farm 15, 313 and 216, because their location was further with respect to the rest.

Figure 5.4 shows the same set of farms expressing the inventory over time in a graphic mode. Inventory of batches at the beginning of the time horizon are those in orange and the subsequent ones suggested by the model in green. A period corresponding to the first 24 weeks is shown. As observed, farms 15 and 188 were not used in this period. However, the model maximized the occupancy of farms 14, 197, 313, 114, 296 and 140. The importance of those farms is explained by the lack of idle periods and the maximum number of batches created.

Farm	Farm Capacity (C)	Initial Batch s. (1)	Batches created (2)	Average Batch s. (3)	% Diff. (C) & (1)	% Diff. (C) & (3)
15	1,200	228	1	1,200	526	100
14	200	82	3	200	244	100
197	360	310	2	360	116	100
313	200	116	1	200	170	100
114	1,208	582	3	1,079	185	89
168	2,834	865	3	1,606	186	57
296	1,040	595	3	1,017	171	98
216	312	271	1	312	115	100
188	2,996	1,196	2	1,171	98	39
140	1,280	1,063	3	1,224	115	96

TABLE 5.2: Sample of 10 fattening farms with (1) the batch size according to the company strategy; (2) the number of batches created along the time horizon; (3) the average batch size; (4) comparison between initial batch size and those suggested by the model; and (5) comparison between the average batch size created compared with farm capacity.

These farms' analyses gave valuable information to the company for planning their production strategy. Hence, the company can detect under used farms and increase the number of pigs resulting in a higher production and better occupation rate. As a consequence, the cost per pig produced is reduced with an efficient allocation of resources.

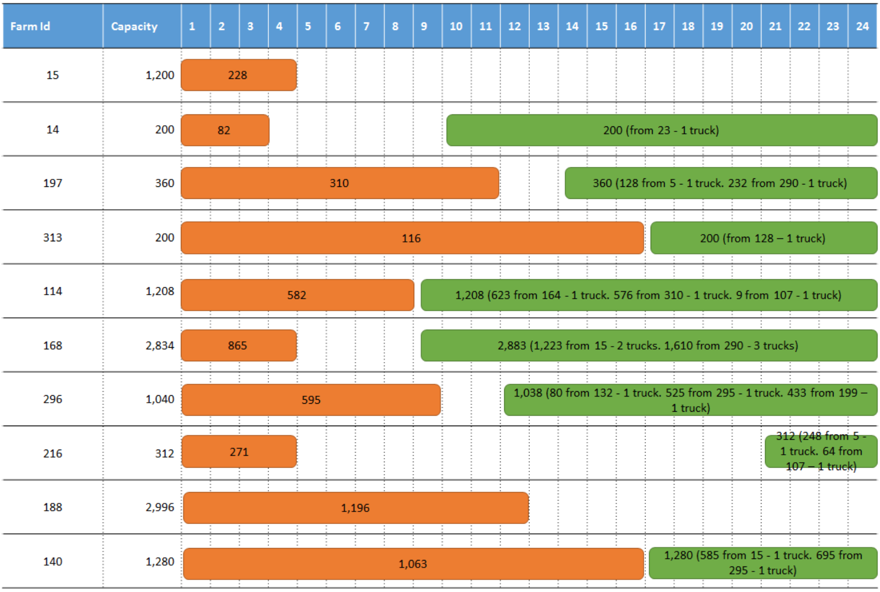

FIGURE 5.4: Initial batches created by the company (in orange) and the batches created by the model (in green) in fattening farms including the number of animals, origin and trucks needed for the transportation in the first 24 weeks of the time horizon

One of the most practical decision is to plan how, how many and when the animals have to be transported. The model was capable of creating a weekly transportation schedule. The schedule was intended to be sent to the third-party in charge of transportation, informing them about the number of animals to transfer, the trips required, the origin and destination with a pre-agreed cost of transport. The schedule allows farmers to be informed about the number of animals to be selected for transportation. Table 5.3 shows an example of the schedule with origins (sow farms), destination (rearing farms) and the animals to be transported in the first week of the time horizon.

Finally, the model demonstrated that the company had farms with an occupation rate below one in all the phases. For this reason, the model was used to explore the tentative benefits for the company operating at full capacity and determining capacity requirements at different phases. To do so, and to analyze future bottlenecks a fictive sow farm capable to produce enough piglets to reach the overall capacity of the system was introduced. Once solved, the model reported a bigger production as expected (8,079 vs 6,585 piglets per week). Accordingly, the global occupancy was also affected with an increment till 97% and 85% in rearing and fattening farms respectively. As the margin of benefit per pig produced was 52.8 Euros, the maximum purchase price of piglets would be 70.15 Euros to operate at full capacity. The total number of additional piglets to purchase would be 1,494.

5.5 CONCLUSIONS

In this paper, a production planning model for a pig supply chain based on a mixed-integer linear problem for the pig production process is formulated. The model was tested using real data from a Spanish company.

Firstly, we stated the importance of the new capabilities of the model, like the marketing window and the use of batch (AIAO) management, as some of the common practices in the fattening farms for the industry. Then, it was demonstrated that the model is capable of supporting and helping managers to make decisions regarding where, when and how many pigs should be transported in a period of a week; the batches to be created, planning the weekly transport of animals and evaluating the occupancy rate of each farm to assess the overall production capacity.

We outlined the use of the model to perform simulations, which is useful to explore decisions like the addition or deletion of farms in the system from a portfolio of available ones, farm use transformation (for instance, from

Origin	Destination	# Trips	# Animals
4	14	1	300
132	132	1	372
4	140	1	205
14	140	1	546
17	140	1	74
15	15	2	1,223
8	137	1	595
18	137	1	575
294	5	1	232
9	5	2	740
4	1	1	301
132	1	1	203
4	127	1	35
17	128	2	1,179
	Totals	17	6,580

TABLE 5.3: Example of transportation schedule from sow farms to rearing farms in week 1.

fattening to rearing or vice versa), re-planning production, coordination of transfers and farm locations. Problems in the production process regarding flow of animals, throughput and capacities along the PSC were detected beforehand allowing the company to react accordingly. Then, it was found that the rearing phase was the bottle-neck in the actual system and farm occupation rate could be improved by 22% purchasing additional piglets. A maximum purchase price of 70.15 Euros per piglet was estimated beneficial for the company. Other alternatives would be to acquire rearing farms or transforming fattening farms into rearing farms.

Finally, such other intangible benefits of the model as shorter meetings or less time wasted re-scheduling production were considered as strengths by the company. The model can also be adapted to different multi-farm multi-site production systems due to its flexibility when setting up the parameters.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Batallé S.A. and in particular of Josep Reixach for providing the data and giving assistance in the development of this project. Esteve Nadal-Roig and Lluis M. Plà wishes to acknowledge the financial support of the Spanish Research Program TRA2013-48180-C3-P and CYTED program for supporting the thematic network BigDSSAgro (P515RT0123). Antonio Alonso-Ayuso wishes to acknowledge the financial support of the Spanish Research Program MTM2015-63710-P.

6

OPTIMAL PLANNING OF PIG TRANSFERS ALONG A PIG SUPPLY CHAIN.

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Handbook of Operations Research in Agriculture and the Agri-Food Industry. *Volume 2015. International Series in Operations Research & Management Science, vol 224. Springer*.
DOI: 10.1007/978-1-4939-2483-7_1

Abstract: This chapter presents the formulation and resolution of a stochastic mixed integer linear programming model for pig production planning. The aim of the model is to optimize the entire pig supply chain according to the number of farms operating for the same company or cooperative. The model maximizes the total revenue calculated from the income of sales to the abattoir and the production costs. Production cost depends on each type of farm involved in the process. Factors like farm capacity, trucks available, reproduction management policies and transportation costs are taken into account. The proposed model considers a medium-term planning horizon and specifically provides optimal transport planning in terms of animals to be transported and number of trucks needed. Uncertainty in sale prices is explicitly incorporated via a finite set of scenarios. The algebraic modelling software OPL Studio, in combination with the solver CPLEX both from IBM ILOG are used to solve the different instances considered. The results of an averaged single scenario (deterministic instance) are useful in assessing the suitability of the stochastic approach. Finally, the conclusions drawn from the study including an outlook are presented.

Keywords: *Stochastic linear programming; Pig supply chain management; Transport planning*

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6.1 INTRODUCTION

A pig supply chain is a complex process in which a group of several farms, such as breeding, rearing and fattening, and one or more abattoirs work together to produce pigs. Pigs are slaughtered and converted into pig meat to be distributed among retailers. This is the result of a transformation of the pork sector from the traditional far-row-to-finish farms to a bigger, more industrialized, controlled and efficient pig production systems ([3, 92]. Furthermore, concerns about environment, food quality and animal welfare are becoming the new challenges for the pig industry. Modern and intensive production of pigs is becoming more and more specialized. The size of facilities is increasing and the production process is structured through three phases: the first phase focuses on producing piglets, the second phase focuses on rearing the piglets and the third and last phase focuses on fattening the pigs and delivering them to the abattoir. For each of these phases, a set of specialized farms (i.e. sow farms, rearing farms and fattening farms respectively) are involved. As result, private companies and cooperatives tend to integrate farms and abattoirs and coordinate their operations into pork supply chains by using tighter vertical coordination linkages [6]. Planning simultaneously pig production and transport of animals along the supply chain greatly advances the efficiency of both processes [97].

Thus, this chapter presents a general formulation of a stochastic mixed integer linear programming model with the aim to optimize the production planning of a pork supply chain based on a previous seminal proposal [57]. The model maximizes the total revenue of the chain. Income depends on animals sold to the abattoir and main cost summarizes animal feeding, doses of insemination, labour, transportation and veterinary expenses. A finite time horizon of three years is considered on a weekly basis. As a result, the proposed model provides the best solution for production planning, that is, the flow of animals among farms and towards the abattoir, the number of animals to be produced and transferred at each phase and stage, the number of trucks and optimal replacement policy for each sow farm, as well as the optimal delivery of fattened pigs to the abattoir. The formulation presented makes possible to envision new opportunities for operations research methods to be successfully applied to the pork supply chain management optimization [47]. In this regard, we identify some extensions of the model that we plan to address in the future.

6.2 MODELLING PIG SUPPLY CHAINS

Although the literature in models for supply chain production and transport is wide [97], modelling of agricultural supply chains is not so extensive [98]. However research dealing with pork supply chains agrees on the importance of planning pig production along the entire chain to coordinate productivity and quality improvement strategies [14]. This is so because most of the literature to support the decision making on the pig sector have only been focused on operations on single farms, while the pork supply chain management involves the coordination of sets of farm units at different phases [6, 57, 95]. Hence, the modern structure of the pig sector, based on pig supply chains requires the new modelling approaches to tackle actual problems. For instance, more than one farm per phase and more than one phase has to be considered. So far, modelling approaches for the pig industry had been developed to mainly improve the productivity of individual farms. Some of these studies made use of Markov decision processes and simulation models [95] and focused on a sow farm which is reasonable since it is the most complicated part of the production process. Assumptions of the models imposed by researchers to avoid complexities reduced the interest to practitioners beyond strategic decisions. For instance, the homogeneity of parameters over time or the randomness of parameters like prices were not accompanied with updating methods allowing more precise results for short or medium-term decisions [6]. Original strategies to cope with this situation have been presented considering some constraints aimed at the modelling of a sow farm embedded into a pork supply chain [56]. Other authors proposed a mixed integer linear programming model to optimize the entire supply chain, taking into ac-count the constraints of companies having the three phases [57, 86].

The pig supply chain (PSC) considered in this paper involves three different farms: sow, rearing and fattening farms (see Figure 6.1). The PSC model assumes all the farms and the abattoir are owned by the same company. The transport flow among the different farms including the abattoir, the load to be transported and the structure of the agents taking part in the PSC model are depicted in Figure 6.1. Hence, according to that, the first phase produce piglets and takes place on sow farms. Sows are inseminated and are expected to become pregnant. If not, there are limited additional attempts until a successful conception happens, leading to a farrowing and subsequent lactation period. Otherwise, the sow is culled and sent to the abattoir for infertility reasons. The aim of sow farms is to wean the

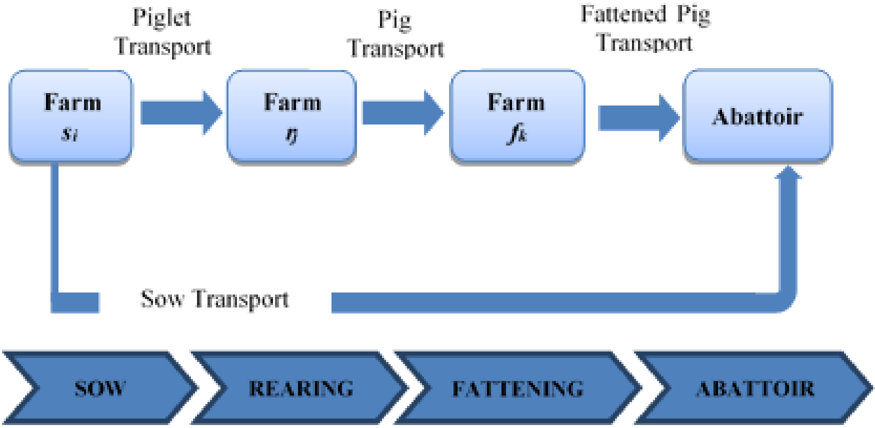

FIGURE 6.1: Pig production System. Stages and transport.

maximum number of piglets to be transferred to rearing farms. The second phase involves piglets transferred to rearing farms to be fed for a specific number of weeks until they reach a weight of around 20 kg. Finally, in the third phase, pigs are transferred to fattening farms. Fattened pigs are delivered to the abattoir once they have reached a marketable weight. Fattening farms are filled and emptied at a time with batches of animals, this is, the so-called all-in-all-out management system. This strategy has been demonstrated useful for disease prevention and control because avoid the contact between animals belonging to different batches and allows the farmer to sanitize the facilities.

