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Citation for published version:
Rijpkema, WA, Rossi, R & van der Vorst, JGAJ 2012, 'Process redesign for effective use of product quality information in meat chains' International Journal of Logistics Research and Applications, vol 15, no. 6, pp. 389-403., 10.1080/13675567.2012.745840

Digital Object Identifier (DOI):
10.1080/13675567.2012.745840

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Author final version (often known as postprint)

Published In:
International Journal of Logistics Research and Applications

International Journal of Logistics: Research and Applications
Vol. 00, No. 00, Month 2009, 1–23

RESEARCH ARTICLE

Process redesign for effective use of product quality information in meat chains

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ISSN: 1367-5567 print/ISSN 1469-848X online

DOI: 10.1080/1367556YYxxxxxxxx
http://www.informaworld.com

Abstract

To fulfil segmented consumer demand and add value meat processors seek to exploit quality differences in meat products. Availability of product quality information is of key importance for this. We present a case study where an innovative sensor technology that provides estimates of an important meat quality feature is considered. Process design scenarios that differ with respect to sorting complexity, available product quality information, and use of temporary buffers are assessed using a discrete event simulation model. Results indicate that increasing sorting complexity by use of advanced product quality information results in a reduction of processing efficiency. Use of production buffers was found to increase processing flexibility and mitigate negative effects of high sorting complexity. This research illustrates how use of advanced product quality information in logistics decision making affects sorting performance, processing efficiency, and the optimal processing design, an area that has so far received little attention in literature.

Keywords: Product quality information; Food Supply Chains; Manufacturing flexibility; Simulation; Meat

1. Introduction

As witnessed in several recent studies (Akkerman *et al.* 2010, Grunert 2006) there is a growing interest from retail and consumer organizations in high-quality, healthy and convenience food. As a result, demand for product quality features such as colour or taste has become more segmented and product variety has increased substantially. This allows food processors the opportunity to add extra value by adjusting their production strategies to serve segmented demand (Grunert 2006). In order to serve segmented consumers, demand preferences of customer segments must be translated into clear process and production specifications for food processors (Grunert *et al.* 2004, Perez *et al.* 2009). Furthermore, supplied products must be sorted and processed to different customer segments that value specific product quality features most. The flexibility of the supply chain design to sort products to end market demand, of course, must allow the effective exploitation of available product quality information.

Recent developments in ICT and sensing technology have improved the means to gather, communicate and process product quality information (Kumar *et al.* 2009). These innovative technologies allow processing companies to gather and use advanced product quality information in their planning processes (Chen and Tu 2009). It allows food processors to identify products suitable for premium segments, and it offers opportunities for more advanced sorting of food products. Sorting to a larger number of segments will, however, also increase the complexity of product sorting and processing, which might reduce processing efficiency and increase the demand for processing flexibility. A higher sorting complexity might therefore make a more flexible process design favourable, for instance by introducing slack in production by use of buffers (Hallgren and Olhager 2009).

In a literature review on quantitative operations management approaches in food supply chains Akkerman *et al.* (2010) found that use of product quality information in logistics decision making in food supply chains was noted in some research, but remains a challenging research area. We contribute to this field of literature by assessing use of advanced product quality information in product sorting at a meat processor. This paper presents a case study of a large European meat processing company. The company faces variation in quality features of animals delivered to them (e.g. weight, meat leanness), resulting in variation in processing performance and final product quality. We consider the use of an innovative sensor technology to sort for an advanced meat quality feature, the water holding capacity (WHC), that affects sensory appearance and processing characteristics of meat products. The WHC is usually measured by the vapour loss over a period of time, also known as drip loss (Forrest *et al.* 2000). Products with a low or a high drip loss generally cause more problems during processing and consumption, although the magnitude of problems caused by a high or low drip losses depends on the type of end product (O'Neill *et al.* 2003). Until recently there was no low-cost, fast, non-destructive and accurate method to determine WHC under commercial conditions. Recent research has identified an innovative sensor based on near infrared spectroscopy technology (NIRS) as a suitable method to estimate WHC in meat products (Prevolnik *et al.* 2010). A review article on applications of NIRS revealed that this technique is used to assess quality features of a variety of food products (Huang *et al.* 2008). The work by Huang et al. does, however, not discuss the effects of acquiring more product quality information on the sorting performance and complexity. In this case study we therefore assess the use of NIRS-estimates of WHC in sorting for advanced product quality features. Since product quality estimates provided by a sensor comes with estimation errors not all products will be sorted correctly. Henceforth, sorting for advanced product quality information increases sorting complexity, it might therefore make use of an alternative, more flexible, processing layout favourable. A simulation model was developed to test how sorting for advanced product quality information affects sorting performance and processing efficiency. The option to use product sorting buffers was also included to assess how sorting complexity affects performance of systems with or without sorting buffers. Process designs that differ with respect to product sorting complexity, availability of product quality information, and use of these sorting buffers are analysed using this simulation model.

The paper is structured as follows. First, a review of current literature was used to gain insight in topics relevant to this case study (Section 2). This review includes topics such as supply chain flexibility, supply chain redesign strategies, performance measurement, and application of modelling techniques in food supply chains. The literature review is followed by an analysis of the processing chain of the industrial partner, followed by a detailed analysis of the processes we consider in this case study. The findings of this process analysis is given together with process design scenarios and key performance indicators (KPIs) in Section 3. Section 4 discusses the simulation model elements, model inputs, and the simulation instance. The simulation results are given in Section 5, and the discussion and conclusions in Section 6.

2. Theoretical framework

In the last decades there has been much emphasis in industry and academic literature on the reduction of supply chain inefficiencies, which has resulted in a variety of management principles such as just in time (Mackelprang and Nair 2010). This led to the so-called lean paradigm, which considers the expenditure of resources for any goal other than end customer value creation to be wasteful (Shah and Ward 2007). Whereas the focus of the lean paradigm is mainly on eliminating waste, in other supply chains a trend towards responsiveness to fluctuating customer demand and market turbulence is observed, also called supply chain agility (Gunasekaran *et al.* 2008). Which strategy is most effective depends on the supply chain characteristics; in supply chains with primarily functional products with low demand uncertainty the focus should be on efficiency and leanness, whereas for products with unpredictable demand and high levels of product variety a supply chain design with a focus on flexibility and agility is more appropriate (Christopher and Towill 2000).

