DEGREE PROJECT, IN MACHINE DESIGN , SECOND LEVEL
STOCKHOLM, SWEDEN 2015

Auto tuning of a vacuum conveyor

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Autotuning of a vacuum conveyor

KTH Industrial Engineering and Management

Master of Science Thesis MMK 2015:73 MDA 507

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Abstract

The modern industry is steadily facing new demands for more energy efficient solutions. These improvements can come from technological advances, using existing technology smarter or a combination of the two. Today a vacuum conveying system is manually tuned for each factory application when installed and is in most cases not handled afterwards except for maintenance reasons. This in combination with the difficulties in tuning a system to run efficiently and robustly whilst offering high capacity indicates that a large number of systems are running with non optimal settings. The aim of this thesis was therefore to explore the possibility of introducing an auto tuning property to the vacuum conveying system and investigate the possible benefits. This thesis has investigated two main components for such an auto tuner, the system design and optimisation strategy. The system design is critical for allowing process control and monitoring. In the optimisation the main challenge was to robustly produce good results for a wide variety of materials. Based on this a laboratory system was developed that monitored the capacity, efficiency, gentleness and robustness performance of the conveying. This information was then used in an evolutionary optimisation algorithm based on differential evolution to find the best settings for optimal performance.

The results of this thesis indicate that such a system would offer benefits both in terms of initial tuning and run-time performance. The suggested auto tuner is adaptable to a large set of materials with varying material properties and demands on the conveying process. The time required for the laboratory rig to optimise within a region with only small deviations in performance is comparable to that of a human operator. Also with the added benefit of never having to stop the optimisation process, thus constantly improving performance and counteracting environmental changes.

Keywords: Vacuum conveying, Auto-tuning, Differential evolution, Conveying control, Mechatronics.

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Sammanfattning

Den moderna industrin möter ständigt nya krav på ökad effektivitet. Dessa förbättringar kan komma utifrån tillämpning av ny teknologi eller bättre utnyttjande av befintlig teknologi eller en kombination. Idag när en vakuum transportör installeras finjusteras den manuellt för att uppnå önskad prestanda och hanteras därefter ofta inte bortsett från underhållsarbete. Detta i kombination med svårigheten att justera ett system så att det går effektivt och robust samtidigt som en god kapacitet upprätthålls föranleder slutsatsen att många system ute i industrin inte presterar optimalt. Målet med detta examensarbete var därför att utreda möjligheten att skapa en automatisk system inställare samt utvärdera de möjliga fördelarna och nackdelarna. Arbetet har undersökt två huvudkomponenter i en sådan automatisk system inställare, system design och optimerings strategi. System design var vital för att tillåta styrning och monitorering av systemet och optimerings strategi för att tillförlitligt kunna prestera goda resultat trots skiftande beteende med olika material i systemet. Baserat på detta utvecklades en laboratorie-utrustning som övervakade kapacitet, effektivitet, robusthet och försiktighet i varje transportcykel. Denna information nyttjades sedan i en evolutionär algoritm baserad på differentierad evolution för att finna de optimala system-inställningarna.

Arbetet indikerar att ett sådant system skulle erbjuda prestanda-fördelar både i driftsättande och kontinuerliga driften av en vakuum-transportör. Den föreslagna automatiska system inställaren kan anpassas till en stor mängd material och skilda krav på önskat driftläge för systemet. Tiden för att optimera systemet så att de större variationerna i prestanda uppnås är jämförbar med en mänsklig operatör men kan fortlöpa över tiden och ständigt söka förbättringar på ett sätt som ej är möjligt för en mänsklig operatör.

Nyckelord: Vakuum transportör, Auto tuner, Diferentierad evolution, Transportör styrning, Mekatronik.

Acknowledgements

I would like to extend my gratitude towards everybody who made this thesis possible. First of all my supervisors Fredrik and Baha from KTH and Piab AB. From Piab Gustav has contributed with his patience with though questions and Sai-Kit with new perspectives on tricky problems.

Then I would also like to mention my girlfriend Sandra for being that constant positive force that makes any obstacle easier.

Last but not least I would also like to mention my main inspiration during this education being my grandfather Lars.

Stockholm, 06 2015

Nomenclature

A	Area $[m^2]$
m	Mass [Kg]
n_0	Relation between material and air speed in the pipeline
p	Pressure [Pa]
R	Gas constant
T	Temperature [K]
t	Time [s]
V	Volume $[m^3]$
v	Speed $[\frac{m}{s}]$

Glossary

Arduino DUE A board of the open source electronics project Arduino. vii

HIL Hardware In the Loop. A testing equipment that runs in real-time on the specific plant with both hardware and software. vii

Matlab Computational software from Math-works. vii

PID A standard controller strategy used in the industry. P stands for proportional, I for integral and D for derivative feedback. vii

PM Piab's power rating specified for each pump. vii

Pneumatic conveying The process of conveying raw or finished materials using air as energy medium. vii

Simulink Simulation software for Matlab. vii

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Introduction

Conveying is the process of moving material between specified points and pneumatic conveying is the process of conveying with air pressure as energy medium [8]. Pneumatic conveyors can be divided into two main types of systems. Pressure type systems that utilize air pressures above atmosphere and thus pushes the material in the pipeline. Vacuum system based on suction of the material in the pipeline with pressures below atmosphere in the receiving end.

Today Piab AB manufactures and sells vacuum conveying equipment for a wide range of applications in terms of transported materials. All control of the system is handled by pneumatic timers that sets the system behaviour over time and manual ball-valves that determines the flow characteristics for both air and material. Today when a new equipment is installed at a factory all controls are tuned to give a system that works in the desired manner and these are often not tuned to adapt to changes in the environment of the system or the material being transported. In addition factories often wish to have the same type of equipment to transport different materials for convenience purposes leading to equipment running in sub-optimal conditions if it is operational at all.

1.1 Background

Starting up and tuning a vacuum conveying system is by knowledgeable users sometimes referred to as a special art. A number of different settings in the system are to be considered to achieve a stable and secure, yet efficient set up of the system. Together with environmental aspects such as humidity and temperature as well as quality of different material batches of the same material and the batch cycling timing are some of the challenges that are to be considered creating the “Auto Tuning” system.

1.2 Purpose

The purpose of the master thesis is to produce a prototype equipment based on one of Piab current conveyors and to answer a number of research questions related to the prototype. The research questions to be answered are:

- Could auto-tuning be realised, by means of a working prototype setup?
- How should the effect of external disturbances be counteracted and the risk of complete stop in the conveying process minimized?
- Can the system given a reasonable guess of initial system settings optimize the process with regards to robustness, capacity and efficiency?

1.3 Delimitations

The thesis aims to fulfill the demands the questions described above in purpose, although boundary's for the scope have also been identified. Firstly the aim of this thesis is a study regarding the stated research questions, the transformation into a product shall not be a part of the work carried out. Secondly, cost of components and their manufacturing possibilities shall not be evaluated but the technology they are based upon shall be available to the industrial application.

1.4 Method

The method used for this thesis shall initially focused on understanding the theory of operation for the vacuum conveyor and running the system to build an understanding for the entire process of conveying. The main focus will be to determine important parameters to control and measure. Information shall also be gathered from the larger field of pneumatic conveying and the applicability evaluated.

Following this a laboratory system is to be designed, manufactured and tested. The process will be described in the implementation section. Firstly the optimisation algorithm shall be tested in simulations based on data collected from the HIL-rig. The system shall then subjected to a predetermined set of material chosen to represent a wide variety of materials and the performance monitored.

Finally the performance data shall be evaluated regarding differences in simulations and real-life tests as well as general performance of the system.

1.5 Report outline

This report starts with determining a frame of reference, where the theoretical base forming the foundation for this thesis is described. After this follows implementation where the theories described in frame of reference is implemented into the test-rig developed for this thesis. Verification subjected the developed test-rig for a predetermined set of tests, firstly data gathering aimed at allowing simulations of optimisation and secondly at running the optimisation algorithm. Following these sections, discussion and conclusions addressing the consequences of the results achieved will be carried out. Lastly future work will end the report and describes suggested future actions to enhance or improve the outcome of this thesis.

Theoretical Framework

2.1 Mass flow of air through ejector pump

Today Piabs core competence lies within the design, manufacturing and sales of multi-stage vacuum ejectors. Vacuum ejector technology is based upon nozzles that accelerate the air travelling through it and thus decreasing the pressure and by placing an inlet at the narrowest where the pressure is at a local minima a vacuum pump will have been created. By stacking these in parallel higher air flow performance can be achieved. An overview of the layout of a vacuum ejector is shown in Fig. 2.1

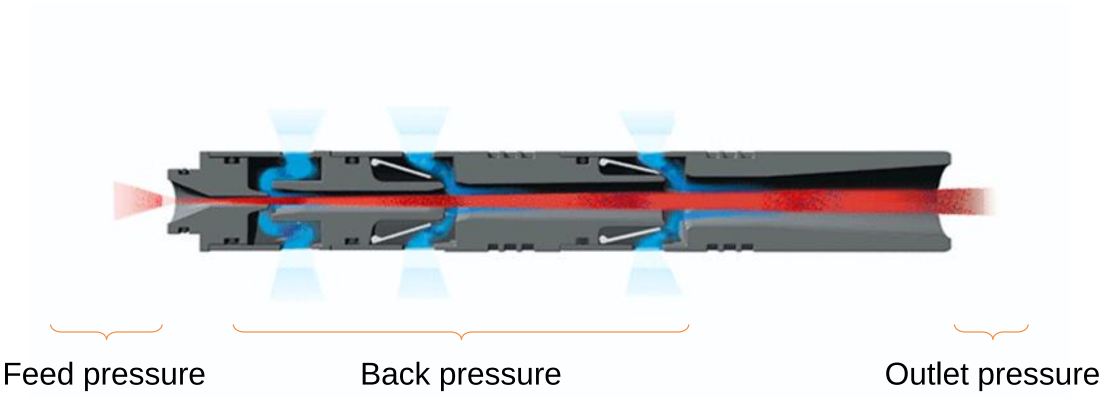

Figure 2.1: Section view of a multi-stage vacuum ejector, showing the different pressure regions

The air flow performance that is of interest in this study depends upon the differences between feed , outlet and back pressure of the ejector. Feed pressure is present at the intake of the ejector whilst outlet is defined as the point of exhaust. Back pressure is the pressure present at the vacuum inlet. The outlet pressure is by definition always assumed to be atmospheric pressure and thus the feed pressure determines the flow through the ejector. Pressure close to atmospheric at the vacuum intake will give a large difference to that inside the ejector and give a high air flow through the intake, the closer the back pressure comes to that given by the air-flow induced pressure in the narrow part of the ejector the lower the resulting air flow becomes. A higher feed pressure will result in a higher air speed in the ejector, thus giving a lower pressure in the narrow part.

The vacuum ejector or often referred to as cartridge mostly used in conveying applications is SI-32 presented in appendix A. This is due to a good balance between high flow rates at low vacuum levels and the ability to reach relatively high vacuum levels. The pump used in this study is a PiPremium 200 consisting of 16 stacked SI-32 cartridges. The performance data originates from measurements from a number of operational cases as described in the data sheet shown in appendix A where flow data from different driving pressures and vacuum levels can be observed.

2.2 Flow characteristics in conveying, material flow phases, v_{air} and pressure drop

At first the ideal gas law [10] was used to describe the air flow in the system as can be observed in Eq. (2.1).

$$p \cdot \dot{V} = \dot{m} \cdot R \cdot T \tag{2.1}$$

$$\frac{p \cdot \dot{V}}{T} = Constant \tag{2.2}$$

The conveying process can also be approximated to a isothermal process [1] where the mass is preserved resulting in a mathematical description of the air behaviour as in Eq. (2.5).

$$T_1 = T_2 \tag{2.3}$$

$$R \cdot T_1 = R \cdot T_2 \tag{2.4}$$

$$p_1 \cdot \dot{V_1} = p_2 \cdot \dot{V_2} \tag{2.5}$$

$$1, 2 \quad are \quad arbitrary \quad points \quad in \quad the \quad conveying \quad system$$

Performance of all ejector pumps are normalized using Nl/s to allow for easy comparison, Nl/s is defined as $litres/s$ given atmospheric pressure $p_{atm} = 101325Pa$ and a constant temperature of $20°C$. Using Eq. (2.5) results in the Eq. (2.8) describing the airspeed v_{air} at a given point 2 if point 1 is defined as being at the sender and thus at atmospheric pressure.

$$v_{air} = \dot{V_{air}}/A_{air} \tag{2.6}$$

$$v_{air} = Nl/s \cdot \frac{p_2}{p_1} \cdot \frac{1}{A_{air}} \tag{2.7}$$

$$v_{air} = Nl/s \cdot \frac{p_2}{p_{atm}} \cdot \frac{1}{A_{air}} \tag{2.8}$$

$$A = A_{air} + A_{material} \tag{2.9}$$

$[Nl/s]$ is converted to $[m^3/s]$ by p_2/p_{atm} multiplication and thus the airspeed in a given point can be calculated according to Eq. (2.9). As is evident from Eq. (2.9) the area of flow A_{air} has a large impact upon v_{air} and for the same amount of flow the speed will differ based upon the material content in the pipeline. Also worth noting is the increase of $\dot{V_{air}}$ in the pipeline, as the pressure in the pipeline goes from approximately atmosphere at the sending station to operating vacuum level of the pump. This will result in that the maximum air speed will be present at the end of the pipeline given that the material concentration in the pipe remains constant.

The pressure drop over a section of pipeline can be determined according to both the air flow and material resistance against movement. Bends will have a large impact on the performance of a conveying system, this due to the fact that they give rise to pressure drops and thus limits conveyor performance due to saturation of the pump. The pressure drop over a bend can be attributed not to the actual drag on the air caused by the bend but the re-acceleration of particles after the bend [3]. The cause of this is that the particles inertia prevent them from turning fast enough and they therefore hit the wall of the bend and then lose their momentum, this leads to increased drag between air and particles, thus resulting in increased pressure drop. Therefore the pressure drop does not occur in the bends but instead in the following sections, although the root cause still remains the bend. Thus bends will only have a marginal impact on the pipeline if only air is passing through but the influence will increase if the material content is increased.

2.3 Stability of flow regime and pickup speed characteristics

According to literature the saltation velocity is defined as the air velocity when particles start to leave the suspended flow and settle on the bottom [12]. The saltation velocity can also be viewed as the border between dense and dilute phase flow [12] of the entire pipe cross-section . When saltation occurs and a static layer of particles is formed at the bottom the air will occupy a smaller area and thus the air speed will increase and possibly increase above the saltation speed and thus initiating dilute flow. This will often produce system that naturally oscillates between different modes of flow as the airspeed goes up as plugs are formed and thus promoting dilute flow, creating a cyclic behaviour.

2.4 Dilute and dense phase flow characteristics

In conveying two main forms of material flow exists. These are dilute and dense phase that are used for different purposes and materials [8]. The phases and the gradual transition between is visualised in Fig. 2.2.

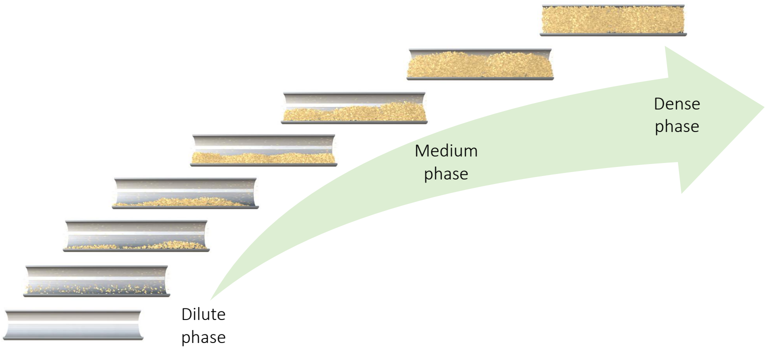

Figure 2.2: The two main phases of material flow possible in a vacuum conveyor and the gradual transition between

However they can be formed in the same equipment and in some situations even coexist within different sections of the system.

The main parameters that determines what kind of flow that is possible and likely to form will depend upon the material and its interaction with the conveying equipment but the air speeds relation to the saltation velocity and material concentration are highly influential [16]. Dense phase constitutes relatively low speed of conveying and high material concentration that is not evenly distributed in the pipeline, the particles are not free flowing in air but constantly in contact with other particles or the pipe-line walls [8]. Dilute phase sometimes referred to as storm phase on the other hand requires velocities higher than the saltation velocity for the give material and lower concentration of material thus resulting that the material is suspended in the air-flow [8] [16].

2.4.1 Dilute phase flow characteristics

Dilute phase conveying is characterised by the air speed being higher than the saltation velocity and the material flowing suspended in the air. The pressure variations are low in the pipeline due to small variations in material concentrations. Frequent crashes between particles as well as particles and wall can lead to problems with degradation of material and wear on equipment. This is the mode of transport that is possible for the largest variation of materials due to the free flowing nature of the particles is possible for all kinds of particles [16]. The limitations regarding possible material originates from the equipments limitations such as pipe dimensions, feeding openings, air speed possible etc.

Dilute phase is characterised by being a highly robust mode of transport since their is low risk of stops due to that the particles are constantly suspended in the flowing air. The efficiency will often be lower than dense phase because of the ratio between material and air will be lower. This will also imply that for most materials where both phases are possible the capacity will be lower in dilute phase since the same pump limitations applies [8]. Generally the efficiency of a system running dilute phase will be low due to large quantity of air needed to suspend and transport the material.

2.4.2 Dense phase flow characteristics

Not all materials are possible to transport in dense phase, the determining characteristics for this is mainly the gas diffusion and the cohesive properties of the material [15] . If these parameters are not suitable for dense-phase the pipeline will be blocked for velocities below the saltation velocity and no material transport occur. The dense phase flow can in turn be divided in two main modes of flow being moving bed flow and plug type flow [15].

Moving bed flow consists of a settled layer of material on the bottom of the pipe and wave formations on the top, thus all the material in the pipeline is gradually moving along the pipe.

Plug type flow is defined as plugs of material travelling in the pipeline covering the entire cross-sectional area. While these plugs are maintained in the conveying process they will have a speed that is closely related to the air speed of the system and the permeability of the material itself. These two subgroups within the dense phase does not have a distinct limit at which one is said to abruptly change to the other. Instead they are viewed as which characteristics are more prominent along a sliding scale.

2.5 Mass flow rates and flow regimes estimation in the conveying system

The flow of material in a conveying system can be estimated in several different ways. Some of these available technologies are load cells, level detectors, ECT sensors and pressure transducers [5], [2], [9].

Load cells measures the weight of the material that was transported by either measuring the weight loss at the sending station or the added weight at the receiving station or a combination of the above two. This is a robust measurement that has been used for a long time in the industry but measurements hard to make available at points in time other than the end of each cycle due to vibrations [2].

Capacitive sensor another technology that is widely spread in the industry but mostly used as level detectors in low turbulence zones such as receiving vessels where the material observed is approximately static and low levels of disturbance expected. The capacitive sensors differs from the load sensors in that the measured quantity is volume opposed to mass [18].

ECT sensors are still quite complex to set up and operate so that the information can improve the conveying cycle. The information gathered describes exactly how the material is distributed in the pipeline, thus it is mostly used in advanced systems used in large installations or by the academia due to the large knowledge needed to maintain such a plant [19].

Pressure sensors are widely used by all branches of the industry and they accurately describes how the system is currently operating, pressure variations can strongly indicate the type of flow present but so far has not been able to accurately enough predict the material content to be used as limit switch in a general application [21].

2.6 Material speed

When determining how gentle the conveying cycle one of the main considerations is how fast the material is travelling in the pipeline. A low speed indicates that any collisions would be low energy and thus small risk of degradation. An estimator for the material speed that gives estimated limits for the speed was therefore developed. The estimator is based upon that the material is travelling relative to air (2.6) and that it occupies a section of the pipeline as seen in Fig. 2.3. In the Fig. material is visualised as occupying a certain section of the cross section which is reasonable for dilute phase transport, however if material is transported in dense phase this will not hold true. Instead the picture should be viewed as a time-average over a larger time span, for example a conveying cycle.

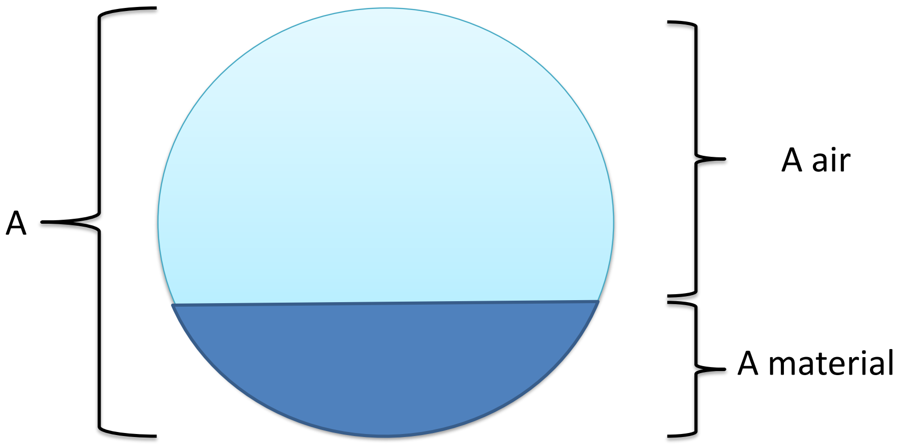

Figure 2.3: Area components between material and air averaged over time in the pipe-line

To develop this estimator a number of basic assumptions were made and can be seen below in Eq.s (2.10)-(2.15).

$$A = A_{air} + A_{material} \tag{2.10}$$

$$\dot{V}_{material} = \frac{V_{batch}}{t_{batch}} \tag{2.11}$$

$$\dot{V}_{air} = Nl/s \cdot \frac{p}{p_{atm}} \tag{2.12}$$

$$v_{material} = \frac{\dot{V}_{material}}{A_{material}} \tag{2.13}$$

$$v_{air} = \frac{V_{air}}{A_{air}} \tag{2.14}$$

$$v_{material} = n_0 \cdot v_{air} \tag{2.15}$$

$$0 \leq n_0 \leq 1 \quad \text{due to permeability}$$

Thereafter a relation between area occupied and volumetric flow was developed, still

n_0 exact value is not known.

$$(2.15)(2.14)(2.6) \mapsto$$

$$\frac{\dot{V}_{material}}{A_{material}} = n_0 \cdot \frac{\dot{V}_{air}}{A_{air}} \tag{2.16}$$

$$\frac{A_{air}}{A_{material}} = n_0 \cdot \frac{\dot{V}_{air}}{\dot{V}_{material}} \tag{2.17}$$

$$(2.10)(2.17) \mapsto$$

$$\frac{A - A_{material}}{A_{material}} = n_0 \cdot \frac{\dot{V}_{air}}{\dot{V}_{material}} \tag{2.18}$$

$$A_{material} = \frac{A}{1 + n_0 \cdot \frac{\dot{V}_{air}}{\dot{V}_{material}}} \tag{2.19}$$

Using the Eq.s above the material speed $v_{material}$ can be deduced below.

$$(2.10)(2.19) \mapsto$$

$$v_{material} = \frac{\dot{V}_{material}}{\frac{A}{1+n_0 \cdot \frac{\dot{V}_{air}}{\dot{V}_{material}}}} \tag{2.20}$$

By inserting the limits of n_0 the theoretical limits of material speed can be estimated.

$$(2.20)(2.15)(2.11)(2.12) \mapsto$$

$$\frac{V_{batch}}{A \cdot t_{batch}} \leq v_{material} \leq \frac{V_{batch}}{A \cdot T_{batch}} + Nl/s \cdot \frac{\frac{p}{p_{atm}}}{A} \tag{2.21}$$

By definition Eq. (2.21) is based upon averaging over a larger time in order for mainly Eq. (2.10) to be correct. As can be observed in (2.21) the estimator will give a large span for dilute phase conveying due to it mostly relying on air drag and thus giving a wide span of material flow speed. The estimator will instead be more precise for dense phase transport as plugs have a lower air permeability that free flowing particles and thus travelling at a closer rate to the air. It can also be noted that the lower bound will be unrealistic for most materials as it is based on the assumption that the material has travelled as a solid piece within the pipeline.