6.3 GENERAL FORMULATION OF THE MODEL

6.3.1 *Mathematical background on stochastic programming*

Stochastic linear models provide a suitable framework for modelling decision problems under uncertainty arising in several applications [99]. Consider the following general form of a two-stage stochastic programming model that follows the Deterministic Equivalent Model (DEM) [64]:

(SP1)

$$z_{SP1} = \min_{x,y,k} c^T x + \sum_{k=1}^{K} p_k q_k^T y_k \tag{6.1}$$

s.t.

$$Ax = b \tag{6.2}$$

$$T_k x + W_k y_k = h_k \quad \forall k \in \Omega \tag{6.3}$$

$$x, y_k \geq 0 \tag{6.4}$$

where x is the n_x-vector of the first stage variables, which may include 0-1 variables; y_k is the n_y-vector of the second stage variables for scenario $k \in \Omega$, c is a known vector of the objective function coefficients for the first stage variables, b is the right hand side vector for the first stage constraints, A is the first stage constraint matrix, p_k is the likelihood of the scenario k, h is the right hand side vector for the second stage constraints, q_k^T is the vector of the objective function coefficients for the second stage variables, while T_k is the technology matrix and W_k is the recourse matrix under scenario k, $\forall k \in \Omega$.

The structure of the uncertain information in the two-stage stochastic linear model SP1 can be visualized as a tree, where each root-to-leaf path represents one specific scenario, ω, and corresponds to one realization of the whole set of the uncertain parameters linked at the first stage by the non-anticipativity constraints [100]. In Figure 6.2a, the scenarios are shown independently. Solving the problem for each scenario would produce wrong solutions. Thus, non-anticipativity constraints are added to force all the scenarios have the same first stage variables (Figure 6.2b). The flexibility of these models is related to their multiperiod nature, i.e. be-sides the first stage variables that represent decisions made in face of uncertainty, the model consider second stage decisions, i.e. recourse actions, which can be taken once a specific realization of the random parameters is observed. Hence, the vector x represents the same decision at the first stage (St1) for all scenarios while the remaining decision variables y_s are dependent of the corresponding scenario, $s \in S$.

6.3.2 *Mathematical formulation*

In our approach, the uncertain parameters are those related with future sale prices. Uncertainty is represented in the model by a set of possible scenarios, S, with corresponding probabilities p_s. A mixed integer linear programming model was developed to determine optimal planning of pig transfers along a pig supply chain over a finite time period. To present the multiperiod formulation, the following notations were used:

Sets and indexes:

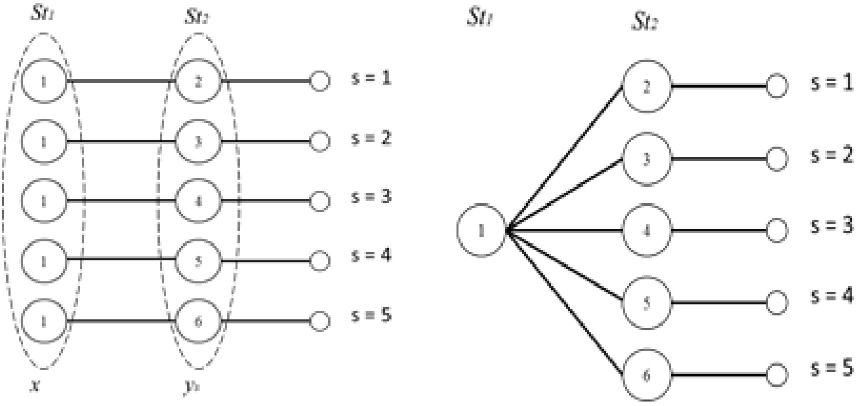

FIGURE 6.2: Scenarios of a two-stage stochastic model. (a) Individual scenario representation (b) Compact representation

$S = \{s\}$ a finite set of scenarios.

$T = \{t\}$ a finite set of periods in weeks.

$T_1 \subset T$: a subset of T corresponding to the periods of the first stage

$H = \{h\}$ the set of farms conforming the pig supply chain.

$H = B \cup R \cup F$ disjoint partition of farms, being B the set of sow farms, R the rearing farms and F the fattening farms.

$E = \{e\}$ set of growing stages of pigs expressed in weeks, from birth date to the delivery to the abattoir.

$E = E_B \cup E_R \cup E_F$ disjoint partition of growing stages of piglets (or pigs) housed in different facilities (B,R or E) being E_B the lactation period (from the birth to the weaning of piglets), E_R the rearing period (from weaning to the beginning of the fattening) and E_F corresponding to the fattening period.

X : set of physiological states in which sow lifespan is divided.

$X_a \subset X$ set of physiological states in the end of which sows are culled and sent to the abattoir, a.

$X_g \subset X$ set of farrowing states in the end of which farrowing take place and piglets born.

$W = \{w\}$ set of growing stages at the end of the fattening phase when pigs can be sent to the abattoir (marketing time window).

Parameters

IN_{he} initial inventory of pigs of age e and farm h.

K_h farm capacity in number of sows if $h \in B$ or pigs if $h \in R \cup F$.

p_{ij}^{bs} transition probabilities of sows from i to j, with $i, j \in X$ in sow farm $b \in B$ and scenario s.

LS_{nbts} litter size at parity n, on sow farm b, at week t and scenario s.

$TR_{hh^*ts} = C_{ts}d(h, h^*)$ cost of transport from h to another farm or to the abattoir at week t and scenario s; where C_{ts} is the unitary cost per km of a truck at week t and scenario s, and $d(h, h^*)$ distance in km from farm h to another farm or to the abattoir, $h^* \in H \cup \{a\}$.

$CSOW_{hits}$ unitary cost per sow on farm h, physiological state i, week t and scenario s including feeding, doses of insemination, labour and veterinary expenses.

EX_{hets} unitary cost in farm h per piglet/pig, at age e, week t and scenario s, including feeding, labour and veterinary expenses.

p_{hets} sale price per kg of sows ($e = 0$; $h \in B$) or pigs ($e \in W$; $h \in F$) sent to the abattoir at week t and scenario s.

ka_h load capacity per truck transporting animals from farm h to the abattoir.

kg_h load capacity per truck transporting animals from farm h to another farm.

π_{bits} steady state inventory of the total number of sows at physiological state $i \in X$ in the sow farm b at week t and scenario s.

D_{ts} minimum demand of the abattoir at week t and scenario s.

AW_{ets} average live weight of pigs at fattening stage e, week t and scenario s.

AW_{its} average live weight of culled sow at state $i \in X_a$, week t and scenario s.

Decision variables

I_{hets} inventory of piglets on farm h, age e, week t and scenario s.

A_{hts} inventory of pigs on farm h, week t and scenario s to be transferred to the next stage in the chain.

A_{brts} inventory of piglets sent from b to r, at week t and scenario s.

A_{rfts} inventory of piglets sent from r to f at week t and scenario s.

A_{fets} inventory of pigs sent from f to the abattoir at fattening stage $e \in W$, at week t and scenario s.

Nka_{hts} number of trips from $h \in B \cup F$ to the abattoir at week t and scenario s.

$Nkg_{h_1h_2ts}$ number of trips from h_1 to h_2 being either $h_1 \in B$ and $h_2 \in R$ or $h_1 \in R$ and $h_2 \in F$ at week t and scenario s.

Let us note that farms are of different types, then $H = \{B \cup R \cup F\}$ and this partition of the farms' set is related to the age of pigs growing on them. More formally: $E \times H = E \times \{B \cup R \cup F\} = E \times B \cup E \times R \cup E \times F = E_B \times B \cup E_R \times R \cup EF \times F$, being $E = E_B \cup E_R \cup E_F$ and $E_B \cap E_R \cap E_F = \emptyset$. Therefore, without loss of generality, in what follows, the use of pairs (e,h) will refer only to $E_B \times B$ or $E_R \times R$ or $E_F \times F$.

6.3.2.1 *Structure of the objective function*

The objective of this model is to get the maximum benefit achieved by optimizing the production planning of the pig supply chain from sow farms to the abattoir. This benefit is represented by the gross margin calculated by the summation of incomes from pigs sold to the abattoir minus the total amount of expenses (such as feeding, doses of insemination, labour and veterinary expenses) and the transportation cost incurred for each farm. The model is formulated in a weekly basis given most of the activities on farm, transportation between phases and to the abattoir occurs regularly at this time frame. Therefore, the objective function is the summation of the total gross margin weighted per scenario of each farm over the time horizon, gm_{hts}. The gross margin per scenario farm and period is calculated from the income, v_{hts}, minus cost, c_{hts}, and hence:

$$\max z = \sum_{S \in S} p_s \sum_{h \in H} \sum_{t \in T} gm_{hts} = \sum_{s \in S} p_s \sum_{h \in H} \sum_{t \in T} (v_{hts} - c_{hts}) \tag{6.5}$$

Where the income per scenario is the sale value of culled sows π_{bats} and fattened pigs A_{fets} sent to the abattoir according to the sale price and total pig weight at each marketable stage, that is: $v_{hts} = p_{h_0ts}AW_{ts}\pi_{bats}$ if $h \in B$ or $v_{hts} = \sum_{e \in W} p_{hets}AW_{ets}A_{hets}$ if $h \in F$. Notice that $v_{rts} = 0$ because not marketable product is produced. The costs are computed as transport cost and the rest of costs including feeding, doses of insemination, labour and veterinary expenses:

$$c_{hts} = \sum_{h^* \in H \cup \{a\}} TR_{hh^*ts}Na_{hh^*ts} + \sum_{i \in X} CSOW_{hits}\pi_{hits} + \sum_{e \in E} EX_{hets}I_{hets} \tag{6.6}$$

Total transport cost per week and scenario is calculated according to the number of trips needed to transfer pigs from one farm, h_1, to an-other one, h_2, or to the abattoir, a. This total cost depends mainly on the distance between these farms, $d(h_1, h_2)$, in km, therefore:

$$\sum_{h^* \in H \cup \{a\}} TR_{hh^*ts}Na_{hh^*ts} = \sum_{h \in H-R} TR_{hats}Nka_{hts} + \sum_{b \in B}\sum_{r \in R} TR_{brts}Nkg_{brts} + \\ + \sum_{r \in R}\sum_{f \in F} TR_{rfts}Nkg_{rfts} \tag{6.7}$$

6.3.2.2 *Constraints of the model*

The different constraints affecting the planning of transfers along the pig supply chain including deliveries to the abattoir can be formulated as:

$$\sum_{i \in X} \pi_{bits} \leq K_b \quad b \in B, t \in T, s \in S \tag{6.8}$$

$$\sum_{e \in E} I_{hets} \leq K_h \quad h \in H - B, t \in T, s \in S \tag{6.9}$$

$$\pi_{bits} - \sum_{j \in S} p_{ji}^{bs}\pi_{bjts} = 0 \quad i \in X, b \in B, t \in T, s \in S \tag{6.10}$$

$$I_{b1ts} \leq \sum_{n \in X_g \subset X} \pi_{bnts}LS_{nbts} \quad b \in B, t \in T, s \in S \tag{6.11}$$

$$I_{he0s} = IN_{he} \quad e \in E, h \in H, s \in S \tag{6.12}$$

$$I_{be+1ts} = I_{bet-1s} \quad b \in B, e \in E_B \setminus \{|E_B|\}, t \in T \setminus \{1\}, s \in S \tag{6.13}$$

$$I_{re+1ts} = I_{ret-1s} \quad r \in R, e \in E_R \setminus \{|E_R|\}, t \in T \setminus \{1\}, s \in S \tag{6.14}$$

$$I_{fe+1ts} = I_{fet-1s} \quad f \in F, e \in E_F \setminus \{W\}, t \in T \setminus \{1\}, s \in S \tag{6.15}$$

$$I_{fe+1ts} = I_{fet-1s} - A_{fet-1s} \quad f \in F, e \in W \setminus \{|W|\}, t \in T \setminus \{1\}, s \in S \tag{6.16}$$

$$I_{r|E_B|+1ts} = \sum_{b \in B} A_{brt-1s} \quad r \in R, t \in T \setminus \{1\}, s \in S \tag{6.17}$$

$$\sum_{r \in R} A_{brts} = A_{bts} \quad b \in B, t \in T, s \in S \tag{6.18}$$

$$I_{f|E_R|+1ts} = \sum_{r \in R} A_{rft-1s} \quad f \in F, t \in T \setminus \{1\}, s \in S \tag{6.19}$$

$$\sum_{f \in F} A_{rfts} = A_{rts} \quad r \in R, t \in T, s \in S \tag{6.20}$$

$$A_{f|E_F|ts} = I_{f|E_F|ts} \quad f \in F, t \in T, s \in S \tag{6.21}$$

$$\pi_{bits} \leq Nka_{bts}ka_b \quad b \in B, i \in X_a, t \in T, s \in S \tag{6.22}$$

$$A_{fets} \leq Nka_{fts}ka_f \quad f \in F, e \in W, t \in T, s \in S \tag{6.23}$$

$$A_{h_1h_2ts} \leq Nkg_{h_1h_2ts}ka_{h_1} \quad h_1 \in B \cup R, h_2 \in R \cup F, t \in T, s \in S \tag{6.24}$$

$$\sum_{f \in F} A_{fts} \geq D_{ts} \quad f \in F, t \in T, s \in S \tag{6.25}$$

All facilities have a limited capacity. The capacity in sow farms (6.8) depends on the number of sows that can be housed while in rearing and fattening farms (6.9) depends on the maximum number of pigs that can be feed at a time. The abattoir is big enough to accept all pigs produced weekly, so there is no need to limit abattoir capacity, although it would also be possible depending on the case study.