Flexibility in processing is therefore of key importance for supply chains that face great uncertainty and variability in demand. A variety of redesign principles are available to increase flexibility and responsiveness of supply chain planning and control, such as allowing time and capacity in plans and operations by use of product buffers (Klibi *et al.* 2010). Supply chain flexibility is seen solely as a positive supply chain characteristic in many literature contributions, although there is a limit in the degree to which a supply chain can be flexible whilst meeting demand and operating efficiently (Stevenson and Spring 2007). Decision makers should carefully assess the effect of measures to increase flexibility on profitability and efficiency before investing in them (He *et al.* 2011). For example, when buffering products, capital costs are incurred. Specific food supply chain characteristics (e.g. low level of innovation, mature markets, low levels of added value) make a lean process design favourable. However, other characteristics (e.g. perishability, high demand variability) require food processors to be flexible and responsive in manufacturing. Furthermore many food products have a divergent production process (i.e. the product is disassembled rather than assembled), where more product quality information is available after each processing step. The combination of these specific characteristics makes it difficult for food processors to adopt an either lean or agile process design, and demands food processors to be both efficient and flexible (van der Vorst *et al.* 2001).

Grunert (2006) indicates that food processors may add extra value by serving advanced customer segments. This will increase the complexity that food processors face, and requires them to adopt a more flexible and agile supply chain design. Furthermore a specific focus on use of product quality information in product sorting is necessary. This focus incorporates acquiring product quality information, understanding food systems and consumer preferences, and use of decision support models to improve food quality and product availability throughout the supply chain (van der Vorst *et al.* 2011). An extensive literature review on quantitative operations management approaches and challenges in food distribution by Akkerman *et al.* (2010) concludes that use of product quality information in decision making in food supply chains was seen in some recent work, but that it remains a challenging research area.

From this literature review we conclude that some characteristics of food supply chains require a specific focus on product quality information. Combined with market trends towards segmented consumer markets in food supply chains this leads to the conclusion that food processors need more processing flexibility to satisfy demanding customers and add extra value. New technological developments make it possible to gather and use more product quality information. These changes in markets and technologies might, therefore, lead food processors to redesign their supply chain to increase the variety of products the produce by advanced sorting for product quality.

3. Case description

This section gives an overview of the processing chain that is analysed in this paper. The process analysis is based on a number of visits and interviews with company experts. Setting of KPIs, development of process design scenarios, and intermediary results are discussed with company experts such as operations management staff, production planners, plant managers and quality managers to ensure validity of our findings.

A description of the supply chain under consideration in this case study is given in Section 3.1. Section 3.2 provides a detailed analysis of the processing steps we consider in this case study. Section 3.3 describes the process design scenarios we compare in this study, which are assessed based on performance indicators discussed in Section 3.4.

3.1. *Supply chain description*

We present the processing chain of a large European meat processor owning multiple slaughterhouses and processing locations. This processor buys livestock which are slaughtered, processed, and delivered to retail and wholesale companies. An overview of the consecutive processing steps performed at the slaughterhouse is given in Table 1. In processing steps where the throughput-time is either very short, or the capacity is not limiting in the processing line this is indicated by -. This involves, among others, killing, cleaning, eviscerating, veterinary inspection and carcass grading. During the slaughtering process each animal is converted into two carcasses (i.e. half animals) with measured product quality features (i.e. weight, fat thickness, lean meat ratio, muscular quality, and gender).

After slaughtering carcasses are sorted into separate carcass classes based on the product quality features. Carcass classes are used to create a preliminary match between a group of carcasses and potential end products and markets. Although generic information on carcass quality features does not give a perfect prediction of the product quality of individual carcass parts it is still useful to make a rough match between carcasses classes and end products.

Sorting of carcasses is synchronized with the rate of slaughtering at approximately 1120 carcasses per hour. Sorted carcasses are chilled overnight, after which the carcass classes are transferred class by class to the processing room. Carcass processing starts with the primal cut, which divides the carcass into several main parts. After the primal cut, product quality information of individual parts (e.g. weight, fat thickness) is gathered. Based on the product quality information that is available individual carcass parts are sorted to end product groups. The sorted carcass parts can be either processed directly, or be processed after temporary storage. For temporary storage carcass parts need to be transferred to a storage facility, which involves manual labour. Carcass parts are customized to order specifications by a number of processing steps (e.g. debone, trim fat, remove tail, remove tailbone). These processing steps are performed at a number of processing stations, and involve manual labour. Since the processing steps are highly standardized employees that perform this manual labour can be transferred from one processing station to the next with limited transfer time. If, however, several end product groups are processed simultaneously all processing stations required in production of at least one of the end products groups need to be manned, regardless of the rate at which they are operating.

Insert Table 1 around here.

3.2. *Process analysis*

In this case study we consider sorting and processing of hams. We will therefore focus on a description of the processing chain from carcass cutting to processed hams in the remainder of this section.

Insert Figure 1 around here.

A schematic overview of the ham processing chain is given in Figure 1. The carcass classes slaughtered the day before are chilled and available in the cooling room. Planners combine information on available carcass classes with information on demand for ham products to make a preliminary match between each of the carcass classes and demanded ham products. Each ham originating from a carcass class is currently matched with a limited number (2-4) of end products, based on the expected quality of hams originating from a particular carcass class (e.g. a fat carcass on average yields a fat ham), and the demand for ham products. As an example: a ham originating from carcass classification X may be allocated to ham product A if it has more than 25 mm of fat and a weight above 13 kg. The ham will be allocated to product B if it has between 18 and 25 mm of fat and a weight between 12.8 and 15 kg. If the ham does not fit the specifications of product A or B it will be allocated to product C.

After the preliminary match between carcass class and ham products is made, the carcasses are cut into parts by the primal cut. After the primal cut more detailed quality information of individual carcass parts is gathered (e.g. ham fat thickness, ham weight). Based on the gathered product quality information and the quality specifications of ham product groups matched with that particular carcass class each ham is sorted to an end product.

In the current processing system three ham quality features are measured and used for product sorting, being weight and the fat layer thickness at two places. Other ham quality features related to the quality of meat are difficult to determine under commercial slaughterhouse conditions, and are currently not used for product sorting. These quality features do, however, affect the sensory appearance, shelf life, and processing characteristics of meat products (Rosenvold and Andersen 2003). In this case study we assess the use of NIRS-estimates of WHC in sorting for advanced product quality features.

