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Research paper

Exploring the performance of system changes in Dutch broiler production to balance animal welfare, ammonia emissions and particulate matter emissions with farm profitability

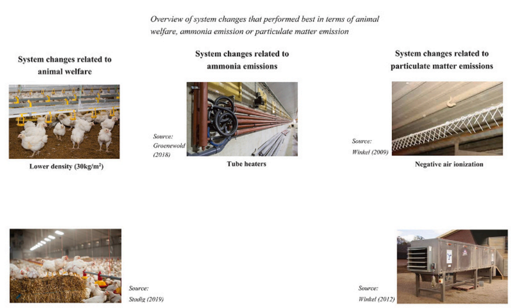
Luuk S.M. Vissers *, Alfons G.J.M. Oude Lansink, Helmut W. Saatkamp

Business Economics Group, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, the Netherlands

HIGHLIGHTS

- The European Union set up goals to improve the sustainability of broiler production.
- This paper aimed to explore the performance of combinations of system changes in broiler production.
- The performance of each combination was evaluated by developing a benefit-of-the-doubt composite indicator.
- Combinations including an air ionization system for PM_{10} reduction and tube heaters for NH_3 reduction performed best.
- The insights can support decision making in improving the sustainability of current broiler production systems.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: In response to societal concerns, the European Union set up goals to address the negative impact of intensive broiler production on animal welfare, the environment and human health.
OBJECTIVE: This paper aimed to 1) explore combinations of system changes that perform best in terms of farm income, animal welfare, emissions of ammonia (NH_3) and particulate matter (PM_{10}) and 2) are robust to changes in society's expectations relating to animal welfare and environmental sustainability.
METHODS: The prevailing system in the Dutch broiler market was used as a baseline for evaluating system changes. Animal welfare, NH_3 emissions and PM_{10} emissions were the three external factors chosen for this evaluation. Farm income was quantified by the net return to labor and management (NRLM). Expert knowledge elicitation was used to identify system changes that were likely to be implemented in the baseline system. Combinations were made by selecting system changes from each of the chosen external factors. A deterministic model was used to calculate the effect of each combination of system changes on net return to labor and management. The performance of each combination was evaluated by estimating a benefit-of-the-doubt composite indicator.
RESULTS AND CONCLUSIONS: Results show that 8 out of 70 combinations indicated a better outcome and were more robust to potential changes in society's expectations relating to animal welfare and environmental sustainability. These combinations included two or more of the following system changes: 'lower density' (30 kg/

* Corresponding author at: Hollandseweg 1, 6706 KN Wageningen, the Netherlands.
E-mail address: luuk.vissers@wur.nl (L.S.M. Vissers).

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m^2), '2 types of enrichment', and 'daylight'. Furthermore, these combinations included 'tube heaters' for the abatement of NH_3 emissions, and 'negative air ionization system' or 'ionization filter' for the abatement of PM_{10} emissions. To compensate for the decrease in NRLM associated with these practices and abatement techniques, a price premium was required that ranged between 4.8 and 18.5 eurocents/broiler. We conclude that combinations including animal welfare related system changes (lower density, enrichment and/or daylight), tube heaters and an ionization technique performed best and were robust to changes of societal expectations of these external factors.

SIGNIFICANCE: The insights obtained from this paper can support decision making in improving the sustainability of current broiler production systems.

1. Introduction

Since the mid-20th century, stakeholders in the European broiler supply chain co-developed intensive broiler production systems to address the increasing demand for safe and cheap food in sufficient quantities. More recently these systems have been criticized by European citizens because of a perceived effect on animal welfare (AW), the environment and human health (Homidan et al., 2003; Bessei, 2006; Cambra-López et al., 2010), defined as external factors. In the past two decades, the European Union (EU) passed legislation on AW, food safety and the environment to address these concerns (European Council Directive, 2007, 2009, 2016). Stakeholders in the broiler supply chain introduced more extensive broiler production systems to address the critique on AW. These systems provided a higher level of AW, but had a higher environmental impact relative to conventional systems (Leinonen et al., 2012; Bracke et al., 2019). Therefore, the attempts by the EU and private sector are deemed to be insufficient by European citizens as criticism persists as of today (Eurobarometer, 2016). In order to address the persistent societal critique, the EU agreed upon new goals for the next ten years. In 2016, the European Commission (2020) introduced the Farm to Fork strategy, which set goals specific to the agri-food sector such as a reduction in the nutrient losses and the sales of antimicrobials for farmed animals by 50% in 2030. A potential pathway towards achieving these goals is to improve the sustainability of current broiler production systems. To improve the sustainability of these systems, investigation into the impact of specific, objective system changes[1] on farm income is of great importance. However, it is currently unclear which system changes address external factors in an income-efficient manner.[2]

Earlier studies, such as Wagner et al. (2015) and Vissers et al. (2021), developed an integrated model to analyze the effectiveness and cost-efficiency of system changes on external factors in poultry production. Wagner et al. (2015) investigated the effect of ammonia (NH_3) and Particulate Matter (PM) related system changes with regards to their costs for farmers and their benefits for society. Vissers et al. (2021) analyzed the synergies and trade-offs between AW, antibiotic use, NH_3 emissions and PM_{10} emissions in broiler production systems. While Wagner et al. (2015) considered only system changes related to NH_3 and PM emissions, Vissers et al. (2021) considered only AW related system changes. Therefore, these studies do not consider the costs and benefits of broiler production systems that include combined system changes of AW, NH_3 and PM_{10} emissions. Another shortcoming of both studies is that they ignore the potential for addressing AW, NH_3 emissions and PM_{10} emissions simultaneously by combining these system changes, and the impact of these combinations on farm income. Because of these shortcomings, the existing studies are not able to answer the following questions:

- How can the performance of system changes on farm income and external factors be measured?
- What are the best performing system changes to address these external factors?
- To what extent is the performance of these system changes robust to changes in the societal attitude towards these external factors?
- What is the price premium or subsidy required to compensate for the decrease in farm income associated with these changes?