It is assumed that sow farms are operating under a steady state derived from the herd structure at equilibrium (6.10). This is because sow herd dynamics is modelled as a Markov Decision Process [48]. The number of piglets born alive weekly will depend of the number of sows at farrowing, being $X_g \subset X$ the subset of reproductive states of a sow with a farrowing, and the averaged litter size (6.11). All farms have an initial inventory of piglets or pigs at the beginning of the planning horizon (6.12). This initial inventory affects the flow of animals along the chain in the succeeding weeks and over the time horizon period which is being considered. Pigs which are fed on farms grow from one stage to the next one. We assume that all pigs are fed under the same regime and kept in groups of the same age. Each group grow accordingly to their age and the average live weight, consumption and mean daily gain is known for calculation. Therefore, the inventory must reflect this changing situation week by week over the time horizon. Inventory constraints can be stated for each phase of the supply chain ((6.13)-(6.15)). Additional constraints are added to represent the time window for marketing fattened pigs representing that not all pigs reach at the same time a marketable weight (6.16). No casualties are considered during the growing process. They could be taken into account when animals are transferred to the following phase in the chain or these constraints could be relaxed by using inequality constraints. The number of piglets to be transferred to the rearing or fattening farms has to be entered the same week. After completing the expected time for the phase, all of them exit also at the same time. For this reason, piglets sent to rearing farms cannot exceed the total number of piglets weaned (i.e. of age $|E_B|$) nor do the pigs starting the fattening phase exceed the number of pigs finishing the rearing phase (6.17) and (6.18). Similarly, this also happens with piglets reared (6.19) and (6.20) and ready to be transferred to fattening farms (i.e. of age $|E_R|$) and pigs fattened (6.21) and ready to be delivered to the abattoir (i.e. of age $|E_F|$). Furthermore, a minimum capacity of the batch (lower bound) could be fixed complementing the upper bound represented by the farm capacity.

Constraints affecting transportation are related to the capacity of each truck. Animals sent to the abattoir are heavier than those transferred between farms and so, different capacities or trucks may apply. Hence, (6.22) and (6.23) represents the number of trucks used to transport culled sows or fattened pigs to the abattoir respectively and (6.24) the number of trucks needed to transfer animals among farms. Optionally, a minimum weekly demand to assure some level of operation at the abattoir can be stated by (6.25).

6.3.2.3 *Non-anticipativity constraints*

Notice that constraints (6.8)-(6.25) represents s independent scenarios (see Figure 6.2). We must define the non-anticipativity constraints linking the different scenarios by fixing the same decision variables at the first stage of the model. Hence the following constraints are added for such purpose:

$$I_{hets} = I_{het1} \quad h \in H, e \in E, t \in T_1, s \in S \tag{6.26}$$

$$A_{hts} = A_{ht1} \quad h \in H, t \in T_1, s \in S \tag{6.27}$$

$$A_{brts} = A_{brt1} \quad b \in B, r \in R, t \in T_1, s \in S \tag{6.28}$$

$$A_{rfts} = A_{rft1} \quad r \in R, f \in F, t \in T_1, s \in S \tag{6.29}$$

$$A_{fets} = A_{fet1} \quad f \in F, e \in W, t \in T_1, s \in S \tag{6.30}$$

$$Nka_{hts} = Nka_{ht1} \quad h \in H, t \in T_1, s \in S \tag{6.31}$$

$$Nkg_{h_1 h_2 ts} = Nkg_{h_1 h_2 t1} \quad h_1, h_2 \in H, t \in T_1, s \in S \tag{6.32}$$

6.4 COMPUTATIONAL RESULTS

6.4.1 *Model setup and basic case*

In order to illustrate the suitability of the deterministic model resulting from the consideration of one scenario and the corresponding stochastic extension when considering several scenarios at a time a case study is presented. Basic parameters of the study were taken from standard values under Spanish conditions and recorded in the BD-Porc databank (national record keeping system hosted at `http://www.irta.es/bdporc/`, accessed 07 Aug 2014), and do not correspond to a specific farm. The total set of farms per phase owned by a theoretical vertical integrated company are four sow farms, four rearing farms and eight fattening farms plus one abattoir. Since there are three types of origins when collecting animals (sow, rearing and fattening farms) and three types of destinations to deliver them (rearing and fattening farms plus the abattoir), two transfers are feasible between farms of different type (sow to rearing or rearing to fattening farms) and the rest of transports are directed to the abattoir (sow and fattening farms). The transportation cost from sow farms to the abattoir is considered and corresponds to culled sows. The entire set of parameters data is summarized in tables 6.3-6.7. For all the farms, parameters like farm capacity and initial inventory are required. For simplicity, the herd size of each sow farm will be taken as a parameter combined with the steady state of the herd structure determining accordingly the associated piglet production. Thus, sow farms operate at a constant rate of occupancy of lactation facilities. The road distances between farms and between farms to the abattoir are also required. The inventory of sow, rearing and fattening farms is given in number of piglets per lactation, growing or fattening stage respectively. The abattoir requires a minimum pig demand for this kind of chains where the product pushes along the chain instead of being pulled by demand. No risk of overflow capacity of the abattoir is considered because slaughtering capacity is larger enough to slaughter all pigs produced. The sale price is based on the historical series recorded by Mercolleida, the main Spanish auction market for pigs (`http://www.mercolleida.com/mercados-ganaderos/porcino/`, accessed 14 March 2013). Two different series are considered depending on the meat quality of the animal namely whether they come from the fattening farms or from sow farms, that is, commercial pigs or culled sows. Other considerations regarding the value of pigs include carcass classification depending on lean percent, carcass weight and back fat thickness (SEUROP classification is mandatory in EU abattoirs). Sows and pigs are valued assuming experimental distributions of these traits.

The finite time horizon is set to three years. The maximum number of parities cycles for sows is nine. According to usual practices in Spain, lactation period and both rearing and fattening stages for piglets are set to four, six and eighteen weeks respectively as maximum. Capacity of trucks, weight of animals and unitary transport cost are taken into account according to the age of animals transported and distance conveyed. The number of available trucks is not taken into consideration explicitly, only the number of trips required for transportation.

To develop the model, the modelling language IBM ILOG OPL has been used. The solver CPLEX v12.2 solved the model in a laptop computer (Pentium Dual-Core CPU at 2.1GHz and 4Gb RAM). Microsoft Excel has been used for storing data, both input parameters and outputs, for its ease of use and flexibility to manage data. The integration into an Enterprise Resource Planning (ERP) can enable a simple adoption of the system by any company through the maintenance and update of a XLS file with the list of parameter like the inventory of animals for each farm, real prices and unitary costs considered by the model.

6.4.1.1 *Basic example. Deterministic model*

The deterministic model is build reducing the set of scenarios to one, $|S| = 1$, and then the non-anticipativity constraints ((6.26)-(6.32)) are not necessary. Strictly speaking, decision variables of the proposed model representing the number of animals are integer and non-negative variables. However, the computational time consumed for calculations in preliminary tests when all decision variables related to animals were considered integer, made the pure integer model inappropriate for practical purposes [56]. Furthermore, the loose of precision considering these variables as real was neglectable. As a consequence, only decision variables related to number of trucks and trips were considered integer relaxing the integrality condition for the rest. Beyond this relaxation, the first stage represents the roller horizon where decisions must be implemented before new environmental changes could be appreciated or taken into account for an update of the solution. Specific parameters of the linear programming model are detailed in tables 6.3-6.7. Figures corresponding to the size of the deterministic model are presented in Table 6.1. The maximum average reward of the represented PSC was 3,231 thousands of euros per year with an overall occupancy of the available facilities of 97%. Moreover, optimal solution provided the scheduling of the number of piglets and pigs to be transferred week by week and the way (from where to where). The occupancy rate was more than 0.97 over the time horizon of planning and never reached the full occupancy. Inspecting the solution was discovered a rational behaviour related to the preferred usage of the nearest farms to the abattoir and so, reducing cost transport while keeping the rest of the operational cost constant.

CPLEX	Value
Variables	68,057
Constraints	47,655
Non-zero-coefficients	199,088

TABLE 6.1: Report of the size of the deterministic model

Sensitivity analysis. To prepare the extension of the model into a stochastic linear programming model and also, to value the impact of the uncertainty of model parameters on the optimal solution two additional cases were considered. The optimistic case, where the sale price paid by the abattoir was increased a 5%, and the pessimistic case where the sale price was reduced by 5%.

The rest of parameters of the model concerning the productivity of the system are maintained. In all cases an average of 473 piglets produced every week was considered. The system always produce as much piglets as it is possible regardless the sale price. The average occupancy of the system is also the same. The variations over time in the sale price and the marketing window have a limited impact on the technical performance of the system not sufficiently relevant on average. Despite of this, the farms' occupation taken individually varies considerably from farm to farm, and also affecting directly to the farmers' revenue. Figure 6.3a and 6.3b show an example of two fattening farms' occupancy throughout the time horizon. Changes in the farm occupation can be observed, in particular at the beginning and at the end of the time horizon due to the initial and final inventory. In both cases the occupancy rate is high.

While technical operation of the PSC is slightly affected by the scenario (either optimistic or pessimistic), it is not the same regarding the economic performance. Main economic outcomes are shown in Table 6.2. Economic

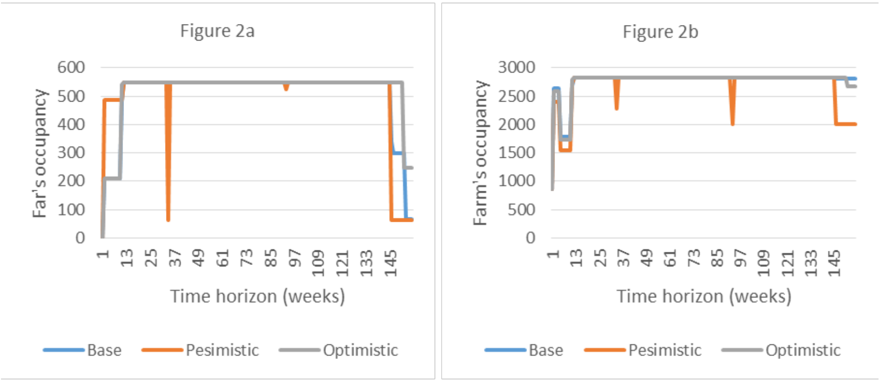

FIGURE 6.3: Representation of two fattening farm's occupancy with capacity of 600 (a) and 3000 pigs (b). Models: Base, optimistic (+5%) and pessimistic (-5%) sales prices.

indicators such as the benefit and income increase according to the sale price whilst cost remains almost the same showing a decreasing trend in the pessimistic case and increasing in the optimistic case. These variations are also related to the marketing window in which the model tries to achieve the higher benefit by selling the animals at the best price. The sales prices do not affect the production planning committed unless they are lower enough to force the system to not produce piglets. As is shown in Table 3 changes of 5% in the sale price provoke changes of more than the 10% in the benefit. The overall benefit ranges from 8,687 to 10,721 thousands of euros. Therefore, uncertainty seems to have an important impact on economic results of the whole PSC.

6.4.1.2 *Basic example. Stochastic model*

Stochastic model formulation requires the generation of a set of scenarios S. In that case the full model have to include the non-anticipativity constraints ((6.26)-(6.32)) linking all the scenarios. To illustrate and assess the suitability of the stochastic approach three scenarios were defined in this example. Again, the sale price as uncertain parameter was considered to be modelled by scenario. Therefore, the optimistic, normal or standard and pessimistic scenarios were defined in correspondence with the values of high, average and low sale prices respectively. Time horizon was of 152 weeks as with the deterministic example and $T1 = \{1\}$.

	Base	Pessimistic	Optimistic
Cost of animals	10,755	10,706	10,782
Difference vs base		-0.45%	0.26%
Cost of transport	38	38	38
Difference vs base		-0.33%	0.29%
Total cost	10,793	10,745	10,821
Difference vs base		-0.45%	0.26%
Income	20,488	19,432	21,843
Difference vs base		-5.16%	6.61%
Benefit	9,695	8,687	11,022
Difference vs base		-10.40%	13.69%

TABLE 6.2: Economic indicators for the 3 cases in thousands of Euros.

The resolution of this formulation give an optimal profit (RP) of 3,235 thousands of €/year. The results confirmed also a globally high rate of occupancy. However in that case, a different behaviour for each scenario is observed and reveals the lower occupancy in the pessimistic scenario. The optimistic scenario reached the maximum occupancy of the PSC sooner and it was maintained more weeks over the time horizon (figure 6.4).

Concerning the sales behaviour (see figure 6.5) shows how the scenarios tend to take advantage of the marketing window making the sales not steady. Furthermore, the pessimistic scenario shows a singular capability to sell more animals than the rest of scenarios at some weeks to maximize the income.

