Multi-Objective Optimization of an Aerodynamic Feeding System Using Genetic Algorithm

Jan Busch, Peter Nyhuis

***Abstract*—**Considering the challenges of short product life cycles and growing variant diversity, cost minimization and manufacturing flexibility increasingly gain importance to maintain a competitive edge in today's global and dynamic markets. In this context, an aerodynamic part feeding system for high-speed industrial assembly applications has been developed at the Institute of Production Systems and Logistics (IFA), Leibniz Universitaet Hannover. The aerodynamic part feeding system outperforms conventional systems with respect to its process safety, reliability, and operating speed. In this paper, a multi-objective optimisation of the aerodynamic feeding system regarding the orientation rate, the feeding velocity, and the required nozzle pressure is presented.

***Keywords*—**Aerodynamic feeding system, genetic algorithm, multi-objective optimization.

I. Introduction

THE purpose of the research for optimal parameter values in the aerodynamic feeding system is to maximise the orientation rate of workpieces in the feeding line. However, there are cases in which it can be necessary to consider parameters themselves as objectives. For instance, it is conceivable that in addition to achieving the highest possible orientation rate, it is also desired to attain minimum nozzle pressure, so as to reduce the costs of the compressed air required. Consequently, what began as a case of mono-objective optimisation has become a multi-objective nature. The aim of this paper is to show how the mathematical model of workpiece orientation in an aerodynamic feeding system, that was hitherto considered solely mono-objective, can be expanded into a multi-objective model and subsequently solved with the aid of a multi-objective genetic algorithm.

II. Multi-Objective Optimisation Using Genetic Algorithm

There are many problems in practice that are characterised by competing objectives, in which sole concentration on one objective alone leads to unacceptable results with other objectives [1], [2]. In the field of engineering science, it is common to place a focus on several objectives simultaneously [1]. In multi-objective problems, no single optimal solution exists, but only a quantity of pareto-optimal solutions, in which no objective can be improved without causing degradation of the other objectives [3].

Genetic algorithms are a popular metaheuristic, suitable for the solution of multi-objective problems [1]. Around 70% of all approaches towards solving multi-objective problems with the aid of metaheuristics are based on evolutionary methodology [1]. For example, [4] used a genetic algorithm for solving a bi-objective transportation problem. A genetic algorithm for a multi-criteria flow shop scheduling problem was proposed in [5]. In addition, in [6], i-objective optimisation was executed by minimising total wire length and failure in printed circuit board design. Moreover, [7] used a multi-objective genetic algorithm to design telecommunication networks.

In general, there are two ways of modifying algorithms with regard to multi-objective optimisation. The first involves transferring the individual objectives into a single objective function. The other is to view all objectives except for one as restrictions. Objectives are incorporated in the set of restrictions by setting relatively arbitrary upper and lower limits for each individual objective. [1] This might have an effect on the solution space, such that certain parameter combinations that would lead to a desired objective function value are excluded from the optimisation process.

According to [1], the first way, in which individual objectives are merged within a fitness function, is the classic approach to solve multi-objective problems by using genetic algorithms. Fonseca and Fleming also write that the procedure of weighting individual objectives in an aggregated objective function is a common method of solving multi-objective formulations [2]. However, it is necessary to standardise and weight the individual objectives [1]. The great advantage of this method is the simplicity of its implementation [1]. The main difference between genetic algorithms used for solving multi-objective problems and conventional genetic algorithms is the modified fitness function [1].

One difficulty encountered when modelling all objectives in a single fitness function is to select the values of their weightings [1]. It must be taken into account that even small changes in weightings can lead to strongly fluctuating results [1].

III. Mathematical Formulation of Multi-Objective Optimisation in an Aerodynamic Feeding System

The process of workpiece orientation in the aerodynamic feeding system is performed on an inclined plane with a

Jan Busch, M.Sc., is with the Institute of Production Systems and Logistics (IFA) at Leibniz Universitaet Hannover (LUH), Garbsen, 30823 GER (corresponding author; phone: +49 511 762 19808; fax: +49 511 762 3814; e-mail: busch@ifa.uni-hannover.de).

Peter Nyhuis, Prof. Dr. Ing. +habil, is with the Institute of Production Systems and Logistics (IFA) at Leibniz Universitaet Hannover (LUH), Garbsen, 30823 GER (phone: +49 511 762 3390; fax: +49 511 762 3814; e-mail: office@ifa.uni-hannover.de).

gradient α and lateral inclination β (Fig. 1).