2.7 System performance

The capacity of a given conveying system can be represented by Eq. (2.22) according to the literature [6].

$$G = \frac{P_t}{R} \tag{2.22}$$

$$G = massflux[Kg/s]$$

$$P_t = Difference \quad in \quad pressure \quad over \quad system \quad [Pa]$$

$$R = Conveying \quad resistance$$

Today Piabs early estimation [7] of the required conveying system is based on their PM number that describes the power rating and is defined in Eq. (2.23) below.

$$PM_{number} = \dot{M} \cdot L_{distance} \tag{2.23}$$

$$\dot{M} = \frac{PM_{number}}{L_{distance}} \tag{2.24}$$

$$\dot{M} = mass \quad flow[tonnes/h]$$

$$L_{distance} = effective \quad length \quad compensated \quad for \quad bends \quad [m]$$

This can be seen as a power rating and Piab today attributes each pump with a specific PM_{number} as a guideline in selecting the correct pump for a given task [18]. Both of these Eq.s ((2.22),(2.23)) can clearly be seen to be a description of the same basic phenomena being the mass of transported material given a certain power and resistance of the conveying pipeline. For a pneumatic conveyor the power added into the system depends on the pressure of the inlet that thus also constitutes a given flow of material.

A vacuum conveying system the same basic principles but instead of increasing pressure at the sending station air is removed at the receiving station giving a lower pressure, thus only 1 bar difference over the entire pipeline is theoretically possible. For the ejector driven vacuum system the power added will depend on the feed pressure to the system. A high vacuum level during transport will predict low air flow and the opposite for vacuum levels close to atmosphere and thus the pump will operate at approximately steady power level regardless of vacuum level of the system. Piab also recognises that their main sources of resistance in the conveying system come from the length the material to be transported and number of bends it undergoes and can thus an equivalent resistance can be calculated for each application [7].

2.8 Differential Evolution DE

A number of traditional optimisation strategies were considered for this thesis, bisection, Newton–Raphson ,brute force and differential evolution methods were some of the candidates. Brute force method was eliminated simply by the time required required for ensuring good optimisation. Bisection and Newton–Raphson methods were eliminated due to their need of differentiable functions, still it would have been possible to employ a differentiation based on measurement. However the level of performance would not be known before the optimisation rendering the formulation of the minimisation criteria a mayor issue. Differential evolution solved many of these issues with the added benefit of scaling of the search area over time allowing for continuous operation. Differential evolution is an optimisation method based upon the idea of natural selection. The method was created by Ken Price and Rainer Storn [20]. The strengths of the method lie with not needing to differentiate the function to be minimized whilst still allowing for robust optimisation.

The method can be broken down into three main steps for implementation. These steps are mutation, selection and creation of next generation. The process is visualised in Fig. 2.4. Initialization creates a initial population of potential solutions also called agents, this proceeds start-up of the optimisation process and is therefore not shown in Fig.2.4. The position of these agents in the solution space is critical for optimising performance, both in terms of ability to find a optima and the number of generations required before all the agents are in close proximity of a solution.

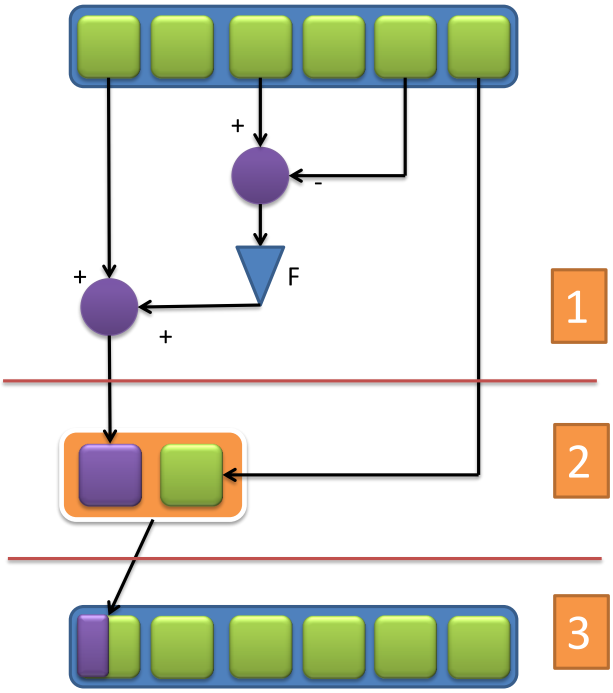

Figure 2.4: Visualisation of the Differential Evolution process, the numbers 1-3 indicate the different step of the optimisation method

The first step in Fig. 2.4 is the mutation step, one randomly selected individual sometimes refereed to as parent is added a vector. This vector originates from the difference of two other randomly selected individuals multiplied by a mutation factor F. Thus the mutation will give rise to children that will be more similar the parents the lower the spread within the population. Secondly the selection takes place, the children created in mutation is compared to a parent in terms of the cost function value (3.2). The winner with the lowest cost function value takes place in the next generation. Thirdly the first two steps are repeated until all parents in the old generation has been challenged by one new child, when this is fulfilled the next generation population is made into the current population and the process starts over.

The rate of convergence will be dependent upon both stochastic events and the behaviour of the function to minimize. The main benefit of the search method is the adaptation of the search area in relation to how uniform the population is as shown in Fig. 2.5. Thus a population that has evolved to within a small area of a optima will use smaller steps to gradually tune the performance whilst a population that still has not converged will search a wider area.

The mutation factor F will scale this area of search by a common factor in all dimensions. For small values of F the algorithm will behave as each agent is part of a homogeneous population and a large value will artificially create a diverse population.

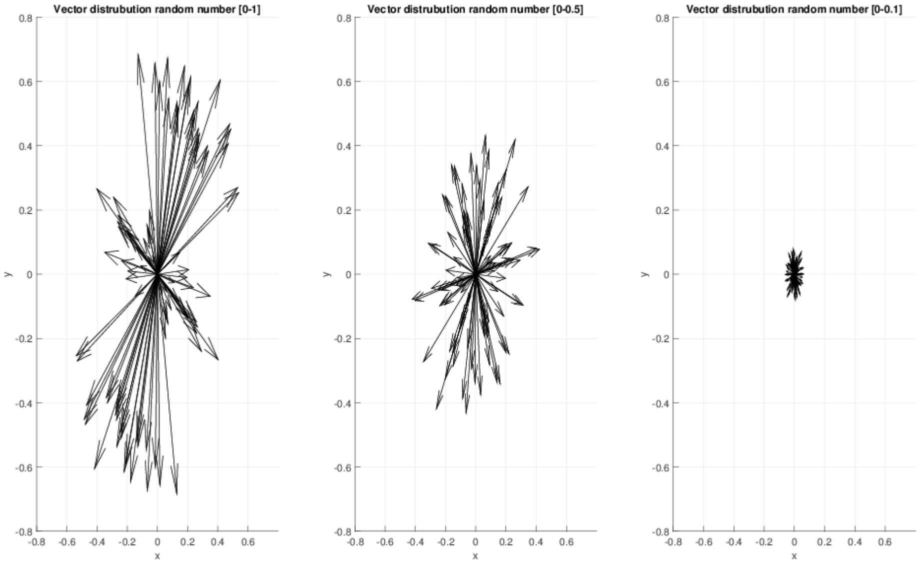

Figure 2.5: Vector difference between vectors for populations consisting of randomly distributed numbers within the limits stated with the largest differences within the populations on the left-hand side

The process is not restricted towards convergence the population but a change that drives the population in a new direction will result in larger divergence within the population that expands the search area.

The time required for a potential optima to evolve will be dependant on the mutation steps ability to locate better running conditions and the time required to reach the next generation. Both these parameters will depend on the number of individuals in a population, a large number will give high probability of finding a good optima but negatively influence the convergence speed.

2.9 Current Piab system

The system currently manufactured and sold by Piab is a completely pneumatically controlled system. One of the main reasons for this being the risk of explosions due to the potentially explosive atmosphere created when certain materials are conveyed. The friction induced buildup of static electricity that can also give disturbances to an electrical system. For this reason the control equipment consists of pneumatic timers although there are alternative control systems using solenoid valves available for usage in electrically controlled systems. Also pneumatic systems are considered to be very robust, the main components of the current system are presented in Fig. 2.6 below.

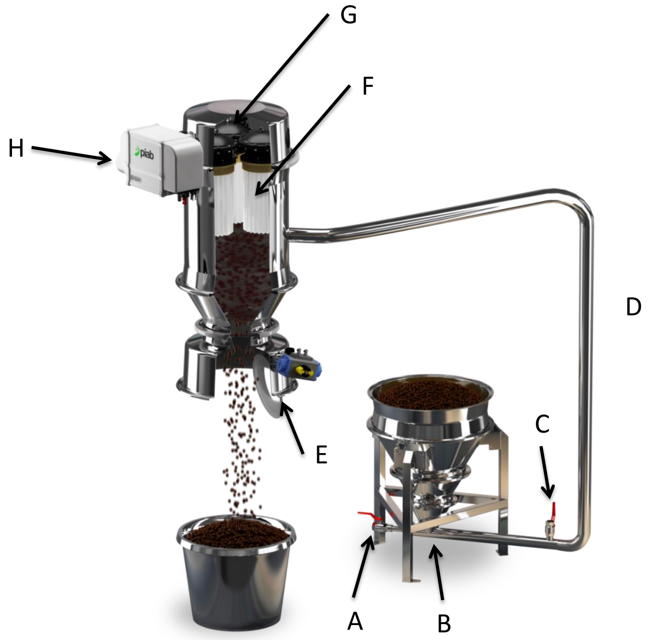

Figure 2.6: Picture of a standard system manufactured and sold by Piab, the bucket is however not a standard equipment [4]. A-H indicates individual components of the system

A depicts the carriage air valve that consists of a manually controlled ball valve. Point B shows the linear opening between material in the sending station and the pipe-line, the size of this is adjustable by a manually adjustable rod. In C is the second carriage air valve, its usage is highly debated in the Piab organisation. The headquarters in Sweden maintain that in most circumstances it offers no benefit although others claim it is of the utmost importance [18], in this thesis it has been used as a emergency valve due to its location. D shows the pipe-line which consists of pipe or hose alternatively a combination of the two, in practice the shape, size and path can vary widely. Point E is the bottom hatch that seals or opens the conveyor, one of the most common fault-points since it is a moving component that still needs to be air-tight when in a closed position. F points at the filter used to separate the stream air and material from each other, as material can not pass it collects in the conveyor until full. In point G the filter chock can be seen, it is essentially a container loaded with pressurized air that can be released at a given point to blow away unwanted particles from the filter. H shows the ejector pump that drives air through the pipe-line and thus conveying material in the process, it is powered by pressurized air.

Operation of the system can be divided into two main states, conveying and emptying. In the conveying state the hatch is closed and the pump powered, this gives an flow of both material and air in the pipeline that is filtered by the filter. When a specified time has passed the system goes to the emptying state. Emptying takes place with the hatch open and pump not running, initially one or two filter chocks might be used to clean the filter and keep it from clogging up. If a material has bridging properties such that it may not leave the conveyor or sending station by itself fluidisation can be used. Fluidisation works by adding pressurised air along the contact surface, thus breaking apart any structure formed by the material.

Implementation

3.1 System design

The overall system was designed to use the same functions as the system currently sold by Piab, the reason for this was to evaluate the concept of auto-tuning in comparison to a known system setup. For this study the equipment used was a PiPremium pump 200, pipe diameter $51mm$, total pipe-length of 12 metres with a 2 metres high vertical section and 2 bends. In order to allow for this it is although necessary to have the control parameters actuated via a digital implementation.

The system was realised as a HIL-rig in MATLAB Simulink using 2 Arduino DUE as a link between software and hardware, all data collected was transmitted to Matlab for further processing. An overview of the system is shown in Fig. 3.1.

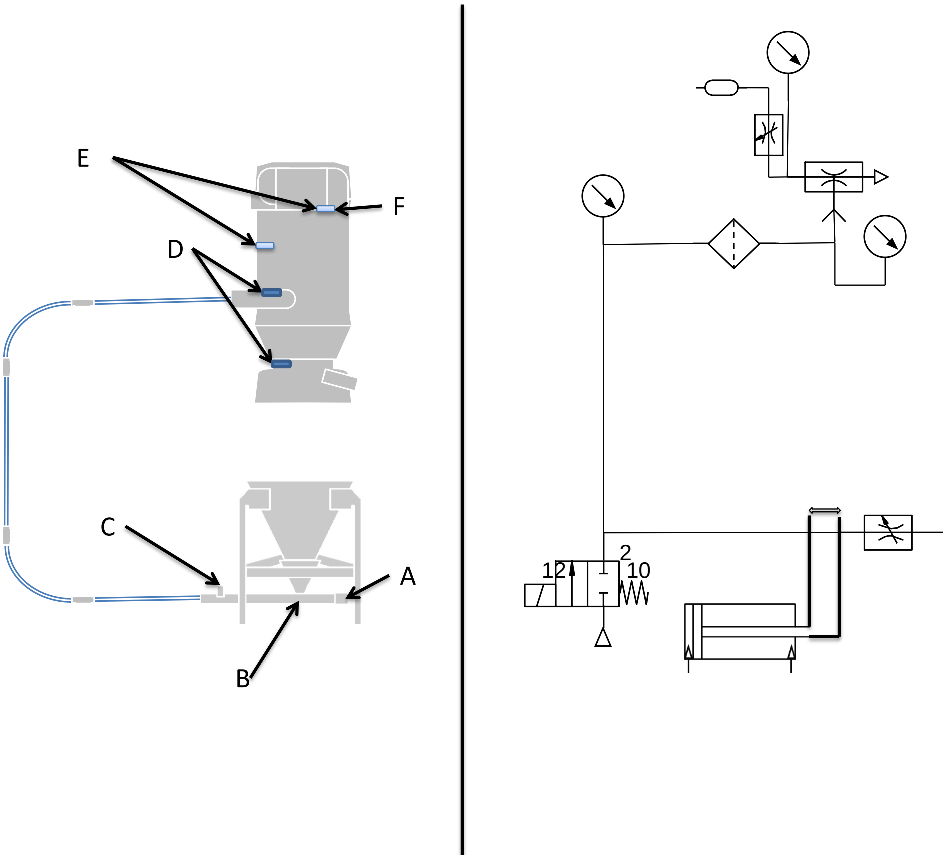

Figure 3.1: On the left is a system overview where A-F indicate individual components added to the standard Piab system. On the right is a pneumatic diagram describing the operation of the system

Point A corresponds to the carriage air valve, a $1[inch]$ proportional valve controlled by an 8-bit signal. Point B corresponds to the linear opening of the bottom part of the sending station, controlled by a linear motor with $100[mm]$ range also controlled with an 8-bit signal. In C is a binary electronically actuated valve used as an emergency valve. The level detectors shown in points D are binary capacitive sensors that detect material within proximity of the sensor, a $4[mm]$ pressure hose has been added to allow for a jet of air over the sensor to counteract material buildup and following false signals on the sensor. Points E shows the position of the two vacuum level sensors, one is situated in the same compartment as the material enters and the other is situated inside the pump. F shows the location where the pressure sensor and pressure regulator used for control of the pump are situated. Both the filter-chock and opening of the bottom hatch has remained exactly the same functionality as the original system but the control valves have been changed to solenoid valves.

The system operates as a state machine illustrated in Fig. 3.2.

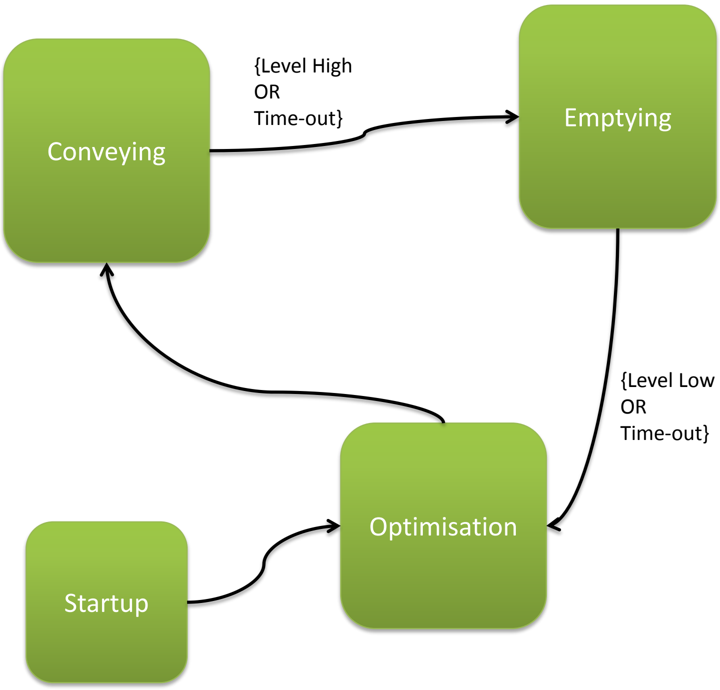

Figure 3.2: System state machine describing how the system operates during runtime

The Startup state is where the initialisation of initial population for optimisation takes, also all of the overall system attributes such as length of timeout, fludisation etc are defined. Conveying phase is where the system is conveying material, the pump is actively controlled and data regarding the performance is captured, the event that triggers a transition from this state is the signal that the conveyor is full of material or that the time for a timeout is exceeded. In Emptying state the conveyor opens the bottom hatch and based upon the settings in Startup uses fluidisation or not, the triggers for transition are the same as the Conveying state but instead of high level reached the event is low level reached. Due to that the low level sensor can not be mounted exactly at the bottom of the conveyor a extra time-delay was also introduced. Optimisation state implements a differential evolution algorithm based upon the data collected in the conveying state and sets the control parameters for the following cycle.

3.2 Pump flow controller

The operational data for the PiPump 200 can be found in the data sheet provided by Piab in appendix A. However this data-sheet only covered the normal operational case in which the pump is supplied with drive pressure between $4 - 6 Bar$.

To allow for estimation of the air flow even if not at these specified operational points linear interpolation was used and can be observed in Fig. 3.3.

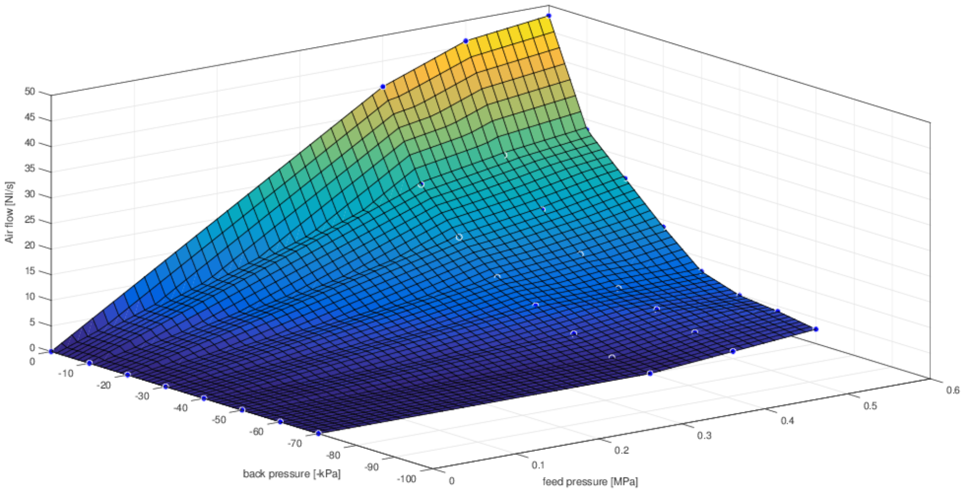

Figure 3.3: Linear interpolation of the pump flow curve. z-axis refers to Nl/s whilst x and y refers to feed pressure and back pressure

This linear interpolation was deemed sufficient within the working range of the pump. The working range is lower bounded by a driving pressure of $0Bar$ and upper bounded by $6Bar$ as this is the highest rated operational feed pressure. From this, a linear look-up table was created that estimated the air flow given the feed pressure and back pressure and a controller was to be designed given this information.

Firstly the system was run in open loop control with white noise input to the proportional valve controlling the pump, the pipeline was approximately $2[meter]$ long and no material was present. Two sets consisting of six minutes of data each was collected. These data sets were used in the MATLAB identification toolbox to estimate an arx-model of the system. Two models were estimated arx483 and arx7103 presented in appendix C that produced a good fit to the collected data, the first set of data was used as base for estimation and the second for validation. The step responses of these two models can be observed in Fig. 3.4. The reason for estimating two models was that a higher order model would produce better results but more likely to fit the environmental noise present at the time of measurement. Thus both the models of different orders were used to counteract this phenomena.

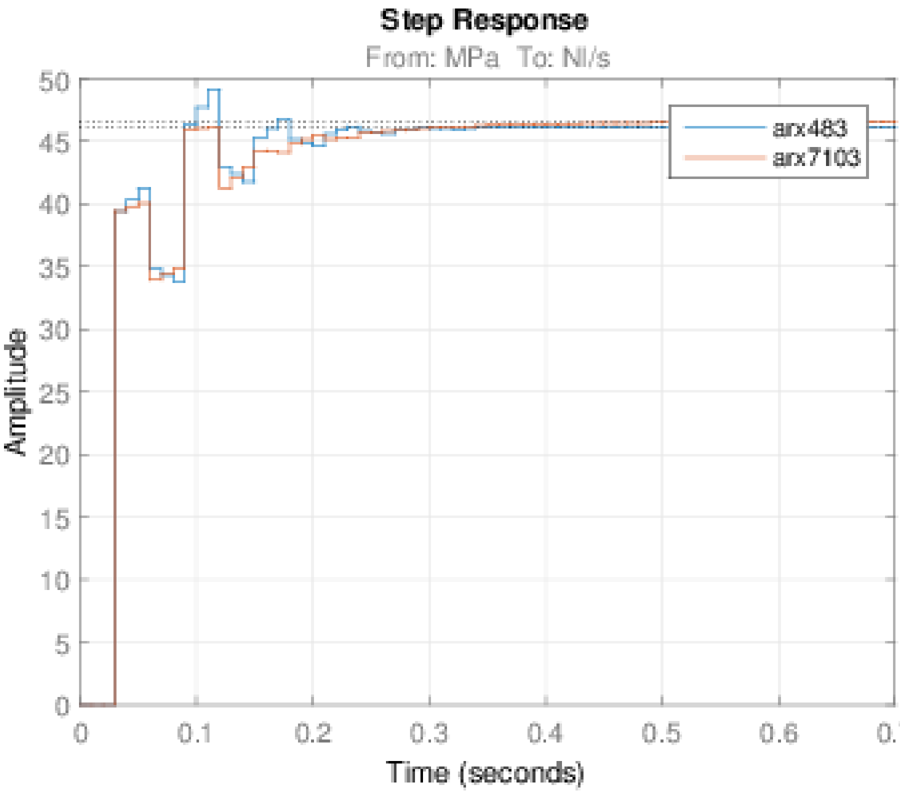

Figure 3.4: Step response of the estimated models to a step of $6Bar$ being maximum feed pressure

These models could then be used to tune the controller, the sample time was chosen to be 0.01 seconds. The rise time of the system was approximately 0.06 seconds and a sample time of 0.01 was deemed sufficient based on simulations.

The controller was designed in Simulink as a PID discrete time controller shown in Eq. (3.1) where the auto tuning PID function of Simulink was used to produce the results.

$$F = K_p + K_i \cdot \frac{T_s}{z-1} + K_d \cdot \frac{1}{T_f + \frac{T_s}{z-1}} \tag{3.1}$$

$$K_p = 0.0172977071047705$$

$$K_i = 0.603243193088098$$

$$K_d = -0.000469305024915623$$

$$T_f = 1/26.4123571239903$$

$$T_s = 0.01$$

The simulated performance of this controller can be observed in the step response below in Fig. 3.5.