In addition, just to analyze the importance of the time horizon and final inventory on the outcome of the first 52 weeks different instances for T=78, 104, 130 and 156 were solved. It was observed (data not shown) that the time horizon has a very little influence on the first 52 weeks because in all instances the objective function never reported differences greater than a 0.08%. Even less is the impact on the expected profit for the first stage period represented by the first week (less than 0.02% in the worst case).

Another aspect of interest was to see the impact of different number of weeks considered in the first stage. The reason was to consider if the production planning including the transfer of animals could be done bi-weekly or monthly. Therefore, new instances were solved for a different range of

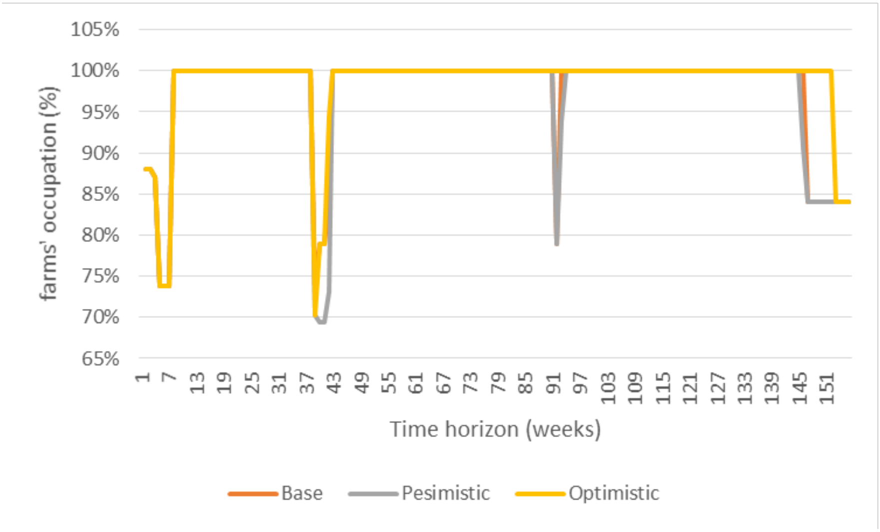

FIGURE 6.4: Representation of the behaviour of the occupancy rate of the PSC with 3 scenarios.

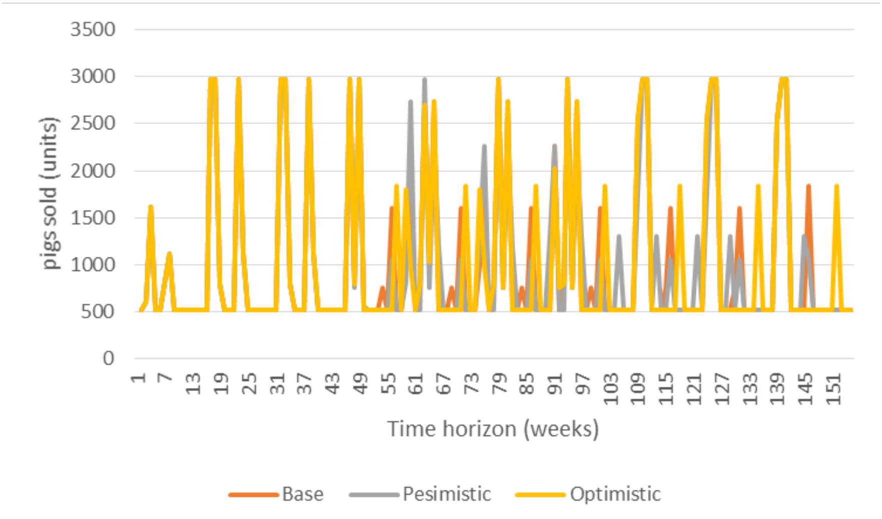

FIGURE 6.5: Representation of the sales behaviour regarding three scenarios.

weeks in the first stage. The increment of weeks in the first stage showed a linear reduction in the profit in agreement with the loose of variability represented.

Inspecting the solution of the deterministic models with respect to the stochastic one, with the first 4 weeks as the first-stage, we compute the expected value of perfect information (EVPI), defined through the following expression:

$$EVPI = \sum_{c \in C} p_s \Phi^s - RP \tag{6.33}$$

being Φ^s the optimal value of the deterministic model when it was solved (separately) for each scenario s in Ω and RP the optimal value of the stochastic model. For our study the EVPI=9,801-9,707 = 94 thousands of euros. EVPI measures the value of knowing the future with certainty. This is how much the farmer would be ready to pay to obtain perfect information about the dynamic behaviour of future sale price.

Additionally, the Value of the Stochastic Solution (VSS) was computed. Roughly speaking, it measures how good or bad results to use the optimal solution of the stochastic model instead of the deterministic one. Then, the Value of the Stochastic Solution is defined as VSS=RP-EEV, where EEV is the expected value assuming expected yields and expected parameters fixing the optimal values at the first stage. In our case, the VSS= 9,707-9,663=44 thousands of euros, this is the cost of ignoring uncertainty in choosing a decision.

6.4.2 *Conclusions and future work*

Despite the advantages of the stochastic solution shown in the previous section, the preliminary results of the model themselves indicate opportunities for improvements, mainly in two areas. First one, the management of an important amount of farms involved in a PSC by a better coordination among them; second one, the required relaxation of the integrality condition for several variables reducing the computational time and making feasible and possible the use of the model in practical condition for a PSC company.

The practical extension of the model considering more breeds and other sanitary constraints to fit particular PSC companies will make the model more complex. Hence, the resolution of such instances will require more computational power and/or the parallelization of the model. Our contribution then, emphasizes the importance and complexity of new decision-making tasks regarding the modern organization of the pork sector, rationalize the flow of animals over the chain providing a planning tool capable of updating the flow conveniently anticipating changes or reacting face to them.

Finally, the presented model is flexible, allowing a deterministic or stochastic formulation. The stochastic version can deal with the uncertainty of some parameters like the sale price and complemented with a more accurate growth and reproductive performance modeling like litter size, mortality rate or culling rates, but also likely changes in feed cost, labour, medicines, etc.

Parameter	Value
Farms (in units):	
Sow farms	4
Rearing farms	4
Fattening farms	8
Time horizon (in weeks):	156
Sow's phycological states:	10
Production stages for piglets/pigs (in weeks):	
Sow farms	4
Rearing farms	6
Fattening farms	18
Transportation capacity (in units):	
From sows to rearing farms:	700
From rearing to fattening farms:	700
From sows /fattening farms to the abattoir	240
Animal cost (in Euro / week) Sows:	4.85
Piglets in sow farms:	1.874
Piglets in rearing farms:	2.66
Piglets in fattening farms:	4.382
Transportation cost (Euro / trip):	1
Minimun weekly demand in piglets:	500
Weekly litter size:	0.518

TABLE 6.3: General parameters of the model.

Farm #	Type	Capacity (in units)	Initial stock (in units)
1	Sow	1,200	1,049
2	Sow	600	448
3	Sow	1,450	1,203
4	Sow	2,400	2,004
5	Rearing	300	101
6	Rearing	800	759
7	Rearing	2,800	2,633
8	Rearing	3,000	1,537
9	Fattening	1,200	228
10	Fattening	200	82
11	Fattening	548	2
12	Fattening	360	310
13	Fattening	1,663	18
14	Fattening	200	116
15	Fattening	1,208	582
16	Fattening	2,834	865

TABLE 6.4: Farm's capacities.

To rearing	Distance from sow farm # (km)			
farm #	1	2	3	4
1	18	5	36	33
2	14	6	42	34
3	48	31	36	5
4	18	5	36	33

TABLE 6.5: Distances from sow to rearing farms.

To fattening farm #	Distance from rearing farm # (km) 1	2	3	4
1	204	199	186	204
2	0	7	36	0
3	52	56	34	52
4	49	55	46	49
5	45	46	10	45
6	45	45	9	45
7	40	44	24	40
8	51	55	36	51

TABLE 6.6: Distances from rearing to fattening farms.

From fattening farm #	To the abattoir
1	205
2	5
3	47
4	44
5	41
6	40
7	35
8	45

TABLE 6.7: Distances from fattening farms to the abattoir.

A TWO-STAGE STOCHASTIC MODEL FOR PLANNING TACTICAL DECISIONS IN THE PIG PRODUCTION PROCESS.

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Submitted to European Journal of Operational Research.

Abstract: This paper focuses in the pig production process based in a three-site structure with the aim to deal with the tactical decisions for increasing the capabilities of the system and the overall production based on the fluctuations and uncertainty of future sales price. This is, helping managers with the decisions of purchasing additional piglets and renting farms for increasing the system capacity. We propose a two-stage stochastic model with sales price as stochastic parameter and in a finite time horizon. The model maximizes the benefit of the system by considering the piglet production in sow farms and the flow and transportation of animals throughout the entire production process. In the case of fattening farms, the all-in-all-out management (AIAO) and a marketing window for selling the pigs to the abattoir are also modelled. The model is solved by reproducing a small-size company based in Catalonia (Spain) and it is able to maximize the use of the current farms capacity by purchasing piglets in the finite time horizon specified. Additionally, the model identifies bottle-necks in the system and proposes a renting strategy of farms according to the overall system behavior. We also compare the value of the stochastic solution versus the deterministic concluding the stochastic version provides better results. The paper fulfills the need of modelling the overall pig production system and contributes to help in the tactical decisions taking into consideration all the agents in the pig production system.

Keywords: *Operations planning; Operations strategy; Pig production; Stochastic model; Pig supply chain.*

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7.1 INTRODUCTION

The Spanish pig sector experienced an organizational change in the last years. Pig producers and other agents such as abattoirs, feed mils, meat processors and transportation companies are organized under the direction of one enterprise or cooperative (the so-called integrator) forming a Pig Supply Chain (PSC) [82]. In a PSC, the agents are integrated and coordinated by using vertical linkages with the aim to increase its efficiency. In the case of the pig production process, which is also included in the PSC, also experienced organizational changes. The pig production process is divided into three phases (maternity, rearing, and fattening) and appears the farm's specialization.

At this point, integrators, with the whole vision of the chain, and PSC managers take decisions not only affecting individual agents but the entire PSC. Those structures have brought benefits as previous researchers stated [84]. Despite it, the decision-making process increases in complexity because of the number and the coordination between of all agents involved [56].

In this paper, we focus on tactical decisions to maximize the efficiency and to add flexibility to the entire pig production process which is a key to ensuring competitiveness in the organizations [58]. Under the herd management perspective, PSC's managers analyze the pig production system with the aim to balance the productive capabilities. In Spain, the pig production system is a *'push'* system [14]. In other words, the production is determined by the pig producers' plan and capabilities instead the abattoir's demand. Based on that, managers might balance the pig production according to the expected sales price which impact in the margins, where the competitiveness between integrators made those margins to diminish as some authors also stated [46]. Despite the pig sales price presents seasonability, it presents uncertainty, and it is accentuated because the pig production life cycle is large (between 34 and 36 weeks since a sow is inseminated until the pigs are sold to the abattoir). Additionally, balancing the production implies that housing capacities in the following production phases need to be adapted according to the expected production and more specifically when the production increases. Those decisions, are often taken without any analytic tool despite being complex and presenting a high impact on the whole system.

In Operations Management and more precisely in Optimization, the pig sector was widely studied from a herd management perspective, but most of the papers were developed to solve specific problems in individual farm operations [95]. For instance, the problem of sows' replacement was studied in [48–52, 56] and papers concerning to pig deliveries to the abattoir was also found in [15, 39–42, 44, 46, 54, 101]. Other papers can be found in the literature taking into consideration two or more agents in the PSC [41, 55, 56]. However, balancing the pig production making the system more flexible requires more coordination of the pig production process. In other words, papers having the complete inventory / age from the maternity phase until the pigs are sent to the abattoir are scarce in the literature. In [101] developed a model taking into consideration the three production phases with functionalities that are present in the pig production process such as marketing window, batches management, and transportation schedules. The study focused on the operational and tactical decisions but does not include the problem stated above.

In this paper, we propose to extend the model in [101] by adding the functionalities needed for balancing the production by the purchases of new piglets and consequently managing farm's capacities when those reach their limit by renting farms in the rearing and fattening farms.

We propose a two-stage stochastic model having the sales price as a stochastic parameter. Dantzig, in [102], introduced stochastic programming (SP). Since then, SP has been widely used in real problems such as business, finance and production planning. A recent review concluded SP is one of the most used techniques for dealing in planning problems [18, 103].

Hence, the main objectives of this paper are: 1) to analyze the impact of a stochastic sale prices in the decision process, 2) to evaluate and to explore the alternatives of the system in order to increase or maximize the profits, making the PSC more agile and adaptable to uncertainty in which other authors stated is key for being competitive [59–61], and 3) to highlight the complexity of the system in terms of performance when executed with different farms' configuration.

The paper is organized as follows: in Section 2, a detailed description of the pig production process considered in this paper is presented. Section 3 presents the resulting model. Section 4 analyzes the results of the model based on a case study. Finally, the main conclusions and future work are outlined in section 5.

7.2 THE PIG PRODUCTION SYSTEM PROCESS

The pig production process studied in this paper is composed of three phases (Fig. 7.1). The first phase (Maternity) aims to produce piglets. The piglets' production might vary depending biological factors and the sow's productive rates but are quite stable. Once the pigs are produced, they stay in sow farms during certain weeks until they are weaned. Then, the piglets are transferred to the rearing phase for a certain number of weeks which is the growing stage until the piglets are ready to be transferred to the fattening phase. This last phase aims to fatten the pigs until they reach a marketable weight until they are sold to the abattoir.