To answer these questions, this paper aims to explore combinations of system changes that perform relatively best in terms farm income and external factors, and are robust to changes of societal expectations of these external factors. The insights obtained from this paper can support the development of broiler production systems that deliver the greatest combinations for reduced environmental emissions, improved animal welfare and reduced risks relating to human health. Furthermore, the study can provide insights for determining the minimum price premium or subsidy needed to get support for the systems among farmers.

2. Approach

A five-step approach was developed and applied to a Dutch broiler production system to assess the effect of altering the production system using defined system changes on AW, NH_3 and PM_{10} emissions, and farm income. First, the baseline system that was used for implementation of the system changes is described. Second, the external factors and system changes considered in this study are discussed. This is followed by a description of the model that was used to calculate the impact of the system changes on the external factors and farm income. Fourth, the system changes are compared in terms of their overall performance using the benefit-of-the-doubt method. Finally, a sensitivity analysis was conducted to test the sensitivity of the overall performance of the system changes to fluctuations in the feed price and producer price.

2.1. Select baseline broiler production system

The new Dutch retail standard system was selected as the baseline system, as this is the prevailing system in the Dutch fresh meat market (Saatkamp et al., 2019). The new Dutch retail standard contains the minimum requirements on AW of Dutch retailers, which go beyond the minimum legal requirements laid down by the EU (European Council Directive, 2007). The requirements of this standard entail a slower-growing breed (max. growth rate 50 g/day), a maximum stocking density of 38 kg/m^2 and the provision of straw bale enrichment. Table 1 shows the attributes of the new Dutch retail standard system. We assumed that this system included two techniques for reducing NH_3 and PM_{10} emissions, i.e. indirect heaters with circulation and a heat exchanger. These techniques were selected as they are widely used in the new Dutch retail standard system (H.H. Ellen, personal communication, 2020).

[1] In this paper, we define a system change as a change of the production system in one of the following aspects: 1) a different management practice 2) a change in the housing design or 3) implementation of an end-of-pipe air treatment technique.

[2] A system change is considered to be income-efficient when an external factor is reduced by a certain level with a minimum decrease in farm income.

Table 1
System attributes of the baseline system (obtained from Vissers et al. (2021)).

System attribute	Unit	Production system
		New Dutch Retail Standard
Broiler type	Type	Hubbard JA 987
Length growth period	days	49
Weight at delivery	g	2380
Stocking density	kg/m^2	Max. 38
Straw bale enrichment	# bales/ 1000 broilers	Min. 1
Grain enrichment	g/broiler	Not required
Length dark period	hours/day	Min. 6
Light intensity	lux	Min. 20
Natural light	yes/no	Not required
On-farm hatching	yes/no	Not required
Early feeding	yes/no	Not required
Empty barn period	# days	7
Litter type	Type	Wood shavings
Feed composition	Type	Concentrates +15% wheat
Feeding phases	# phases	4
Management of manure	Type	Disposed at end of production cycle
Flock size	# broilers	81,035
Veterinary medicines	Type	Antimicrobials and coccidiostats
Outdoor access	yes/no	Not required
NH_3 abatement technique	Type	Indirect heaters with circulation
PM_{10} abatement technique	Type	Heat exchanger 13% PM_{10} emission reduction

2.2. *Identifying societal expectations for animal welfare and environmental sustainability*

A list of external factors related to Dutch broiler production was obtained from Vissers et al. (2021). Based on this list, expert knowledge elicitation (see Supplementary Material A for the list of experts and their expertise) was used to identify the external factors that are key drivers in the development of Dutch broiler production systems in the next ten years (2020–2030). A time span of ten years was selected because the time scale of a transition driven by aroused public opinion on societal issues is usually a decade (Buurma et al., 2017). External factors including AW, NH_3 emissions, odour emissions and PM_{10} emissions were selected by the experts. Odour emissions were not considered in further analysis, as data about odour emissions were lacking for the new Dutch retail standard production system. Since odour from broiler houses is a complex mixture of odorous compounds typically composed of volatile organic compounds (Dunlop et al., 2016), it was also not possible to estimate the odour emissions originating from the baseline system using expert knowledge elicitation. For the selected external factors, expert knowledge elicitation was carried out to identify the system changes that are likely to be implemented in the baseline system in the next ten years. Table 2 provides an overview of the selected system changes, and their likelihood for implementation. The selection of the system changes may be biased due to the research interests and/or experience of the experts. Therefore, we included a substantiation of the selected system changes in Supplementary Material B. On top of the system changes selected by the experts, the management practices and NH_3/PM_{10} abatement techniques already applied in the baseline system were considered in the analysis (defined as 'no system change' in Table 2).