After a ham is allocated to an end product group it is processed by a number of processing steps that make this ham specific to the order (e.g. remove tail, remove tailbone, trim fat). A ham is processed either directly at the processing stations (multiple ham products will be processed at the same time), or after temporary storage. In case of temporary storage the hams are loaded to special storage hooks, which involves manual labour. After temporary storage the groups of sorted hams are processed group by group (serial processing). In a processing setup without use of buffers multiple ham end products are processed at the same time (parallel processing). Parallel processing of end products might result in a lower processing efficiency, since processing stations might not be used to full capacity. In case processing buffers are used a delay between the start of ham sorting and processing is set by the decision maker. Buffering of hams is undesirable, due to the perishable nature of meat products, where product buffering may reduce the microbiological quality (Raab *et al.* 2008), and it might result in product weight losses due to shrinkage (Huff-Lonergan and Lonergan 2005). The decision maker therefore wants to finish sorting hams of a carcass class before processing of these hams starts, while minimizing the total delay to reduce the meat weight losses. The minimum time between the start of carcass sorting and ham processing is, therefore, determined by the time required to sort all parts within the largest carcass class. After the specific processing steps belonging to the end products have been performed the processed ham products are packed and delivered to end customers. Packing and delivery is outside the scope of this case study.

3.3. *Process redesign scenarios*

Based on the literature review, insight obtained in current practice and the available infrastructure the project team decided to assess process designs that differ with respect to three variables. First of all the designs differ in the number of WHC segments to which products are sorted (i.e. the number of WHC classes used). In the current design there is no sorting for WHC (i.e. 1 segment), in the alternatives we distinguish sorting to 3 and 5 WHC segments. A maximum of 5 segments was chosen since keeping more than 5 flows separated at the same time is too complex in the current infrastructure. Furthermore marketing more than 5 WHC segments is expected to be difficult. The second factor that is varied in the process design scenarios is the availability of product quality information. The information levels we distinguish are i) no WHC-information, ii) WHC estimates with uncertainty, and iii) perfect WHC-information of a particular ham product. Information levels i) and iii) refer respectively to the current situation where no WHC-information is available, and the ideal situation. Information level ii) represents the situation where NIRS-based WHC estimates are used. The third factor that is varied is whether hams are temporarily buffered after sorting, or processed directly. Recall that product buffering will result in product weight losses and an additional labour investment, whereas direct processing involves parallel processing of various end products, which might reduce labour efficiency of processing. A schematic overview of the process design scenarios is found in Figure 2, where the difference between direct processing and the buffered processing strategy can be observed in the upper and lower figure respectively.
Insert Figure 2 around here.

Based upon the three design parameters with 3, 3, and 2 alternatives respectively a total of 18 different process design scenarios can be distinguished. Four process design scenarios are, however, excluded since in case of only 1 quality segment it is not necessary to consider designs that differ in the availability of product quality information. A summary of the remaining 14 process design scenarios can be found in Table 2. To simplify the scenario names a coding is used, in which the first number indicates the number of segments that is sorted to (1, 3, or 5), the second letter indicates the available product quality information (I = irrelevant, N = no information, E = quality estimates, and P = perfect information), and the third letter indicates the processing strategy (B = buffered, N = non-buffered).
Insert Table 2 around here.

In this overview the current way of operating is represented by process design scenario 1IN. In that case no advanced product sorting is used, no advanced product quality information is available, and products are directly processed. The other process design scenarios differ with respect to the sorting complexity (either sorting to 3 or 5 segments), the availability of product quality information, and the use of buffers.

3.4. *Performance measurement*

In collaboration with the industrial partner, and based on common performance indicators found in literature, four KPIs are defined to assess the performance of process design scenarios. These KPIs relate to (i.) labour costs in processing, (ii.) costs of ham buffering, (iii.) order compliance, and (iv.) expected customer claim costs. Customer claim costs, in the form of price discounts, are a common measure in meat supply chains to compensate for deviations to customer specifications. Other common performance indicators in meat chains, such as raw material yield, are influenced at decision levels outside the scope of this research and are omitted from the study.

The first performance indicator, labour costs, is driven by labour consumption at the processing stations during the time that each of the processing stations is manned. Measurements showed that on average 2 labour-minutes are required to open a processing station, and another 5 labour-minutes for closure of a processing station. Average labour costs of € 30,- per hour are assumed, and total labour costs are divided by the total weight of all processed carcass parts to present labour costs in € /ton ham end product. Labour costs related to ham buffering are accounted for in the buffering costs. Labour consumption before product sorting or after processing (e.g. packaging or labelling) is left out of consideration, since this is not affected by differences in process design scenarios.

The second performance indicator, the cost of product buffering, consist of two parts, being the weight losses during the product buffering period, and the labour required for ham buffering. The average weight loss during buffering is approximated at 0.044 % per hour, based on a set of 993 weight loss measurements over a period of 24 hours. The standard error of this average weight loss was 0.001015 %, which is approximately 2.3 % of the average weight loss. By multiplying the average weight loss ratio with an average price of meat products (€ 2.40 per kg) the average costs of weight losses during product buffering is approximated at € 1.06 per ton per hour. The total costs of weight losses during buffering are determined by multiplying the weight of individual hams with their residence time in the buffering room and the approximated costs of weight losses per hour. The labour consumption for loading and unloading of hams in process designs with buffered production is determined by multiplying the number of buffered hams with an average labour consumption of 12 seconds for loading and unloading of a carcass parts. Average labour costs of € 30,- per hour are assumed, and total labour costs are divided by the total weight of processed hams to convert labour costs to € /ton ham products. The sum of weight loss costs and buffer-labour costs are presented as buffering costs.

The sorting performance is evaluated in two ways: (i.) the ratio of products that is incorrectly sorted to an end product group, and (ii.) the expected customer claim costs per ton of product. The first rate is determined by checking the rate of products that do not fulfil the requirements of the end product group it is assigned to. We assume customer claim costs in the form of price discounts that are proportional to the deviation from customer specifications. Total customer claim costs are determined by multiplying the deviation from customer specifications of hams that are incorrectly sorted with both ham weight and a discount rate of € 0.05 per kg per deviation unit. This discount rate is determined in collaboration with company experts based on experience with earlier customer claim costs. By dividing the total claim costs by the total ham weight we acquire average claim costs per ton product, which is an important indicator for sorting performance.

4. Simulation modelling

In Section 4.1 the various elements and relationships of the discrete event simulation model are discussed. The input data that are used in the experiments are given in Section 4.2, whereas the simulation instance we consider in this paper is described in Section 4.3.

4.1. *Model elements and relationships*

A common approach in quantitative analysis of supply chain designs that include stochastic elements is the use of simulation models. Several simulation approaches can be distinguished, of which discrete event simulation is an appropriate method for tactical and operational decision making (Kellner *et al.* 1999, van der Zee and van der Vorst 2005). This modelling technique is most widely used in business and manufacturing industries (Jahangirian *et al.* 2010). In a review on simulation in supply chains Terzi and Cavalieri (2004) indicates that discrete-event simulation is a suitable method to evaluate design scenarios, since (i) companies can perform a what-if analysis prior to taking a decision, (ii) various design scenarios can be compared without interrupting the real system, and (iii) it permits time compression so that timely policy decisions can be made. In what follows we therefore propose a discrete event simulation model. The model is implemented using the Stochastic Simulation in Java (SSJ) toolbox (http://www.iro.umontreal.ca/ simardr/ssj/indexe.html).