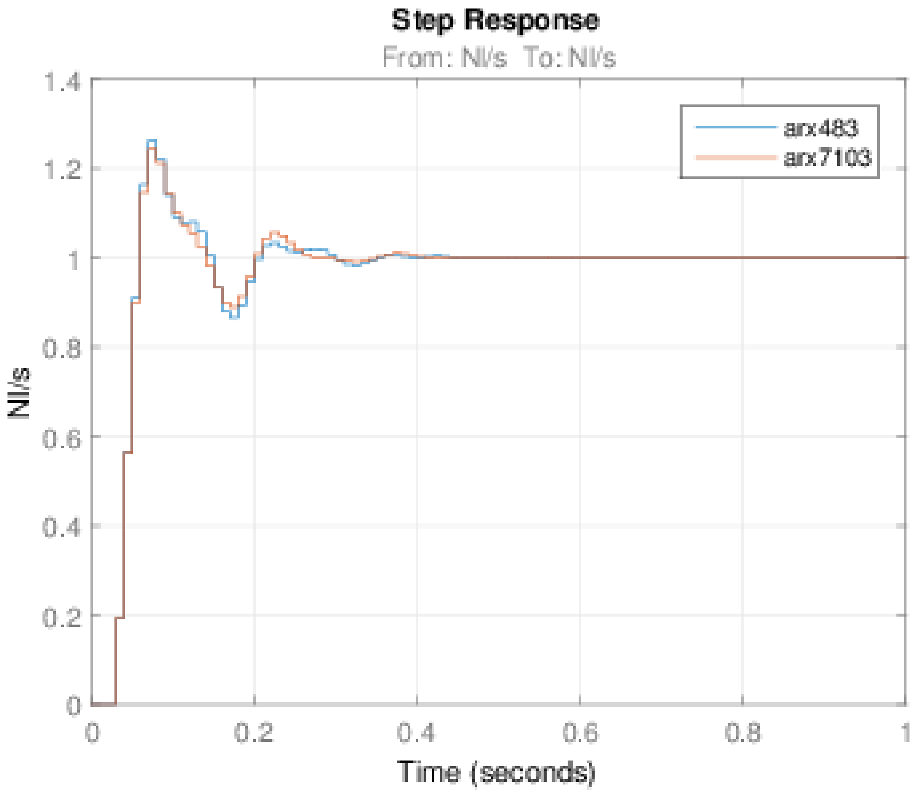

Figure 3.5: Simulation of developed flow controller

As can be observed in Fig. 3.5 above, the simulated closed-loop system has a low damping coefficient and is quite oscillating, this is due to the fact that the system is desired to be able to tolerate a high degree of disturbance caused by material in the pipeline. The difference between the two models can be observed in table 3.1 and mainly the performance improvements in system rise necessary to counteract the disturbances expected when running with materials in the pipeline.

Table 3.1: Results of simulated models in Matlab

	Open loop		Closed loop	
	arx483	arx7103	arx483	arx7103
RiseTime:	0.0600	0.0600	0.0200	0.0300
SettlingTime:	0.2100	0.2400	0.2400	0.2500
Overshoot:	6.2494	0	26.2555	24.2685
Undershoot:	0	0	0	0

To evaluate the air flow controller performance based on these simulations, the system was tested without material in the pipeline but with a longer pipe-section. The result of that test can be observed in Fig. 3.6 and it is clearly evident that the longer pipe has a damping effect on the system.

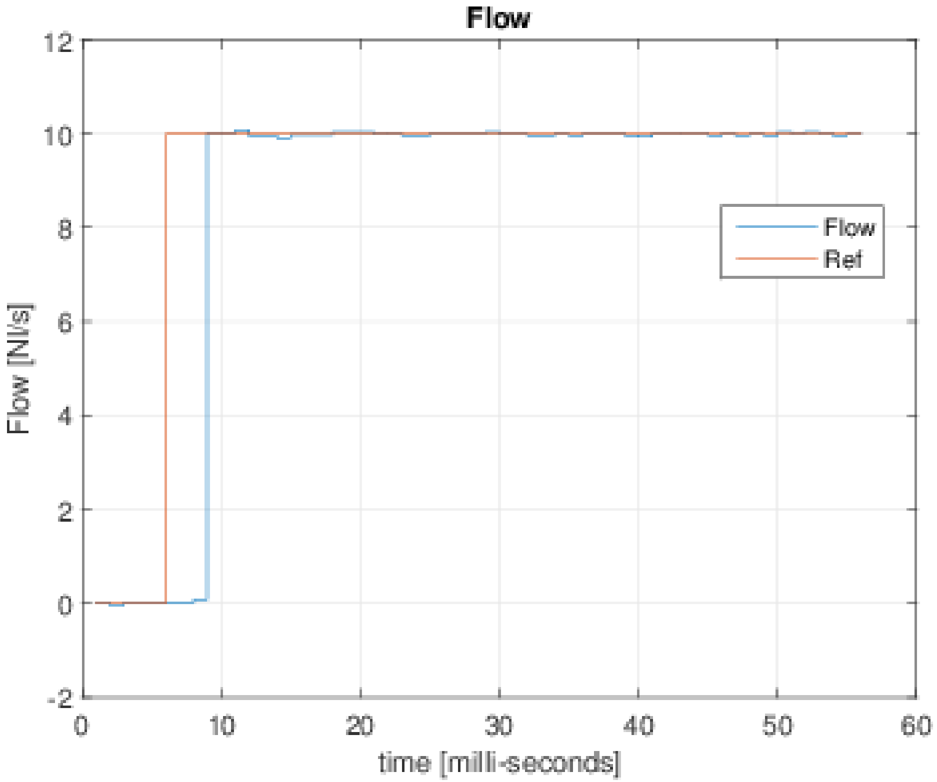

Figure 3.6: Flow controller results in a pipeline with only air

Following this, the performance of the controller with material in the pipeline was evaluated at a worst case operation. As discussed in the frame of reference the dense phase of transport shows the largest pressure fluctuations and thus the most disturbances in the air flow. Two types of materials were used for these tests, flour and plastic pellets. Flour was chosen because it has low permeability of air and can give rise to heavy slugs in the pipeline. Plastic pellets was also chosen since it has high permeability and high particle mass and thus conserves a lot of energy within each moving slug. As can be observed in Fig. 3.7 the flour has quite low impact upon the system, the initial overshoot can be attributed to the evacuation of the air within the closed system of the conveyor and the oscillations are dampened within a short time span, the residual ringings are from slugs moving and causing disturbances to the system.

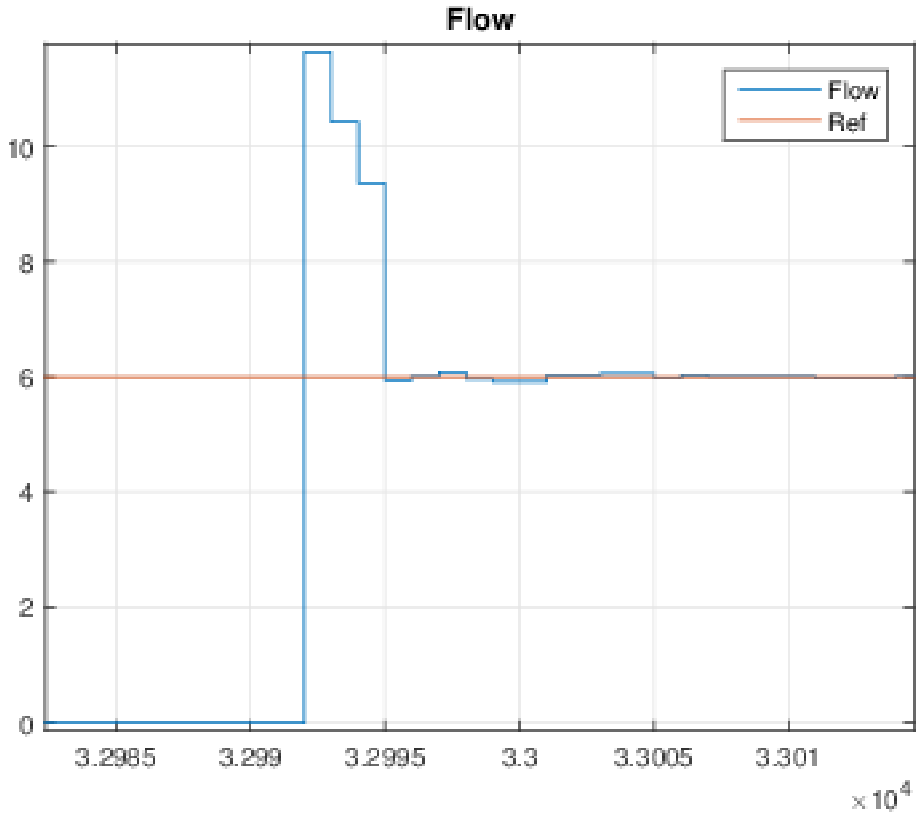

Figure 3.7: Flow controller with flour, y-axis refers to Nl/s and x-axis to milliseconds

In Fig. 3.8 the step response given plastic pellets is visibly less damped and the system does not stop oscillating over time. The initial overshoot on the other hand is effectively removed probably due to the higher permeability and the oscillations are relatively small in amplitude.

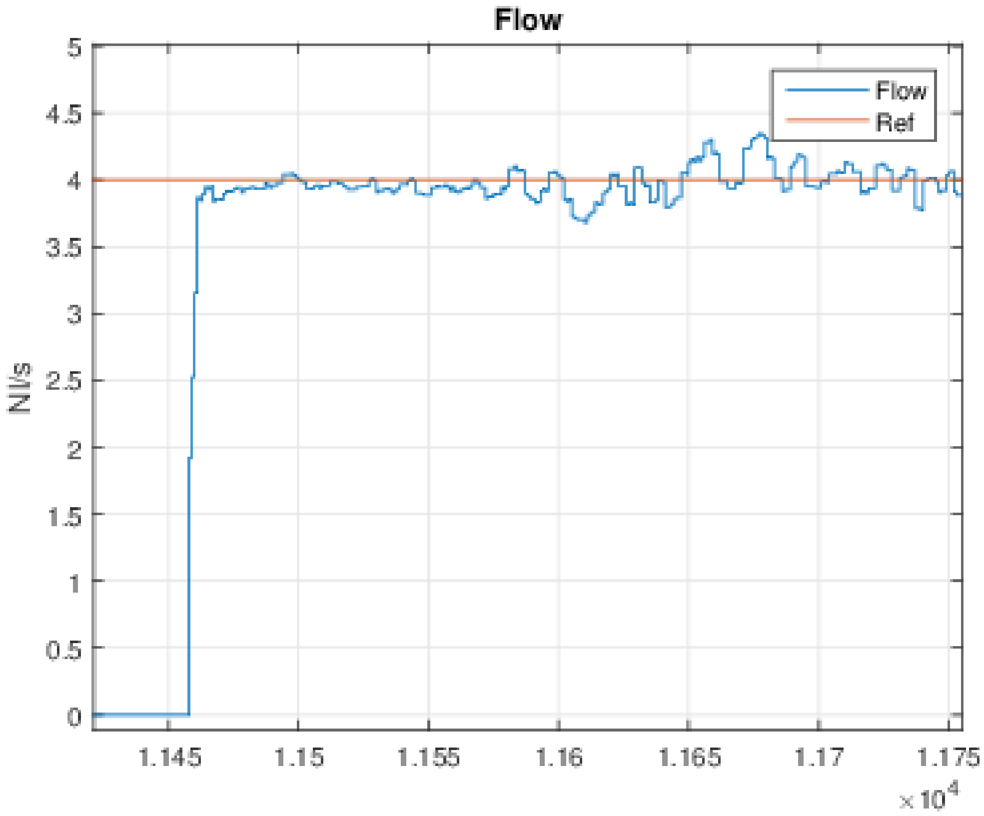

Figure 3.8: Flow controller with plastic pellets,y-axis refers to Nl/s and x-axis refers to milliseconds

From these test the developed flow controller was deemed sufficient for the application.

3.3 Parameters of system optimisation

The system performance was divided into four main parameters to evaluate performance of the system during run-time. These were capacity, efficiency, robustness and gentleness towards the conveyed material.

Capacity is defined as the volume of transported material per unit of time. In this study this corresponds to the time required to fill up the receiving vessel since the volume is predefined by the level sensor. Any deviations caused by uneven distribution of material is disregarded and viewed as measurement noise.

Efficiency is defined as the energy in the form of pressurized air used in relation to the volume of material transported, as for capacity the volume is also fixed thus the pressurized consumed during one fill-cycle will be the implication. As the preparation of pressurized air uses energy this becomes a measurement of energy used in relation to work carried out.

Robustness is the system's sensitivity to environmental changes. According to the litterature [11] an indication of the system sensitivity is the pressure deviations in the receiving vessel. Large amplitude of the deviations indicates that the material is transported as plugs experiencing high friction. The opposite is also true and material transported in lean phase will not produce large pressure variations even though the receiver might experience low pressure. Since friction is the primary source of energy loss and cause of down-time [17] the variance of pressure is therefore interesting as an indication of system robustness. A low value indicates little friction between pipeline-walls and material or short and light slugs or dilute phase resulting in lowered risk of complete stops. The variance estimates the difference in energy bound in an individual slug in comparison to the energy bound in the entire pipeline. From the perspective of robustness it is desirable to have an as evenly as possible energy distribution over the pipe system since the applicable driving pressure is restricted by the maximum 1 bar difference to atmosphere. This leads to that the available pushing force on each section is restricted by the pressure difference and an even distribution allows for pressure fluctuations within the pipe system that prevents blockage.

The gentleness of the process is how violently the material is transported and thus the probability of degradation. This is mainly governed by the phase of transport and velocity within the pipeline and the main parameter governing transport phase being material velocity, $v_{material}$.

3.4 System optimisation

This thesis aims to optimise the performance in relation to the criteria listed above by minimizing the cost function C (3.2).

$$\begin{gathered} C = \sum a \cdot Capacity + b \cdot Efficiency + c \cdot Robustness \\ v_{material} \leq \text{Gentleness constraint} \end{gathered} \tag{3.2}$$

Since materials mostly have a well defined degradation point it was concluded to be a reasonable approach to implement control of it as a fixed upper boundary for material speed and not as a parameter for optimisation, since destroyed material is not of interest nor is excess gentleness beneficial. Thus it was not tested within this thesis but a boundary on the material speed that in practice leads to dense-phase flow in combination with the efficiency parameter could be an effective control strategy if gentleness demands exists. This due to that if the system effectively is limited to the dense phase the most efficient mode of transport will be that which incorporates as little acceleration and de-acceleration of the material as possible thus limiting the external forces on the material and risk of degradation.

The control strategy chosen for this thesis is differential evolution (DE) combined with classical control theory since this mix can be made to encompass many of the desired traits of the wanted system behaviour. The optimisation strategy of DE was chosen since it is meta-heuristic and thus does not depend upon knowledge of the material being conveyed and thus does not depend upon a model of the material in the conveyor which today is not available This is a very interesting approach to this problem for that reason since it is known that the characteristics of each material differs between different manufacturers and batches thus adding to the generality of the proposed system.

In order to achieve a general system the meta heuristic property is important as every attempt to model a material will either be very general or suffer from limited applicability due to the limitation that every material shall behave in a modelled way. Two main starting area strategies for finding the optimal point of operation have been envisioned for this thesis. The first is to generate the starting population over a set that is covering the entire solution space, thus containing all optima. The second approach shall be to generate the starting population in the systems most robust area of operation being high flow and low material content and to observe if any notable differences between the two approaches can be observed. These populations consists of the desired flow rate, linear position of the feed opening and the opening of the carriage air valve. After each cycle the performance parameters are evaluated and a cost value is assigned.

3.5 System characterisation

To provide a material database upon which to design the basics of the system data was collected from the system at run-time and a special material characterisation schedule was developed that tested all possible settings for the sender with a given interval that can be observed in table 3.2. Once the table was tested, air flow setting was increased and the table re-run until the entire range of air-flow had been tested.

Table 3.2: Table describing the resolution of the tests carried out for the linear position and carriage air valve. The table was re-run for air flow references with a resolution of $0.5 Nl/s$

Linear position %	Valve %
0	0
0	25
0	50
0	75
0	100
25	0
25	25
.	.
.	.
.	.
100	100

This resulted in a set of data describing the behaviour of the material's properties over an area of allowed system settings. This data was linearly interpolated to form an approximation covering the entire solution space. The performance criteria listed above have been recorded following each cycle.

3.5.1 Plastic pellets

Plastic pellets were the first material to be characterized according to this method and the results can be seen in Fig.(3.9,3.10,3.11,3.12). In the figures the influence of the non-listed variable have been averaged as to present a good picture of that parameter's influence. As can be observed in Fig.(3.9) the main parameter that influences capacity is air flow and that the capacity is increasing for higher flow, however the performance is bounded by the pump. This is assessed to be attributed to the large particle size that allows air to pass through large concentrations of material and the low friction and fluid like behaviour that minimizes the influence of the sending station.

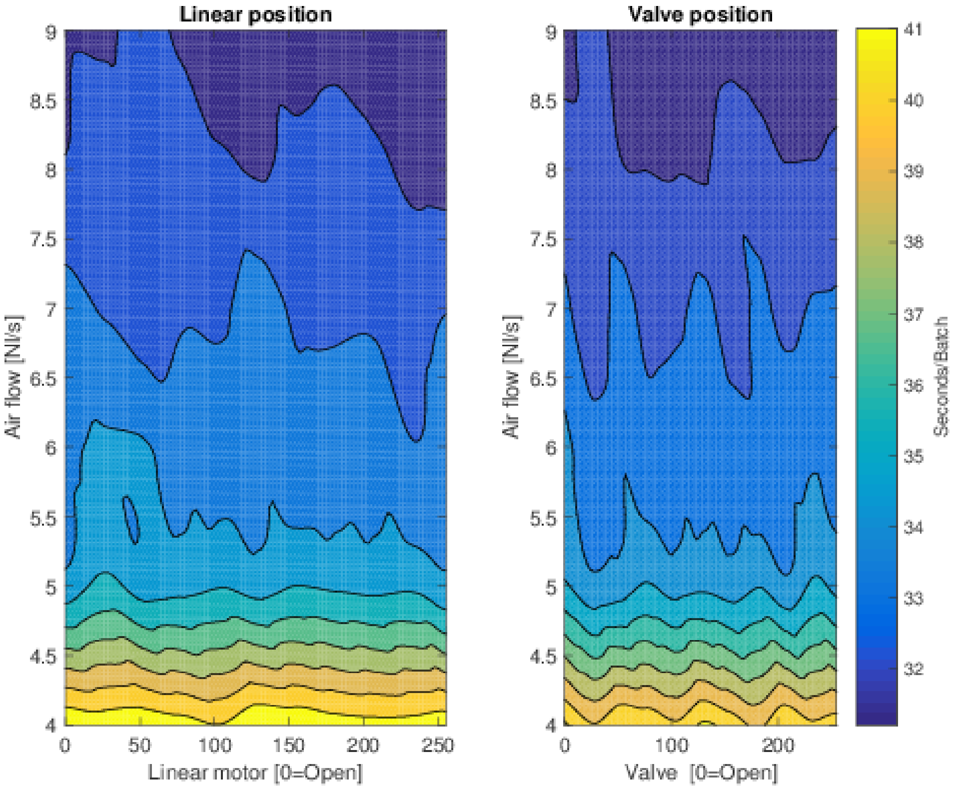

Figure 3.9: Capacity for the system running plastic pellets measured in seconds per batch

In Fig.(3.10) another interesting phenomena can be observed and that is the formation of areas with high efficiency and these coincide with where the system is running smoothly with low noise and the plug forming is rhythmic and predictable. Thus it appears the system has some sort of internal frequency.

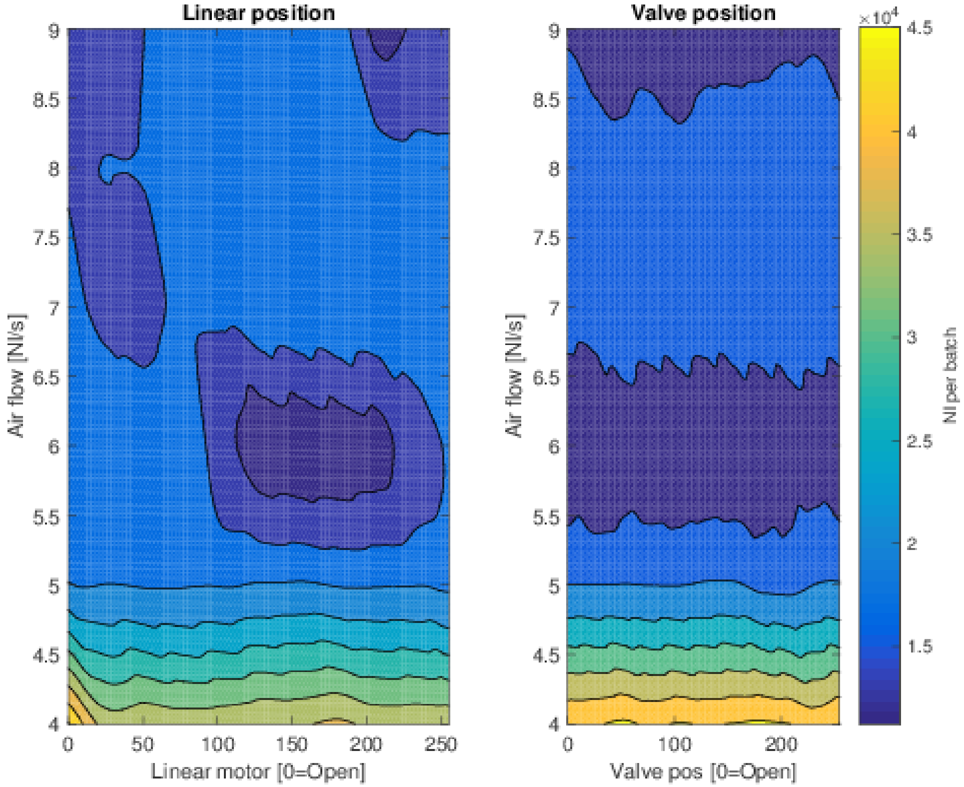

Figure 3.10: Efficiency for the system running plastic pellets measured in Nl per batch

The acquired data regarding the standard deviation in pump pressure can be seen in Fig. 3.11. As plastic pellets in this setup exclusively created dense phase transport it can be seen as the lower standard deviation for higher air flows can be attributed to faster plugs that are not as heavily influenced by friction.

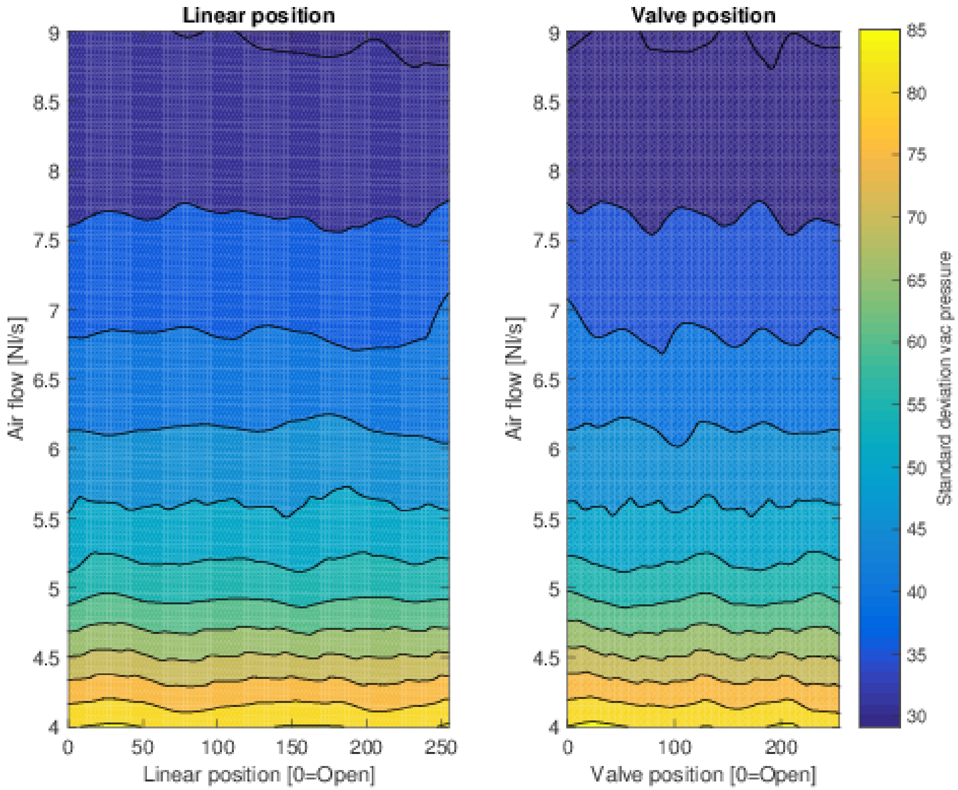

Figure 3.11: Robustness for the system running plastic pellets measured in standard deviation of the vacuum pressure

The plastic pellets were on their own very insensitive to external forces and very unlikely to break from impact in the pipeline. Their shape and size is however similar to materials that are fragile and for example used in the pharmaceutical industry. For this reason Fig. (3.12) is interesting because it shows that the air flow has the largest influence upon material speed but that also the material speed is closely linked to the capacity of the system. This since if the plugs formed in the conveying process are similar the capacity will depend upon the speed of each individual plug. Thus it can be concluded that a material speed limit will in practice be implemented as a air flow limit for this material.