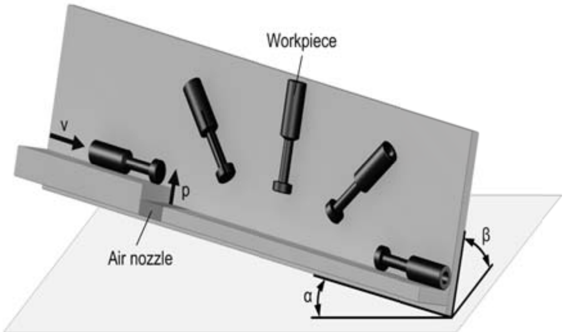

Fig. 1 The aerodynamic orientation [8]

The workpieces are fed on to the plane at a constant initial velocity v. On sliding down the inclined plane, they move past a nozzle that emits air under constant pressure p. The angular momentum induced by the air jet causes incorrectly positioned workpieces to undergo a turning motion, while correctly oriented workpieces remain in their original positions. The aerodynamic orientation process uses asymmetrical workpiece properties, such as the projected shape or locally differing flow resistances. The actual aim of aerodynamic orientation is to maximise the orientation rate. In practice, however, other scenarios are also conceivable.

Taking into consideration the cost of compressed air, the aim is to minimise nozzle pressure p as far as possible. The maximisation of nozzle pressure is therefore not considered. Furthermore, the focus is not on minimisation of velocity v. In case of the desire to achieve a lower feeding rate, this can be effected by reducing the quantity of workpieces being fed into the aerodynamic orientation process. What is relevant, however, is the maximisation of the velocity v. To avoid accumulation of the workpieces on the inclined plane, the velocity v must be correspondingly high at a high workpiece feeding frequency. All combinations involving either maximisation or minimisation of either the angle of gradient α or angle of inclination β are of no practical relevance and are therefore not considered. Accordingly, the following optimisation scenarios are conceivable:

1. Maximisation of orientation rate accompanied by minimisation of nozzle pressure p.
2. Maximisation of orientation rate accompanied by maximisation of velocity v.
3. Maximisation of orientation rate O accompanied by minimisation of nozzle pressure p and maximisation of velocity v.

Before the fitness function of the genetic algorithm for identifying optimum parameter values is adjusted, it is necessary to standardise the remaining objectives to be considered according to [1]. The value range of the orientation rate is drawn on for this purpose. The rate of orientation can take on values between 0% and 100%. Therefore, it varies within a value range of 0 to 100. Accordingly, the objectives p and v are adjusted such that their minimum/maximum values correspond with a value of 0 or 100 respectively. The settings of the nozzle pressure p vary within the range 0.22 bar to 0.28 bar. Velocity v can be set between 63 m/min and 77 m/min. The following values can therefore be assigned for the nozzle pressure p:

$$0.28\ \text{bar} \triangleq 0 \quad (1)$$

$$0.22\ \text{bar} \triangleq 100 \quad (2)$$

The anti-proportional correlation between the pressure and the value range allocated to it is explained by the fact that unlike the orientation rate, the pressure is to be minimised. Therefore, a higher standardised value for the nozzle pressure corresponds with a lower actual nozzle pressure and vice versa. The following values can be assigned for the velocity v:

$$63\ \text{m/min} \triangleq 0 \quad (3)$$

$$77\ \text{m/min} \triangleq 100 \quad (4)$$

From these correlations, it is possible to establish the following functions for standardised nozzle pressure p_N and standardised velocity v_N:

$$p_N(p) = \frac{-5{,}000}{3} * p + \frac{1{,}400}{3} \quad (5)$$

$$v_N(v) = \frac{50}{7} * v - 450 \quad (6)$$

The two terms from (5) and (6) are incorporated into the original fitness function for the maximisation of the orientation rate O determined by design of experiment [9], resulting in the following maximised multi-objective fitness function Z, in accordance with (7).

$$Max\ Z = g_O * O + g_p * p + g_v * v \quad (7)$$

g_O, g_p and g_v represent the weightings of the three objectives orientation rate O, nozzle pressure p and velocity v. Moreover, the following conditions apply to g_O, g_p and g_v.

$$(g_O, g_p, g_v) \in \mathbb{R} \mid 0 \leq (g_O, g_p, g_v) \leq 1 \quad (8)$$

$$\sum_i \mathrm{g_i} = 1 \quad (9)$$

With the aid of the function according to (7) and taking into account restrictions according to (8) and (9), it is possible to model all of the multi-objective optimisation scenarios presented in this section.

IV. Results and Interpretation of the Multi-Objective Optimisation of the Aerodynamic Feeding System

To investigate the various values of the objectives O, p and v, the respective weightings g_O, g_p and g_v are modified in steps of 0.1. For example, consideration of the orientation rate O and nozzle pressure p could lead to weightings of $g_O = 0.9$ and $g_p = 0.1$ or $g_O = 0.8$ and $g_p = 0.2$.

A. Results of the Multi-Objective Optimisation with Analytical Determination of the Orientation Rate

The results of the simultaneous optimisation of orientation rate *O* and nozzle pressure *p* are presented in Fig. 2 in a value range of $g_p = 0.1$ to $g_p = 0.9$. In accordance with (9), the value for g_O is found from $g_O = 1\text{-}g_p$. A total of 10,000 simulations were performed for each weighting ratio.