The moving items in the simulation model we consider are Carcasses and Hams. Each Carcass is sorted to a CarcassClass, which has a set of specifications for carcass quality features. Carcasses are cut into three carcass parts class by class at a fixed processing rate, and we simulate only the Ham part. Each Ham receives a HamQualityEstimate. Based on the HamQualityEstimate and the set of available HamOrders each ham is allocated to one of the HamOrders. These HamOrders contain a set of specifications including the CarcassClass the Ham should originate from, the allowed Ham quality specifications, and a list of HamProcesses that have to be performed to fit the HamOrder. After sorting the Ham is either transferred directly to the HamProcessors, or temporarily buffered in the HamBuffer, depending on the process design. At the HamProcessors the Hams are processed serially at the same rate of carcass cutting. After the last HamProcess has been performed the Ham is finished, and performance data is gathered.

Process design scenarios in this simulation differ with respect to the number of WHC segments in the HamOrders, the WHC quality information available in the HamQualityEstimate, and the use of a HamBuffer. Prevalence of WHC is simulated by randomly assigning a WHC value to a ham following an empiric prevalence of WHC. This product quality is used as the real WHC. In scenarios where no product quality information is available products are sorted randomly, unrelated to the real WHC of that product. In scenarios where WHC estimates are available these estimates are generated based on the real WHC plus a random estimation error, which follows the empirical estimation errors. If perfect WHC information is available the real WHC is used for product sorting.

For performance measurement the throughput time of Hams between cutting them from the Carcass up to the moment where they are fully processed is monitored. Next to that we monitor whether the Ham actually fulfils the WHC-specifications of the order it is processed to, and if not, what the deviation from the customer specifications was. This data is used to determine the rate of Hams that does not fulfil order specifications and the customer claim costs respectively. The labour consumption in processing and buffering is determined by measuring the total time the ham processing units have been opened, and by multiplying the number of buffered hams with the average labour consumption for ham buffering.

4.2. *Input data*

Our industrial partner provided, together with data regarding the relation between quality features of carcasses and hams, a large dataset with carcass quality data. The output we present in this paper is based on a simulation that includes 70728 carcasses originating from 12 separate carcass quality classes slaughtered in 15 consecutive days. A set of quality specifications for ham end products is available for each of the 12 separate carcass quality classes. After carcass classes are cut into carcass parts the hams are sorted to 3 main end products each, which can be subdivided into various WHC-segments depending on the process design.

The industrial partner provided a dataset containing both the estimated (using the NIRS technology) and the real WHC (determined by measuring the drip loss over a period of 24 hours) of 993 samples. The prevalence of different levels of real (measured) drip loss in the available samples can be observed in Figure 3. We approximated the standard deviation of the NIRS estimation error at 0.80% based upon the 993 paired samples of both the real (measured) WHC and the predicted WHC. This value is used to generate WHC estimates in scenarios 3EN, 3EB, 5EN, and 5EB. The specifications of the 3 and 5 WHC-segments are chosen to make segments that are roughly equal in size. In case of sorting to 3 WHC-segments each segment therefore contains about 33 % of the hams (lower, middle and upper segment), whereas the 5 segments each contain approximately 20 % of the hams, in line with market demand.

Insert Figure 3 around here.

4.3. *Simulation instance*

The quality features of individual hams are simulated based on available carcass data and the relation between quality features of whole carcasses and hams. One hundred simulation runs were used to assess each process design scenario, and due to the large number of carcasses in each simulation run the model outputs showed little variation within the 100 replications.

A total of 9 possible ham processing steps are incorporated. To make the labour requirement of the various end-products comparable we adjusted the various end product recipes by assigning the same number of processing steps to each of the end products. This results in comparable labour requirement for each end-product group.

In case of non-buffered production (design scenarios 1IN, 3NN, 3EN, 3PN, 5NN, 5EN, and 5PN) carcasses that are cut are directly processed at the processing line, resulting in a short throughput-time. In case of buffered production a period of 1,5 hours was used between the start of carcass cutting and the processing of sorted hams. This ensured that all hams from a carcass class were sorted before processing starts, while the increase in throughput-time caused by buffering is minimal.

5. Results

This section presents the results of the analysis of the process designs in Section 5.1. Furthermore, Section 5.2 gives more insight in the sensitivity of model outputs to changes in sensor information accuracy.

5.1. *Scenario analysis*

The developed simulation model allows for a detailed analysis of the performance of all process design scenarios. In this paper we limit the output to the KPIs discussed before; the aggregated performance data can be found in Table 3 and Figure 4. To simplify interpretation of the results the properties of the process design scenarios are given in Table 3 as well. All costs in this section are given in € per ton of product. The average daily throughput was 61.3 ton of hams per day, which, with an average value of € 2.40 per kg, represents a value of approximately € 147.000 per day. A cost-reduction of € 5.00 per ton therefore represents a saving of 0.21 %, or € 307 per day. Since profit margins are typically below 1 % in this industry (Anonymous 2012), this is a significant improvement.

Insert Table 3 around here.

As mentioned in Section 3.3 the process design scenarios differ in (i) the number of WHC segments that is sorted to, (ii.) the available product quality information, and (iii.) whether the sorted hams are directly processed or temporarily buffered. The rate of products that does not fulfil customer specifications, and the expected claim costs, and costs for labour and product buffering are given in Table 3 and Figure 4. Please note that the costs for investments in sensor equipment are not included in this overview. Furthermore the additional value that can be obtained by advanced product segments is not included. To make sorting to advanced product segments economically feasible, the increase of costs due to segmentation should at least be compensated by the added value of advanced quality segments.

The results in Figure 4 and Table 3 reveal that use of WHC estimates in sorting to 3 or 5 segments will reduce expected claim costs compared to the current situation (no WHC information) by 73 % and 66 %, respectively. This shows that, despite uncertainty in WHC estimates, use of NIRS dramatically reduces expected customer claim costs. The output also reveals that the average deviation from customer specifications for incorrectly sorted products is smaller in case WHC estimates are used, since the relative reduction of customer claim costs is stronger than the reduction of incorrectly sorted hams in case of WHC estimates. Note that, although advanced products sorting results in significant cost increases, the increase is relatively modest compared to the average product value of € 2400 per ton.