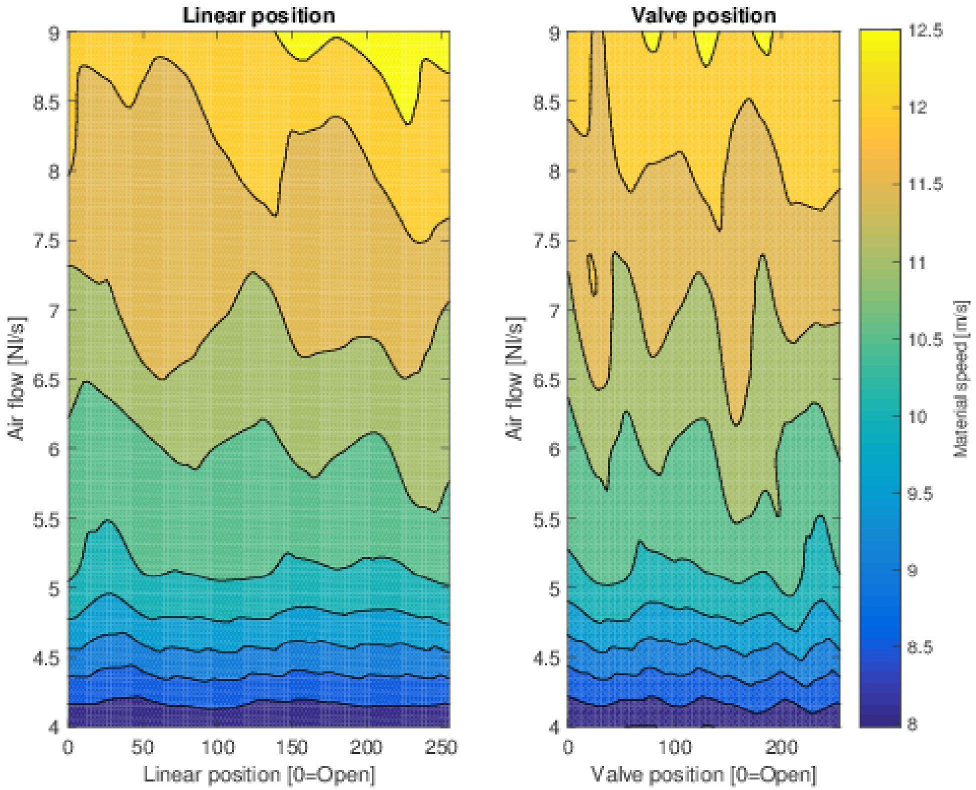

Figure 3.12: Max material speed for the system running plastic pellets measured in meters per second

3.5.2 Flour

Following this, flour was characterized according to the same methodology as plastic pellets and the results can be seen in Fig.(3.13,3.14,3.15,3.16). Flour as a material features greatly reduced fluidity in comparison to plastic pellets this is obvious if Fig.s 3.13 and 3.9 are compared. The lower fluidity gives that the parameters linear opening at the sender and carriage air has a much larger influence upon if and how materials enters the pipeline. Although flour also gives dense phase transport in this setup the size and shape of plugs are mostly determined by the linear opening and amount of carriage air.

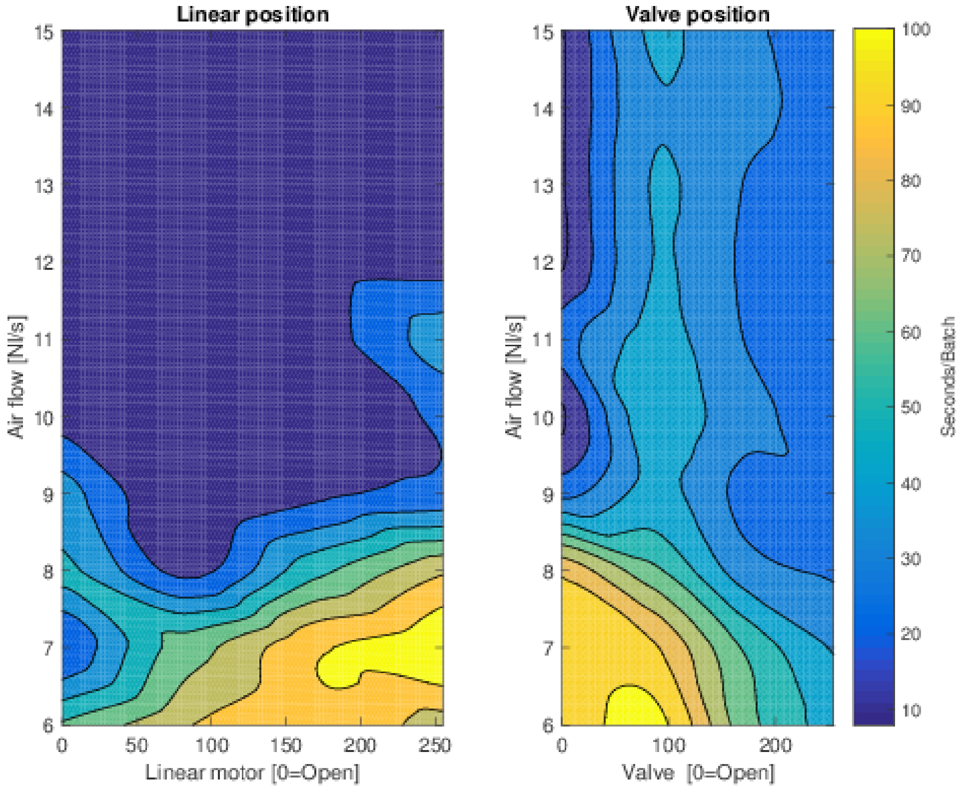

Figure 3.13: Capacity for the system running flour measured in seconds per batch

Since the formation of plugs is highly adaptable with low air permeability, the power required will be more dependant upon the plugs formation and fluid dynamics rather than friction against the pipeline walls. This is evident in Fig. (3.14)since the power consumption per batch is relatively steady with exception for low air velocities that come close to the saltation velocity.

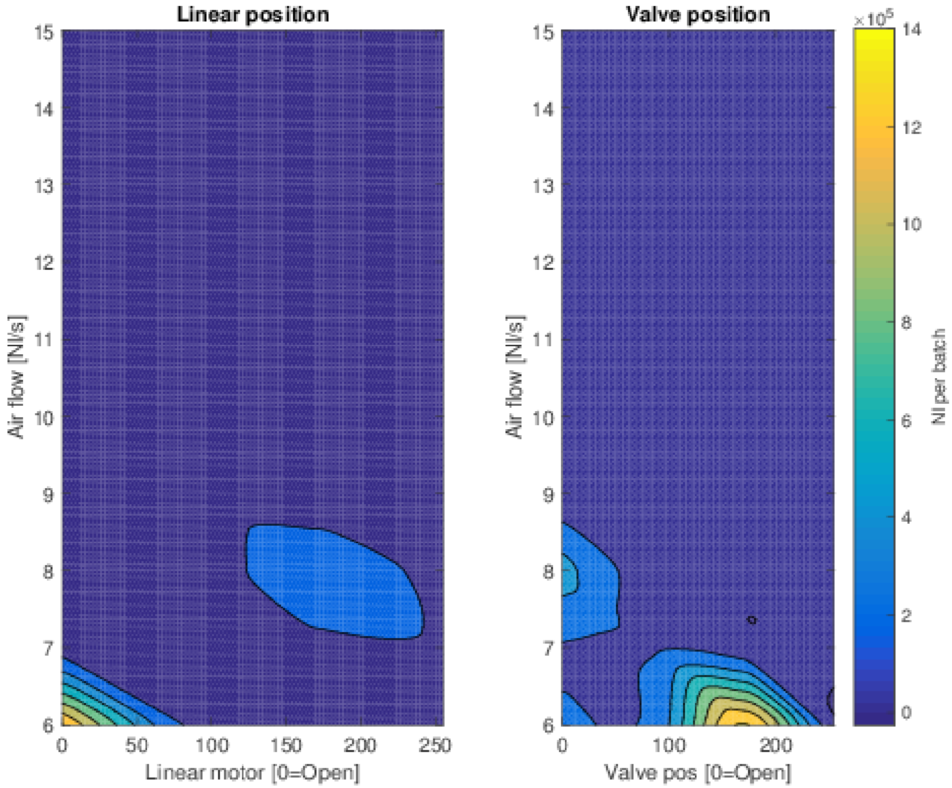

Figure 3.14: Efficiency for the system running flour measured in Nl per batch

The main cause for the differences between the plastic pellets and flour shown in Fig.s 3.15 3.11, where especially the valve setting influences the character of the plugs. For plastic pellets generally the same type of plug is formed irregardless of settings. The flour features more differences in the plugs shape both in terms of length and edge geometry depending on settings. Thus it is visible that the shape of plugs formed has a large influence upon the standard deviation as for plastic pellets that has relatively unchanged plugs but more of a momentum at higher air flows that decreases the amplitude of pressure variations but flour shows a number of different plug apperances and in pressure variation terms a certain relation between carriage air and air flow as is visible by Fig. 3.15.

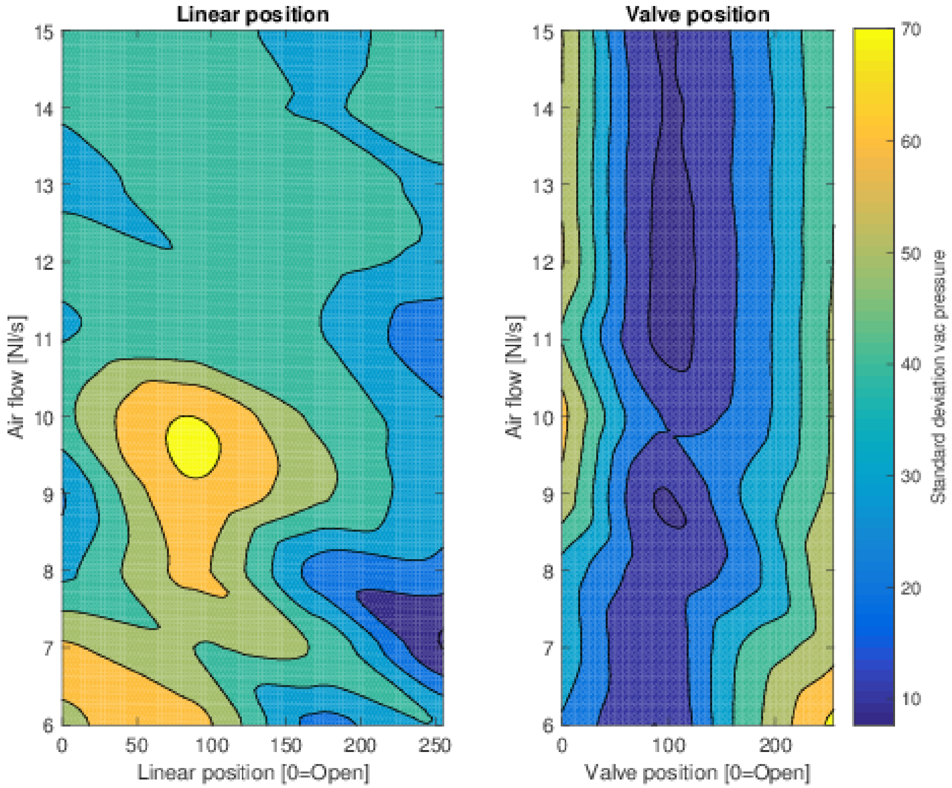

Figure 3.15: Robustness for the system running flour measured in standard deviation of the vacuum pressure

Due to the fact that flour has low permeability against air it is expected that the flow control would be clearly linked to material speed. As can be seen in Fig. 3.16 this prediction was shown to hold up but also that the type of plugs formed will influence the speed range within that the material speed can be bounded.

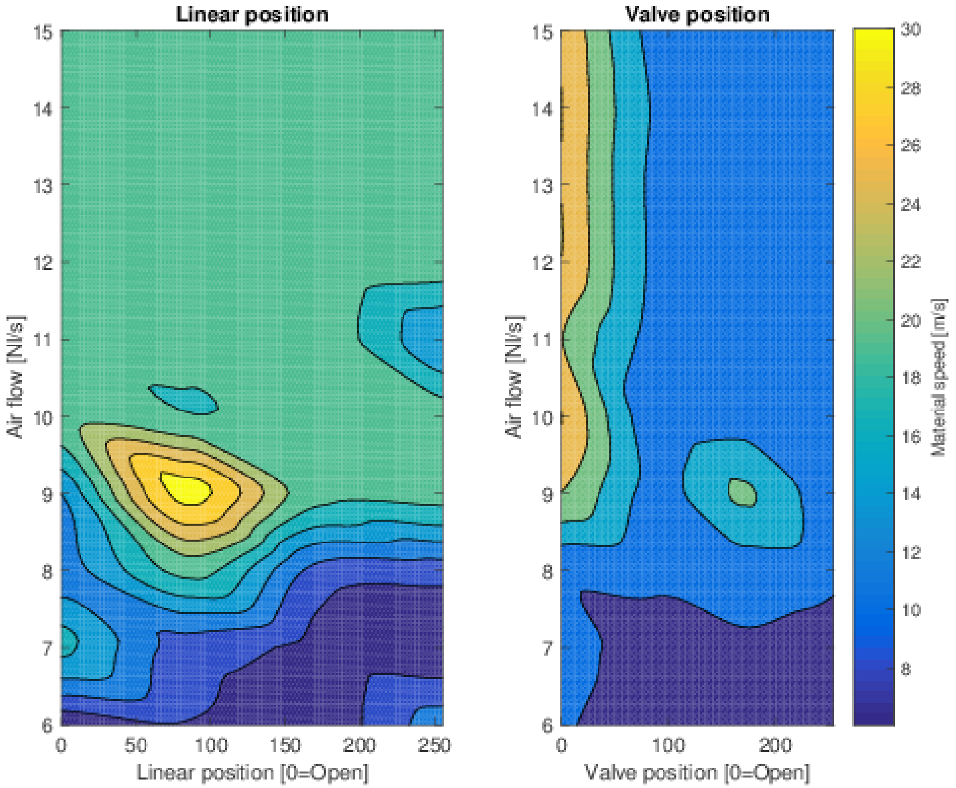

Figure 3.16: Max material speed for the system running flour measured in meters per second

3.6 Differential Evolution

3.6.1 Starting area

Possibly the most important step of the optimisation process is the selection of starting area. A bad selection can cause inability of the system to convey material over the entire starting point area resulting in no result to improve upon or lead to optimal points being excluded from the search area. Two main approaches have been envisioned for selection of starting points, these being robust, general and as a sub-strategy to general optimised. A robust set of starting points is based upon initiating the population within an area that is deemed to have very low risk of stop. This area shall be characterised by high air flow, small opening area in sending station and large quantities of carriage air. Such an starting population will be a very robust characteristics and gradually evolve towards the optima contained in its set. If the optimisation criteria has the lowest value on the edge of this set the set will expand in that direction and thus gradually move towards optimal performance from a robust direction. The benefits of this approach is the robustness but it comes at the cost of time and the fact that the found optima will be that with a clear path from the starting area.

General starting points based upon spreading the starting points over the entire available solution area thus all optima should be covered by the search but since the area to cover is large, the optimisation process will be slow. Optimisation is based upon prior knowledge of the material to be transported, if the region where the optima is to expected be found is known this information can give better performance of the system. This by minimising the search area and thus spacing the population more densely within the correct area. This procedure will minimize the risk of the stochastic differential evolution missing the global optima but is completely dependent upon the information supplied to be correct.

In this project it was decided to as far as possible use the general approach. This because there was little prior information available and that it was desirable to search the entire solution space to find the global optima. Due to the fact that the conveying process will stop at a low air flow in a given pipe and material and the restrictions of the pump this gives the area of the starting population in air flow. The linear opening and valve should as far as possible be maintained to cover the entire setting range.

3.6.2 Pitfalls and bad parenting

Differential evolution depends heavily upon individual readings from individual cycles, whilst the cycles are not entirely independent from each other as was discovered early on this thesis. This is because the initial state of the pipeline will influence the early stages of the suction cycle.

The performance of an individual cycle will depend upon the settings in real time but also the history of earlier cycles as the inherited state of the pipeline. This can lead to the promotion of sub-optimal running conditions based upon one reading taken at very specific conditions and thus not generally applicable. To counteract this phenomena, the current parents can each n cycles be reinitialised, this can be achieved by running them on the system and updating their cost function according to the latest value. This would expose bad parents to substitution if their cost function value is not repeatable.

Another phenomena that has been observed is that if a sensor can be triggered into giving a false reading such as powder swirling up on the level detector before the conveyor is full thus giving the system incorrect information that can result in the optimisation being towards creating disturbances rather than optimisation actual performance. This should be counteracted either by improved hardware or digital filtration of the signal.

3.6.3 Algorithm description

The algorithm used in this thesis is described in Fig. 3.17. Starting area is manually defined in the initiate population and is then tested in test population and the population is thereafter tested every 10th generation. It can also be seen that the child must be superior to the parent, thus if they posses the same performance the parent will remain in the population.

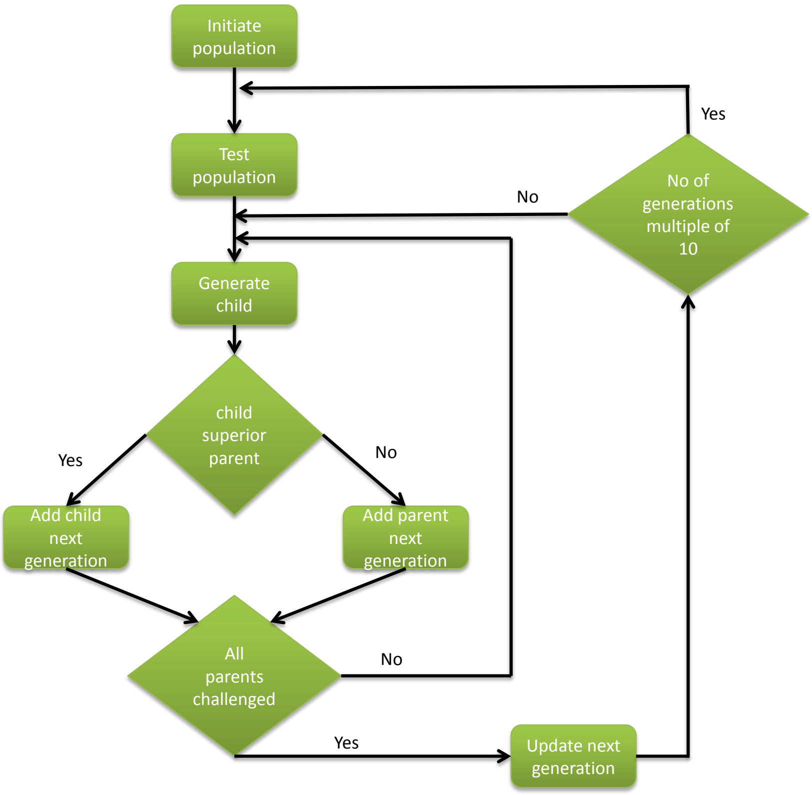

Figure 3.17: Flowchart for the optimisation algorithm

This algorithm was designed to provide a good balance between fast convergence and robust operation for the intended usage.

3.6.4 Optimisation simulations

Plastic pellets were based upon experience from Piab rather insensitive to system settings and for this reason often used in demonstration units since the difference between different settings are quite low. This is because of their large particle size and low friction between particles that gives very low tendency towards bridging and wide variety of transport modes. This can be observed in Fig. 3.18

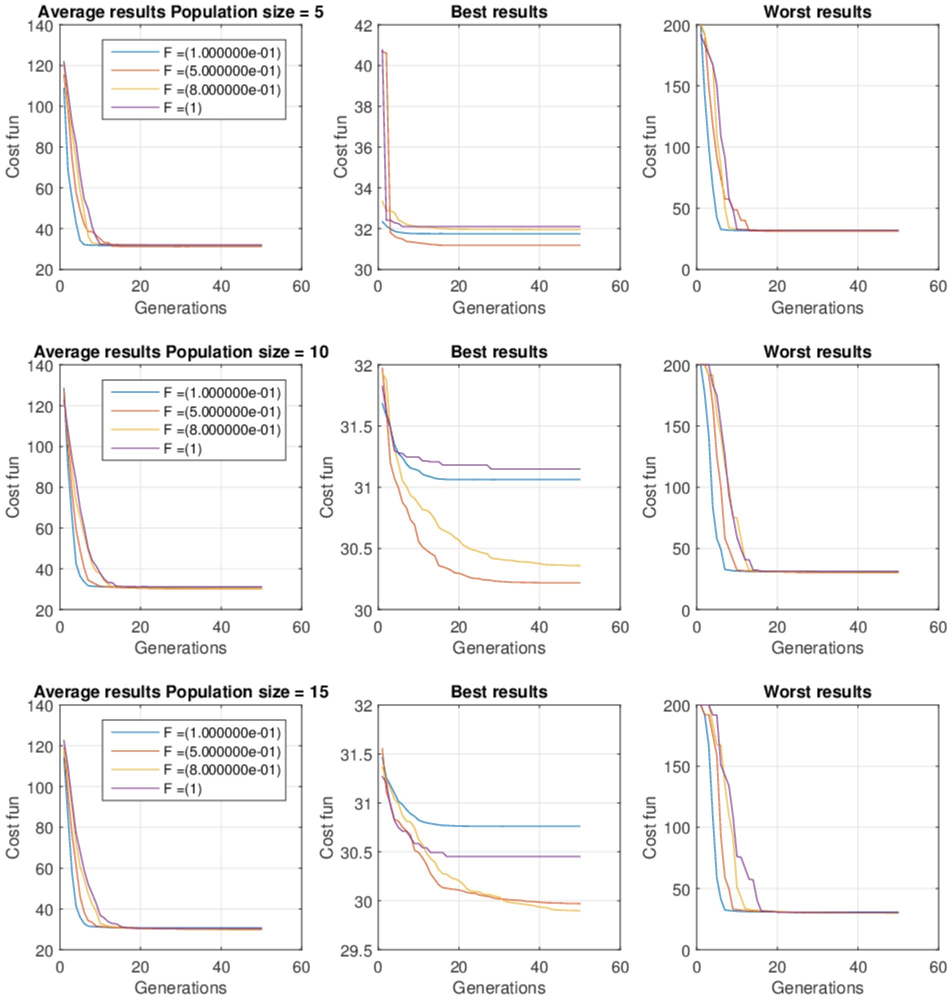

Figure 3.18: Simulated DE performance for plastic pellets with cost function solely based on capacity based on different population sizes and mutation factor F

This results in a low difference in the performance results of the initial population as can be seen in the figure above. The time required for a specific number of generations is linearly dependent upon the size of the population and as can be seen in the worst results. A smaller population will faster discard the less favourable solutions in terms of number of generations. Thus the time required to have all the solutions within a given performance radius of the best solution will be greatly reduced by means of a small population. On the other hand a large population will have a much greater probability of finding a better solution than a small population given that they cover the same set.Another benefit of a large population is that it is less sensitive to short terms disturbances since the whole population might not have shifted before the disturbance ends. Thus the choice of population size will be a trade-off between fast convergence to a discovered optima or robust optima finding and noise rejection.