2.3. *Calculating the effect of the system changes on animal welfare, environmental sustainability and net farm income*

2.3.1. *Farm income*

Based on the chosen system changes, combinations were made by selecting system changes from each external factor. Technically infeasible combinations of system changes were excluded from further

Table 2
Overview of the system changes selected in this study and likelihood to be implemented in the new Dutch Retail standard system in the next 10 years.

External factor	System changes	Likelihood
Animal welfare	1. 2 types of enrichment[1] + daylight[2]	High
	2. Lower density[3] + 2 types of enrichment	Low
	3. Lower density + daylight	Low
	4. Lower density + 2 types of enrichment + daylight	Low
	5. No system change	Low
NH_3 emissions	1. Tube heaters[4]	High
	2. TerraSea[5]	Low
	3. Chemical air scrubber, 70% NH_3 reduction, 35% PM_{10} reduction	Low
	4. No system change	Low
PM_{10} emissions	1. Negative air ionization system	High
	2. Ionization filter	Low
	3. Heat exchanger 31% PM_{10} reduction	Low
	4. No system change	Low

[1] Types of enrichment: 2 straw bales/1000 broilers and 2 g grain/day/broiler.
[2] Daylight: 3% of surface area.
[3] Reduction from 38 kg/m^2 to 30 kg/m^2.
[4] Tube heaters are installed inside the broiler house nearby the side wall inlets. The intake air passes through the air inlet and is warmed up by the tube heaters. The hot air absorbs moisture that evaporates from the litter. The moisture-rich air is removed with ventilation fans.
[5] In the Terrasea system, intake air passes through heat exchanger tubes where an energy transfer (heating or cooling) takes place. Water runs through these tubes, which cools the air in the summer and warms it in the winter. A chemical air scrubber removes ammonia, odour and particulate matter from the exhaust air.

analysis, resulting in 70 feasible combinations (out of potential 80 combinations). The deterministic model of Vissers et al. (2021) was used to calculate the external factors and farm income originating from the baseline system, and the effect of each combination of system changes on the external factors and farm income. In line with Vissers et al. (2021), we assumed that 81,035 broilers were reared the baseline system. Farm income was measured as the net return to labor and management (NRLM) and was computed as total revenues minus total costs excluding labor costs in euro per farm per year. The technical performance indicators, input prices and producer prices were obtained from Blanken et al. (2019). Table 3 provides an overview of the annual costs of each system change. Currently, farmers can apply for a subsidy for which 40% of the investments costs in an indoor PM_{10} abatement technique are reimbursed (Netherlands Enterprise Agency, 2020). This reimbursement applies only to indoor PM_{10} abatement techniques with a reduction efficiency of 45% or higher. Only the 'negative air ionization system' meets this requirement. Therefore, a 40% reduction in the investments costs was considered for this technique. The producer price was assumed to be fixed. Hence, system changes that enhance production costs lower the NRLM. Furthermore, floor surface area was assumed to be fixed. Hence, a lower stocking density implies less broilers reared in the poultry house. The net present value method was used to calculate the total subsidy required to compensate for the decrease in NRLM associated with the system changes. The decrease in NRLM was discounted over a period of 12.5 years, which is based on the economic lifespan of the NH_3 and PM_{10} abatement techniques (Blanken et al., 2019). The decrease in NRLM was discounted to present values using a 2.33% discount rate (Blanken et al., 2019). The formulas that have been used to calculate the required price premium and subsidy are provided in Supplementary Material C.

2.3.2. *External factors*

The external factors NH_3 emissions and PM_{10} emissions were expressed in kg per farm per year and include only emissions at the farm gate. The NH_3 and PM_{10} emissions originating from the baseline system

Table 3
Overview of selected system changes and their impact on external factors and annual costs.

External factor	System change	Δ Welfare Quality Index score	Δ kg NH_3/animal place/year	Δ kg PM_{10}/animal place/year	Δ Production costs (eurocents/animal place/year)
Animal welfare	1. 2 types of enrichment + daylight	+21.2[1]	0%	0%	+14.3[2]
	2. Lower density + 2 types of enrichment	+61.6[1]	0%	0%	+45.5[2]
	3. Lower density + daylight	+59.8[1]	0%	0%	+37.2[2]
	4. Lower density + 2 types of enrichment + daylight	+71.3[1]	0%	0%	+48.9[2]
	5. No system change	0	0%	0%	0
NH_3 emissions	1. Tube heaters	0	−82%[3]	0%[3]	−1.0[4]
	2. TerraSea system	0	−70%[5]	−35%[5]	+50.0[4]
	3. Chemical air scrubber	0	−70%[3]	−35%[3]	+88.0[4]
	4. No system change (Indirect heaters with circulation in baseline)	0	−49%[3]	0%[3]	−4.0[4]
PM_{10} emissions	1. Negative air ionization system	0	0%[6]	−49%[6]	+9.0[4]
	2. Ionization filter	0	0%[6]	−57%[6]	+36.0[4]
	3. Heat exchanger 31% PM_{10} reduction	0	0%[6]	−31%[6]	+11.0[4]
	4. No system change (heat exchanger 13% PM_{10} reduction in baseline)	0	0%[6]	−13%[6]	−5.0[4]

[1] Vissers et al. (2019).
[2] Vissers et al. (2021).
[3] Expertise Centre Infomil (2019a).
[4] Blanken et al. (2019).
[5] Ellen et al. (2014).
[6] Expertise Centre Infomil (2019b).