Insert Figure 4 around here.

Table 3 and Figure 4 also show that increasing sorting complexity in the current process design (with no buffer) by sorting to 3 or 5 WHC segments will increase labour costs by 80 % for both cases. If sorting buffers are used (scenario 1IB) the increase in labour costs resulting from sorting to 3 or 5 WHC segments is limited to 35 and 46 % respectively. The product buffering costs (€ 8.52 per ton) do not outweigh the labour cost reduction in the current sorting complexity (€ 4.50 per ton) for scenarios without sorting for WHC (scenario 1IN vs. 1IB). For scenarios with 3 or 5 WHC segments the use of temporary buffers does reduce overall costs by on average € 4.81 and € 3.60 per ton respectively (scenarios 3NN, 3EN, 3PN vs. 3NB, 3EB, 3PB, and scenarios 5NN, 5EN, 5PN vs. 5NB, 5EB, 5PB).

Table 3 also shows the effect of different levels of product quality information on sorting performance. As indicated before we do not distinguish different levels of availability of quality information in the current scenario, since in this scenario products are not sorted for WHC anyway. As expected 0 % of the products are incorrectly sorted if perfect information is available (scenarios 3PN, 3PB, 5PN, 5PB). Furthermore if no advanced product quality information is available (scenarios 3NN, 3NB, 5NN, 5NB) a high rate of products will not fulfil customer specifications (66 % for 3 segments, 79 % for 5 segments) and expected customer claim costs will be high (on average € 61.80 for 3 segments, and € 76.60 for 5 segments). The expected customer claim costs of process design scenarios that use WHC estimates is, compared to sorting without WHC information, reduced with on average 73 % for 3 segments, and 66.4 % for 5 segments. This would reduce the expected daily customer claim costs by € 2766 and € 3094 for 3 and 5 segments respectively (or 1.9 and 2.1 % of the total turnover) if compared to a situation where no quality estimates are available. More insight in the sensitivity of both claim costs and the rate of incorrectly sorted hams for changes in sensor accuracy can be found in Section 5.2.

5.2. *Sensitivity to sensor accuracy*

To gain insight into the sensitivity of sorting performance for changes in sensor accuracy and thereby the estimation error we conducted a sensitivity analysis. Figure 5 shows the sensor accuracy, represented by the standard deviation of the estimation error around the real product quality, against the expected customer claim costs. This is done for both sorting to 3 and to 5 WHC segments. The current sensor has an estimation error with a standard deviation of 0.8, and in the experiments the standard deviation of the estimation errors was varied between 0.5 and 1.2. This is expected to be a realistic range for operational sensor accuracy; a higher estimation error than the current best estimate might occur if concessions to sensor accuracy are done to reduce operational costs, whereas future improvements in the NIRS technology might result in a lower estimation error.

Figure 5 shows that the expected customer claim costs rise with higher estimation errors. This indicates that if the estimation error is lower the added value from advanced sorting that is required to make advanced sorting profitable is also reduced. In Figure 5 we also observe that the increase in customer claim costs with higher estimation errors is larger if sorting to more segments. The insights obtained from Figure 5 can be used to analyse the potential gain of acquiring technology that provides better quality estimates.

Insert Figure 5 around here.

6. Discussion and conclusion

Consumer demand for food products has become more segmented with respect to product quality features in recent years. This provides opportunities for food processors to add extra value by differentiating product flows. Many food processing companies struggle to differentiate product flows to serve segmented market, due to specific characteristics of food products (e.g. a divergent production process, homogenous product quality, a multitude of product quality features, and product quality features that are difficult to determine).

Food processors therefore need effective mechanisms to differentiate product flows despite complicating factors. Gathering and using product quality information is of key importance for advanced product sorting. To assess the use of product quality information in product sorting at a meat processing company a model was developed that simulates a ham sorting and processing chain. Fourteen process design scenarios were defined that differ with respect to (i) the number of segments that is sorted to, (ii.) the available product quality information, and (iii.) whether the sorted hams are directly processed or temporarily buffered. The sorting performance is assessed based on expected customer claim costs, order compliance rate, labour costs, and buffering costs.

Based on the results presented in Section 5.1 we conclude that use of product quality estimates in product sorting is an effective approach to reduce customer claim costs while sorting products to multiple segments. By simulating sorting performance of scenarios with perfect information, scenarios with no information, and product quality estimates that differ in accuracy (Section 5.2) we give insight in the advantages /disadvantages of acquiring more/less accurate product quality information on expected claim costs.

The findings reveal that with a low sorting complexity (no sorting for advanced product quality features) the use of production buffers increased overall costs with 25 %. This confirms the claims made by He *et al.* (2011) that decision makers should carefully assess the effect of measures to increase flexibility on profitability and efficiency before investing in them. For more complex sorting (3 or 5 segments) the use of production buffers resulted in a reduction of overall costs between 3.4 and 16.7 %. This suggests that higher processing complexities makes use of processing buffers favourable, which confirms findings by Hallgren and Olhager (2009).

The findings of this case study can be used by practitioners to determine (i) the process design that is most appropriate for a specific sorting complexity, (ii.) the extra costs that can be expected if sorting for more product quality features, (iii.) the order compliance and customer claim costs that can be expected if sorting with the current accuracy of product quality estimates. Furthermore, the approach presented in this paper enables practitioners that face segmented customer demand to develop and assess responsive and flexible supply chain configurations. The most appropriate product mix and processing strategy can be determined based on the added value of advanced quality segments. In general it can be said that a higher sorting complexity makes the use of sorting buffers favourable, whereas better quality predictions reduce the expected customer claim costs.

Future research should determine the consumers' willingness to pay for special product segments. This can be used, in combination with model outputs, to determine whether the added consumer value outweighs the investments in sensory equipment and the expected increase in processing costs. Please note that advanced product sorting will not only yield premium products; some segments will have a product quality lower than average, resulting in a lower market value.

With this case study we provide a case example of how the use of advanced product quality information affects the design of food processes, an area that did not yet receive much attention in the literature. Furthermore we illustrate the importance of flexibility in segmented food supply chains, and confirm claims by Stevenson and Spring (2007), who stated that there is a limit in the degree to which a supply chain can be flexible whilst meeting demand and operating efficiently. Our results indicate that there is a trade-off between the sorting complexity resulting from use of advanced product quality features and the processing efficiency. An interesting direction for future research would be to assess the effect of sorting for advanced product quality features in other supply chains with high levels of segmentation. Furthermore it would be interesting to assess how other redesign principles (e.g. mechanization, postponement, modularity) affect the performance of food supply chains with high levels of segmentation.