Flour is in contrast to plastic pellets highly dependent upon the amount of carriage air and geometrical opening because of low permeability for air and high tendency towards bridge buildup. Thus as an effect of this the optimisation will generally be slower as can be seen in Fig. 3.19. To be able to convey flour and have an effective discharge fluidisation is needed and the material is highly subjective to wear from traveling in the pipeline.

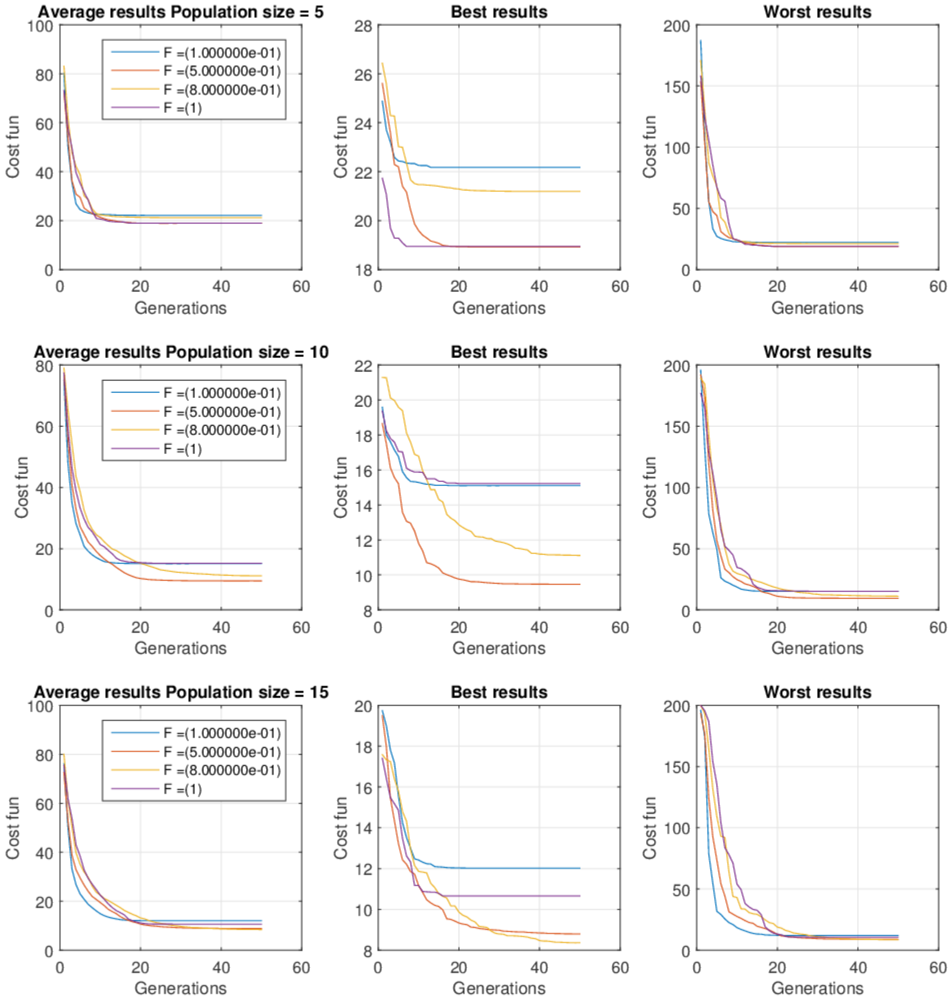

Figure 3.19: Simulated DE performance for flour with cost function solely based on capacity based on different population sizes and mutation factor F

As stated above the settings have a much larger impact upon the achieved performance of the system and thus the selection algorithm will have a larger impact upon the population. The mutation factor F will also be more evident as it determines the search area at a given time. In the literature it is often recommended to use $0 < F < 1$ [13] as this will provide robust settings for most optimisation problems, as can be observed a large number will provide a larger relative search area. This is evident through observing the best result over generations, a large number will search a large area and find a few but significantly improved result but a lower value will increase the best result more incrementally.

Thus the conclusion is that the choice of mutation factor will be a trade off between the need to globally and locally search for an optima to achieve the best performance. Based upon the desired traits of the system, it was concluded after discussions with the company-supervisor that the main focus should be the improvement of the worst and average results. Based upon the simulations, a good compromise for these desired traits was to use a population size of 10 individuals as this seemed a good compromise between fast population evolution and good probability of robustly finding an operational optima for both materials. The mutation factor of 0.5 was chosen because as can be seen in Fig. 3.18,3.19 this gave results that found good optimas whilst still providing gradual performance increase in all simulations.

Verification

In order to verify the performance of the system a set of materials presented below was selected by Piab. The materials were chosen to represent the span of materials typically used in a conveyor and to include some of the most encountered materials.

Materials:

- Plastic pellets
- Flaxseed
- Sugar
- Rye flour
- Flour
- Confectioners sugar

Given these materials it was concluded that the thesis was to focus on the capacity performance of the system. This since capacity is the most important factor for users according to Piab [7]. With regards to capacity the most important factors regarding the performance are average capacity and suppression of the worst results. The method used was to firstly deploy a purely capacity based optimisation and if this does not provide an adequate solution the root cause analysis shall be investigated and the optimisation process is adapted.

4.1 Material characterisation and simulations

Based upon collected data of performance for each material in accordance with the method in section 3.5, simulations of the optimisation were performed. These simulations were carried out to test the designed optimisation algorithm, they would not take dynamical effects such as history and initial state of the pipeline into consideration. The main parameter of importance in these simulations is to evaluate the time required to achieve a certain level of optimisation.

4.1.1 Plastic pellets

Plastic pellets were in the simulations fast to converge towards a common solution as can be seen in Fig. 4.1 and after 27 generations the 3 lines are impossible to tell apart. This optimisation in large steps indicates that the optimum performance area is relatively large. Thus the worst performance takes a long time to improve the worst result but when it does the performance is not far from the best. Given that the starting area for the optimisation algorithm is correctly chosen the optimisation algorithm should perform well since there will be a distinct difference between different results.

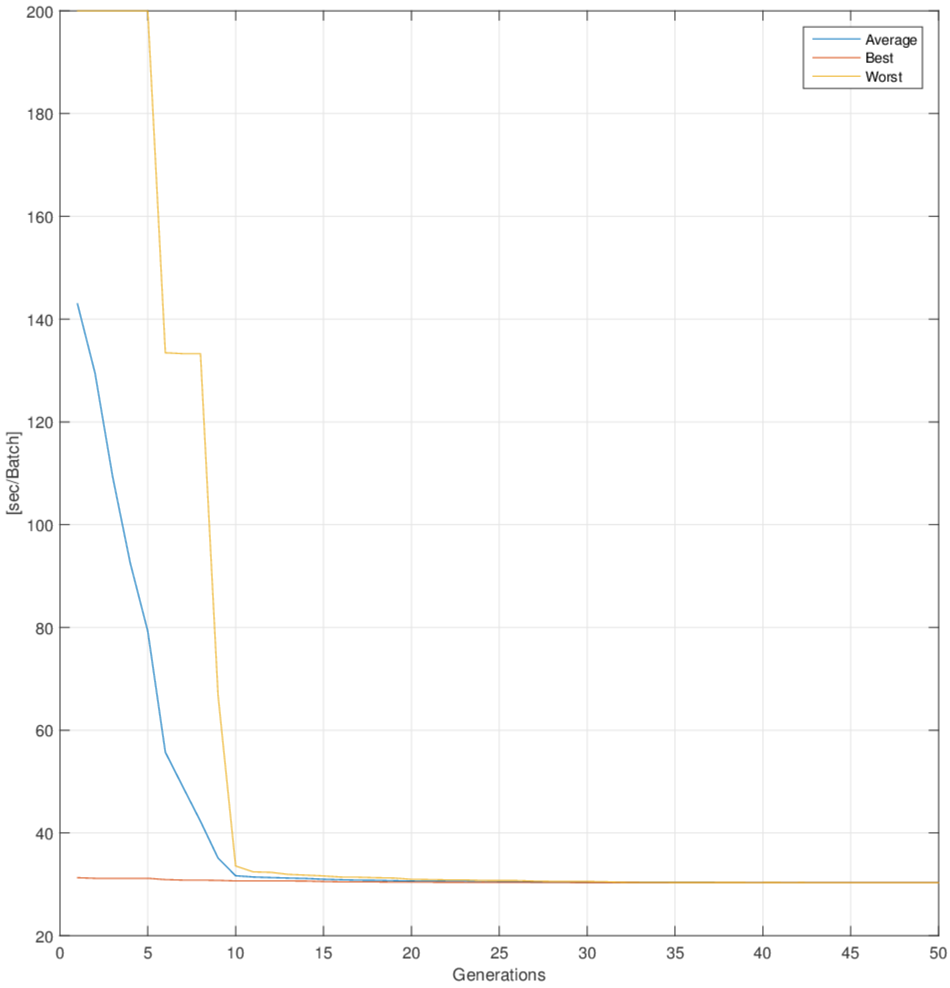

Figure 4.1: Plastic pellets simulated performance results optimising for solely capacity

4.1.2 Flaxseed

Flax-seed takes a long time to converge towards a steady optima and the 3 lines converge steadily over time.This is clearly visible in Fig. 4.2 The small incremental improvements indicate that the optimisation will be highly sensitive to noise. This in combination with the irregularities of such a natural material gives a material potentially hard to optimise. Still the material does not reach a time-out for any settings but the process could with high certainty benefit from a more limited starting set.

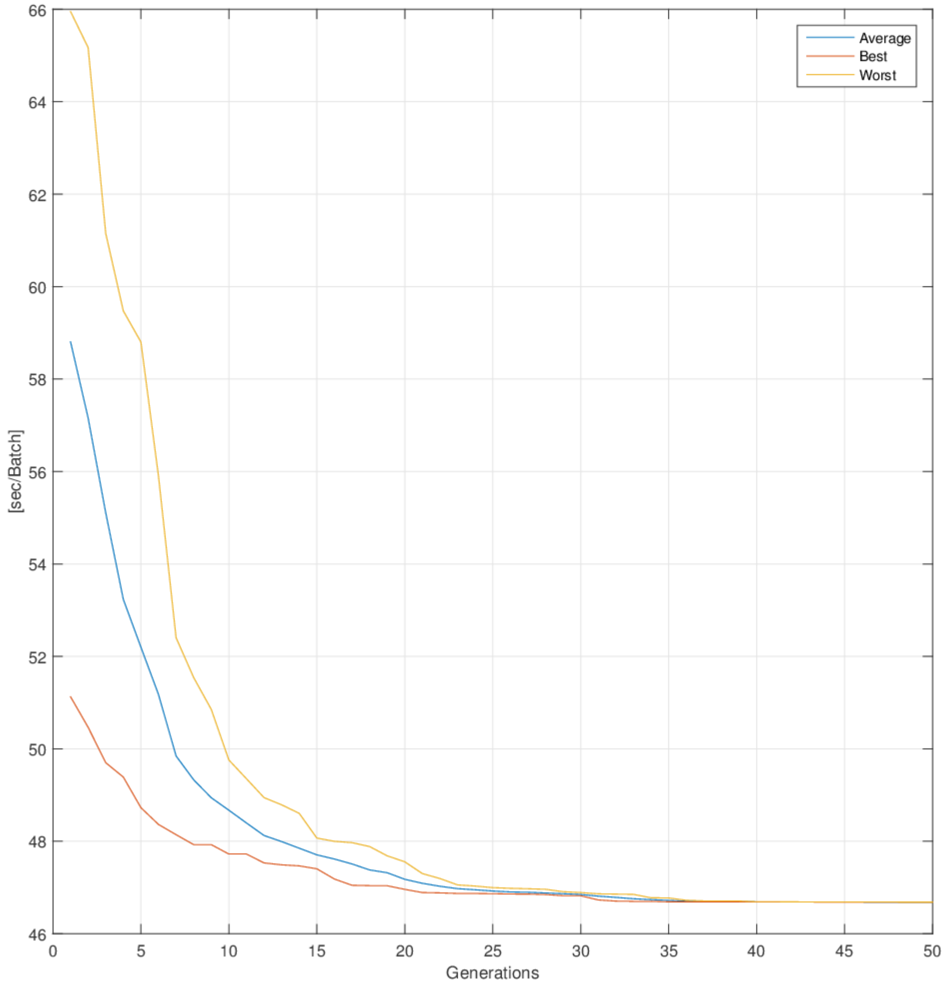

Figure 4.2: Flaxseed simulated performance results optimising for solely capacity

4.1.3 Sugar

Sugar was fast to converge as can be seen in Fig. 4.3 with respect to the best result although the suppression of the worst results appear to be a much slower process.

Also worth observing is the large steps in improvements of the result, this could give an appearing random optimisation.

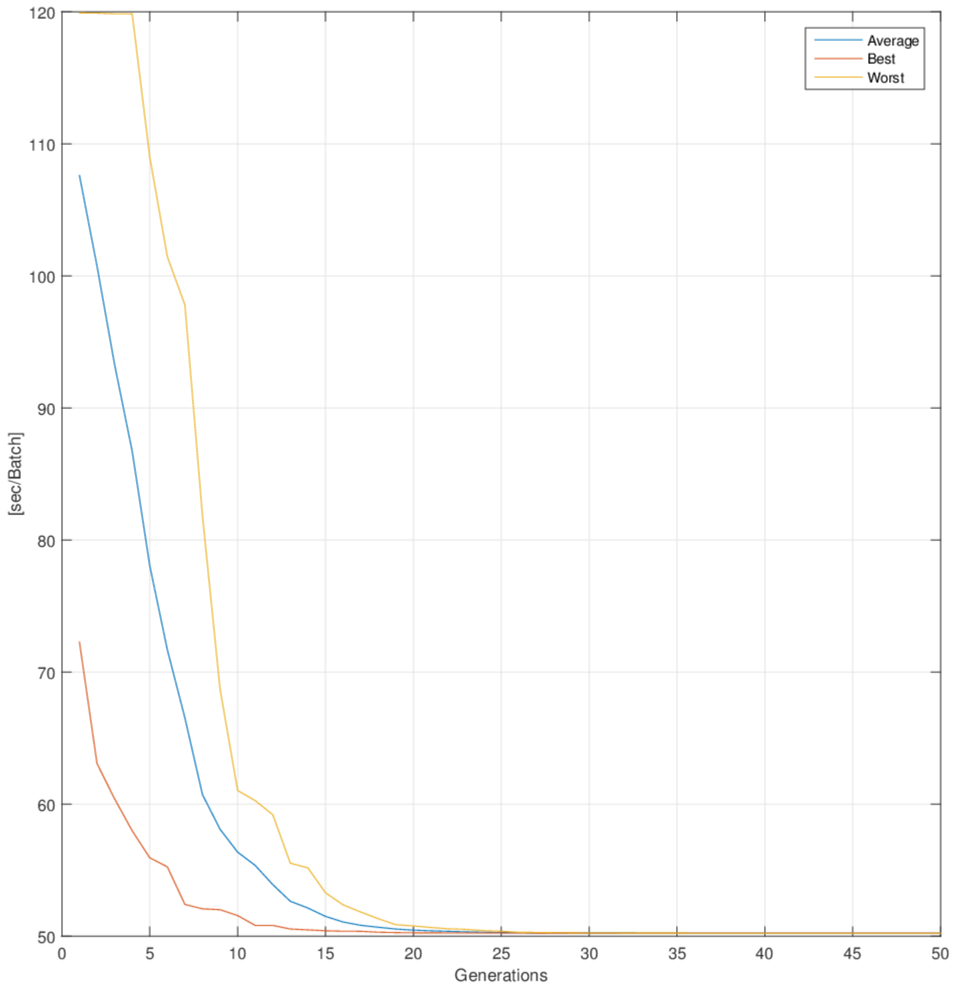

Figure 4.3: Sugar simulated performance results optimising for solely capacity

4.1.4 Rye flour

Rye flour showed large resistance towards conveying thus limiting the data that could be collected for as base for the simulations as the system if run under sub-optimal conditions would produce a stop. Within this small area there still exists low performance points but the fast convergence is likely due to the small distance evolved. As simulation for the robust starting are of the initial population in proximity of the desired solution Fig. 4.4 is an indication to the results. Thus showing the value of extra information to the system and how it could be implemented whilst the system has unstable areas of operation.

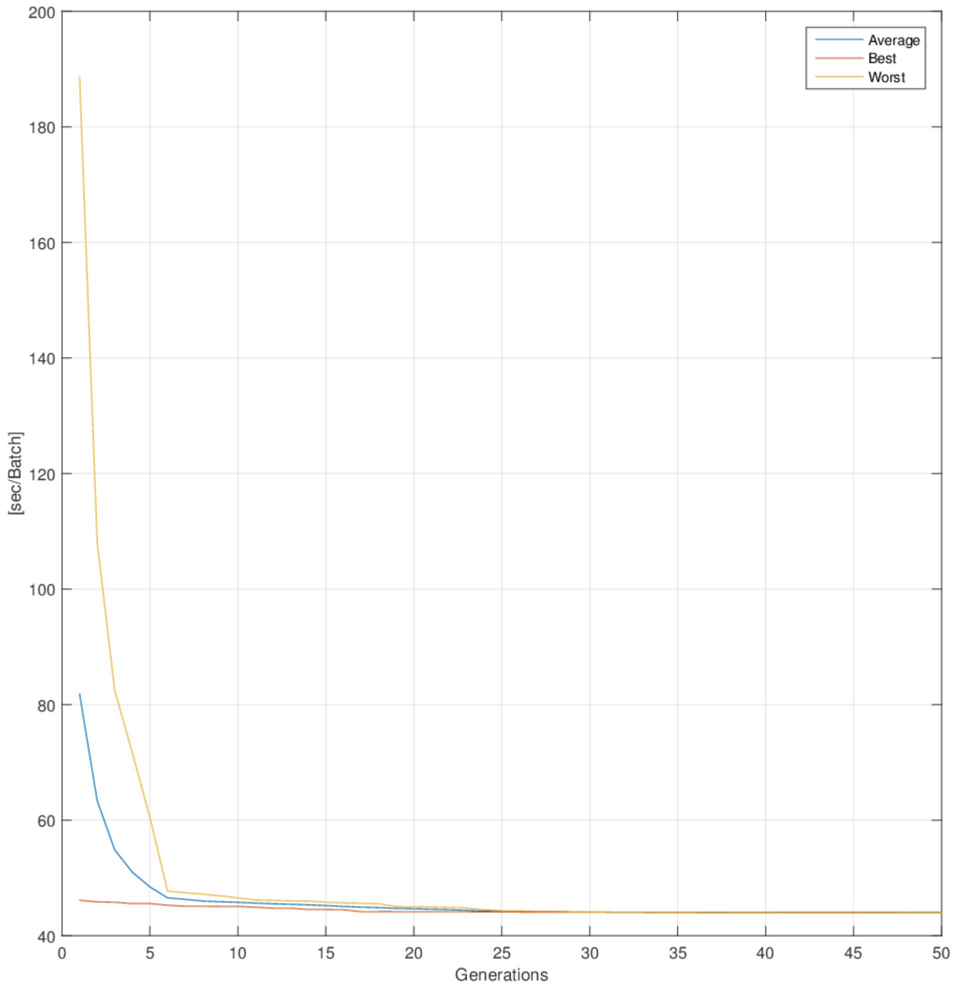

Figure 4.4: Rye flour simulated performance results optimising for solely capacity

4.1.5 Flour

Flour showed no robustness issues like rye flour and thus no problem in collecting the data for running the simulations. As can be seen in Fig. 4.5 the decrease of both average and worst performance is initially fast over the first 10 generations, at this point improvements start to level out until the 3 lines converge at approximately 25 generations. This behaviour is likely due to that flour has a wide area within which reasonable performance is achieved but a smaller area within that gives the best results.

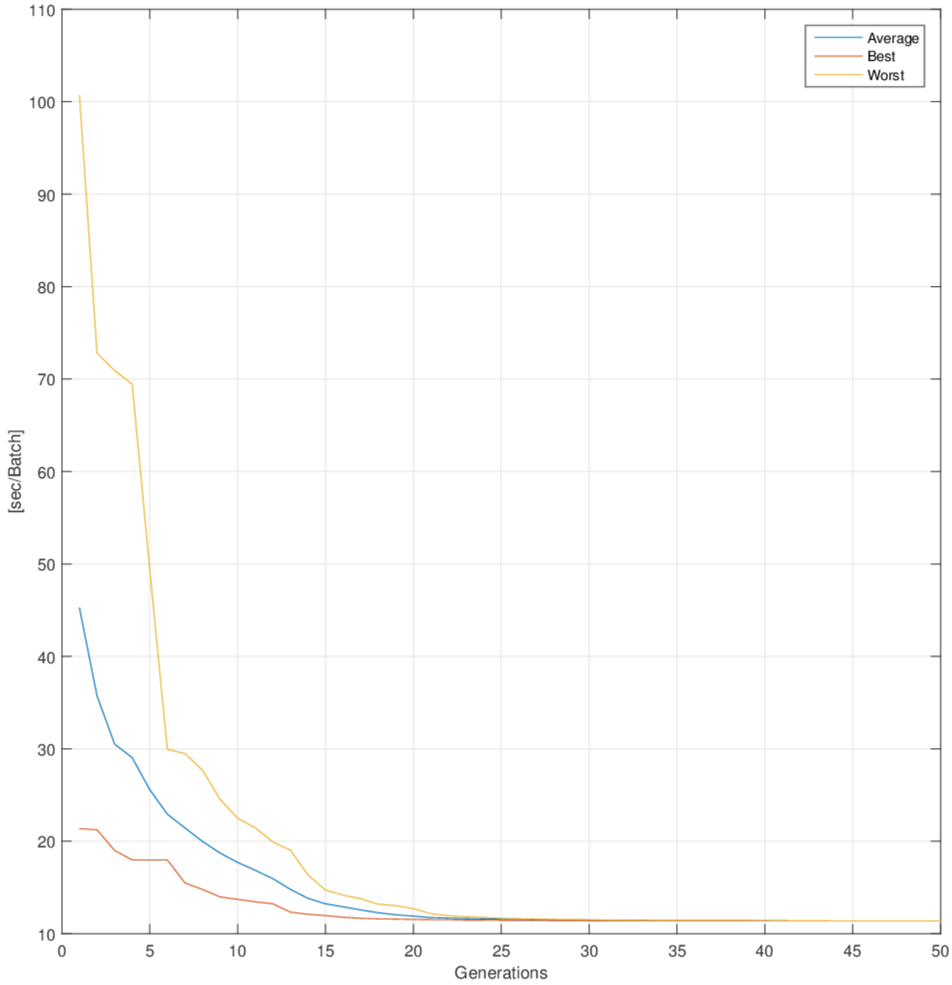

Figure 4.5: Flour simulated performance results optimising for solely capacity

4.1.6 Confectioners sugar

Confectioners sugar was in simulations similar to flour as seen in Fig. 4.6. The main difference lies within that confectioners sugar had an operating are with closed carriage air valve and large linear opening where it was prone to overfilling the pipeline and letting air bubbles pass on the top of the pipeline. To avoid this occurring and thus influencing following cycles, the area within which this phenomena occurred was excluded from the simulations. In this way better simulations that were not to influenced by the history of the pipeline as the measurement cycle was carried out. It can also be noticed that the improvements occur in a large number of small steps indicating that the area of the best performance is quite small.