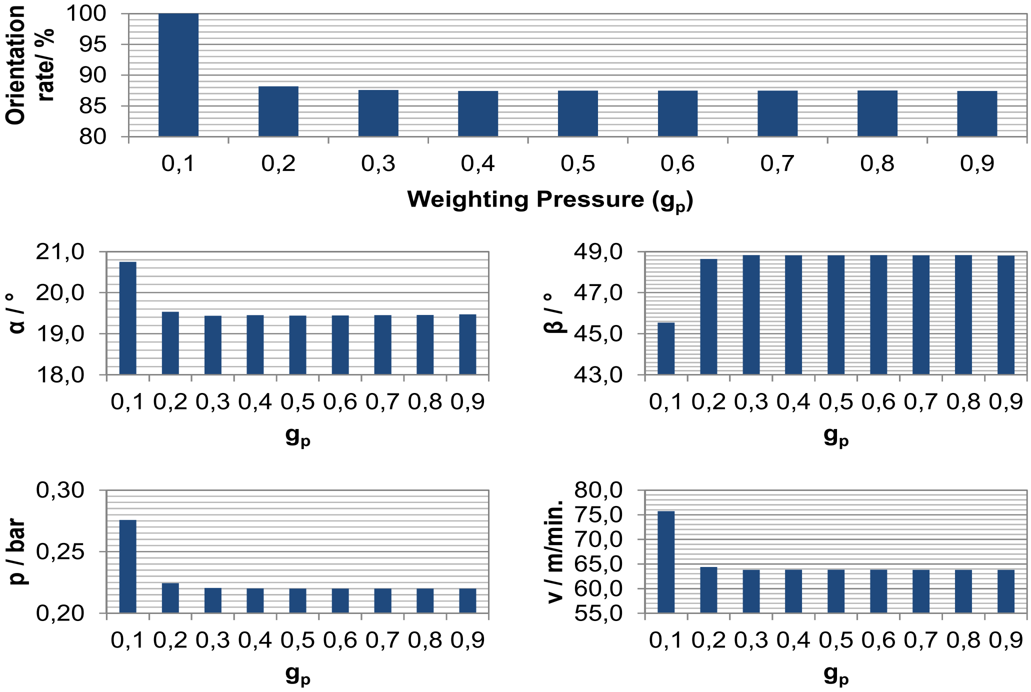

Fig. 2 Results of simultaneous optimisation of nozzle pressure *p* and orientation rate *O*

It is striking that the orientation rate does a jump from $O \approx 100\%$ to $O \approx 88\%$ when the weighting is increased from $g_p = 0.1$ to $g_p = 0.2$ and subsequently remains approximately constant when g_p is increased further. The pressure drops as expected as the weighting increases from $p \approx 0.275$ bar when $g_p = 0.1$ to $p \approx 0.224$ bar when $g_p = 0.2$ and ultimately to $p \approx 0.22$ bar when $0.3 \leq g_p \leq 0.9$. A similar progression can be observed with the velocity *v*. It falls from $v \approx 75.7$ m/min when $g_p = 0.1$ to $v \approx 64.4$ m/min when $g_p = 0.2$ and subsequently $v \approx 63.8$ m/min when $0.3 \leq g_p \leq 0.9$. The great similarities in the progression of nozzle pressure *p* and velocity *v* are due to the high level of interaction between these two parameters, as identified by [10]. Busch et al. also noted a high influence of nozzle pressure and velocity on the orientation rate [10]. This fact explains the similar progressions between nozzle pressure and velocity on the one hand and orientation rate on the other. Moreover, the two angles α and β alter significantly when $g_p = 0.1$ changes to $g_p = 0.2$. The angle of gradient a drops from $\alpha \approx 20.7°$ when $g_p = 0.1$ to $\alpha \approx 19.5°$ when $0.2 \leq g_p \leq 0.9$. The angle of inclination β rises from $\beta \approx 45.5°$ to $\beta \approx 48.8°$.

As with the drop in velocity *v*, the drop in α is due to the fact that workpieces must slide correspondingly slower over the nozzle as the nozzle pressure falls to ensure that the duration of force is sufficient to produce the angles of rotation required to effect a turn.

The increase in β can be explained by the fact that as lateral inclination increases, the proportion of the workpiece's weight that counters rotation falls. Accordingly, the increase in β ensures – as does the reduction in α and *v* – that incorrectly oriented workpieces tend towards rotation rather than remaining in their original orientation, even if the nozzle pressure is too low. However, it should be noted that the influence of the angles α and β is very slight compared to that of *p* and *v* [10]. However, despite their low impact, the results show that they should not be neglected in the optimisation process, because they attune themselves in accordance with the weighted objectives and are though important factors in maximising the objective function. For example, an increase in α and a reduction in β by 2° each, when $g_p = 0.5$ ($p \approx 0.22$ bar and $v \approx 63.8$ m/min) would produce an orientation rate of no more than 79% rather than 88%.