were obtained from Vissers et al. (2021). The NH_3 and PM_{10} reduction efficiencies of the abatement techniques were obtained from Expertise Centre Infomil (2019a) (see Table 3). Tools developed by the Dutch National Institute for Public Health and Environment (2017) and the Dutch Ministry of Instrastructure and Water Management (2020) were used to calculate the NH_3 and PM_{10} reduction efficiency from each combination of system changes. Vissers et al. (2021) found that the system changes 'lower density', '2 types of enrichment' and 'daylight' elevate PM_{10} emissions (expressed in g PM_{10}/animal place/year) (Vissers et al., 2021). Furthermore, they found that a reduction in stocking density may elevate NH_3 emissions (expressed in kg NH_3/animal place/year). However, Vissers et al. (2021) provide only a qualitative assessment of the effect of these system changes on NH_3 and PM_{10} emissions. Since a quantitative assessment of these effects was lacking, we assumed that the system changes do not affect PM_{10} emissions and NH_3 emissions.

The level of AW was indicated by the welfare quality index score (Welfare Quality Protocol®, 2009). The welfare quality index score of the baseline system was obtained from Vissers et al. (2019). This study was also consulted to obtain the effect of the system changes 'lower density', '2 types of enrichment' and 'daylight' on the welfare quality index score. Cambra-López et al. (2009), Bokkers et al. (2010) and Van Harn et al. (2015) analyzed the effect of the selected NH_3 and PM_{10} abatement techniques on technical performance and/or welfare related parameters such as footpad dermatitis and mortality. These studies did not find statistically significant differences between the techniques on broiler performance and welfare related parameters. Based on these findings, we assumed that the implementation of the selected techniques in the baseline system did not affect the welfare quality index score and the technical performance indicators.

2.4. Evaluate performance of combination of system changes

The performance of each combination of system changes was evaluated by developing a composite indicator. A composite indicator is a mathematical aggregation of a set of sub-indicators for measuring multidimensional concepts that cannot be captured by a single indicator (OECD, 2008). Composite indicators are increasingly used for performance comparisons, benchmarking and policy evaluation and is used in wide-ranging fields such as economy, society and technological development (OECD, 2008). In this study, the composite indicator consisted of four sub-indicators, i.e. NRLM, level of AW, NH_3 emissions and PM_{10} emissions (see Fig. 1).

Various weighting methods can be applied to aggregate the sub-indicators into a composite indicator, such as a linear aggregation method or the benefit-of-the-doubt approach (OECD, 2008). The benefit-of-the-doubt approach as proposed by Cherchye et al. (2007) was used to aggregate the sub-indicators into a composite performance indicator. The benefit-of-the-doubt approach is a technique that uses Data Envelopment Analysis to construct an indicator that is defined as the ratio of an observation's actual performance to its benchmark performance (the frontier). A value of 1 implies a performance similar to the benchmark values and a value less than 1 refers to worse performance. Fig. 2 illustrates the approach for two sub-indicators. Observations A, B and C are on the frontier, indicating that they are the best performing observations with a performance score that equals 1. Observation D has a performance score lower than 1, as it can improve the score of sub-indicator 1 without reducing the score of sub-indicator 2 (or vice versa). The performance score of observation D is calculated by the ratio of two distances, namely distance O-B and distance O-D.

The benefit-of-the-doubt model is summarized in eqs. (1), (2) and (3). In the model, I_c corresponds to the composite indicator of a combination of system changes c ($c = 1, \ldots, n$). The variable $y_{c,\, i}$ is the bundle of i sub-indicators ($i = 1, \ldots, m$) generated by a combination of system changes c. The sub-indicators were defined such that 'the more the better' holds. Therefore, NH_3 emissions and PM_{10} emissions were expressed as 'reduced NH_3 emissions and PM_{10} emissions relative to the baseline system'. The 'reduced NH_3 emissions and PM_{10} emissions relative to the baseline system' were obtained by calculating the decrease in NH_3 and PM_{10} emissions caused by a combination of system changes, relative to the baseline system. The weights $w_{c,\, i}$ are the variables of the model. The model optimizes the weights such that the maximum score for each combination is achieved. The benefit-of-the-doubt model was programmed using the package linprog in R

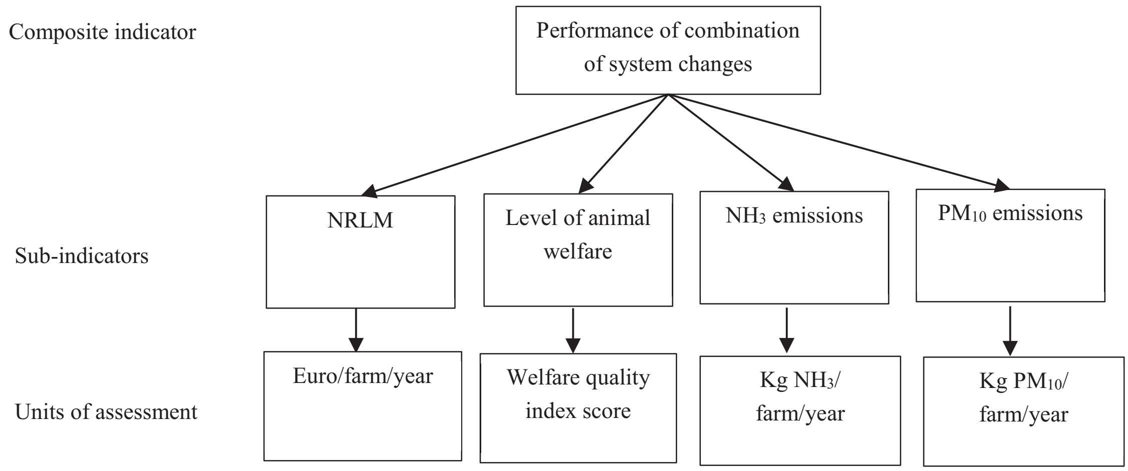

Fig. 1. Decomposition of composite indicator into sub-indicators.