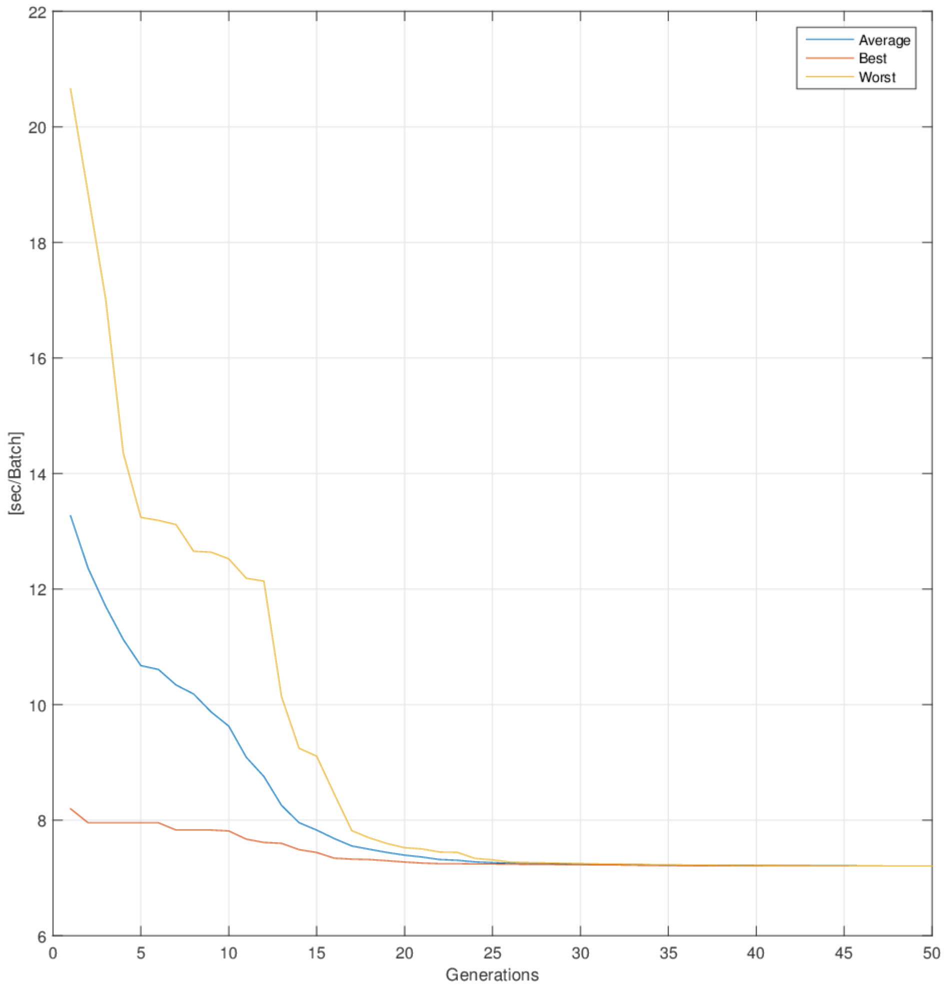

Figure 4.6: Confectioners sugar simulated performance results optimising for solely capacity

4.2 Optimisation procedure results

4.2.1 Plastic pellets

Plastic pellets was firstly tested, the material did not require fluidisation to allow for conveying. The results of the optimisation algorithm can be observed in Fig. (4.7). The optimisation process was in this case extremely fast, especially for the worst performance cycles. Within 5 generations or 50 cycles good performance was reached and appeared very stable around that operation point.

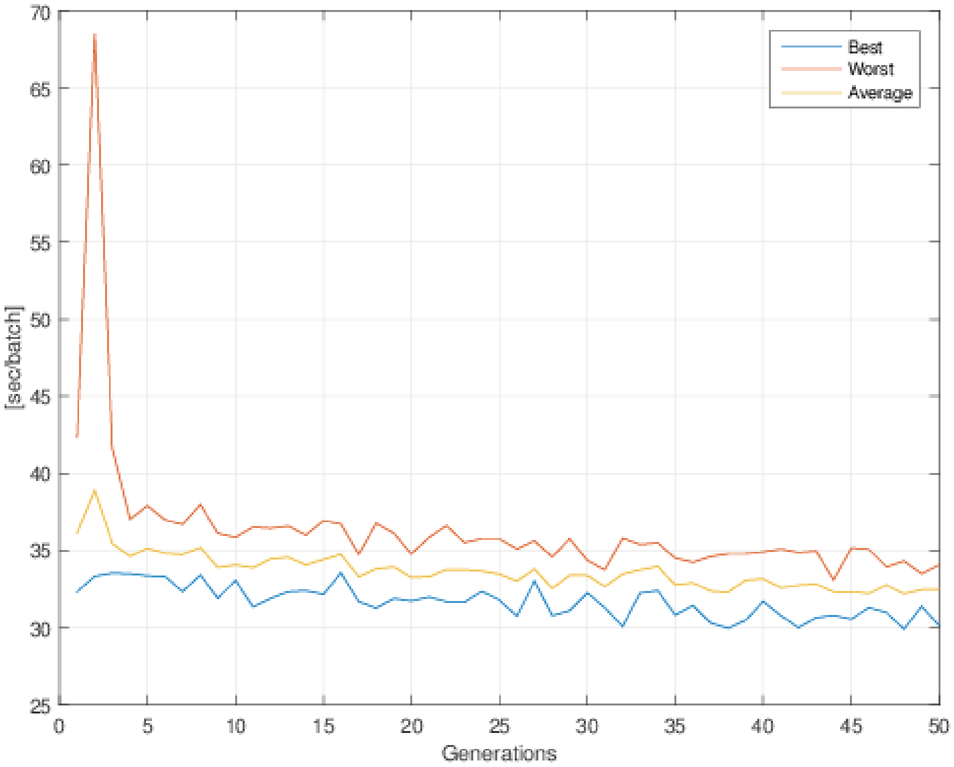

Figure 4.7: Peformance of the system optimisation running plastic pellets, cost function value refers to sec/batch

During the optimisation process the difference within each attribute was monitored and presented in Fig. 4.8. A fast convergence of any attribute could be an indication that it is important to the performance of the system. This since natural selection will be more prominent in those parameters that show the largest influence on performance. For plastic pellets the influence of air flow and the carriage air valve appear to have a large influence on the performance due to their fast convergence whilst linear opening does not appear to have significant influence. This is in line with that the low internal friction of the material counteracts the setting of the linear position and that the carriage air can go in between the large particles.

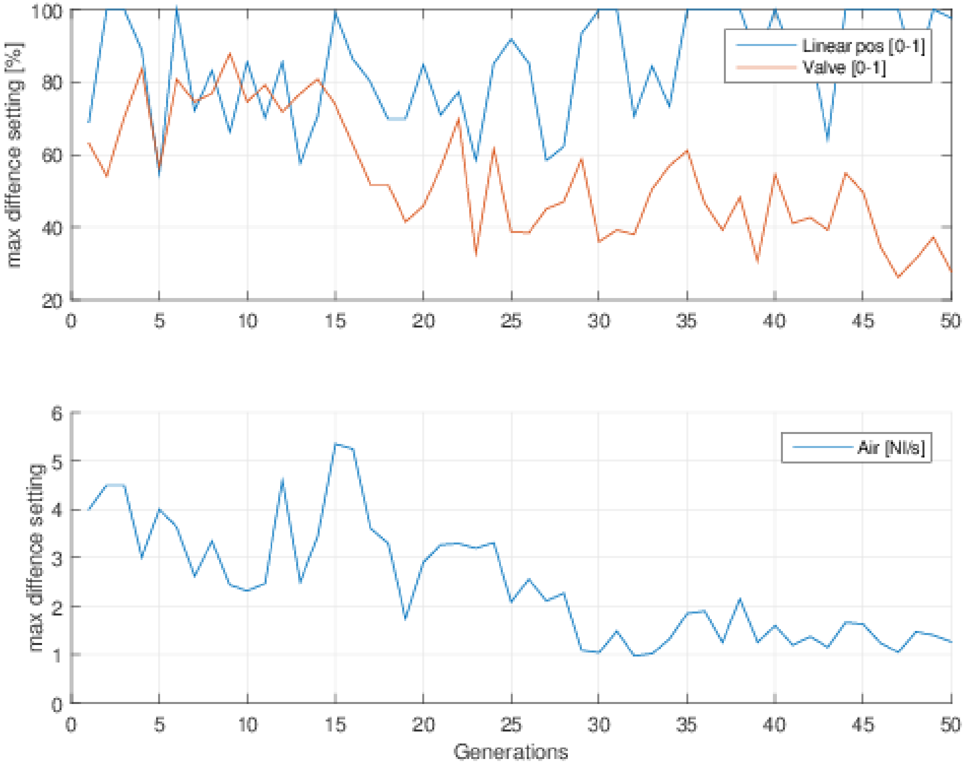

Figure 4.8: Difference within generations over time in optimisation

Following the optimisation over 50 generation's, the final generations attributes can be observed in Fig. 4.9. The relatively small deviation in the attributes air flow and valve within the generation shows that the optimisation process has reached a stage where improvements only are relatively small.

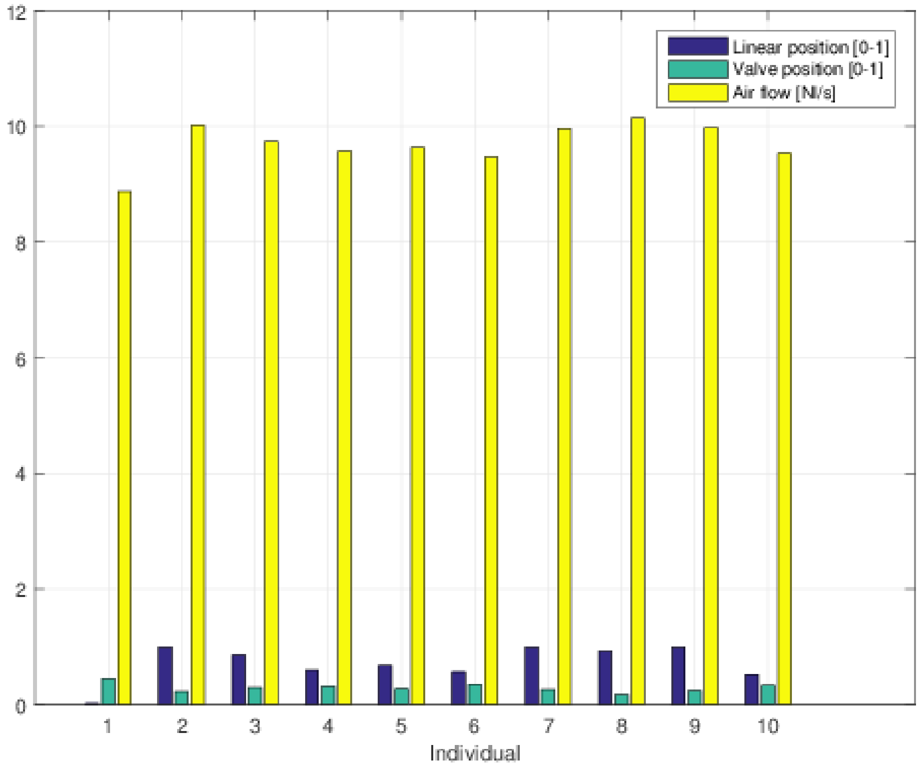

Figure 4.9: Final generation settings, linear and valve position normed to length 1

The performance of this optimisation was deemed sufficiently good with regards to capacity over time due to good average results and no outliers and thus no further test were carried out.

4.2.2 Flaxseed

The results of the optimisation of flaxseed can be observed in Fig. 4.10, the optimisation process is relatively slow but steadily improving the performance. The slow optimisation is deemed to be attributed to the large history dependency of the material, thus the performance of an individual cycle will be dependant upon the one before. Thus the entire population must be evolved to a better area in order to achieve good performance. The reason behind the large history dependency is the low density of the material that results in a low saltation velocity that gives that the pipeline can be cleared even by a low air-speed.

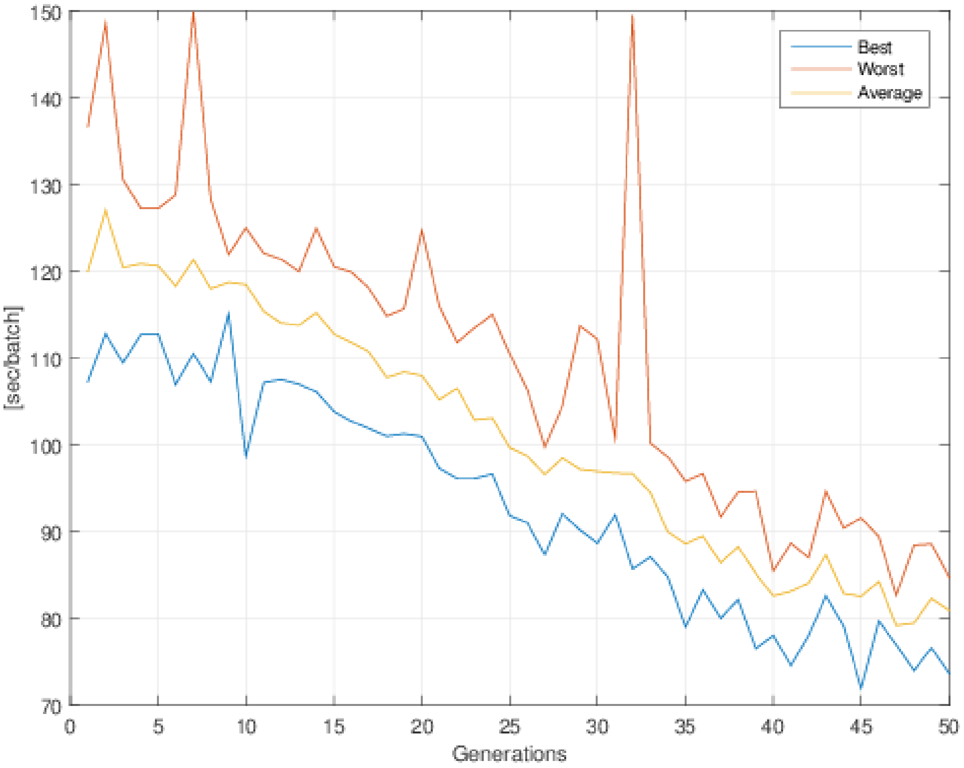

Figure 4.10: Peformance of the system optimisation running flaxseed, cost function value refers to sec/batch

During the optimisation process the difference within each attribute was monitored and presented in Fig. 4.11. From the Fig. it is evident that the sender settings have a large influence, thus the conveying process is mainly governed by the way that material enters the pipe-line.

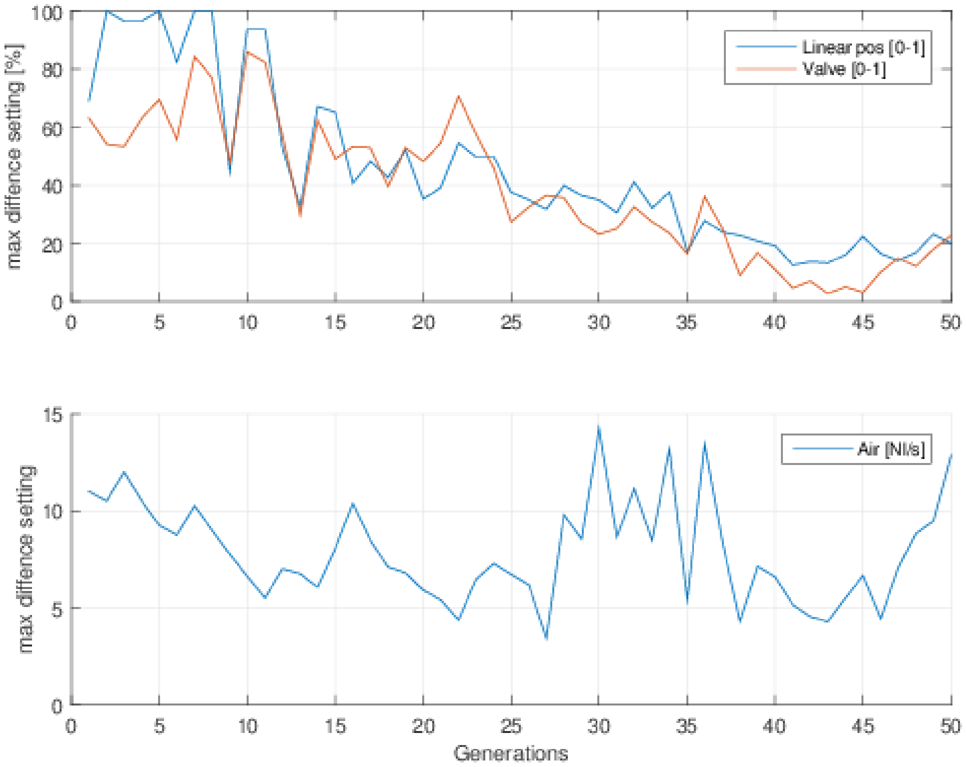

Figure 4.11: Difference within generations over time in optimisation

Following the optimisation over 50 generation's, the final generation's attributes can be observed in Fig. 4.12. The relatively small deviation in settings at the sending station indicates that those settings are relatively optimised. The large variations in air flow could be an effect of material degradation as the flax-seed gradually breaks down into a fine powder during conveying. Thus the optimising process is in the process of adapting to the new material.

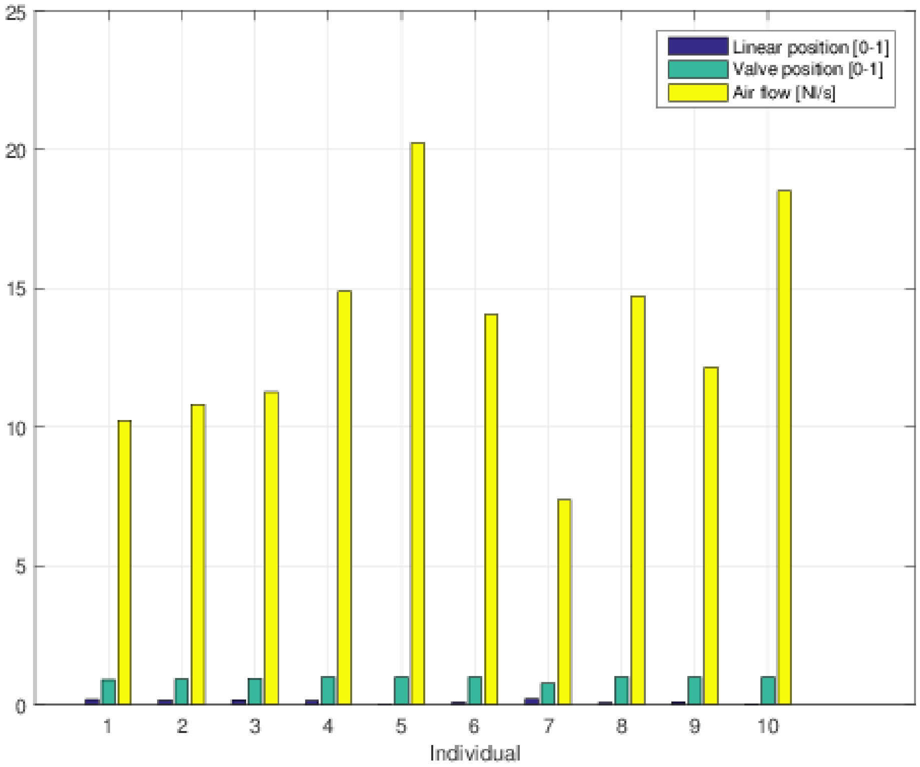

Figure 4.12: Final generation settings, linear and valve position normed to length 1

During run-time flax seeds deteriorated in the conveying process and broke down into smaller particles which in turn give different material conveying characteristics and different setting optima. Given this knowledge the decision was made that this optimisation full-filled the criteria for approved optimisation based on the continuous improvement of the average result over each generation. The last 10 generations also show a clear stagnation of improvements indicating that a good result has been ahieved.

4.2.3 Sugar

Granulated standard sugar as a material presented quite large particle size in the order of $450 - 600\mu m$ according to Brittish sugar [14] and large crystal shapes. The results of optimisation for capacity can be observed in Fig. 4.13. Due to the high inner friction of the material caused by the crystalline structure fluidisation was used at both the sending and receiving station. The optimisation was fast and showed a fast convergence for both the average and worst results over generations, the outliers are believed to have been caused by lumps of sugar disturbing the process.

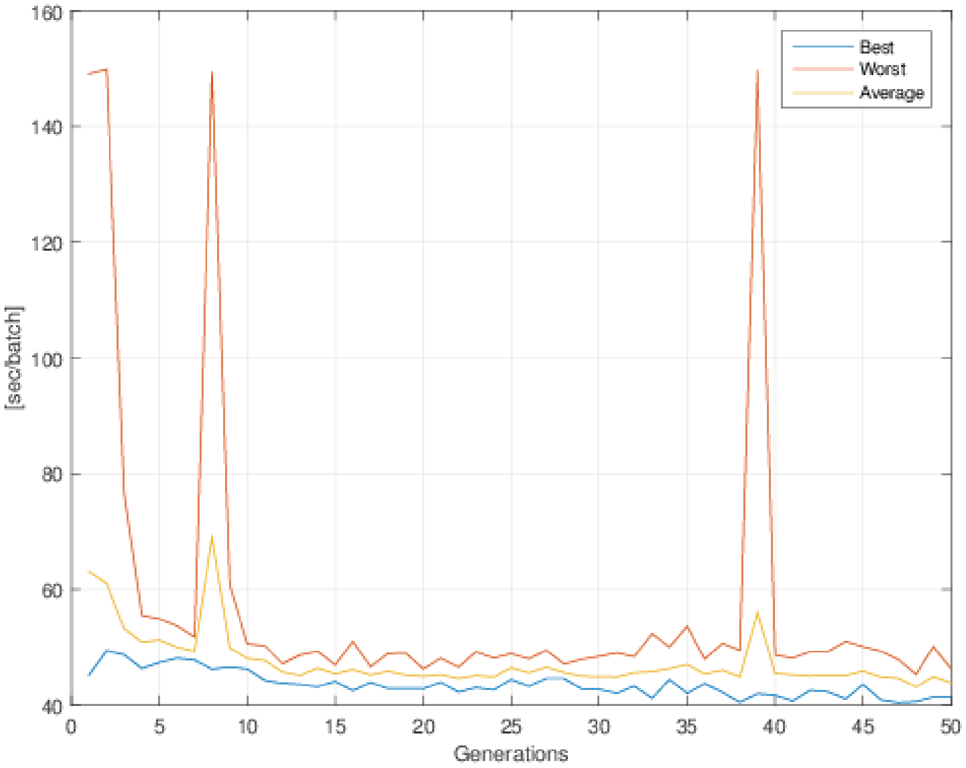

Figure 4.13: Peformance of the system optimisation running sugar, cost function value refers to sec/batch

The optimisation of running parameters for sugar appears to have small commonalities according to Fig. 4.14, although the conveying process evidently has clearly improved the performance. Observing the trend of improvements in the performance over generations whilst the difference of settings remains high indicates that the optimisation algorithm might have found more than one local optima. Since these optima coexist for a longer time-span their performance must be very similar.

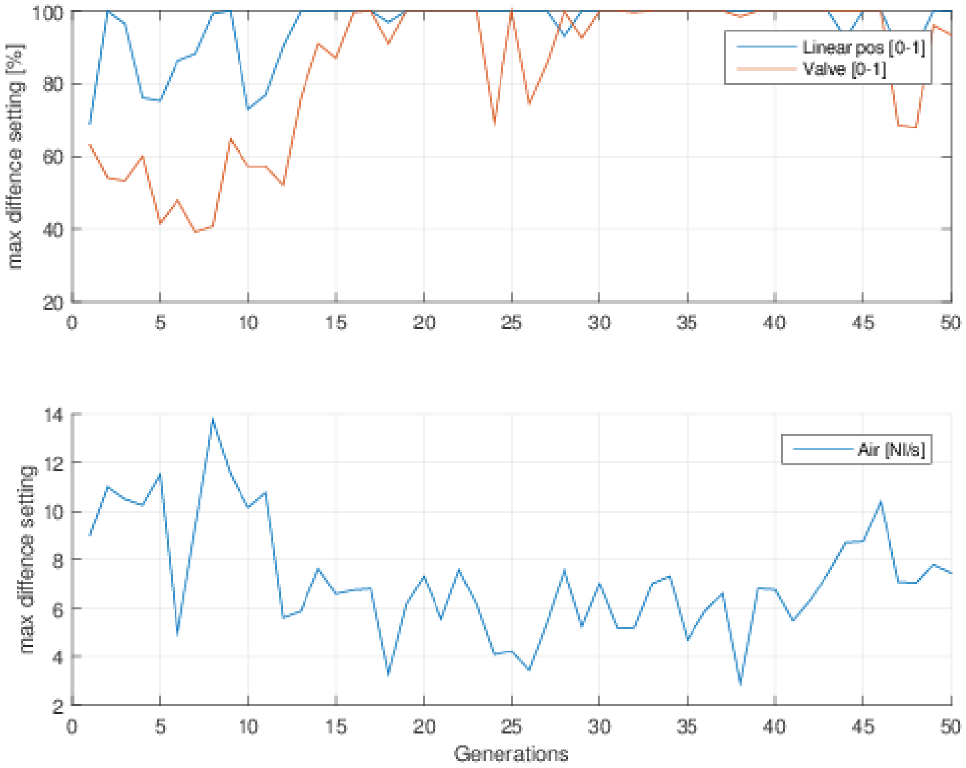

Figure 4.14: Difference within generations over time in optimisation

The last generation can be observed in Fig. 4.15 where the large difference in sending station settings can be observed. From the Fig. 4.15 two main optima appears to exists, valve and linear opening at a open position alternatively both in a closed position.