The results of the simultaneous optimisation of the parameters orientation rate *O* and velocity *v* are shown in Fig. 3 for the value range $g_v = 0.1$ to $g_v = 0.9$.

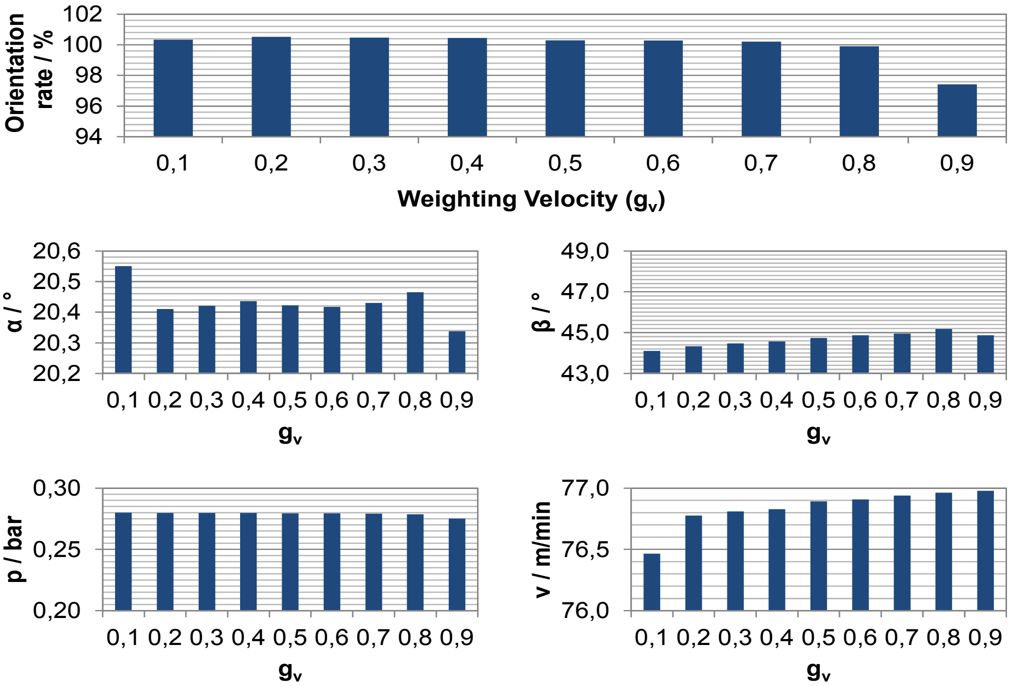

Fig. 3 Results of simultaneous optimisation of velocity v and orientation rate O

The orientation rate O varies within the range $0.1 \leq g_v \leq 0.8$ when $O \approx 100\%$. When $g_v = 0.9$, the orientation rate drops to $O \approx 97.4\%$. Velocity v rises steadily as its weighting increases from 76.5 m/min to 77.0 m/min, although with a weighting of $g_v = 0.1$, the velocity is already high. The strong correlation between velocity and nozzle pressure is also apparent from Fig. 3. Here, the high velocity leads to a constantly high nozzle pressure of $p \approx 0.28$ bar. The values of α and β vary within a smaller interval in comparison with Fig. 2. Thus, α only varies within a range of 20.34° and 20.55° and β within a range of 44.1° and 45.18°. Taking into account the lower and upper limits of a (18.4° - 22.2°) and b (39.8° - 49.6°), it is moreover apparent that both parameters are very close to the mean value of their respective ranges. This observation – that neither α nor β follows any clear or significant trends in relation to the weighting of the velocity g_v – is due to both parameters having only a small impact on the orientation rate in a simultaneous consideration of orientation rate and velocity. To observe the impact of α and β more closely in this scenario, the lower and upper limits are placed in the function determined by the design of experiment, to determine their impact on the orientation rate. With a velocity weighting of $g_v = 0.5$ ($\beta \approx 44.7°$, $p \approx 0.28$ bar, $v \approx 76.9$ m/min) setting α to 18.4° or 22.2° respectively produces a change in orientation rate of max. 0.4%. The change in β to 39.8° or 49.6° respectively when $g_v = 0.5$ ($\alpha \approx 20.4°$, $p \approx 0.28$ bar, $v \approx 76.9$ m/min) produces a maximum fluctuation in the orientation rate of 0.06%. Similar results are produced with other weighting ratios between orientation rate and velocity.