Acknowledgement

Acknowledgements The authors gratefully acknowledge the financial support of the European Community under the Sixth Framework Programme for Research, Technological Development and Demonstration Activities, for the Integrated Project Q-PORKCHAINS FOOD-CT-2007-036245

References

Akkerman, R., Farahani, P., and Grunow, M., 2010. Quality, safety and sustainability in food distribution: a review of quantitative operations management approaches and challenges. *OR Spectrum*, 32 (4), 863–904.

Anonymous, Livestock, meat and eggs in the Netherlands. , 2012. , Technical report, Productschappen Vee, Vlees en Eieren.

Chen, R.S. and Tu, M., 2009. Development of an agent-based system for manufacturing control and coordination with ontology and RFID technology. *Expert Systems with Applications*, 36 (4), 7581–7593.

Christopher, M. and Towill, D., 2000. Supply chain migration from lean and functional to agile and customised. *Supply Chain Management*, 5 (4), 206–213.

Forrest, J., *et al.*, 2000. Development of technology for the early post mortem prediction of water holding capacity and drip loss in fresh pork. *Meat Science*, 55 (1), 115–122.

Grunert, K.G., 2006. How changes in consumer behaviour and retailing affect competence requirements for food producers and processors. *Economia Agraria y Recursos Naturales*, 6 (11), 3–22.

Grunert, K.G., Bredahl, L., and Brunso, K., 2004. Consumer perception of meat quality and implications for product development in the meat sector - a review. *Meat Science*, 66 (2), 259–272.

Gunasekaran, A., Lai, K., and Edwin Cheng, T.C., 2008. Responsive supply chain: A competitive strategy in a networked economy. *Omega*, 36 (4), 549–564.

Hallgren, M. and Olhager, J., 2009. Flexibility configurations: Empirical analysis of volume and product mix flexibility. *Omega*, 37 (4), 746–756.

He, P., Chen, Z., and Xu, X., 2011. On flexibility investment in manufacturing system: A multi-objective decision making method. *Expert Systems with Applications*, 38 (9), 11813–11819.

Huang, H., *et al.*, 2008. Near infrared spectroscopy for on/in-line monitoring of quality in foods and beverages: A review. *Journal of Food Engineering*, 87 (3), 303–313.

Huff-Lonergan, E. and Lonergan, S., 2005. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Science*, 71 (1), 194–204.

Jahangirian, M., *et al.*, 2010. Simulation in manufacturing and business: A review. *European Journal of Operational Research*, 203 (1), 1–13.

Kellner, M., Madachy, R., and Raffo, D., 1999. Software process simulation modeling: Why? What? How?. *Journal of Systems and Software*, 46 (2-3), 91–105.

Klibi, W., Martel, A., and Guitouni, A., 2010. The design of robust value-creating supply chain networks: A critical review. *European Journal of Operational Research*, 203 (2), 283–293.

Kumar, P., *et al.*, 2009. Overview of RFID Technology and Its Applications in the Food Industry. *Journal of Food Science*, 74 (8), 101–106.

Mackelprang, A. and Nair, A., 2010. Relationship between just-in-time manufacturing practices and performance: A meta-analytic investigation. *Journal of Operations Management*, 28 (4), 283–302.

O'Neill, D.J., *et al.*, 2003. Effects of PSE on the quality of cooked hams. *Meat Science*, 64 (2), 113–118.

Perez, C., de Castro, R., and Font i Furnols, M., 2009. The pork industry: a supply chain perspective. *British Food Journal*, 111 (3), 257–274.

Prevolnik, M., Čandek Potokar, M., and Škorjanc, D., 2010. Predicting pork water-holding capacity with NIR spectroscopy in relation to different reference methods. *Journal of Food Engineering*, 98 (3), 347–352.

Raab, V., *et al.*, 2008. Generic model for the prediction of remaining shelf life in support of cold chain management in pork and poultry supply chains. *Journal on Chain and Network Science*, 8 (1), 59–73.

Rosenvold, K. and Andersen, H., 2003. Factors of significance for pork quality–a review. *Meat Science*, 64 (3), 219–237.

Shah, R. and Ward, P., 2007. Defining and developing measures of lean production. *Journal of Operations Management*, 25 (4), 785–805.

Stevenson, M. and Spring, M., 2007. Flexibility from a supply chain perspective: definition and review. *International journal of operations & production management*, 27 (7), 29.

Terzi, S. and Cavalieri, S., 2004. Simulation in the supply chain context: a survey. *Computers in Industry*, 53 (1), 3–16.

van der Vorst, J., Dijk, S.J.v., and Beulens, A., 2001. Leagile supply chain design in the food industry - using decoupling points in an inflexible poultry supply chain with high demand uncertainty -. *The International Journal on Logistics Management*, 12 (2), 73–86.

van der Vorst, J., van Kooten, O., and Luning, P.A., 2011. Towards a Diagnostic Instrument to Identify Improvement Opportunities for Quality Controlled Logistics in Agrifood Supply Chain Networks. *International Journal on Food System Dynamics*, 2 (1), 94–105.

van der Zee, D.J. and van der Vorst, J., 2005. A modeling framework for supply chain simulation: Opportunities for improved decision making. *Decision Sciences*, 36 (1), 65–95.

Tables

Table 1. Processing steps

Process	Process duration	Capacity	Product
Slaughtering	± 20 minutes	560 pigs per hour	Carcass
Carcass sorting	-	1120 carcasses/hour	Carcass class
Carcass cooling	15 hours or more	-	Chilled carcass classes
Carcass cutting	-	1200 carcasses/hour	Carcass parts
Sorting of carcass parts	-	1200 carcasses/hour	Sorted carcass parts
Buffering of carcass parts	Variable	-	Buffered carcass parts

Table 2. Summary of process design scenarios

Scenario number	Number of segments (1, 3, 5)	Product quality information (I, N, E)	Buffered non buffered (N, B)
1: 1IN (current)	1	Irrelevant	Non buffered
2: 1IB	1	Irrelevant	Buffered
3: 3NN	3	Not available	Non buffered
4: 3EN	3	Estimates	Non buffered
5: 3PN	3	Perfect	Non buffered
6: 3NB	3	Not available	Buffered
7: 3EB	3	Estimates	Buffered
8: 3PB	3	Perfect	Buffered
9: 5NN	5	Not available	Non buffered
10: 5EN	5	Estimates	Non buffered
11: 5PN	5	Perfect	Non buffered
12: 5NB	5	Not available	Buffered
13: 5EB	5	Estimates	Buffered
14: 5PB	5	Perfect	Buffered