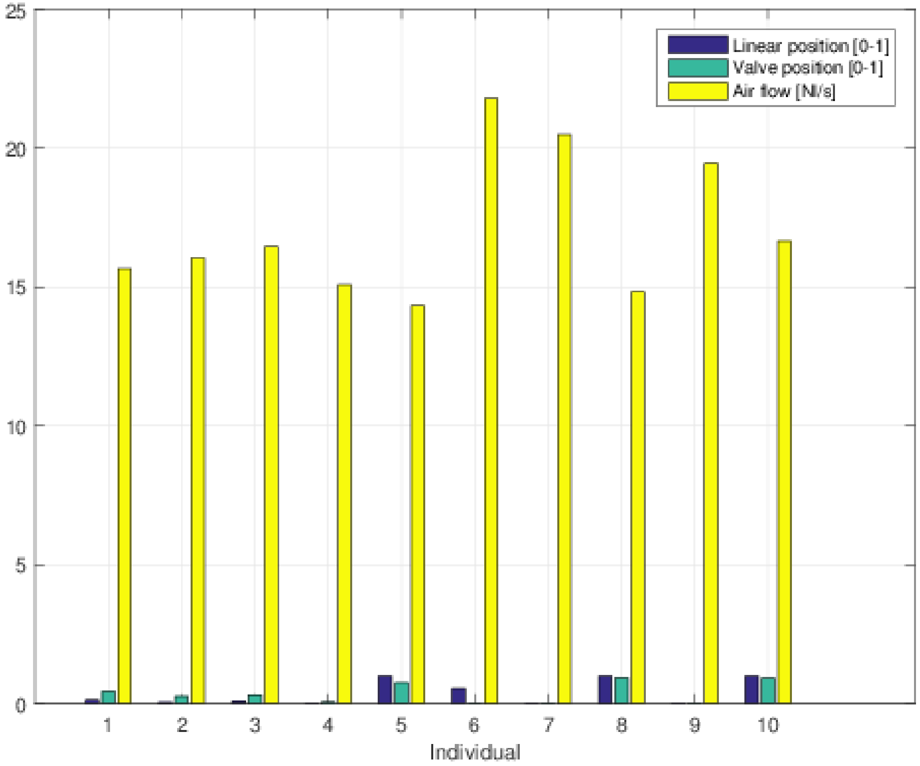

Figure 4.15: Final generation settings, linear and valve position normed to length 1

Given that fluidisation was used for the conveying the lower influence of sending station settings were expected. The existence of two optima within a population that still maintains good performance points towards that the optimisation can occur without too large influence on the run-time performance. Given time one of the optima will probably become dominant but only after it consistently shows better performance than the other. Overall the settings appears not to have changed dramatically over the optimisation procedure, although the results from the process are good and thus deemed sufficient.

4.2.4 Rye flour

The rye flour used in this project were not classified according to a standard but the main components being flour and seed type materials. The flour component presented characteristics very similar to ordinary flour in all aspects. The seed component originated from the seeds not being removed after coarse milling, these were somewhat similar to flax-seeds but had more rough edges due to the milling process. In combination these components made up a material that was very hard to convey, this is due to the flour forming plugs and the seeds acting as barbs effectively creating an airtight blockage that could not easily be resolved. Given the flour components fluidisation was used to ensure robust operation of the system.

Given optimisation towards capacity the process would very quickly yield a stop that required dis-assembly of some part of the pipeline, this was counteracted by using a new cost function that put an even weight on capacity and robustness. Also the starting area was adapted to avoid the areas within which the stops had been observed to occur. The result of this optimisation can be observed in Fig. 4.16.

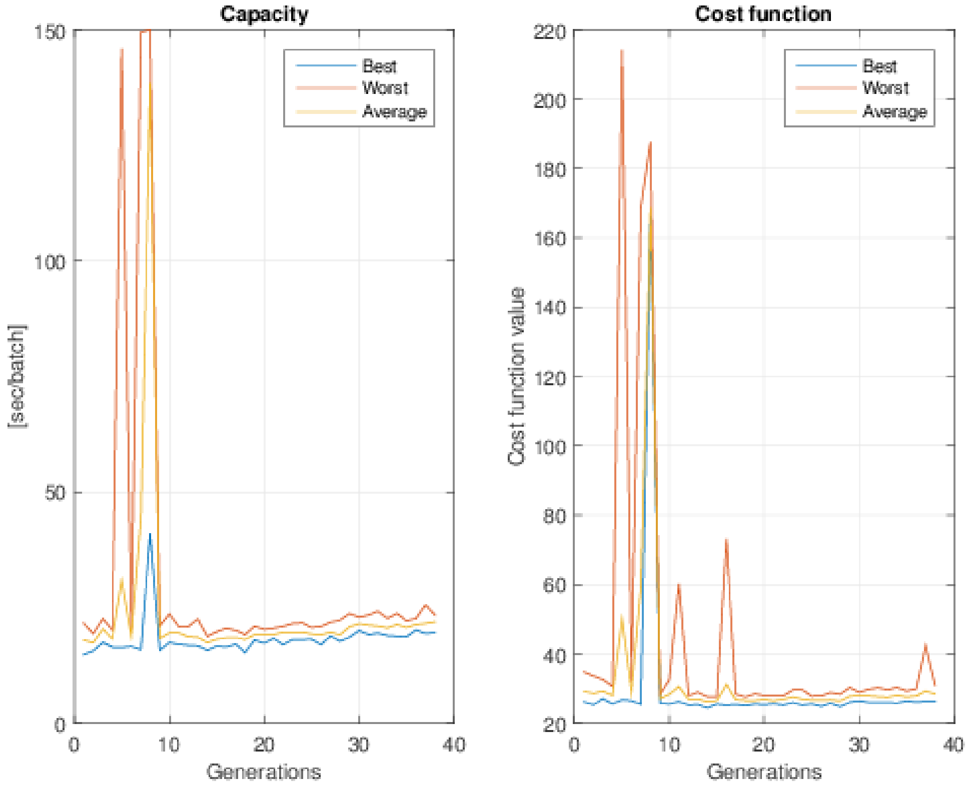

Figure 4.16: Performance of the system optimisation running rye-flour, cost function value refers to a combination of capacity in sec/batch and robustness in standard deviation of vacuum pressure

The settings evolution for this optimisation shows a distinct movement towards a common optima as can be seen in Fig. 4.17. It is also visible that the main components used by the optimisation algorithm used for tuning is the carriage air and the air flow that quickly converges, this can also be an effect of the fluidisation used in the sender. The carriage air influence on the conveying process makes it crucial for controlling the robustness criteria.

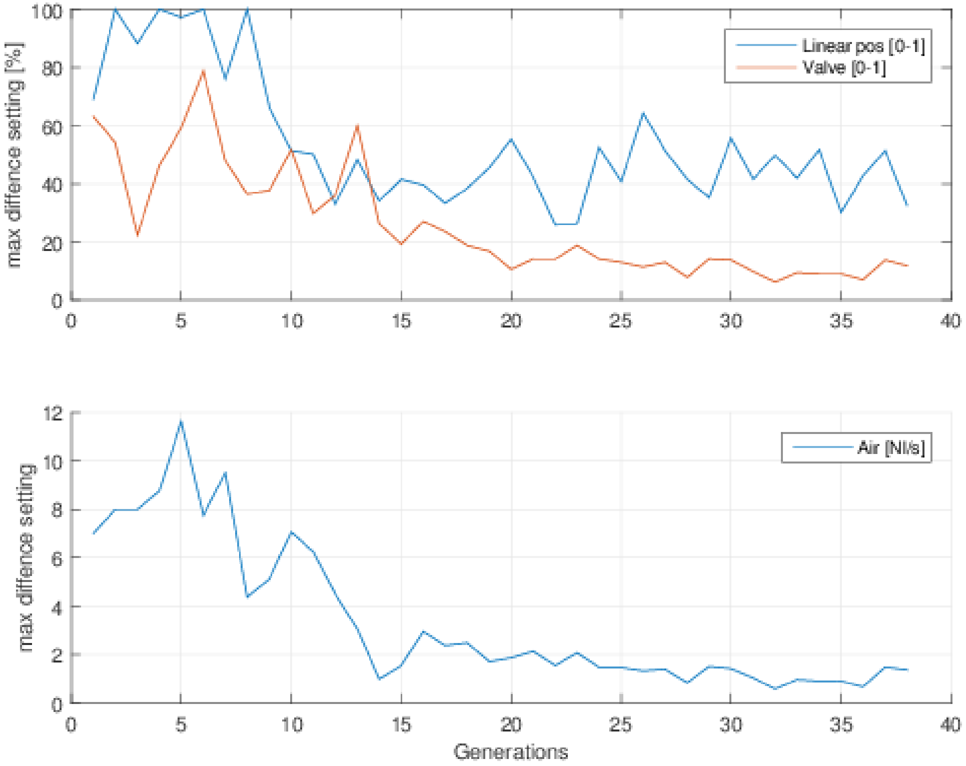

Figure 4.17: Difference within generations over time in optimisation

The high dependency upon all the parameters to achieve a robust conveying with high capacity yields a highly converged set of parameters as can be seen in Fig. 4.18. This level of high convergence appears to be the effect of a narrow area that offers the best performance in relation to the designed cost function.

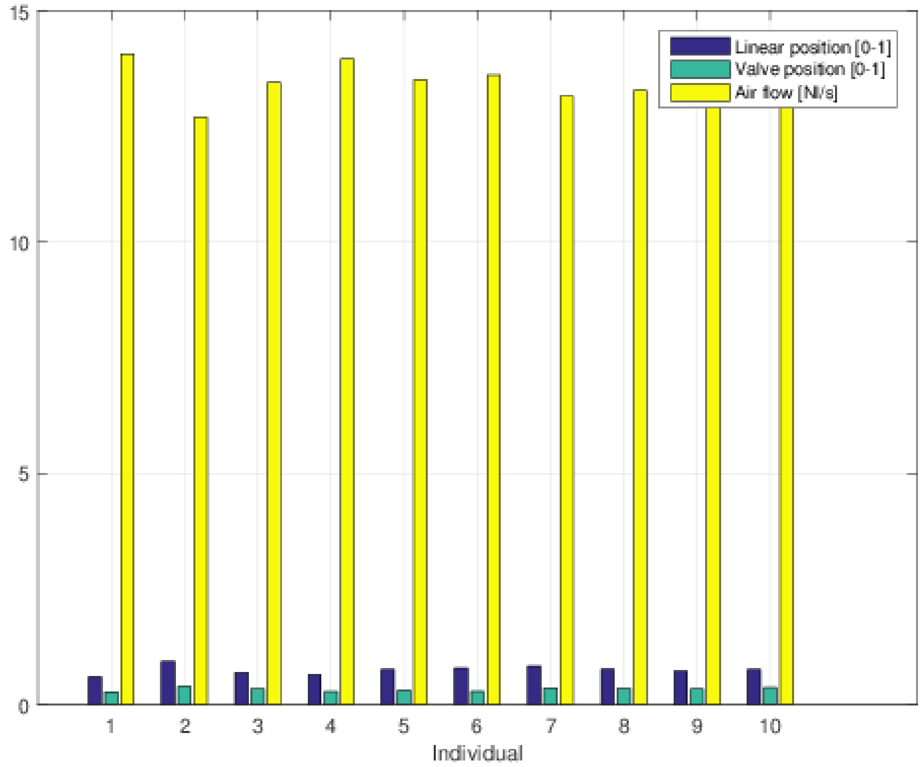

Figure 4.18: Final generation settings, linear and valve position normed to length 1

The result of this optimisation is a population of individuals with a high degree of similarity given in Fig. 4.18 that shows good performance as shown in Fig. 4.16. Thus proving that the cost function can be altered to improve performance in relation to different objectives.

As this optimisation put a large emphasis on the robustness of the process this will of course negatively influence the capacity that will be achieved in favour of robustness. Given that the main goal of this optimisation was capacity it was considered relevant to rerun the optimisation with a cost function consisting of $\frac{2}{3}$ capacity and $\frac{1}{3}$ robustness criteria. The result of this new optimisation is presented in Fig. 4.19. The level of capacity is clearly improved with the increased emphasis in the cost function, the drawback however consists of disturbances in the cost function. These disturbances originate from the robustness criterion and can be viewed as the system is not doing a trade-off between capacity and robustness and thus can not maintain both at a high level.

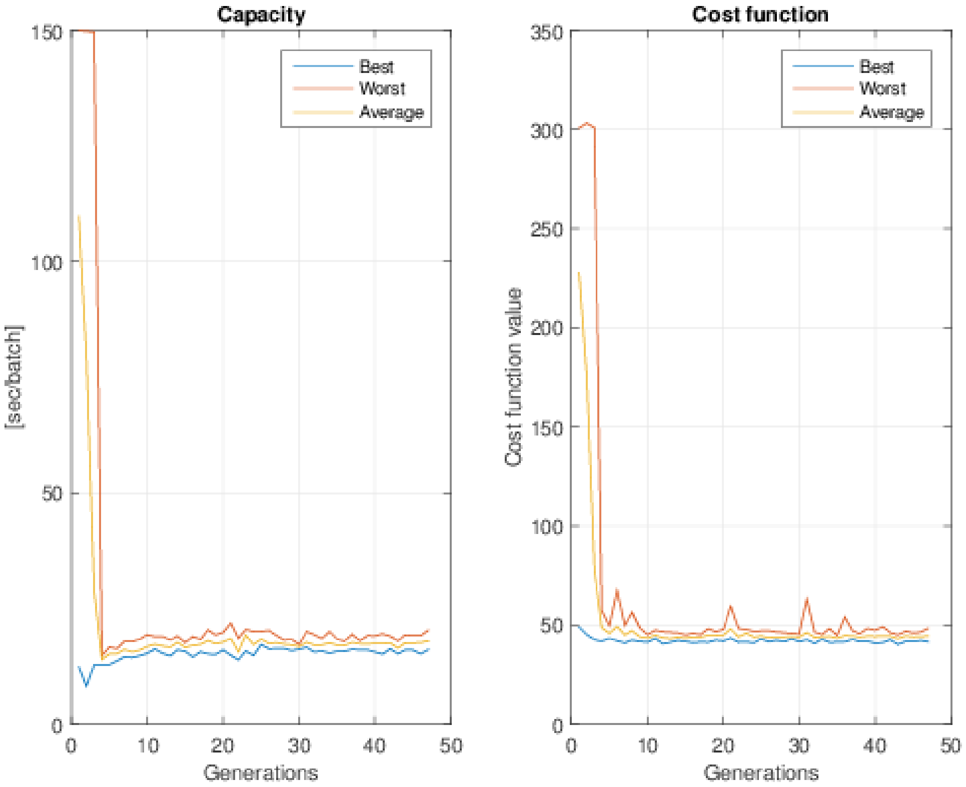

Figure 4.19: Performance of the system optimisation running rye-flour, cost function value refers to a combination of capacity in sec/batch and robustness in standard deviation of vacuum pressure

The behaviour of the system's settings is very similar to that of the earlier test as can be seen in Fig. (4.20). The only major difference visible is the larger difference in air flow settings. This could be an effect of the system increasing air flow to allow for the higher capacity emphasis.

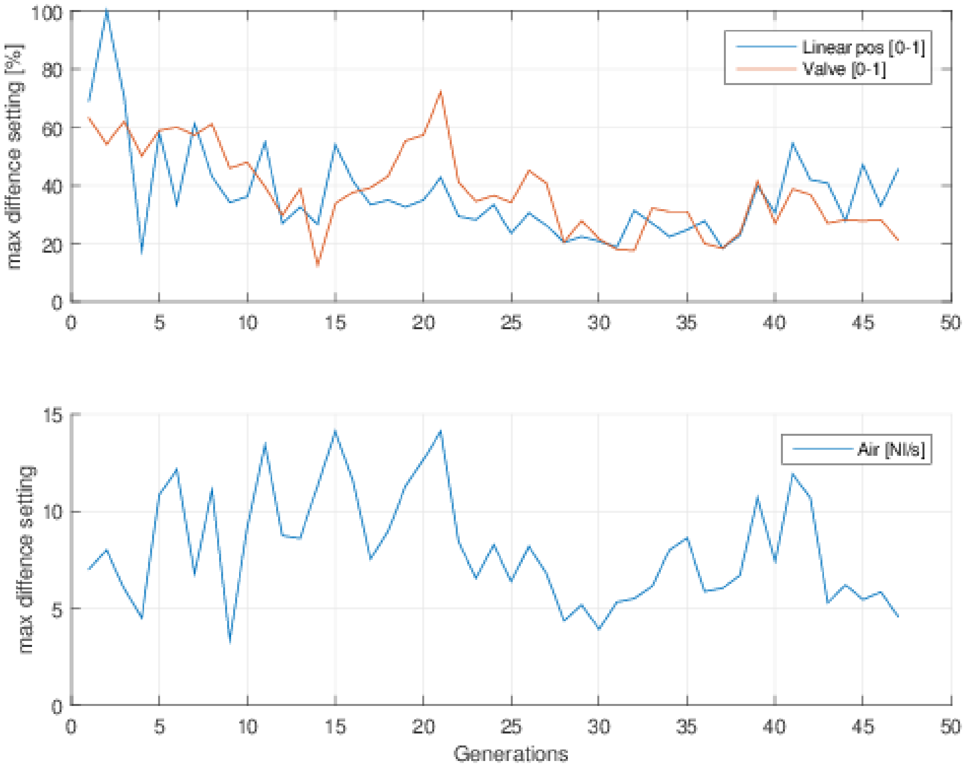

Figure 4.20: Difference within generations over time in optimisation

Also the last generation show small deviations in the sending station as the earlier test as shown in Fig. 4.21. Some differences in the sending station settings compared to the earlier test were visible but the main component was the increased air flow that might also have contributed to the promotion of new settings. Given these two tests and their results, it was concluded that the requirements had been meet, it had also been noted that the seed part of the material that caused the trouble with robustness in conveying were degrading and thus further test would have been running another material.

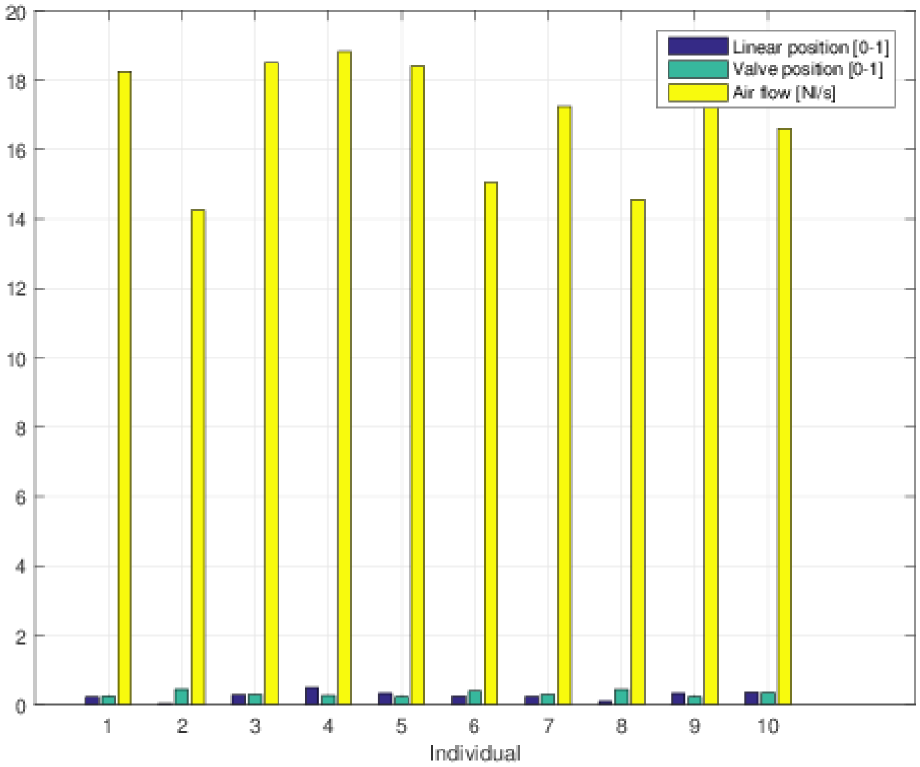

Figure 4.21: Final generation settings, linear and valve position normed to length 1

Rye flour as a material posed robustness issue for conveying, with optimisation towards capacity a stop would quickly occur. If the cost function was altered to also include a certain level of robustness, a balance between robust and high capacity conveying could be achieved. Given this information the material is shown to be able to be transported using a cost function based on both capacity and robustness criteria and thus the design process will lie within designing a reasonable trade-off for the desired traits.

4.2.5 Flour

Flour differs from rye flour since it derives from wheat and all seeds remaining after milling are removed. Thus the material is very homogeneous and consists of a fine powder. The material does require fluidisation due to bridging properties and the results from optimisation for capacity can be observed in Fig. 4.22. During run time flour visibly changed properties, the bridging properties increased and more distinct plugs with lower air permeability formed. Despite this the optimisation process was faster than expected from the simulations in Fig. 4.5.

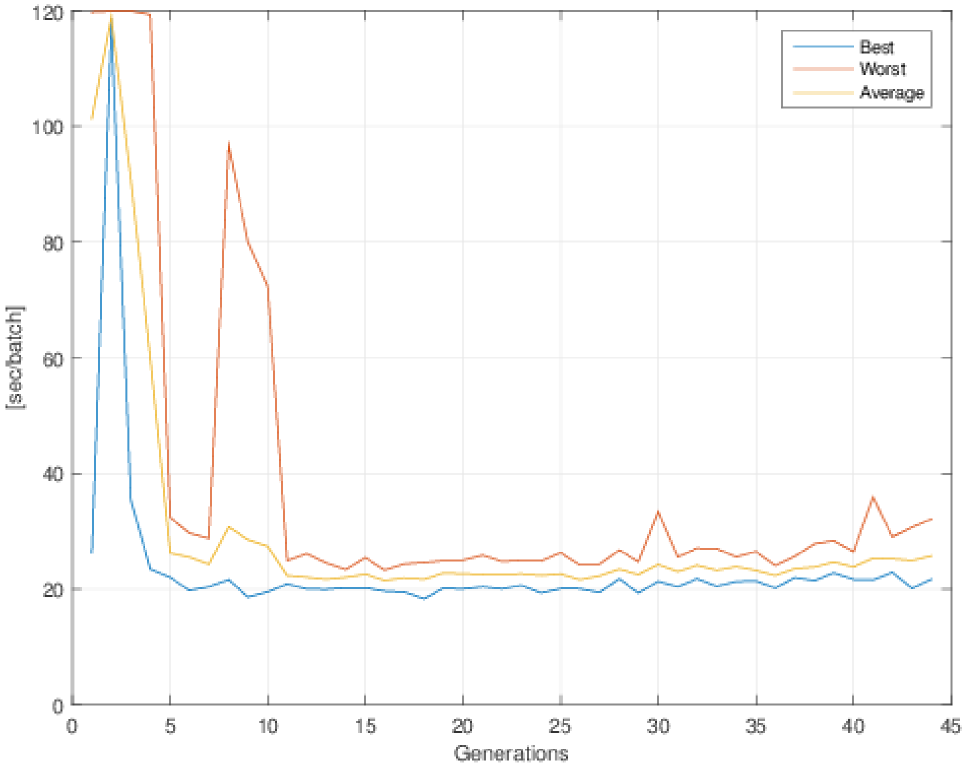

Figure 4.22: Performance of the system optimisation running flour, cost function value refers to sec/batch

The changes in material properties can be observed in Fig. 4.23 as the initial trend is towards a homogeneous population but does not hold for the entire process. Despite this large variation in material properties the carriage air valve has a clear convergence as has been evident in rye flour earlier. This similarity is probably due to the similarities in plug formation that is highly sensitive to carriage air setting.