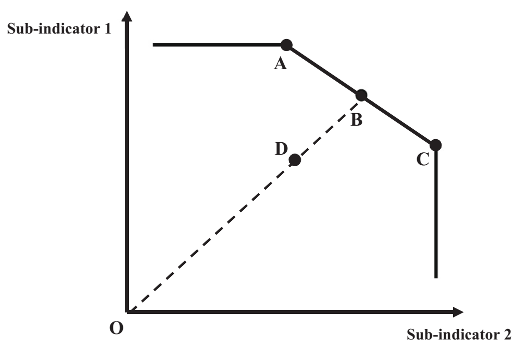

Fig. 2. Schematic representation of an output oriented data envelopment analysis model.

Software (R Core team, 2020).

$$I_c = max \sum_{i=1}^{m} w_{c,i} y_{c,i} \tag{1}$$

Subject to

$$\sum_{i=1}^{m} w_{c,i} y_{j,i} \leq 1 \; i = 1, \dots, m \tag{2}$$

$$w_{c,i} \geq 0 \; c = 1, \dots, n \tag{3}$$

Apart from the non-negativity of the weights, the model hitherto discussed allows weights to be freely estimated in order to maximize the performance score of the evaluated combination of system changes. In practice, society may assign a higher weight to a sub-indicator (e.g. AW) compared to the other sub-indicators. To address this issue, ordinal sub-indicator share restrictions were added to the model. Ordinal sub-indicator share restrictions imply that the sub-indicator shares of sub-indicator i ($w_i * y_i$) are ordinally ranked based on their importance (Cherchye et al., 2007). A default scenario was developed in which a higher importance was assigned to NRLM relative to the external factors (so-called NRLM driven scenario). An equal importance was assigned to the external factors (AW, NH_3 emissions and PM_{10} emissions). Similarly, three scenarios for the external factors (AW, NH_3 and PM_{10} driven) were explored. An overview of the scenarios is provided in Table 4. By changing the ranking of the external factors, the robustness of a performance score to changes in the importance of the external factors was tested. In this study, we assumed that a combination of system changes was robust and performed relatively best when a performance score of 0.90 or higher was achieved in all scenarios.

2.5. Sensitivity analysis

A sensitivity analysis was carried out to test effect of changes in the feed price and the producer price on the performance score of the combinations. The feed price and producer price were selected as Gocsik et al. (2013) show that the income of the broiler farmer is most responsive to changes in these prices. Two scenarios were modeled, i.e. a one standard deviation increase in feed price and a one standard deviation increase in producer price. The standard deviation was calculated by using monthly feed prices and producer prices over a time span of five years (2015–2019). Only yearly producer prices were available for the new Dutch retail standard system. However, monthly producer prices were available for the conventional system. Therefore, the average price premium was calculated by subtracting the yearly producer prices of the conventional system from the yearly producer prices of the new Dutch retail standard system. Consequently, the monthly producer prices of the new Dutch retail standard system were calculated by adding the average price premium to the conventional monthly producer prices.

3. Results

3.1. Calculation of scores for combinations in the NRLM driven scenario

To identify the combinations of system changes that performed best in the NRLM driven scenario, the performance score of each combination was analyzed. An overview of the scores per scenario is provided in supplementary materials D. The results show that in the NRLM driven scenario, a reasonable amount of combinations (9 out of 70) had a performance score of 1. This score implies that it was not possible to reduce an external factor (e.g. AW) without decreasing the NRLM or elevating another external factor (e.g. NH_3 emissions). These combinations contained ‘tube heaters’ or ‘indirect heaters with circulation’ to reduce NH_3 emissions, and a ‘heat exchanger 13% PM_{10} reduction’ or a ‘negative air ionization system’ to reduce PM_{10} emissions. Furthermore, these combinations included ‘no system change’ on AW, or a combination of ‘lower density’ (from 38 kg/m^2 to 30 kg/m^2), ‘2 types of enrichment’ and ‘daylight’. Most combinations (47 out of 70) had a performance score ranging between 0.70 and 0.99. Hence, these combinations were relatively income-efficient, i.e. mitigated the external factors at a relatively small decrease in NRLM. A relatively small amount of combinations (14 out of 70) had a performance score lower than 0.70. These combinations contained a ‘chemical air scrubber’ combined with a ‘negative air ionization system’ or an ‘ionization filter’.

Table 4
Overview of sub-indicator share restrictions per scenario.