Table 3. Performance of process design scenarios

Scenario number	Segments (1,3,5)	WHC information (I,N,E,P)	Buffer (N,B)	Out of customer specifications	Claim costs (€/ton)	Labour costs (€/ton)	Buffering costs (€/ton)	Overall costs (€/ton)
1: 1IN (current)	1	Irrelevant	No	0.00%	€ 0.00	€ 16.00	€ 0.00	€ 16.00
2: 1IB	1	Irrelevant	yes	0.00%	€ 0.00	€ 11.50	€ 8.52	€ 20.02
3: 3NN	3	Not available	no	65.80%	€ 61.76	€ 28.84	€ 0.00	€ 90.60
4: 3EN	3	Estimates	no	32.90%	€ 16.71	€ 28.86	€ 0.00	€ 45.57
5: 3PN	3	Perfect	no	0.00%	€ 0.00	€ 28.81	€ 0.00	€ 28.81
6: 3NB	3	Not available	yes	65.90%	€ 61.85	€ 15.47	€ 8.52	€ 85.84
7: 3EB	3	Estimates	yes	32.90%	€ 16.65	€ 15.55	€ 8.52	€ 40.72
8: 3PB	3	Perfect	yes	0.00%	€ 0.00	€ 15.47	€ 8.52	€ 23.99
9: 5NN	5	Not available	no	79.30%	€ 76.68	€ 28.82	€ 0.00	€ 105.50
10: 5EN	5	Estimates	no	51.00%	€ 26.19	€ 28.82	€ 0.00	€ 55.01
11: 5PN	5	Perfect	no	0.00%	€ 0.00	€ 28.83	€ 0.00	€ 28.83
12: 5NB	5	Not available	yes	79.30%	€ 76.53	€ 16.82	€ 8.52	€ 101.87
13: 5EB	5	Estimates	yes	51.00%	€ 26.25	€ 16.51	€ 8.52	€ 51.28
14: 5PB	5	Perfect	yes	0.00%	€ 0.00	€ 16.88	€ 8.52	€ 25.40

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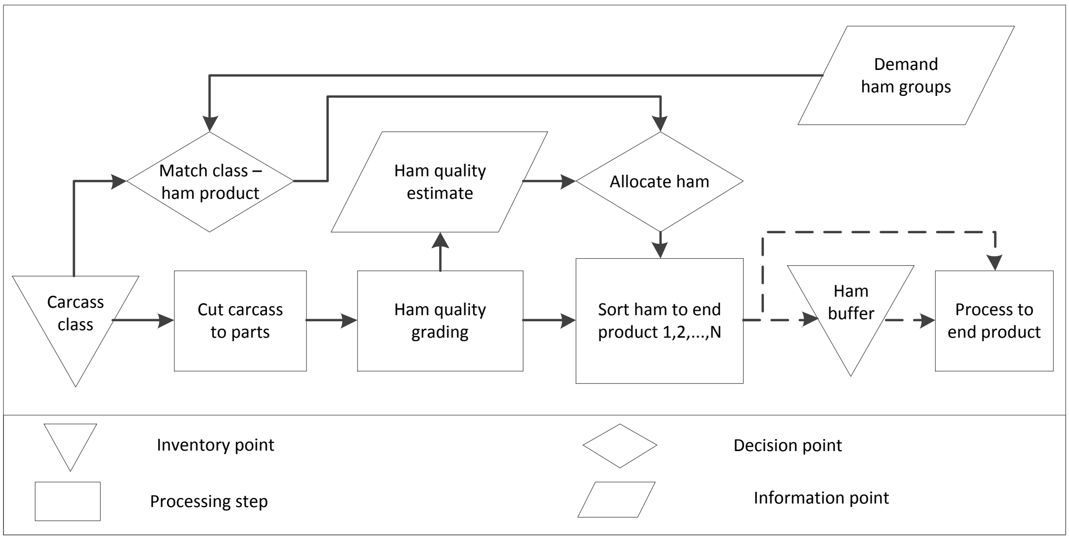

Figure 1. Schematic overview of current processing chain

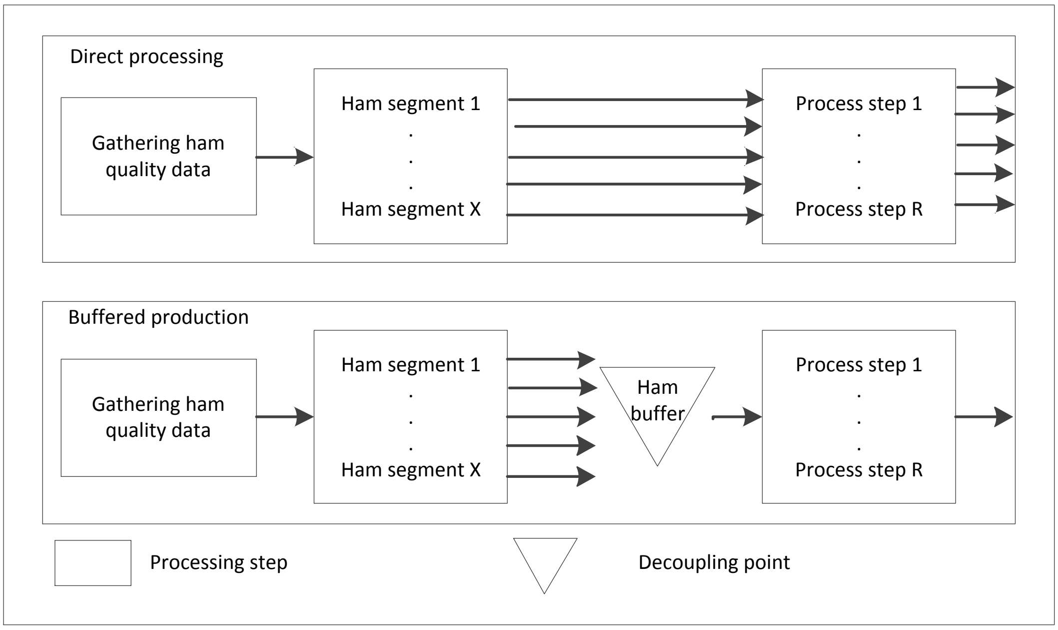

Figure 2. Schematic overview of buffered and non-buffered process design scenarios