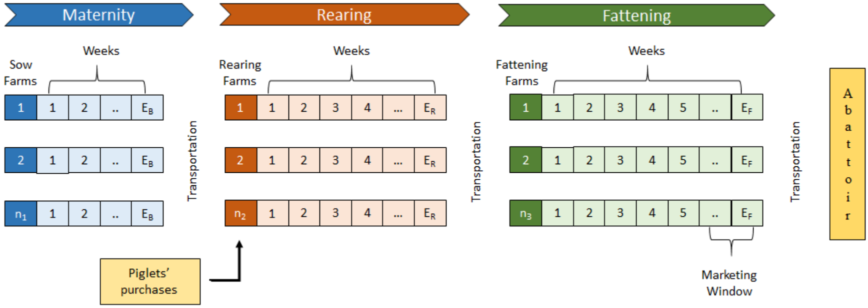

FIGURE 7.1: Pig production process structure

Some essential characteristics of the pig production process studied in this paper are based especially in fattening phase which the use of the all-in-all-out management (AIAO) adds essential constraints in the herd management. Under AIAO management, a fattening unit is not filled until all pigs are not sold to the abattoir. AIAO management is one of the best practices in preventing the spread of illness and disease [15]. Additionally, because of pig's growth is not homogeneous, a marketing window exists in fattening farms which allows sending pigs in different weeks of the fattening phase. Finally, because of the specialization of farms in a three-site system, animals transfers need to the done from farm to farm and farm to the abattoir by using trucks.

For a more detailed description of the pig production process studied see [101].

The pig production process is a '*push*' process [14]. In other words, the decision of producing the products, in this case, pigs, are taken according to the production plan and not to the expected demand of the products (in which it would involve a '*pull*' process). While the pig production process life-cycle is large (between 34 and 36 weeks since the piglets are produced until they are sold to the abattoir), meat processors' satisfies its fresh meat demand in a few or even at a daily basis according to the customers' needs who ask for products. Usually there is no communication in terms of demand between the market and farmers. Once meat plants satisfy its demand, they decide about the rest of products to be produced. Hence supply cannot be constrained by the demand and for this reason, abattoirs set or either a minimum quota or no quota to the farmers accepting as many pigs as possible.

The selling price for the fattened pigs is often based on a reference price agreed weekly by buyers/sellers (producers/abattoirs) in auction markets, like Mercolleida in Spain. Abattoirs also implement additional discounts or premiums for leanness or backfat thickness and carcass weight that represent market preferences within the EU. Carcass classification is mandatory in EU abattoirs according to the Regulation (EEC) No. 1208. It is the so-called SEUROP classification system used to fix the reward system by each abattoir.

Concerning tactical decisions which this paper accounts to, managers have two different options for increasing the production. First, the acquisition of new sows, which is the cheaper option in economic terms, might entail capacities constraints in sow farms which are the more expensive because of the processes included there. Second, the purchase of new piglets, which are incorporated in the rearing or fattening phase, allows companies to have more flexibility to face with prices fluctuations and decreases the lead time to the abattoir. This option also reduces the risk of a long term and expensive investment such as building new sow farms.

By increasing the production might also lead in capacity constraints in the production process and more specifically in rearing or fattening farms. Managers, then, have the option of building or renting farms. In that case, the alternative preferred for rapidly bring income is to rent farms via a contract with owners. Usually, those contracts are made at least on a yearly basis and might have a fixed fee amount plus a variable amount per piglet included in the farm.

7.3 THE TWO-STAGE STOCHASTIC MODEL

The proposed two-stage stochastic linear model, which focuses on piglets' purchases to increase the production taking into account that rearing and fattening farms can be rented, is an extension of the deterministic linear model by [104]. The formulation follows the Deterministic Equivalent Model (DEM) proposed in [64] and [105]. In the current approach, the uncertain parameters are the future sale prices. Uncertainty is represented in the model

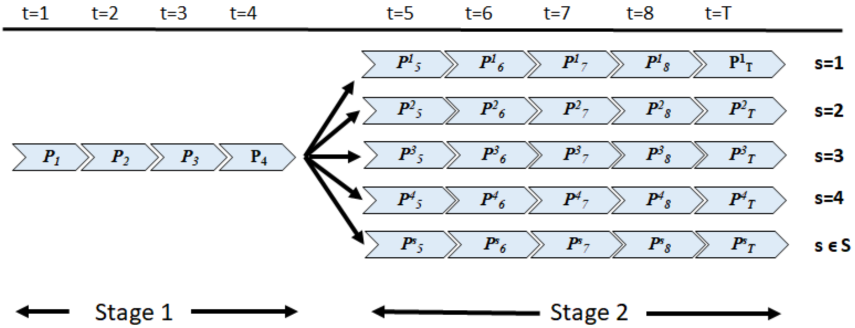

FIGURE 7.2: Scenarios of the two-stage stochastic model

by a set of possible scenarios $\mathcal{C}$, with corresponding probabilities W_c. The flexibility of these models is related to their multiperiod nature (Figure 7.2), i.e., besides the first stage variables that represent decisions made in face of uncertainty, the model considers second stage decisions, i.e., recourse actions, which can be taken once a specific realization of the random parameters is observed. Hence, the decisions at the first stage (St1) are the same for all scenarios while the remaining decision variables are dependent on the corresponding scenario, $c \in \mathcal{C}$. In our case, they represent the total purchases of piglets. Decisions related to renting an additional rearing and / or fattening farm are solely first-stage decisions (they are not dependent on the scenarios) and the decision made will remain throughout the entire time horizon.

Below we present the formulation of the two-stochastic model in detail:

Indexes and sets

$t \in \mathcal{T},$ time horizon (in weeks), $t = 1, \ldots, \mathcal{T}$.

$T_1 \subset \mathcal{T},$ a subset of $\mathcal{T}$ corresponding to the periods of the first stage.

$c \in \mathcal{C},$ finite set of scenarios, $c = 1, \ldots, \mathcal{C}$.

$h \in \mathcal{H},$ farms belonging the PSC, $h = 1, \ldots, H$. $\mathcal{H} = \mathcal{H}_B \cup \mathcal{H}_R \cup \mathcal{H}_F$: Disjoint partition of farms in three phases (sites), $\mathcal{H}_B$ being the set of sow farms, $\mathcal{H}_R$ the set of rearing farms and $\mathcal{H}_F$ the set of fattening farms.

$e \in \mathcal{E},$ Growing period in weeks, $e = 1, \ldots, E$. Set $\mathcal{E}$ represents the productive cycle in weeks of a commercial pig from farrowing to the slaughtering. $\mathcal{E} = \mathcal{E}_B \cup \mathcal{E}_R \cup \mathcal{E}_F$: Disjoint partition of the productive cycle in each phase, i.e. weeks spent by pigs in different facilities, being $\mathcal{E}_B = \{1, \ldots, E_B\}$ the set of weeks corresponding to the lactation period (from birth to the weaning of piglets), $\mathcal{E}_R = \{E_B + 1, \ldots, E_R\}$ set of weeks corresponding to the rearing period (from weaning to the beginning of the fattening) and $\mathcal{E}_F = \{E_R + 1, \ldots, E_F\}$ set of weeks corresponding to the fattening period.

$\mathcal{E}_F^W \subseteq \mathcal{E}_F$ Marketing time window weeks, $e = W, \ldots, \mathcal{E}_F$, at the end of the fattening period where the pigs can be delivered to the abattoir.

$s \in S,$ physiological state of a sow, $s = 1, \ldots ..., S$.

Parameters

$P_{c,t,e}$ expected price of a pig of age $e \in \mathcal{E}$ at period $t \in \mathcal{T}$ at the scenario $c \in \mathcal{C}$. This price is estimated taking into account a distribution of weight and lean percentage for pigs produced in [43] and different carcass qualities (lean content and carcass weight) for the pigs sent to the abattoir.

W_c weight of the scenario $c \in \mathcal{C}$ where $\sum W_c = 1$

$IN_{h,e},$ initial inventory of pigs of age $e \in \mathcal{E}$ in the farm $h \in \mathcal{H}$.

$K_h,$ housing capacity of farm $h \in \mathcal{H}$.

$LS_{h,t},$ litter size at farrowing in sow farm $h \in \mathcal{H}_B$ per week $t \in \mathcal{T}$.

$CP_{t,h,e},$ unitary cost per week $t \in \mathcal{T}$ at farm $h \in \mathcal{H}$ and age $e \in \mathcal{E}$ per piglet (including feeding, medicines, medical care, amortization of sows and associated indirect costs).

$CT,$ unit transport cost per kilometre and per truck.

RR, fixed cost in Euros for renting a rearing farm.

RF, fixed cost in Euros for renting a fattening farm.

$D_{h,h'},$ distance from farm $h \in \mathcal{H}$ to farm $h' \in \mathcal{H}$.

$D_h^A,$ distance from farm $h \in \mathcal{H}$ to the abattoir.

$KN_h,$ capacity, given in terms of number of animals transported, for trucks departing from farm $h \in \mathcal{H}_B \cup \mathcal{H}_R$ to another farm.

KP_h, capacity, given in terms of number of animals transported, for trucks departing from farm $h \in \mathcal{H}_F$ to the abattoir.

$SF_{h,e}$, survival factor for pigs of age $e \in \mathcal{E}$, estimated as the average proportion of pigs surviving at farm $h \in \mathcal{H}$ from one week to the next. Note: this factor depends on h to incorporate different elements, such as the type of farm, location, etc.

β_t, discount factor at week $t \in \mathcal{T}$ to account for the time value of money.

Decision variables not dependant on the scenarios

$z_{c,t,h,s}$, integer variable used for the inventory of sows at the physiological state $s \in \mathcal{S}$ and farm $h \in \mathcal{H}_B$ at week $t \in \mathcal{T}$ and at the scenario $c \in \mathcal{C}$.

$y_{c,t,h,e}$, integer variable used for the inventory of pigs of age $e \in \mathcal{E}_h$ at (the end of) week $t \in \mathcal{T}$ on the farm $h \in \mathcal{H}$ and at the scenario $c \in \mathcal{C}$.

Decision variables dependant on the scenarios

$u^B_{c,t,h,h'}$, integer variable used for the inventory of piglets at week $t \in \mathcal{T}$ transferred from farm $h \in \mathcal{H}_B$ to farm $h' \in \mathcal{H}_R$ and at the scenario $c \in \mathcal{C}$.

$u^R_{c,t,h,h'}$, integer variable used for the inventory of reared pigs at week $t \in \mathcal{T}$ transferred from farm $h \in \mathcal{H}_R$ to farm $h' \in \mathcal{H}_F$ and at the scenario $c \in \mathcal{C}$.

$u^F_{c,t,h,e}$, integer variable used for the inventory of pigs at age $e \in \mathcal{E}^W_F \subseteq \mathcal{E}_F$ transferred from farm $h \in \mathcal{H}_F$ to the abattoir at week $t \in \mathcal{T}$ and at the scenario $c \in \mathcal{C}$.

$n^A_{c,t,h}$, integer variable to control the number of trips at week $t \in \mathcal{T}$ to transport animals leaving the farm $h \in \mathcal{H}_F$ to the abattoir and at the scenario $c \in \mathcal{C}$.

$n_{c,t,h,h'}$, integer variable to control the number of trips at week $t \in \mathcal{T}$ to transport piglets from phase to phase being $h \in \mathcal{H}_B$ and $h' \in \mathcal{H}_R$, or $h \in \mathcal{H}_R$ and $h' \in \mathcal{H}_F$ and at the scenario $c \in \mathcal{C}$.

$\lambda^1_{c,t,h}$, binary variable used for batch control (AIAO), being $\lambda^1_{c,t,h} = 1$ when farm $h \in \mathcal{H}_F$ has pigs of age $e = \mathcal{E}_r + 1$, and $\lambda^1_{c,t,h} = 0$ otherwise.

$\lambda^{2}_{c,t,h}$, binary variable used for batch control (AIAO), being $\lambda^{2}_{c,t,h} = 1$ when farm $h \in \mathcal{H}_F$ has pigs of age $e \in \mathcal{E}_F \setminus \{\mathcal{E}_R + 1\}$, and $\lambda^{2}_{c,t,h} = 0$ otherwise.

ν_1 , binary variable used for stating the need to rent a rearing farm being $\nu_1 = 1$ when the farm is rented.

ν_2 , binary variable used for stating the need to rent a fattening farm being $\nu_2 = 1$ when the farm is rented.