NRLM driven	AW driven	NH_3 driven	PM_{10} driven
AW < NRLM	NRLM < AW	NRLM < NH_3 emissions	NRLM < PM_{10} emissions
NH_3 emissions < NRLM	NH_3 emissions < AW	AW < NH_3 emissions	AW < PM_{10} emissions
PM_{10} emissions < NRLM	PM_{10} emissions < AW	PM_{10} emissions < NH_3 emissions	NH_3 emissions < PM_{10} emissions

3.2. Calculation of scores for combinations in each scenario

The performance score of the combinations was analyzed for each scenario, to assess whether the best performing combinations in the NRLM driven scenario were also robust to changes of societal expectations of the external factors. A combination was considered to be best performing and robust when a score of 0.90 or higher was achieved in all scenarios. Results show that combinations that did not include system changes on AW, NH_3 emissions and PM_{10} emissions did not satisfy this criteria. For instance, combinations that did not include a system change on AW had a maximum score of 0.85 in the AW driven scenario. Combinations that included a 'chemical air scrubber' had a relatively high performance score in the NH_3 and PM_{10} driven scenario (maximum score of 1). However, these combinations performed worse in the NRLM driven scenario (maximum score of 0.68). Therefore, these combinations were not robust. Only 8 out of 70 combinations satisfied the best performing and robust criteria (Table 5). These combinations contained two or more of the following system changes related to AW: 'lower density', '2 types of enrichment' and/or 'daylight'. Furthermore, these combinations included 'tube heaters' to reduce NH_3 emissions, and a 'negative air ionization system' or an 'ionization filter' to reduce PM_{10} emissions. The best performing and robust combinations that included an 'ionization filter' performed slightly worse in the NRLM driven scenario compared to the combinations that included 'negative air ionization system'. Only the combination 'lower density + daylight', 'tube heaters' and 'negative air ionization system' had a performance score of 1 in all assessment areas (NRLM, AW, NH_3 emissions and PM_{10} emissions).

3.3. Impact on NRLM and external factors

For each best performing and robust combination, the effect on NRLM and external factors was analyzed. Furthermore, the price premium or subsidy required to compensate for the decrease in NRLM was analyzed. Table 6 shows the effect of each best performing and robust combination of system changes on NRLM and external factors, compared with the baseline system (see Section 2.1). These combinations were ranked from the best outcome to the worst outcome in terms of NRLM. The first combination included '2 types of enrichment + daylight', 'tube heaters' and 'negative air ionization system'. Results show that this combination reduced all external factors (AW, NH_3 and PM_{10} emissions) at a reasonable decrease in NRLM (−29.3%). To compensate for this decrease in NRLM, a price premium of 4.8 eurocents/broiler or a subsidy of 318.6 thousand euros was required. When comparing the second combination with the first combination, a further reduction in PM_{10} emissions was achieved by replacing 'negative air ionization system' by an 'ionization filter' (−49.4% vs. -41.4%). However, this replacement resulted in a relatively large decrease in NRLM (−54.6% vs. -29.3%). Therefore, a higher price premium (8.9 eurocents/broiler) or subsidy (569.3 thousand euros) was required to compensate for this decrease in NRLM. When comparing the fifth combination with the first combination, the system change 'lower density' (from 38 kg/m^2 to 30 kg/m^2) was included on top of the system changes imposed in the first combination. Adding this system change lowered both PM_{10} emissions and NH_3 emissions. Furthermore, this system change improved the level of AW. However, this system change caused a relatively large decrease in NRLM (−69.7% vs. -29.3%). Therefore, a substantial higher price premium (14.4 eurocents/broiler) or subsidy (767.2 thousand euros) was required to compensate for the decrease in NRLM. The eighth combination included all three AW-related system changes, 'tube heaters' and an 'ionization filter'. The combination mitigated the external factors the most and resulted in the largest decrease in NRLM (−89.7%), compared to the other best performing and robust combinations. A relatively high price premium (18.5 eurocents/broiler) or subsidy (958 thousand euros) was required to compensate for the decrease in NRLM.

3.4. Sensitivity analysis

A sensitivity analysis was carried out to test the sensitivity of the performance scores of the best performing and robust combinations (Table 5) to changes in feed price and producer price. An overview of the performance scores per scenario is provided in supplementary materials D. Fig. 3 shows the performance score of the best performing and robust

Table 5
Overview of performance score of combinations that were robust and performed relatively best.

Nr.	AW-related system change	NH_3-related system change	PM_{10}-related system change	NRLM driven	AW driven	NH_3 driven	PM_{10} driven
1.	2 types of enrichment + daylight	Tube heaters	Negative air ionization system	1.00	0.92	0.99	0.95
2.	2 types of enrichment + daylight	Tube heaters	Ionization filter	0.95	0.90	0.96	0.96
3.	Lower density + daylight	Tube heaters	Negative air ionization system	1.00	1.00	1.00	1.00
4.	Lower density + 2 types of enrichment	Tube heaters	Negative air ionization system	0.99	0.99	1.00	0.99
5.	Lower density + 2 types of enrichment + daylight	Tube heaters	Negative air ionization system	0.99	1.00	1.00	1.00
6.	Lower density + daylight	Tube heaters	Ionization filter	0.96	1.00	1.00	1.00
7.	Lower density + 2 types of enrichment	Tube heaters	Ionization filter	0.94	0.99	1.00	1.00
8.	Lower density + daylight +2 types of enrichment	Tube heaters	Ionization filter	0.94	1.00	1.00	1.00

Table 6
Overview of combinations of system changes that performed relatively best and were robust, and their corresponding effect on NRLM and external factors (changes relative to baseline system).