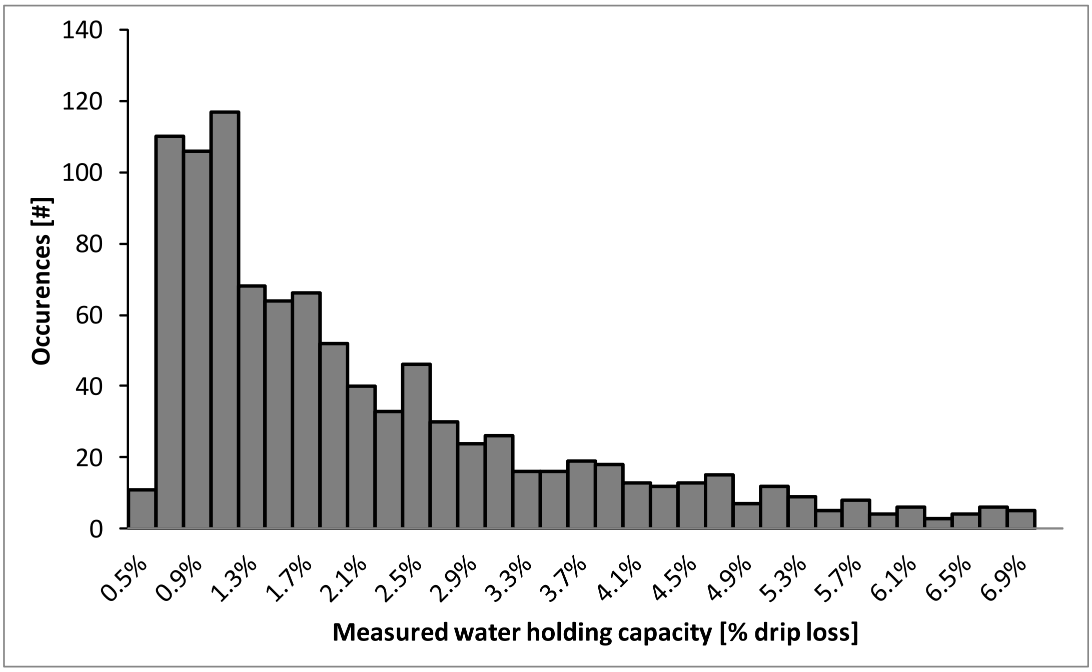

Figure 3. Product quality prevalence, based on 993 samples

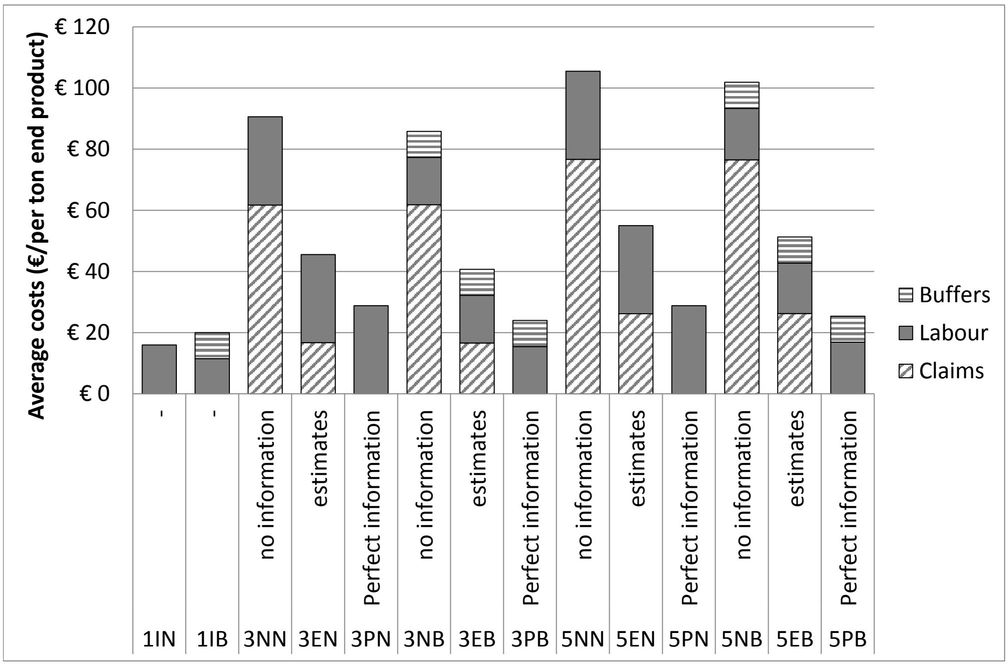

Figure 4. Performance of process redesign scenarios

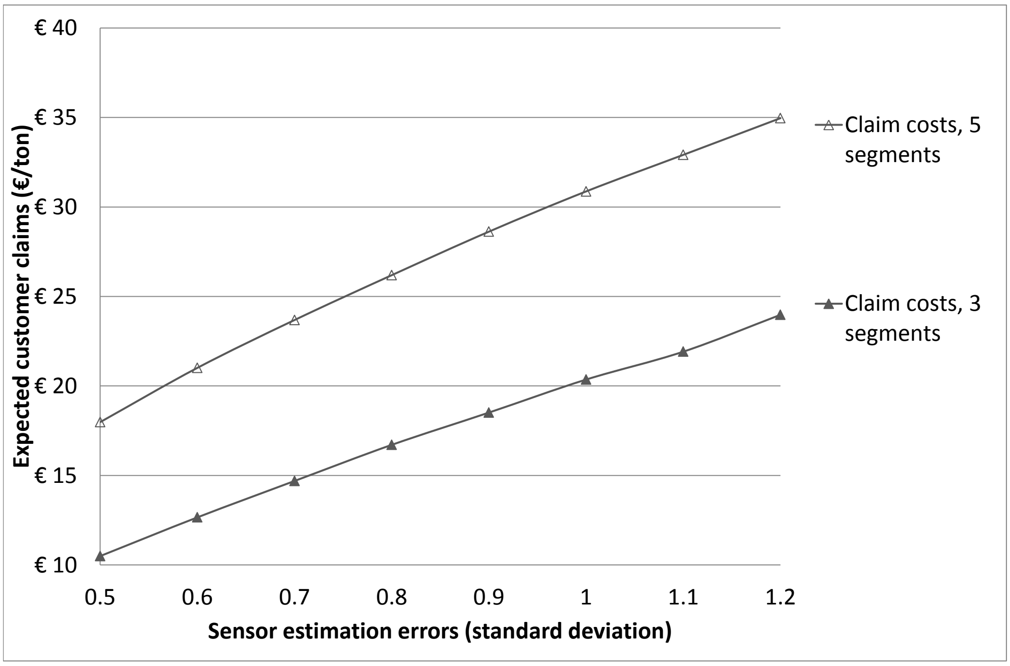

Figure 5. Sensitivity analysis of sensor accuracy

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