These results confirm that the impacts of the angles in a simultaneous consideration of orientation rate and velocity are very small when the nozzle pressure and velocity are close to their upper limits. In contrast, when simultaneously considering the orientation rate and the nozzle pressure, the effect of the angles α and β is larger when the nozzle pressure and the velocity take on values that are close to their lower limits. Accordingly, it can be established that the results of the design of experiment, which show that the impact of nozzle pressure and velocity is significantly larger compared to the angle settings, are confirmed by the investigations on multi-objective optimisation. Furthermore, the investigations performed in this paper show that optimisation must not neglect consideration of the angles, because they have a significant impact on the objectives when pressure and velocity have low values. It can be concluded, following the investigation of the first two scenarios, that a high level of interaction exists between the nozzle pressure and the velocity. High nozzle pressures favour high velocities and low nozzle pressures favour low velocities.

The results of the third scenario, in which maximisation of the orientation rate with simultaneous minimisation of nozzle pressure and maximisation of velocity is investigated, are presented in Fig. 4. The angles α and β will not be presented in a three dimensional diagram in relation to the weightings g_p and g_v, due to their small influence compared to nozzle pressure and velocity.

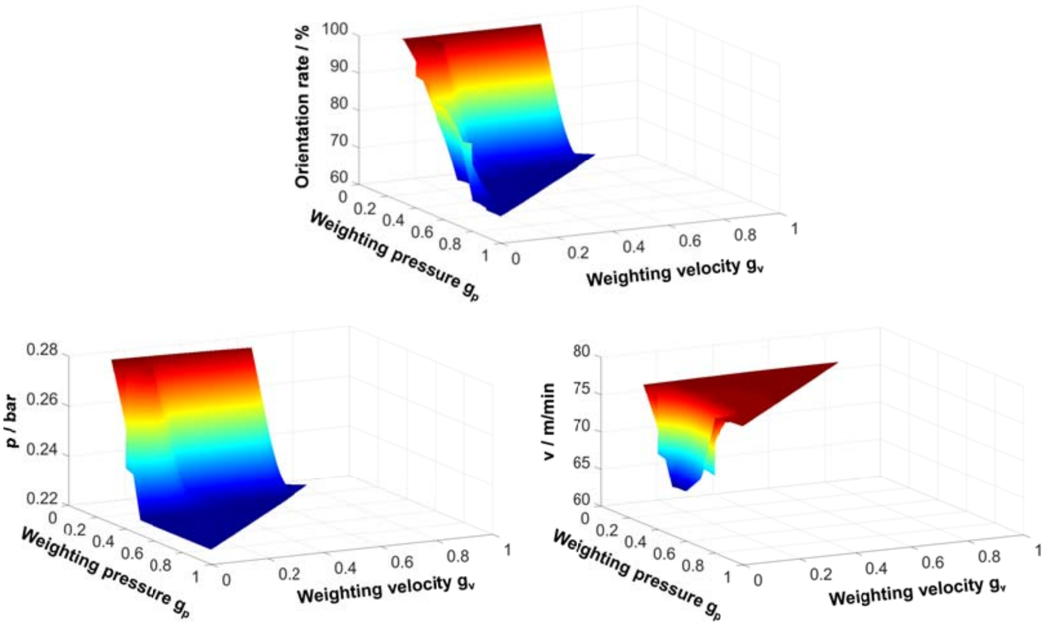

Fig. 4 Results of the simultaneous optimisation of orientation rate *O*, velocity *v* and nozzle pressure *p*

As in the first scenario considered, it can be observed that the orientation rate drops with increasing weighting of the nozzle pressure. The velocity weighting has no significant influence on the orientation rate in this scenario due to the strong interaction between velocity and nozzle pressure. The progression of nozzle pressure with respect to g_p and g_v is similar to that of the orientation rate. This fact could also be observed in the first scenario. The velocity weighting has no significant influence in this case either. The area spanned by velocity in relation to g_p and g_v shows that velocity approaches its upper limit very quickly, irrespective of the pressure weighting. In contrast to the second scenario examined, velocity takes on values close to its lower limit in this scenario when g_v is low. This effect can be explained by the simultaneous weighting of the nozzle pressure, which is not considered in the second scenario. This results in rather low nozzle pressures, which, as previously noted, also lead to low velocities.

To sum up, it can be noted that the strong influence of pressure and velocity on the orientation rate is confirmed by the third scenario examined, and that the strong interaction of these two parameters is again apparent. It is moreover apparent that nozzle pressure has a bigger impact than velocity on orientation rate. This finding was produced by performing the design of experiment [10] and was confirmed by the investigations presented here. In addition, it is apparent that when simultaneously considering velocity and nozzle pressure with a respective weighting of $0.3 \leq g_p, g_v < 0.5$ and a weighting in accordance with (9) of less than 0.4, the orientation rate achieves no values above 70%. This observation can be explained by the findings made in the first two scenarios. There, it was shown that high nozzle pressures favour high velocities and that low nozzle pressures favour low velocities. Simultaneous optimisation with higher respective weightings of both parameters excludes such combinations with a simultaneously high orientation rate, however. This is why the orientation rate is always under 70% in the range of the given weighting ratios. Only with the orientation rate weighting $g_O \geq 0.6$ the orientation rate does make a sudden jump to 100%, as a result of the simultaneous increase in nozzle pressure and velocity.