Objective function

The objective function (7.1) represents the expected total discounted benefit in Euros over for all scenarios $c \in \mathcal{C}$ and the time horizon $t \in \mathcal{T}$ to be maximized.

$$\begin{aligned}
RP = \max & -(RR\nu_1 + RF\nu_2) + \\
& \sum_{c \in \mathcal{C}} W_c \Bigg[\sum_{t \in \mathcal{T}} \beta_t \Bigg[\sum_{h \in \mathcal{H}_F} \sum_{e \in \mathcal{E}_F^W} P_{c,t,e} u^F_{c,t,h,e} - \Bigg(\sum_{h \in \mathcal{H}} \sum_{e \in \mathcal{E}} CP_{t,h,e}\, y_{c,t,h,e} + \\
& CT \Bigg(\sum_{h \in \mathcal{H}_B} \sum_{h' \in \mathcal{H}_R} D_{h,h'} n_{c,t,h,h'} + \sum_{h \in \mathcal{H}_R} \sum_{h' \in \mathcal{H}_F} D_{h,h'} n_{c,t,h,h'} + \\
& \sum_{h \in \mathcal{H}_F} D_{h,a} n^A_{c,t,h} \Bigg) \Bigg) \Bigg] + \beta_T \sum_{h \in \mathcal{H}} \sum_{e \in \mathcal{E}} P_{c,T,e} y_{c,T,h,e} \Bigg] \qquad (7.1)
\end{aligned}$$

The objective function maximizes the expected benefit given by the income produced by the pigs from the fattening farms, which are weekly transferred to the abattoir and deducting the costs associated. It should be noted that fattening farms are only allowed to deliver pigs to the abattoir during a marketing window, once enough pigs on the farm have reached marketable weight. The cost takes into account three items: 1) Renting a rearing and/or a fattening farm which is determined by the binary variables ν_1 and ν_2, 2) The stocking cost which is calculated taking into consideration the number of pigs on each farm and their age. 3) The transportation cost which is calculated per phase with the unitary cost of transportation in Euros per km, the number of trips needed to transport the animals (between farms or to the abattoir) and the distance between origin and destination. Finally, to depict the activity of the system beyond the end of the time horizon considered, the inventory on the farms at the end of the time horizon is valued economically.

Constraints of the model

Initial inventory: Constraint (7.2) fixes the initial inventory $\mathbb{IN}_{h,e}$ at the beginning of the planning horizon.

$$y_{c,0,h,e} = \mathbb{IN}_{h,e} \quad \forall h \in \mathcal{H}, e \in \mathcal{E}, c \in \mathcal{C} \tag{7.2}$$

Piglets' production: Constraint (7.3) represents the piglets' production in the sow farms based in the number of sows $z_{c,t,h,s}$ and the littler size LS. Note that purchases of piglets are modelled by using a virtual farm represented by $\mathcal{H}_B\{1\}$ and allows flexiblity as it is modelled in (7.4).

$$y_{c,t,h,1} = \sum_{s \in \mathcal{S}} LS_{t,h}\, \mathbb{IN}^S_h \quad \forall h \in \mathcal{H}_B \setminus \{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.3}$$

$$y_{c,t,h,1} \leq \sum_{s \in \mathcal{S}} LS_{t,h}\, \mathbb{IN}^S_h \quad \forall h \in \mathcal{H}_B\{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.4}$$

Farms'capacities and farms' renting: We assume that that the sows farms have enough capacity for hosting the piglet's which is determined by the number of sows in each farm. Capacities in the rearing farms are represented by constraints (7.5) and (7.6). Constraint (7.5) represents the farms included in the system which each farm h has a capacity K_h while capacity of rented farm is modelled in constraint (7.6) by adding a virtual farm in the system. In this case, it corresponds to the first farm in the set $\mathcal{H}_R$. Then this virtual farm have its own capacity and distances from sow farms and to fattening farms which are necessary for estimating the transportation costs. The first stage decision v_1 determines the use or not of this farm for all the weeks t included in the time horizon $\mathcal{T}$.

Fattening farms capacities' are modelled in constraints (7.7)-(7.10) similarly to the rearing farms. In other words, constraint (7.7) models the fattening virtual farm being v_2 the first-stage decision to rent or not the farm. Constraints (7.8)-(7.10) limit the capacity in fattening farms included in the system. While the virtual is modelled to be filled in a continuous mode assuming the virtual farm might correspond to one or more facilities, the fatening farms included in the system represented by $\mathcal{H}_F\{1\}$ are filled under using batches (AIAO) in the constraints (7.8)-(7.10).

$$\sum_{e \in \mathcal{E}_R} y_{c,t,h,e} \leq K_h \quad \forall h \in \mathcal{H}_R \setminus \{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.5}$$

$$\sum_{e \in \mathcal{E}_R} y_{c,t,h,e} \leq v_1 K_h \quad \forall h \in \mathcal{H}_R\{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.6}$$

$$\sum_{e \in \mathcal{E}_F} y_{c,t,h,e} \leq v_2 K_h \quad \forall h \in \mathcal{H}_F\{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.7}$$

$$y_{c,t,h,E_R+1} \leq K_h \lambda^1_{c,t,h} \quad \forall h \in \mathcal{H}_F \setminus \{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.8}$$

$$\sum_{e \in \mathcal{E}_F : e > E_R+1} y_{c,t,h,e} \leq K_h \lambda^2_{c,t,h} \quad \forall h \in \mathcal{H}_F \setminus \{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.9}$$

$$\lambda^1_{c,t,h} + \lambda^2_{c,t,h} \leq 1 \quad \forall h \in \mathcal{H}_F \setminus \{1\}, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.10}$$

Growth of animals and transfers between farms: We assume that all pigs are fed under the same regime and grow accordingly to their age. Therefore, the inventory reflects this changing situation over the time horizon considered and has to be updated weekly. Inventory constraints (7.11)-(7.14) are stated for each farm and phase. Later on, after completing the expected growth for the phase, they are all taken out at the same time. Constraints (7.15) and (7.16) states that piglets sent to the rearing and fattening farms cannot exceed the total number of piglets weaned and pigs finishing the rearing phase respectively. Piglets transferred between farms continue the growing process in a new phase, on a new farm according to constraints (7.17)-(7.18).

$$y_{c,t,h,e+1} = \mathit{SF}_{h,e}\, y_{c,t-1,h,e} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T}, e \in \mathcal{E}_B : e < E_B, c \in \mathcal{C} \tag{7.11}$$

$$y_{c,t,h,e+1} = \mathit{SF}_{h,e}\, y_{c,t-1,h,e} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T}, e \in \mathcal{E}_R : e < E_R, c \in \mathcal{C} \tag{7.12}$$

$$y_{c,t,h,e+1} = \mathit{SF}_{h,e}\, y_{c,t-1,h,e} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T}, e \in \mathcal{E}_F \setminus \mathcal{E}^W_F, c \in \mathcal{C} \tag{7.13}$$

$$y_{c,t,h,e+1} + u^F_{t,h,e} = \mathit{SF}_{c,h,e}\, y_{c,t-1,h,e} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T}, e \in \mathcal{E}^W_F : e < E_F, c \in \mathcal{C} \tag{7.14}$$

$$\sum_{h' \in \mathcal{H}_R} u^B_{c,t,h,h'} = y_{c,t,h,E_B} \quad \forall h \in \mathcal{H}_B, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.15}$$

$$\sum_{h' \in \mathcal{H}_F} u^R_{c,t,h,h'} = y_{c,t,h,E_R} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.16}$$

$$y_{c,t,h,E_B+1} = \sum_{h' \in \mathcal{H}_B} u^B_{c,t-1,h',h} \quad \forall h \in \mathcal{H}_R, t \in \mathcal{T} \notin \mathcal{T}_1, c \in \mathcal{C} \tag{7.17}$$

$$y_{c,t,h,E_R+1} = \sum_{h' \in \mathcal{H}_R} u^R_{c,t-1,h',h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T} : t > 1 \tag{7.18}$$

Transportation constraints: Constraints (7.20)-(7.22) compute the number of trips necessary to transport the animals, according to the capacity of each truck. Constraints (7.20)-(7.21) compute the number of trips needed to transport the piglets between the farms while constraint (7.22) compute the number of trips from fattening farms to the abattoir.

$$ \tag{7.19} $$

$$u^{B}_{c,t,h,h'} \leq KN_h \, n_{c,t,h,h'} \quad \forall h \in \mathcal{H}_B, h' \in \mathcal{H}_R, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.20}$$

$$u^{R}_{c,t,h,h'} \leq KN_h \, n_{c,t,h,h'} \quad \forall h \in \mathcal{H}_R, h' \in \mathcal{H}_F, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.21}$$

$$\sum_{e \in \mathcal{E}_F} u^{F}_{c,t,h,e} \leq KP_h \, n^{A}_{c,t,h} \quad \forall h \in \mathcal{H}_F, t \in \mathcal{T}, c \in \mathcal{C} \tag{7.22}$$

Non-anticipativity constraints: Constraint (7.23) refer to the non-anticipativity constraints and corresponds to the first stage piglets' purchases with $t \in \mathcal{T}_1$

$$y_{c,t,h,e} = y_{1,t,h,e} \quad \forall e \in \mathcal{E}_h, h \in \mathcal{H}, t \in \mathcal{T}_1, c \in \mathcal{C} \tag{7.23}$$

7.4 CASE STUDY

7.4.1 *Data and scenario generation*

To illustrate the suitability of the model (7.1)–(7.23) a case study is presented representing a small-medium size company based in Catalonia (Spain) with a total of 30 farms. The structure of farms is composed by 2 sow farms, 4 rearing farms, and 24 fattening farms. The pigs stay on the sow farms for four weeks, six weeks in rearing farms and a maximum of 18 weeks on fattening farms to complete the fattening process. The model assumes that the sow farms operate under a steady state in which the herd structure is in equilibrium. Accordingly, piglet production is derived from the number of weekly farrowing. The productivity of the sows is between 24 and 28 piglets per sow and per year depending on the farm. For simplicity, the survival rate SF is set to 1 in all the phases of the production process. The total weekly production in sow farms is of 775 piglets and capacities for rearing and fattening farms are 6,900 and 22,406 animals respectively. The model is set up for purchasing additional piglets with a limit of 10.000 piglets per week. The limit is big enough to impact as least as possible by the system capabilities. Delivery lead time for purchased pigs is set to 4 weeks. That is the number of weeks needed since the order is done until the piglets reach the rearing farms. The averaged weekly cost per sow is set at 4.85 Euros and includes feeding, insemination, medicines, medical care, purchase amortization, and other related costs. This cost is incurred per pig as a variable and productive cost in the first stage of the production process where the sow farms are involved. The weekly cost of producing piglets is set at 2.06 Euros per piglet, while the total cost for purchasing a piglet is 22.50 Euros (according to the main auction market Mercolleida on Sep 27th 2018). Rearing and fattening pigs costs are set to 2.92 and 4.82 Euros respectively. Pigs exceeding the capacity of the system and therefore hosted in rented rearing or fattening farms has a variable cost increased by a 30%. This is 3.8 and 6.26 Euros respectively. The fixed cost for renting a farm is set to 10.000 Euros yearly and assuming it is under a year contract. The marketing time window on the fattening farms ranged from week 15 to 18 of the fattening period being 100, 104.8, 109.1 and 112.8 kg the average live weight of the pigs respectively.

Regarding transportation, the capacity that one single truck can transport in terms of piglets up to 30 kg is 700. A maximum capacity of 240 pigs is set from the fattening farms to the abattoir. The unitary transportation cost is fixed at 1 Euro/km for all the production process.

To prepare the extension of the model, a total of 27 scenarios are formulated. Sales price are taken from the historical data for 2015 published by Mercolleida, the main Spanish pig auction market located in Lleida. No slaughtering penalties or bonuses for lean content and carcass weight are considered. The scenario tree has been built through the Monte Carlo sampling based method in [81] after adjusting a seasonal ARIMA to the Mercolleida pig's price. The data used to adjust the model started in 2003 and the best-fitted model with R is an ARIMA(2,1,1)(1,0,0)$_{52}$. The four first forecasts are the expected price while for the rest of the weeks the scenario is built simulating the responses using the fitted model. The resulting tree is presented in Figure 7.3.

A 32-week time horizon is considered with the aim to ensure the piglets produced or purchased in the four weeks included in the first stage are sold to the abattoir.

7.4.2 *Evaluating the current production capabilities*

The execution of the scenarios separately (table 7.1) showed different approaches reached. It was observed that five out 27 scenarios purchased the maximum number of piglets allowed in the four weeks corresponding to the first stage of the model. On the contrary, only two out 27 scenarios were not suitable to buy piglets. In this context, the strategy of the renting farms was to rent the rearing farms firstly and then, in case it was necessary the fattening farm. This concluded a capacity bottleneck in the rearing farms of

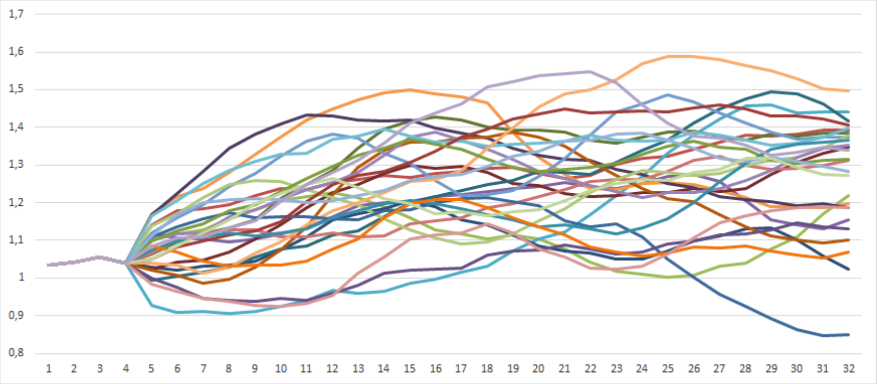

FIGURE 7.3: Sales price (EUR/kg) scenarios used for the experiments

the system. The number of piglets purchased in the first four weeks did not necessarily impact the rented farms but also was dependent on a global picture of each system affected by the sales prices.