Nr.	AW-related system change	NH_3-related system change	PM_{10}-related system change	Δ NRLM in euro/ farm/year	Δ Welfare quality index score	Δ kg NH_3/farm /year	Δ kg PM_{10}/farm /year
1.	2 types of enrichment + daylight	Tube heaters	Negative air ionization system	−25,509 (−29.3%)	+21.2	−2123 (−65.7%)	−892 (−41.4%)
2.	2 types of enrichment + daylight	Tube heaters	Ionization filter	−47,495 (−54.6%)	+21.2	−2123 (−65.7%)	−1090 (−49.4%)
3.	Lower density + daylight	Tube heaters	Negative air ionization system	−53,164 (−61.1%)	+59.8	−2355 (−72.9%)	-1158 (−53.7%)
4.	Lower density + 2 types of enrichment	Tube heaters	Negative air ionization system	−58,495 (−67.3%)	+61.6	−2355 (−72.9%)	−1158 (−53.7%)
5.	Lower density + 2 types of enrichment + daylight	Tube heaters	Negative air ionization system	−60,663 (−69.7%)	+71.3	−2355 (−72.9%)	−1158 (−53.7%)
6.	Lower density + daylight	Tube heaters	Ionization filter	−70,522 (−81.1%)	+59.8	−2355 (−72.9%)	−1135 (−61.0%)
7.	Lower density + 2 types of enrichment	Tube heaters	Ionization filter	−75,852 (−87.2%)	+61.6	−2355 (−72.9%)	−1135 (−61.0%)
8.	Lower density + daylight +2 types of enrichment	Tube heaters	Ionization filter	−78,021 (−89.7%)	+71.3	−2355 (−72.9%)	−1135 (−61.0%)

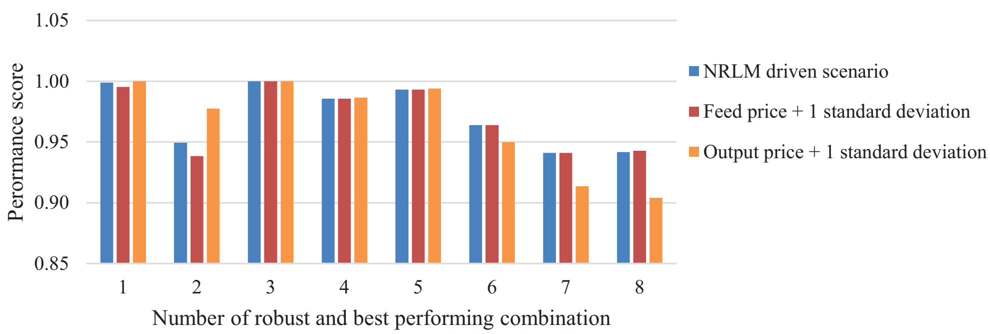

Fig. 3. Performance score of the best performing and robust combinations in the NRLM driven scenario (see Table 6), and in case of a one standard deviation increase in the feed price and producer price.

combinations per scenario. Results show that a one standard deviation increase in feed price only slightly affected the performance score of these combinations. For instance, the performance score of the second combination, which contained the system changes '2 types of enrichment + daylight', 'tube heaters' and 'ionization filter', decreased from 0.95 to 0.94. This finding can be explained by the fact that a higher amount of feed is required when rearing broilers at higher densities (floor surface area assumed to be fixed). Therefore, combinations that did not include the system change 'lower density' were more responsive to an increase in feed price. A one standard deviation increase in the producer price did not or slightly improved the performance score of combinations that did not include the system change 'lower density' (e.g. the first combination in Fig. 3). The performance score of combinations that included the system change 'lower density' decreased. For instance, the sixth combination included the system changes 'lower density + daylight', 'tube heaters' and 'ionization filter'. The performance score of this system change decreased from 0.94 to 0.91. This finding can be explained by the fact that more revenues are 'foregone' in case of higher producer prices, when lowering the stocking density (floor surface area assumed to be fixed).

4. Discussion

This paper aimed to explore the combinations of system changes that were the best in terms of NRLM and external factors, and were robust to changes in the relative importance society places in these external factors. The external factors AW, NH_3 emissions and PM_{10} emissions were chosen in this study. The results show that 8 out of 70 combinations performed well and were robust to potential changes in society's expectations relating to these external factors. All combinations that were robust and performed well included system changes on AW, NH_3 emissions and PM_{10} emissions. These combinations contained two or more of the following AW-related system changes: 'lower density' (from 38 kg/m^2 to 30 kg/m^2), '2 types of enrichment' and/or 'daylight'. In line with our findings, Vissers et al. (2021) show that these system changes improve AW in a cost-efficient manner. The system change 'lower density' resulted in a relatively large decrease in NRLM compared to the system changes '2 types of enrichment' and/or 'daylight'. This finding is in line with Verspecht et al. (2011), and can be explained by the 'foregone' revenues when rearing broilers at a lower density (floor surface area assumed to be fixed). The results show that the system change 'lower density' not only improved AW, but also lowered NH_3 and PM_{10} emissions at farm level. The latter finding can be explained by the lower number of broilers reared in the poultry house when lowering the stocking density. Hence, the system change 'lower density', caused synergy by mitigating multiple external factors (AW, NH_3 and PM_{10} emissions). However, this system change resulted in a relatively large decrease in NRLM compared to the other two AW-related system changes.