B. Results of Multi-Objective Optimisation with Simulated Determination of the Orientation Rate

In Section IV *A*, the values for the orientation rate were determined by means of the fitness function obtained in the design of experiment. In this section, the orientation rate will be identified by means of the existing simulation environment, and the results discussed briefly compared to those of the Section IV *A*. Sole concentration on the results obtained from the fitness function in the design of experiment would mean that they are strongly affected by the interactions between the individual parameters that are determined in the course of the design of experiment and can be found in the resulting fitness function. Against this background, all the experiments will now be presented once again, this time on the basis of an orientation rate determined by simulation. Due to the duration of the simulations, only ten experiments per weighting ratio are performed. The results for scenario 1 are show in Fig. 5.

As with the analytical determination of the orientation rate, here too, the angle of gradient α settles at a mean value of 19.5°. However, in this case, there is no sudden drop in the transition from a g_p of 0.1 to 0.2. As g_p increases, so does β increase, and the nozzle pressure p drops. The very similar progression of nozzle pressure and velocity is however no longer visible in Fig. 5. However, as in Fig. 2, velocity assumes comparatively low values. The drop in orientation rate as g_p increases is also visible. What is striking is the very strong drop in the orientation rate to values close to 50% from a pressure weighting of $g_p \geq 0.4$, in conjunction with a reduction in nozzle pressure. Accordingly, it is apparent that in the simulation, there is a strong correlation between nozzle pressure and orientation rate.

The results obtained by simulation for scenario 2 are presented in Fig. 6. It can be seen that the nozzle pressure is constantly very close to its upper limit, as in Fig. 3. Again, the velocity approaches its maximum value of 77 m/min as g_v increases. The angle of gradient α shows no significant trend, as in Fig. 3. The angle of inclination β increases slightly as g_v increases and varies within a very small interval, as with the analytically determined orientation rate. It is striking that the orientation rate drops very strongly as the velocity weighting g_v increases. Therefore, it can be noted that low orientation rate weightings g_O have a bigger effect in the simulation than in the analytically determined orientation rate.

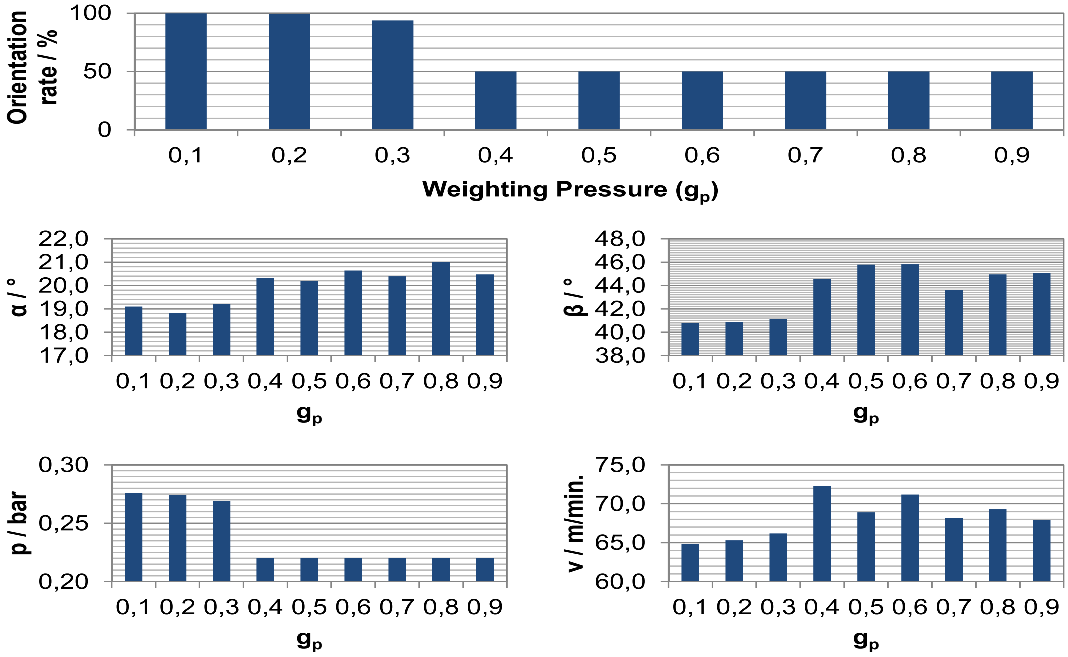

Fig. 5 Results of simulated optimisation of nozzle pressure p and orientation rate *O* with simulated determination of orientation rate *O*