After the analysis of the results, the execution of the scenarios separately returned a wide variety of decisions which were not unique for the scenarios although the decision maker is only able to take one single decision. As can be observed, the profit can vary significantly depending on the scenario. Therefore, in the subsection below we analyzed the solution of the stochastic version against the deterministic one.

The execution of the stochastic model presented a total purchase of 4,065 piglets (3,481; 320; 1,049 and 264 respectively) in the four weeks corresponding to the first stage of the model, triggering the action to rent both, the rearing and the fattening farm. Figures 7.4 and 7.5 show the capacity of the current system in rearing and fattening farms with its maximum occupation and the use of the rented farms. In the case of the rearing farms, the model maximized the capacity for all the 27 scenarios; as a result, to execute the stochastic model. At this point, the use of the rented rearing farm was effective in all the scenarios. Figure 7.4 also stated that the use of the rented farm is lower when the average of the sales price is lower.

In the case of fattening farms, figure 7.5 showed the maximum capacity was not achieved for the scenarios with a sales price below 1.16 Euros (i.e. #2,#3,#6, #11, #18, #21, #23, #25), while in other scenarios (i.e. #13,#20,#24,#26, #27) piglets' purchases and consequently the use of the renting farm was only used to make the fattening farms working at full ca-

		Total Purchases	Opening farms	
Scenario #	Profit (k€)	(4 weeks)	Rearing	Fattening
1	1,968	3,562	*yes*	*yes*
2	1,304	264	*yes*	-
3	1,407	9,066	*yes*	*yes*
4	2,331	41,464	*yes*	*yes*
5	1,687	7,185	*yes*	-
6	1,071	1,189	-	-
7	1,743	797	*yes*	*yes*
8	2,029	5,743	*yes*	*yes*
9	1,652	8,652	*yes*	-
10	2,686	41,464	*yes*	*yes*
11	1,355	7,929	*yes*	-
12	2,290	41,464	*yes*	*yes*
13	1,634	7,483	*yes*	*yes*
14	1,841	987	*yes*	*yes*
15	1,831	1,464	*yes*	*yes*
16	2,104	4,138	*yes*	*yes*
17	3,691	41,464	*yes*	*yes*
18	910	0	-	-
19	2,408	41,464	*yes*	*yes*
20	1,838	10,263	*yes*	*yes*
21	1,042	270	-	-
22	1,737	2,448	*yes*	*yes*
23	1,078	0	-	-
24	1,770	10,256	*yes*	*yes*
25	1,176	2,245	-	-
26	1,636	7,948	*yes*	*yes*
27	2,058	20,996	*yes*	*yes*

TABLE 7.1: Purchases and opening farms for the 27 scenarios executed separatelly

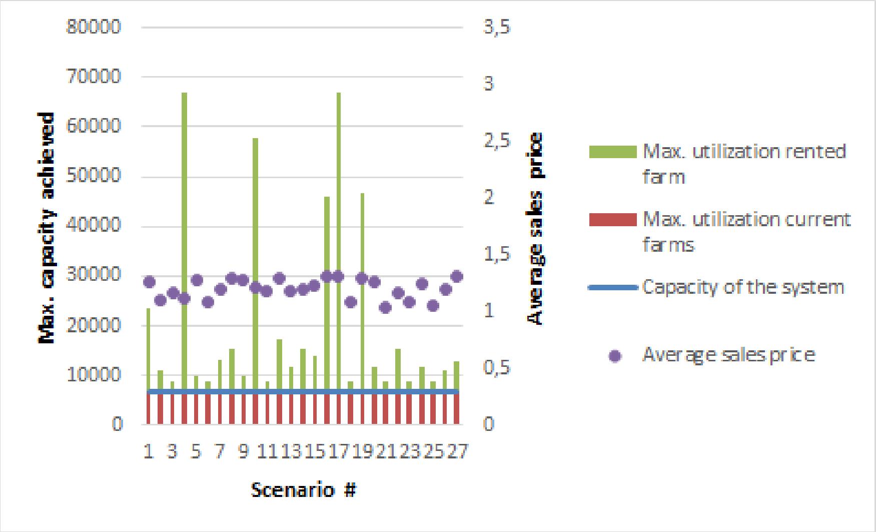

FIGURE 7.4: Current capacities (in blue) and max. occupation achieved vs renting farm per average sales price in rearing farms

pacity. 14 out 27 scenarios used the rented fattening farm for increase the hosting capacities.

7.4.3 *Computational results*

The model was implemented with the IBM ILOG OPL modeling language and solved using CPLEX v12.8 in a Pentium 4 CPU's at 2.1 GHz and 16Gb RAM. Microsoft Excel was used for data storage for both the input and output parameters due to its user-friendliness and flexibility when managing the data and the easy linkage to CPLEX offered by IBM ILOG.

CPLEX was tuned with respect to its default parameters by using [106] and allowing a GAP of 0.5%. This configuration achieved four times reduction of time for smaller instances. Table 7.2 shows the parameter setup in CPLEX for the execution of the model.

The size of the proposed model (7.1)–(7.23) is shown in Table 7.3. The model after 18 hours was solved with a 1.34% GAP.

For evaluating the suitability of the solution of the stochastic model with four weeks in the first stage in a time horizon specified of 32 weeks, we computed the Expected Value of Perfect Information (EVPI). EVPI measures

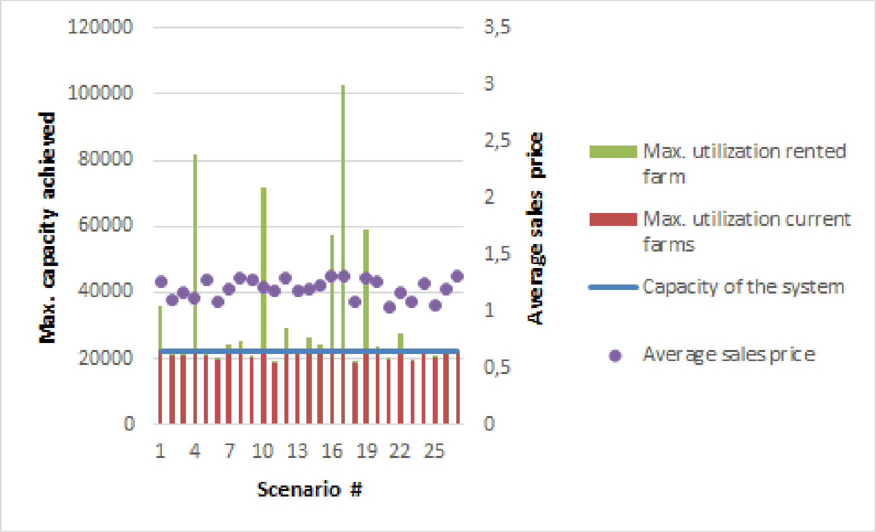

FIGURE 7.5: Current capacities (in blue) and max. occupation achieved vs renting farm per average sales price in fattening farms

Parameter	Value	Description
MIP dive strategy	3	*(Guided dive)*
MIP heuristic frequency	3575	
MIP emphasis switch	4	*(Emphasize finding hidden feasible solutions)*

TABLE 7.2: Set up of parameters in CPLEX

Variables	#
Binary	43,202
Continuous	1,077,435
Constraints	1,172,639
Non-zero coefficients	3,355,467

TABLE 7.3: Size of the model (7.1)–(7.23)

the value of knowing the future with certainty. This is how much the farmer would be ready to pay this year to obtain perfect information about the dynamic behavior of the future sale price. Therefore:

$$EVPI = \sum_{c \in C} p_c \Phi^c - RP \tag{7.24}$$

Being Φ^s the optimal value of the deterministic model when solved separately for each scenario C and being RP the optimal value of the stochastic model. For the study the EVPI = 1,784 - 1,683 = 101k Euros (5.67%).

Later, the Value of the Stochastic Solution (VSS) was also computed. VSS accounts for the advantage of using a stochastic model instead of a deterministic one using the average scenario. Then, the Value of the Stochastic Solution is defined as VSS=RP-EEV, where EEV is the expected value fixing the optimal values at the first stage as a result of the execution of the model using averaged prices. Therefore VSS = 1,683 - 1,598 = 85k Euros (5.05%).

Additionally, and with the aim to prove the practical value of the stochastic solution, an additional experiment was done using 500 scenarios generated by the same procedure than before. Three different executions were done. First, the execution of the 500 scenarios using the deterministic version of the model. This solution represented the best solution given by using perfect information. A second execution of the 500 scenarios was done fixing the first stage variables with the values of the result of the model using a single scenario using expected prices (this is the same problem used to compute the EEV). Finally, a third execution of the 500 scenarios was done fixing the first stage variables with the values found using the stochastic program (this solution is that observed with the RP).

Figure 7.6 shows the empirical distributions found for each type of solution of the profit obtained. We observed that with perfect information there are scenarios which lead to significant profits that none of the other solutions can achieve. This is a natural result since the perfect information will always provide the best answer although it is utopic to have the perfect information. When we compared the expected value solution with the stochastic solution, we observed that the average profit did not differ significantly. However, the right tail (which indicates larger profits) was shorter for the expected value solution, reaching at most a profit of 2,900k Euros. On the other hand, the stochastic solution was prepared to react to future scenarios and being able to provide solutions up to 4000k EUR. The flexibility exhibited by the stochastic solution was not at the expenses of risking to have

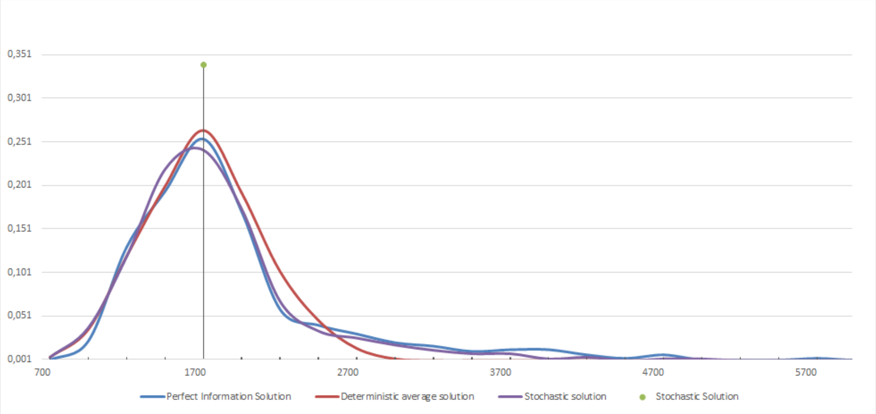

FIGURE 7.6: Density of the profit given the Perfect Information Solution vs the Deterministic solution vs the Stochastic solution

lower profits on the left tail, but it provided a balance with the investments performed and the expected profits.

Moreover, the empirical average expected a profit of the 500 simulated scenarios is 1,720k Euros with a standard deviation of 580k Euros. The value observed of 1,683k Euros as a result of the execution of the stochastic model with 27 scenarios falls with a 95% level of confidence in the average observed in the previous simulation. Therefore 27 scenarios is an appropriate size for the scenario tree.

7.5 CONCLUSIONS AND OUTLOOK

In this paper, we considered a three-phase pig production process system. We stated that there are not many works in Operations Management taking into consideration uncertainty in all the phases of the entire production process and the new decisions derived from this structure.

Therefore, we developed a two-stage stochastic model with the sales price as an uncertain parameter. The model also took into consideration the possibility to purchase piglets and the use of rented farms in the rearing and fattening phases. The model aimed to help managers in the decisions related about how to increase the efficiency of the system by purchasing additional piglets and by increasing the farms' capacities. For testing purposes, we used sample data simulating a small, mid-size company based in Spain.

First, we analyzed the computational results of the two-stage stochastic model (7.1)–(7.23) and showed its computational complexity. We want to highlight the concern to achieve a reasonable computational time because the model's complexity and the amount of data used which might penalize the use of the model for a practical application. Future work directions might lead the use of scenario decomposition methods for improving its performance.

Second, we outlined the capabilities of the model to provide to the SCM's to take the above decisions, stated and demonstrated the importance of those decisions and bearing out its utility. Despite this, the model considered the risk-neutral strategy. This means it didn't consider the impact of the bad scenarios. Therefore, the use of risk-averse strategies might also lead in a future research direction.

Finally, We compared the model with its deterministic version in terms of EVPI, VSS. We concluded that the stochastic version led with more accurate and realistic results than a deterministic version. Additionally, we performed an additional experiment by using 500 scenarios and demonstrated the size of the 27 scenario tree is appropriate.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the CYTED program for supporting the thematic network BigDSSAgro (P515RT0123).

8

GLOBAL DISCUSSION OF RESULTS

This thesis focused on the modeling a three-site production system under a PSC perspective bringing support to solve complex decision-making challenges. The PSC structure corresponds to the modern Spanish pig sector which brings efficiency and competitiveness to the organizations, but at the same time, it is a complex structure because of the grade of the vertical integration between agents.

The thesis reviewed the differences between the Spanish PSC and other structures found in the literature. Depending on the vertical integration degree, the degree of cooperation between agents or the influence between one agent and to the others, each structure might require different decision-making tools.

As a consequence of the literature review, new gaps, concerns and/or challenges were detected under the Spanish PSC structure. All of them were related to the production process such as production planning, coordination, and design planning as well as sustainability which became the objectives of the thesis.

The environmental impact, one of the objectives of this thesis, is currently considered a significant issue in the pig sector. In literature, it was concluded that maternity and fattening are the phases where most of the GHG emissions are generated, being the fattening phase the higher concentration of GHG emissions [23].