Results show that the 8 leading combinations included the system changes 'negative air ionization system' or 'ionization filter' for PM_{10} emission abatement. Cambra-López et al. (2009) found that ionization techniques are more efficient in PM removal compared to conventional technologies (filtration and adsorption). Our study shows that these techniques score highly in terms of their contribution to reducing PM_{10} emissions with a relatively small decrease in NRLM. Results show that the leading combinations included 'tube heaters' for NH_3 emission abatement. Tube heaters contribute to a lower litter moisture content by reducing the humidity in the broiler house (Dutch Ministry of Infrastructure and Water Management, 2018). The litter moisture content is also affected other factors, such as the bedding material and the management practices applied by the farmer (Van Harn et al., 2012; Wood and Van Heyst, 2016). Therefore, the NH_3 reduction efficiency of tube heaters may be affected by these factors. End-of-pipe techniques, such as chemical air scrubbers, reduce NH_3 emissions from animal houses by treating exhaust air (Melse et al., 2006). Chemical air scrubbers can achieve a reduction efficiency up to nearly 100% (Melse and Ogink, 2005). However, knowledge is required for the proper operation and maintenance of chemical air scrubbers. Lack of knowledge may greatly impact the efficiency (Wood and Van Heyst, 2016). In our study, combinations that included a chemical air scrubber performed worst, i.e. led to a relatively large decrease in NRLM. This finding can be explained by the fact that the investment costs and operational costs of scrubber systems are relatively high compared to other NH_3 abatement techniques (Melse et al., 2006). According to Dutch regulations, air scrubbers applied in animal houses should treat the entire exhaust air flow and meet the required minimum removal efficiency. However, as the maximum airflow rate only occurs for a short period of time, most of the time these scrubbers are oversized and underloaded. Melse et al. (2006) found that by combining an air scrubber with air bypass vents, a significant reduction of the investment and operational costs can be achieved while the NH_3 emission rate only slightly increases. Hence, this technique can improve the income-efficiency of air scrubbing systems considerably. Since the investment costs and operational costs of this technique were lacking, we did not consider it in our analysis. Further research is required to assess the effect of an air scrubbers with bypass vents on investment costs and operational costs.

The calculation of the NRLM and external factors had some data and model limitations, which affected the performance score of the combinations. As a deterministic model was used to calculate the NRLM, the sensitivity of NRLM to price fluctuations was not considered. To address this issue, a sensitivity analysis was carried out to test the effect of an increase in feed price and producer price by one standard deviation on the performance scores. The results show that the performance score of nearly all robust and best performing combinations was only marginally affected by an increase in feed prices. In the case of an increase in the producer price, most robust and best performing combinations that included the system change ‘lower density’ performed slightly worse compared to the default situation. Gocsik et al. (2013) show that there is a moderate positive correlation between the feed price and producer price. Since the correlation between the feed price and producer price is not taken into account, the effect of an increase in these prices on the performance score is most likely overestimated. Data on the effect of AW-related system changes (2 types of enrichment, daylight, lower density) on NH_3 and PM_{10} emissions were lacking. Vissers et al. (2021) show that these system changes affect NH_3 and/or PM_{10} emissions. This shortcoming implies that the performance score of combinations that include these system changes is most likely overestimated. However, as these system changes were applied in all robust and best performing combinations, differences between these combinations are most likely small.

The EU has recently agreed upon goals to improve the welfare of farmed animals and to mitigate the environmental burden associated with intensive livestock production systems in the next ten years (European Commission, 2020). The insights obtained from our study support the development of broiler production systems that satisfy these goals. First, our study supports the design of future broiler production systems by showing the combinations of system changes that performed relatively best and were robust to changes in society’s expectations regarding animal welfare and environmental impacts. Second, our study identifies system changes on NH_3 and PM_{10} emissions that are associated with a relatively small decrease in the NRLM. This insight is particularly relevant for EU countries that do not comply with national emission ceilings on NH_3 emissions, such as the Netherlands (European Environment Agency, 2019). Third, our study provides insights for determining the minimum price premium needed to get support for the system among the farmers. The extent to which the increase in production costs can be compensated by a higher producer price ultimately depends on consumers’ willingness to pay for more sustainable production. The Eurobarometer (2016) shows that there is a willingness to pay for more AW-friendly products among EU consumers; however, further research is required to assess consumers’ willingness to pay for products that are more AW-friendly and environmentally-friendly compared to conventional products.

5. Conclusion

This paper aimed to explore combinations of system changes that perform relatively best in terms of farm income, AW and emissions of NH_3 and PM_{10}, and are robust to changes in society’s expectations regarding animal welfare and environmental impacts. The findings from this paper indicate that there is a potential to make changes to the current production system that addresses AW, NH_3 emissions and PM_{10} emissions in an income-efficient manner. We conclude that the best performing and robust combinations included two or more of the following AW-related system changes: ‘lower density’, ‘2 types of enrichment’ and/or ‘daylight’. Furthermore, these combinations included ‘tube heaters’ to reduce NH_3 emissions and a ‘negative air ionization system’ or an ‘ionization filter’ to reduce PM_{10} emissions. The price premiums that were required to compensate for the decrease in NRLM due to implementation of the system changes ranged between 4.8 and 18.5 eurocents/broiler. The ‘best performing and robust’ combination that required the lowest price premium included ‘2 types of enrichment + daylight’, ‘tube heaters’ and a ‘negative air ionization system’. The ‘best performing and robust’ combination that required the largest price premium included all three AW-related system changes, ‘tube heater’ and an ‘ionization filter’. To test the robustness of the results, future research should focus on measuring the potential environmental benefits of changes made to the Dutch broiler production system that are primarily focused on improving AW. Future research could apply this approach to other livestock production systems to assess the potential for improving the sustainability of livestock production systems more widely.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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