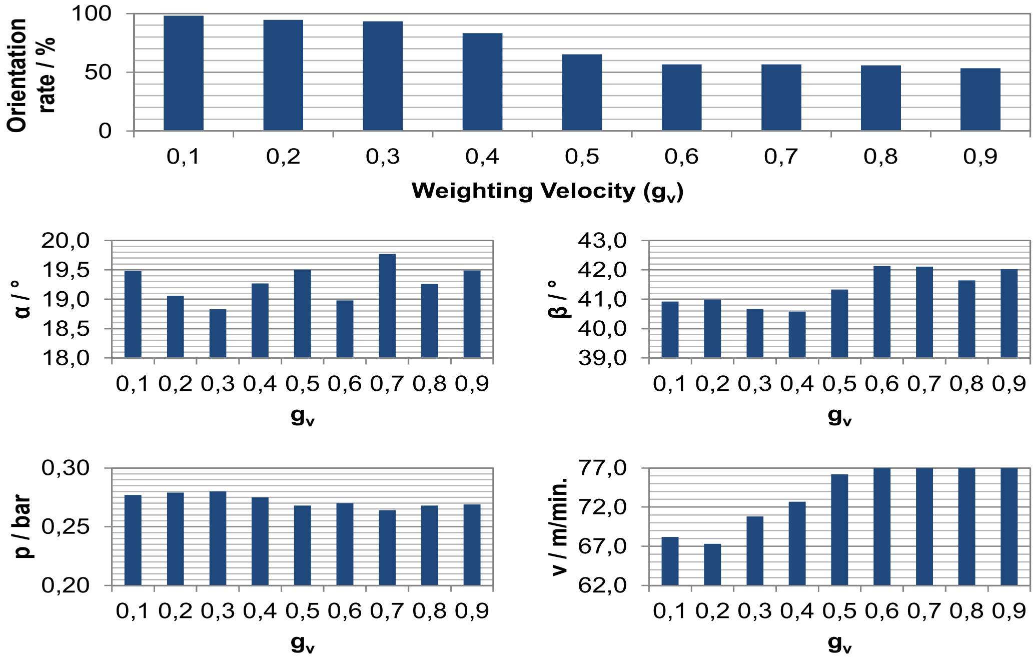

Fig. 6 Results of simulated optimisation of velocity *v* and orientation rate *O* with simulated determination of orientation rate *O*

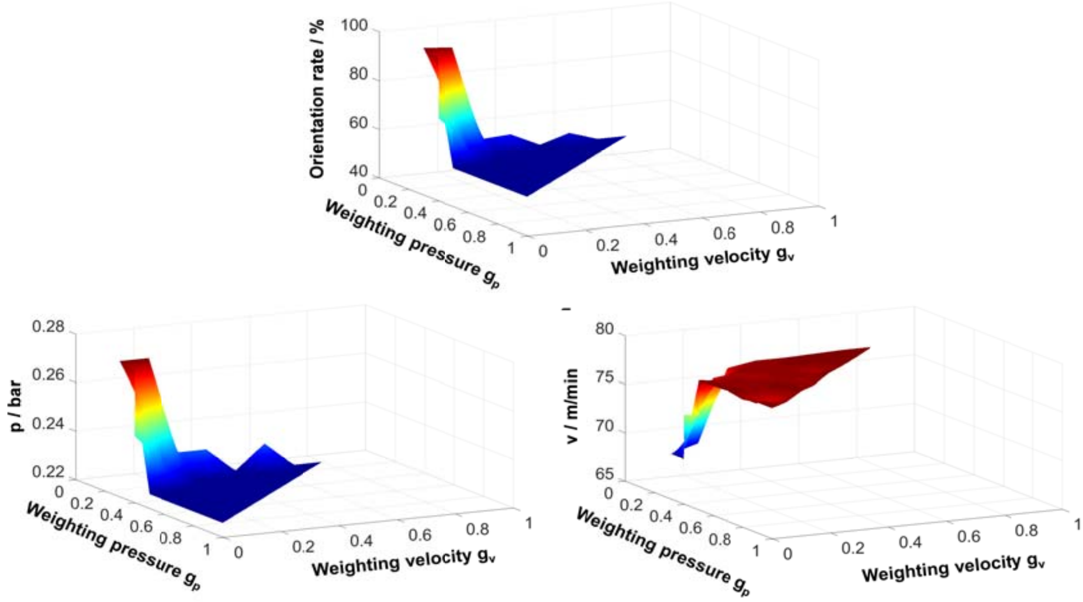

Fig. 7 Results of simulated optimisation of orientation rate (*O*), velocity (*v*) and nozzle pressure (*p*) with simulated determination of orientation rate (*O*)