This thesis presented then, a multi-objective model to explore the trade-off between CO_2 emissions and profit in deliveries to the abattoir. The model contributed as a novel approach to explore the impact of CO_2 emissions under the herd management perspective.

The results stated that the CO_2 emissions caused changes in the delivery policy which reached a decrease of a 26.68% in profit in favor of a reduction of a 13.31% in CO_2 (cf. **Chapter 3**). The results presented entailed delivering the pigs as soon as possible, and the effort to be done in terms of profit was higher than the compensation in terms of reduction of the emissions. Results stated that by decreasing profits by a 4.48% a reduction of the CO_2 emissions of a 6.05% was possible. This fact might allow managers to consider a greener chain while looking for alternatives for a return of the investment.

The results obtained in **Chapter 3** suggested that further studies of the GHG emissions should include the complete vision of the pig production process because of the impact between agents.

Additionally, the production planning process, which was one of the objectives of this thesis, required also the coordination between agents and the complete vision of the production process as some authors stated [4, 6]. This work was scarce in the literature where the unique approach which took into consideration the three phases of the production process was [57].

Then the work was focused on the production planning by developing a model based on the theoretical approach in [57] but under a practical perspective which needed of significant characteristics of the pig production process such as transfers between farms, AIAO management, a marketing window, and survival factor.

The proposal was in **Chapter 4** by incorporating transportation of animals between farms explicitly. The model provided a weekly pig transfer schedule between all the phases of the production process including the number of trips necessary and under the time horizon defined. The model tended to approximate the animals to the abattoir or where the concentration of farms of the same phase was higher according to each farms' capacity and occupancy under the time horizon defined.

The model was applied to a Spanish company and considered helpful in the decision making process in decisions related to the animals' transfers, planning and scheduling the trucks and evaluating the capacities of each farm, phase or the entire system.

The results of the model indicated new improvements such as the inclusion of AIAO management, a marketing window and the evaluation of stochastic parameters like demand and sales price.

Chapter 5 presented a MILP model incorporating AIAO management, a marketing window and the survival factor as the main characteristics. The model contributed by providing schedules of batches and deliveries of pigs to the abattoir under the marketing window specified. The model also contributed to performing evaluations in the system design such as the addition, deletion or transformation of farms (for instance from rearing to fattening farms). Capacities' analysis was also available in the model. For example, results stated that 1,494 additional piglets would be necessary for making the system to work at full capacity being also useful for detecting bottle-neck at a phase level in the production process.

At this point the complexity of modeling such a system was high. Realistic instances involve many agents making the model difficult to solve. However, a size of 162 farms was solved conveniently (2.5 hours with a 0.5 GAP) but a PSC with more than 170 would meet obstacles in practical adoption.

The market showed variation in sales price that are important and suggested the relevance of the sales price as a stochastic parameter. A theoretical approach with the sales price as a stochastic parameter was analyzed in **Chapter 6**. The sensitivity analysis showed that, when the sales price's variations were analyzed globally, it impacted only in the benefit. However, when analyzed farms' capacities, the occupation varied significantly between them. Changes in the individual farm's occupation were motivated by the changes in the deliveries schedule on fattening farms that, at the same time, impacted the entire system in terms of production planning.

On the other hand, the model gave the opportunity also to analyze the time horizon to see how it impacted in terms of results and performance as it was pointed out in **Chapter 4** and **5**. The execution of the model in different time horizon (78, 104, 130, and 156 weeks) shown a very little influence compared with the first 52 week time horizon proposed. Therefore long time horizons which impacted considerably in the performance might not be necessary depending on the kind of decisions to take.

Increasing the efficiency of the pig production process also required the vision of the entire process. At this case, by increasing the efficiency involved having variable pig production and thus the uncertainty of pig sales price impacts significantly in the results. Therefore the models developed in **Chapter 5** and **6** were taken as a basis. The result was a two-stage stochastic model. The model included in its first-stage the decisions for purchasing piglets' in the first four weeks of the time horizon with the aim to increase the productivity and the possibility for renting rearing and fattening farm for balancing the farms' capacities.

The model was executed with a set of 27 scenarios. By executing the scenarios, separately, a wide variety of decisions related to the piglets' purchases and renting farms was stated in which only one decision was allowed. The two-stage stochastic model created presented a purchase schedule in the four weeks included in the first-stage and decisions for renting rearing and fattening farms. Additionally, the analysis performed in with a total of 500 scenarios shown that the initial set of 27 scenarios was appropriate for providing a solution. This statement was related again to the complexity of modeling the pig production process in terms of performance and therefore the practical adoption.

9

GENERAL CONCLUSIONS AND FUTURE DIRECTIONS

The main objective of this thesis was to help in the decision-making process in the pig production process under a PSC perspective by the development of a set of models based on Optimization. As a result of the literature review, the cooperation with other researchers and a company in the pig sector based in Catalonia (Spain) gaps and challenges were detected in the pig production process raising specific objectives that were studied through the chapters of this thesis. Then, this thesis:

- Demonstrated that a wide number of papers were issued so far by utilizing and combining different Optimization methodologies for solving problems in the pig sector.
- Strengthened the work done by previous researchers recalling that integration and coordination are key to being competitive and efficient in the pig sector. For instance, Spanish companies are highly integrated and are one of the leaders in pork production and exportation. However, this thesis concluded that papers in the pig sector integrating two or more agents in the supply chain are scarce.
- Reinforced the current concerns in the pig sector about considering sustainable chains and processes. However, this thesis concluded that even though a wide of studies have been done so far from a sustainable or economic perspective, a gap balancing both of them still exist.
- Concluded there is an opportunity for managers to move the production process, and more specifically the fattening phase, to a greener process.
- Demonstrated that managers could face with uncertainty in the sales price to increase the efficiency of the system.
- Concluded that managers could increase the efficiency in production planning and add flexibility in the system by using the models developed.

- Derived in particular conclusions regarding the practical adoption of the models:
    - **Grade of integration**: Because of the differences and grades of cooperation between agents in the pig production process, it is important to highlight that the models developed in this thesis might not be applicable in companies or cooperatives which are not fully integrated into a PSC structure like the one presented in this thesis.
    - **Standardization of processes and contracts**: Practical adoption of the models by the companies requires processes and contracts well defined and standardized. Exceptions add complexity and might lead in decisions not aligned to the practical situation.
    - **Subject to external agents**: For instance, the model in Chapter 3 might not be applicable until organizations find a return of the investment as a consequence of the reduction of the profit caused by the reduction of GHG emissions or until governmental regulations are issued to empower the reduction of GHG emissions.
    - **Complexity of the models**: The complexity of modeling the three-site production system and the number of agents involved is key for practical adoption.

As a consequence of the realization of this thesis, new research opportunities are detected:

- The constant changes in the sector invite to review constantly the models for adding new capabilities [6]. As an example, some ways to explore are:
    - The impact of other stochastic parameters can be analyzed, for instance, the related to the production, diets and animal welfare.
    - The extension of the models developed, by integrating other agents of the chain, for instance, feed mills.
    - The incorporation of emissions to the whole PSC.
- The models are developed under a risk-neutral strategy. Therefore, the use of risk-averse measures, which has been demonstrated that improve the results versus stochastic models, is a new opportunity of research.

- To reduce the computational effort of the models developed which is key for adoption and further extension of the models. For instance, the use of decomposition techniques like Benders or Lagrange relaxation.
- The adoption of the models for practical use will require the development of friendly and usable Decision Support Systems.

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A

PUBLICATIONS AND OTHER CONTRIBUTIONS

A.1 PUBLICATIONS

A.1.1 *Journal publications*

1. Nadal-Roig, E., Pla, L. & Pla, L. Multiperiod planning tool for multisite pig production systems. *Journal of Animal Science* **92**. ISSN: 15253163 00218812. doi:`10.2527/jas.2014-7784` (2014).
2. Nadal-Roig, E., Pagès-Bernaus, A. & Plà-Aragonès, L. M. Bi-objective optimization model based on profit and CO2 emissions for pig deliveries to the abattoir. *Sustainability (Switzerland)* **10**. ISSN: 20711050. doi:`10.3390/su10061782` (2018).
3. Nadal-Roig, E., Plà-Aragonès, L. M. & Alonso-Ayuso, A. Production planning of supply chains in the pig industry. *Computers and Electronics in Agriculture*. ISSN: 0168-1699. doi:`10.1016/J.COMPAG.2018.08.042` (2018).

A.1.2 *Chapters in books*

1. Nadal-Roig, E. & Plà-Aragonés, L. M. in *Handbook of Operations Research in Agriculture and the Agri-Food Industry* (ed Plà-Aragonés, L. M.) 1 (Springer New York, New York, NY, 2015). ISBN: 978-1-4939-2483-7. doi:`10.1007/978-1-4939-2483-7_1`. `https://doi.org/10.1007/978-1-4939-2483-7_1`.

A.1.3 *Papers under review*

1. Pla-Aragones, L., Pagès-Bernaus, A., Nadal-Roig, E., Mateo-Fornés, J., Tarrafeta, P., Mendioroz, D., Pérez-Cánovas, L. & López-Nogales, S. Economic assessment of pigmeat processing and cutting production by simulation. *Accepted to: International Journal of Food Engineering*.

2. Nadal-Roig, E., Pagès-Bernaus, A., Pla-Aragones, L. M. & Albornoz, V. M. A two-stage stochastic model for planning tactical decisions in the pig production process. *Submitted to: European Journal of Operational Research*.

A.2 CONFERENCES

1. Nadal-Roig, E. & Pla, L. *A mixed integer linear programming model for production planning in the pig industry* in *IN3-HAROSA Workshop, Barcelona, Spain* (2012).
2. Nadal-Roig, E. & Pla, L. *Production planning of supply chains in the pig industry by a mixed integer linear programming model* in *XXXIII Congreso Nacional de Estadística e Investigación Operativa. VII Jornadas de Estadística Pública* (2012).
3. Pla, L. & Nadal-Roig, E. *Optimal planning in a pig supply chain* in *CYTEDHAROSA Workshop. Valparaiso. Chile* (2012).
4. Pla, L. & Nadal-Roig, E. *Production planning in the pig industry by a mixed integer linear programming model* in *25th European Conference on Operational Research. Vilna. Lithuania* (2012).
5. Albornoz, V. M., Pla, L. & Nadal-Roig, E. *Production planning of supply chains in the pig industry by a mixed integer linear programming model* in *2nd Workshop on Food Supply Chain and Wine Supply ChainCouncil Meeting. Valparaíso. Chile* (2013).
6. Nadal-Roig, E., Albornoz, V. M. & Pla, L. . *Optimal production planning by a linear stochastic model for the pig industry* in *26th European Conference on Operation Reserarch (Euro XXVI), Rome, Italy* (2013).
7. Nadal-Roig, E., Pla, L. & Albornoz, V. M. *Multi-stage model for a real instance in a pig Production system* in *20th Conference of the International Federation of Operational Research Societies, Barcelona, Spain.* (2014).
8. Nadal-Roig, E. & Albornoz, V. M. *Two-stage stochastic model for a real instance in a pig production system* in *II Workshop on Optimization Under Uncertainty in Agriculture and Agrifood Industry, Lleida, Spain* (2015).

9. Pla, L., Nadal-Roig, E., Alonso-Ayuso, A. & Albornoz, V. M. *Conditional Value-at-Risk in Stochastic Programs for production planning of pig supply chains.* in *27th European Conference on Operation Research (EURO XXVII), Glasgow, Scotland.* (2015).
10. Nadal-Roig, E. *Empirical analysis of a pig supply chain by a two-stage stochastic program.* in *III Workshop on Optimization Under Uncertainty in Agriculture and Agrifood Industry, Lleida, Spain* (2016).
11. Nadal-Roig, E. & Pla, L. *Planning tool for the multisite pig production system based on stochastic optimization* in *I International Conference on Agro BigData and Decision Support Systems in Agriculture, Montevideo, Urugay* (2017).

A.3 PRE-DOCTORAL STAY

During the realization of this PhD, a stay in the Universidad Técnica Federico Santa María was done. The stay was under the supervision of Prof. Víctor Albornoz, from the Industrial Engineering Department. The stay took place in Santiago de Chile (Chile) between 30-July-2012 and 03-September-2012.

The aim of the stay was to present the problem of the pig production planning process in an integrated system which was presented in Chapter 4. Also, to explore the uncertainty in the pork sales price taking in as an example stochastic models developed by previous researchers.

A.4 AS A LOCAL ORGANIZING COMMITTEE MEMBER

The following corresponds to the participation as a local organizing committee member:

A.4.1 *Congresses and workshops*

1. I Workshop on Optimization Under Uncertainty in Sustainable Agriculture and Agrifood Industry. Lleida (Spain). July 20th to July 23th (2014).

2. II Workshop on Optimization Under Uncertainty in Sustainable Agriculture and Agrifood Industry. Lleida (Spain). July 27th to July 29th (2015).

3. III Workshop on Optimization Under Uncertainty in Sustainable Agriculture and Agrifood Industry. Lleida (Spain). September 5th to September 7th (2016).
4. IV Workshop on Optimization Under Uncertainty in Sustainable Agriculture and Agrifood Industry. Lleida (Spain). September 6th to September 8th (2017).
5. II International Conference on Agro BigData and Decision Support Systems in Agriculture. Lleida (Spain). July 12th to July 14th (2018).

A.4.2 *Summer camps*

1. Euro Summer Institute in OR in Agriculture and Agrifood Industry. Lleida (Spain). July 19th to August 1st (2014).