The results of the simultaneous observation of nozzle pressure, velocity and orientation rate are presented in Fig. 7. As in Fig. 4, the orientation rate *O* falls with increasing nozzle pressure weighting and the velocity weighting has no significant influence on the nozzle pressure or orientation rate. The very similar progression between the spanned area of the orientation rate and nozzle pressure in relation to the weightings g_p and g_v can again be determined in Fig. 7. Velocity again quickly approaches its upper limit as the weighting g_v increases and takes on relatively low values when g_p is low. The biggest difference to Fig. 4 is that the nozzle pressure and accordingly the orientation rate have very low values when $g_p = 0.1$. In Fig. 4, nozzle pressure has a value of $p \approx 0.28$ bar with a weighting of $g_p = 0.1$. In Fig. 7, in contrast, it is close to its lower limit. Not even when increasing the weighting g_v, there is an increase in the values for *p*. This, together with the observation that no similarity in the progression of nozzle pressure and velocity can be determined in Fig. 5, leads to the conclusion that in the simulation the interaction between velocity and nozzle pressure is not as strong as it is in the orientation rate function determined by the design of experiment.

All in all, many similarities but also many differences can be noted when comparing the analytical orientation rate with the one determined analytically with respect to multi-objective optimisation. The differences may be due to the very small random sample used in determining the orientation rate by simulation. Furthermore, some of the assumptions made in the simulation model may have produced differences in the results. It should also be taken into account that the function for calculating the orientation rate as determined in the design of experiment is approximated in relation to the four parameters of the feeding system on the basis of a few selected parameter combinations [10] and is therefore afflicted by inaccuracies. Nevertheless, there are no significant contradictions between the two methods of investigating multi-objective optimisation of the aerodynamic feeding system described. Therefore, it can be assumed that trends in the impacts of individual parameters, interactions between parameters and effects of different weightings of the parameters under consideration as presented will be displayed in similar form in reality.

V. Conclusion and Outlook

This paper focuses on the multi-objective optimisation of workpiece orientation in an aerodynamic feeding system using a genetic algorithm. Besides maximisation of the orientation rate, minimisation of the nozzle pressure necessary required for orientation to decrease costs is considered along with maximisation of the feeding velocity. The investigations were performed for two and for three simultaneously observed objectives. The results show a strong positive correlation between nozzle pressure and feeding velocity. If nozzle pressure is minimised while velocity is simultaneously increased, the orientation rate worsens considerably.

In further research activities, the multi-objective genetic algorithm will be implemented in the control unit of the real-life system.

Acknowledgement

The authors would like to thank the German Research Foundation (DFG) for their financial support of the research project NY 4/51-1.

References

[1] Konak, A.; Coit, D. W.; Smith, A. E. (2006): Multi-objective optimization using genetic algorithms. A tutorial. In: *Reliability Engineering & System Safety* 91 (9), S. 992–1007.

[2] Fonseca, C. M.; Fleming, P. J. (1998): Multiobjective optimization and multiple constraints handling with evolutionary algorithms. I. A unified formulation. In: *IEEE Trans. Syst., Man, Cybern. A* 28 (1), S. 26–37.
[3] Belyaev, A.; Maag, V.; Speckert, M.; Obermayr, M.; Küfer, K.-H. (2015): Multi-criteria optimization of test rig loading programs in fatigue life determination. In: *Engineering Structures* 101, S. 16–23.
[4] Gen, M.; Ida, K.; Li, Y.; Kubota, E. (1995): Solving bicriteria solid transportation problem with fuzzy numbers by a genetic algorithm. In: *Computers & Industrial Engineering* 29 (1-4), S. 537–541.
[5] Murata, T.; Ishibuchi, H.; Tanaka, H. (1996): Multi-objective genetic algorithm and its applications to flowshop scheduling. In: *Computers & Industrial Engineering* 30 (4), S. 957–968.
[6] Deb, K.; Jain, P.; Gupta, N. K.; Maji, H. K. (2004): Multiobjective Placement of Electronic Components Using Evolutionary Algorithms. In: IEEE Trans. Comp. Packag. Technol. 27 (3), S. 480–492.
[7] Kumar, R.; Parida, P. P.; Gupta, M.: Topological design of communication networks using multiobjective genetic optimization. In: 2002 World Congress on Computational Intelligence - WCCI'02. Honolulu, HI, USA, 12-17 May 2002, S. 425–430.
[8] Busch, J.; Quirico, M.; Richter, L.; Schmidt, M.; Raatz, A.; Nyhuis, P. (2015): A genetic algorithm for a self-learning parameterization of an aerodynamic part feeding system for high-speed assembly. In: *CIRP Annals - Manufacturing Technology* 64 (1), S. 5–8.
[9] Busch, J.; Knüppel, K. (2013): Development of a Self-Learning, Automatic Parameterisation of an Aerodynamic Part Feeding System. In: *AMR* 769, S. 34–41.
[10] Busch, J.; Schneider, S.; Knüppel, K.; Nyhuis, P. (2013): Identifying interactions in a feeding system. In: International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering 10, S. 931–937.