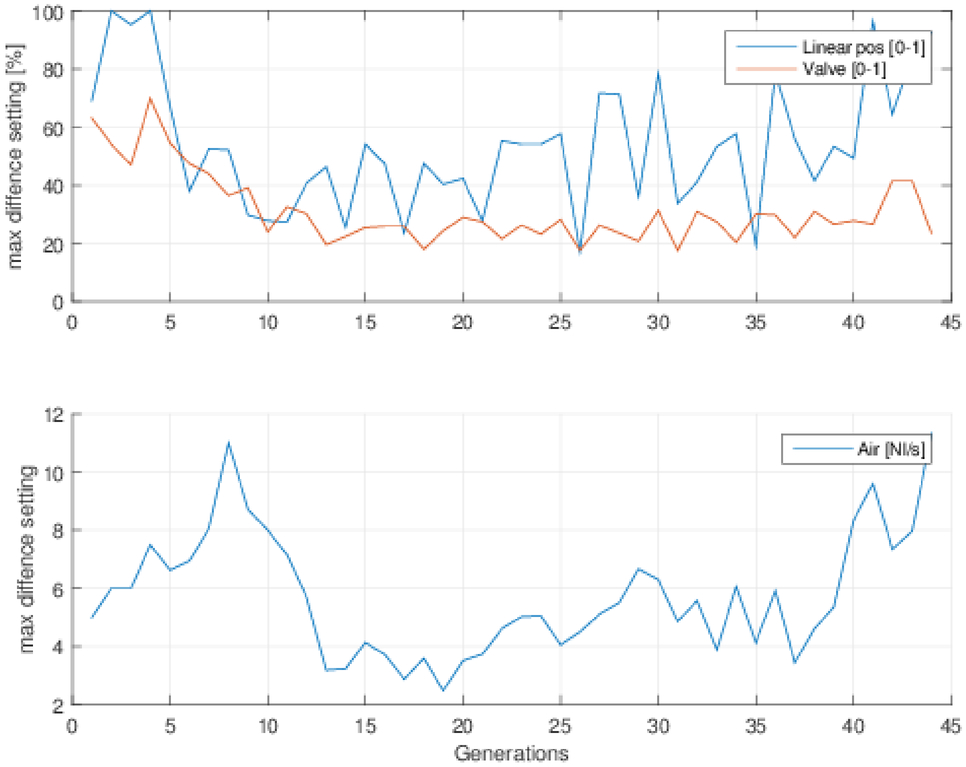

Figure 4.23: Difference within generations over time in optimisation

The population after the optimisation process shows small differences in the carriage air valve settings whilst the other parameters displays larger differences seen in Fig. 4.24 . This in combination with the relatively small deviations in performance observed in Fig. 4.22 gives an indication of the ability in the system to handle changing material properties. The fact that neither air flow or linear position converges whilst still allowing performance shows that the system is constantly testing a wide range of settings and if either would show to have an influence on performance, it would start to converge.

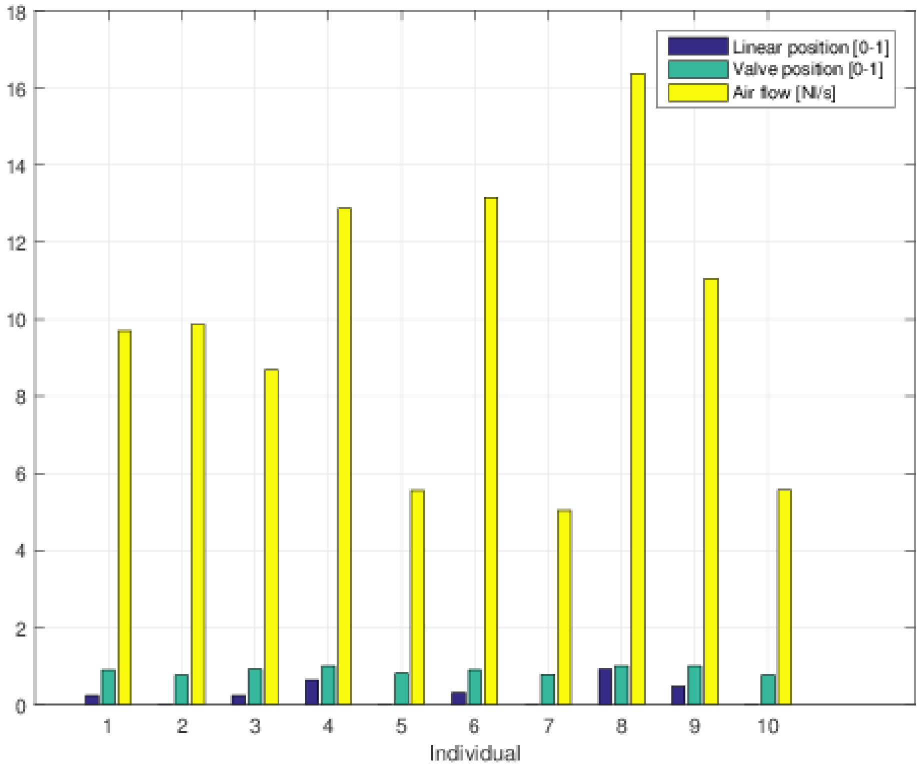

Figure 4.24: Final generation settings, linear and valve position normed to length 1

The results obtained from optimisation of flour were considered to fulfill the desired properties of optimisation due to the good performance and stable results even though observable material degradation. It is also of interest to see the maintaining of search area if incentive for convergence is lacking.

4.2.6 Confectioners sugar

Confectioners sugar is composed of a very fine powder that requires fluidisation for both the sending station and emptying of the conveyor. The material had low permeability towards air and a small particle size whilst still being somewhat bridging. Optimisation was firstly tested only using only capacity as criteria, the result is presented in Fig. 4.25. The result of this optimisation is good best results but the worst results show large problems with the solutions repeatability.

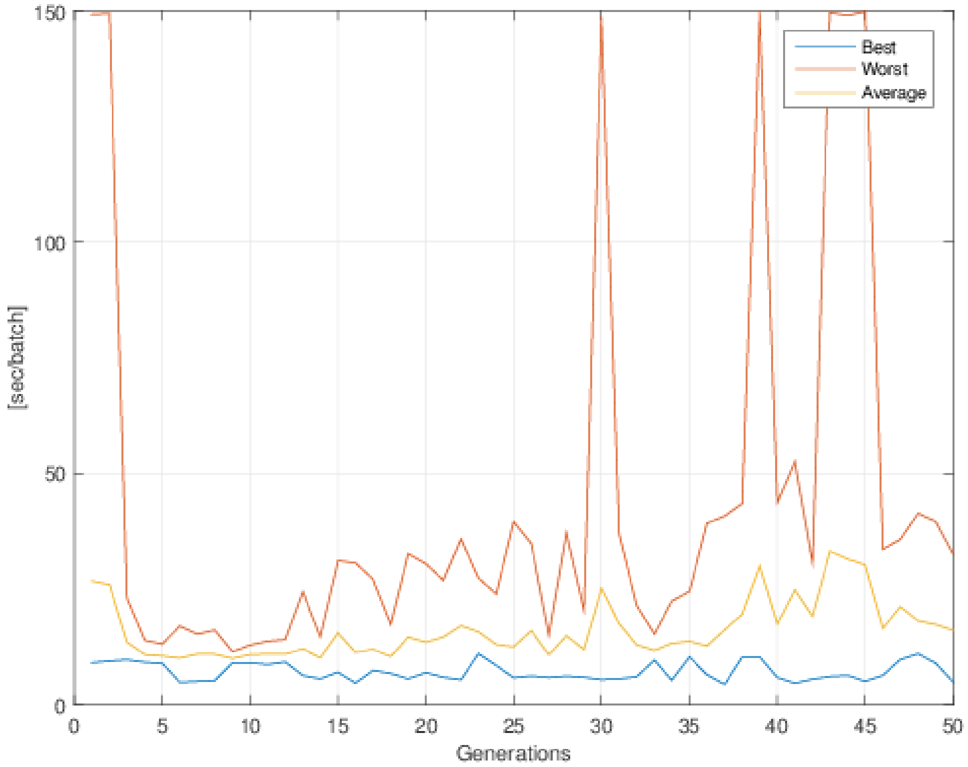

Figure 4.25: Peformance of the system optimisation running confectioners sugar, cost function value refers to sec/batch

When observing the optimisation over time the control parameters converge during the process as can be seen in Fig. 4.26. The figure shows a steady convergence of all parameters indicating that a optima solution is found, this optima might in turn not be suitable for this type of application since it will not reliably perform well. Instead the system is trying to perform one cycle as fast as possible but is missing the bigger picture.

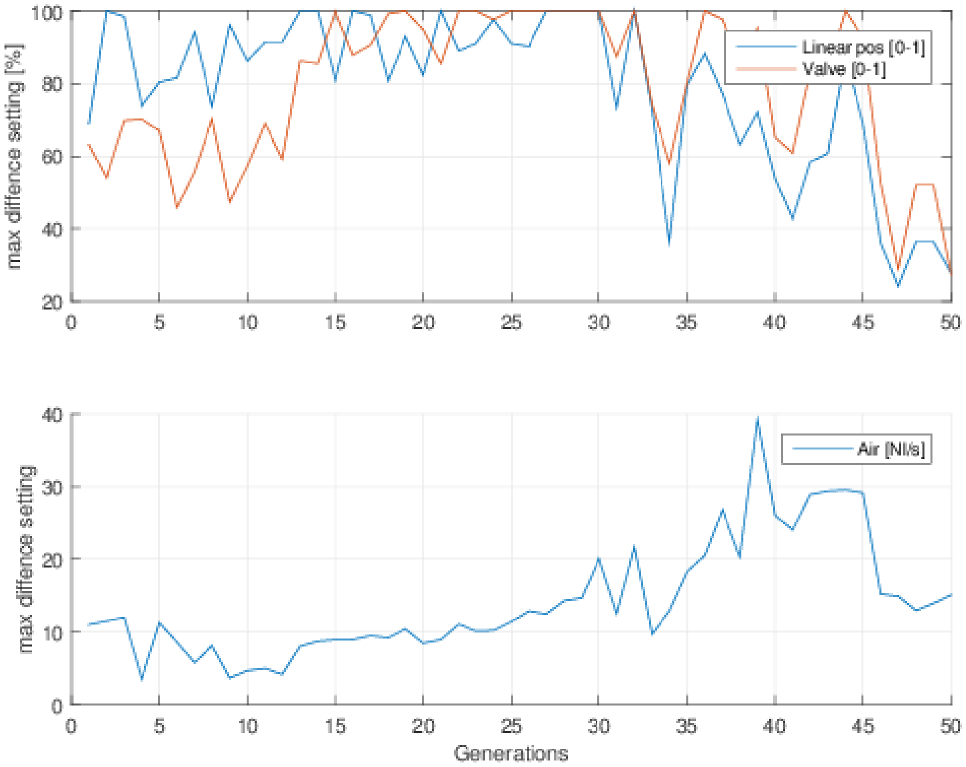

Figure 4.26: Difference within generations over time in optimisation

The final population after optimisation can be seen in Fig. 4.27 and as can be observed all the parameters show small differences, thus implying a optima has been found. The final population is clearly more homogeneous than the performance results indicates.

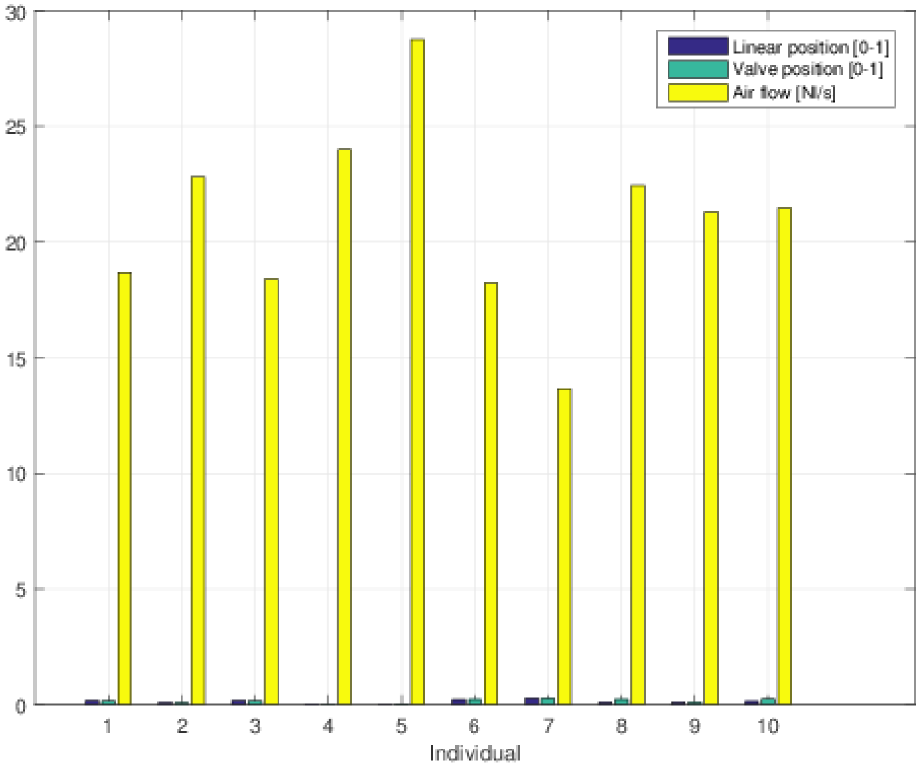

Figure 4.27: Final generation settings, linear and valve position normed to length 1

In the optimisation presented above the best results of each generation were consistently at a good level with few outliers throughout the process but the average result and worst result clearly does not present the same good performance. This phenomena makes that the optimisation does not meet the requirements placed upon it. It was suggested that the solution should be moved from the area of maximum performance in each cycle to allow for better repeatability.

As a result of this a new cost function was developed, the theory was that a too high emphasis on maximum capacity would lead to unstable operation with high maximum performance but with high risk of sub-optimal operation. The new cost function added $\frac{1}{3}$ efficiency and $\frac{2}{3}$ capacity and the result observed in Fig. 4.28. The thought was to give a solution benefiting from the natural frequency of the system. This optimisation is clearly less fast to converge towards an optima and the best result is not performing as good as the earlier approach. On the other hand it counteracts the repeatability problems and provides a better trade-off for the average result.

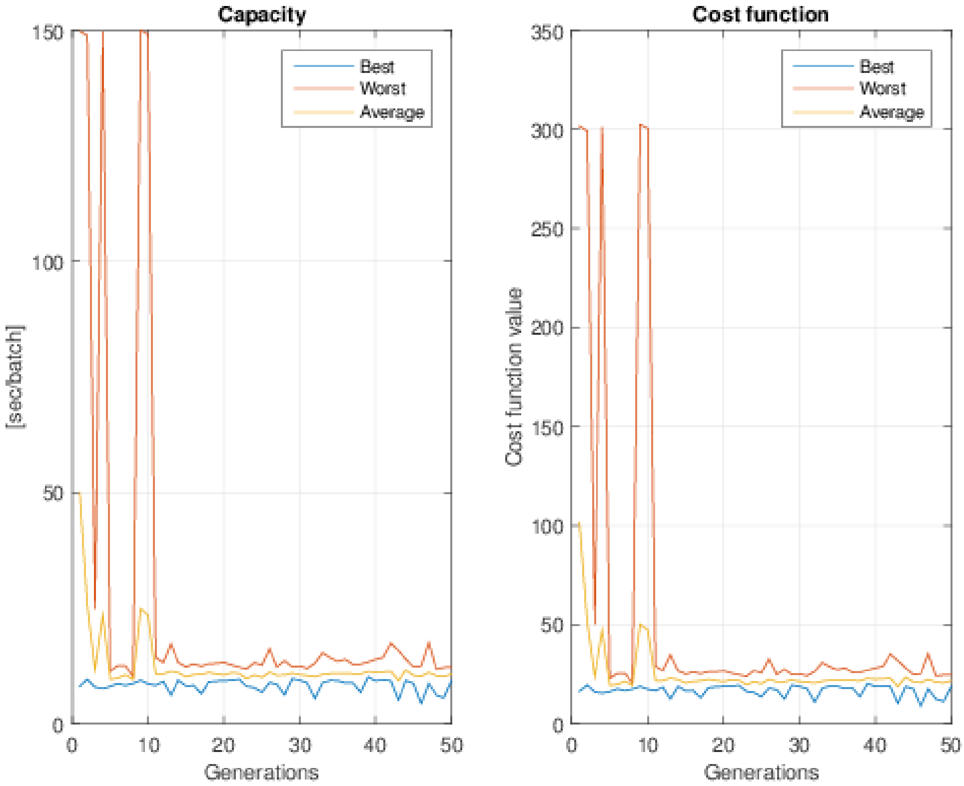

Figure 4.28: Peformance of the system optimisation running confectioners sugar, cost function value refers to a combination of capacity in sec/batch and efficiency in consumed compressed air Nl/batch

The convergence of control parameter as observed in Fig. 4.29 shows a steady progress towards an optima. It can also be noted that the convergence is faster for all parameters indicating that the cost function explicitly promotes an area for operation.

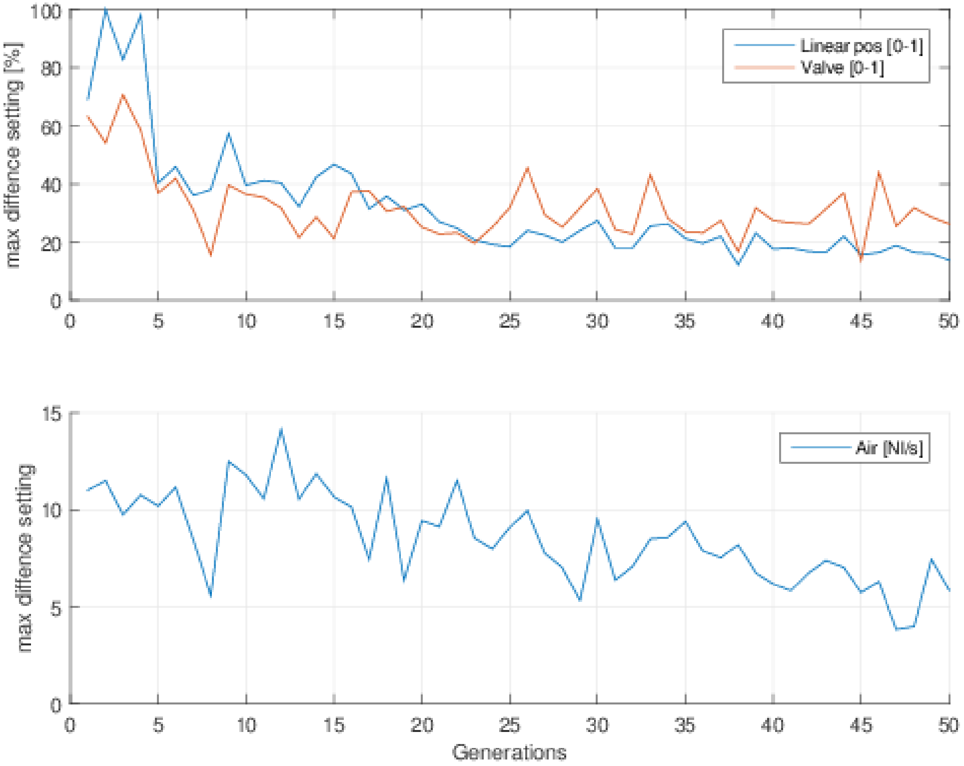

Figure 4.29: Difference within generations over time in optimisation

In Fig. 4.30 the final generation shows a clear difference from the earlier optimisation mainly in the sending station parameters. The main difference lies within the small deviation in sending station parameters, thus indicating a highly tuned behaviour in that part of the system.

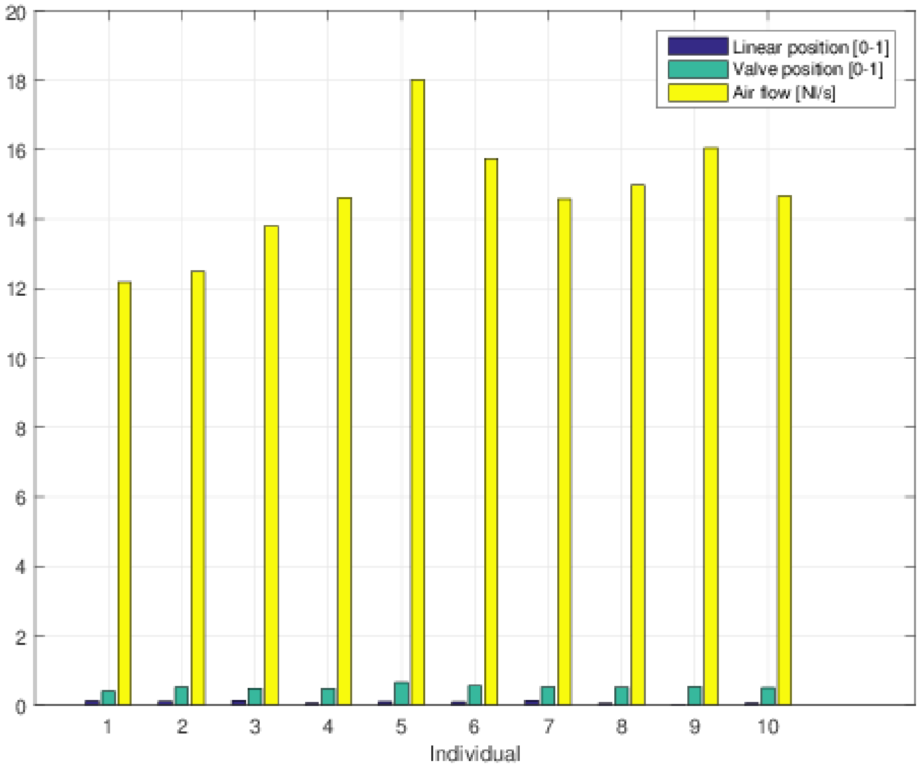

Figure 4.30: Final generation settings, linear and valve position normed to length 1

The combination of capacity and efficiency in the cost function has clearly improved the performance with respect to the average and worst performance in optimisation. These optimisations for confectioners sugar show that a combination of the optimisation parameters can be necessary to produce acceptable results.

4.3 Material degradation

One mayor difference between the test carried out within the scope of this study and actual operation of a plant within a factory is the material supplied to the system. In a real application the material supplied would constantly be replenished, in the laboratory this is not possible simply for reasons that the required amount of material is not realistic to use for this type of tests. Thus for each material the material was manually inspected before and after each test session to give an indication to how degradation might have affected the results. This will of course be a blunt instrument as it will not capture the dynamics of the degradation as the materials are assessed at the end of each test and visually inspected during run-time.

Table 4.1: Estimated material degradation for materials used in the study

Material	Behaviour
Plastic pellets	No degradation evident
Flax-seed	Deteriorates towards finer particles with more spherical shape mixed with powder
Granular sugar	Large degradation, became similar to confectioners sugar after some time
Rye flour	Extremely non-robust conveying with flakes in flour, high friction caused by the lodged in flakes that thus are prone to breaking down into finer particles. Essentially approaches flour the longer this process continues.
Wheat flour	Degrades to finer particles and dust relatively fast, also becomes more bridging. Over time the material is aired and small lumps removed
Confectioners sugar	Generates a lot of fine dust but what is not converted to dust remains unaltered

4.4 Filter performance

During these test a standard approach of 1 filter-chock per emptying phase was used. Throughout all the tests filter pressure drop was monitored and found to be within a small margin of the data-sheet value for all tests. This margin was approximately within $\pm 5kPa$ of the data sheet value D. During runtime a normal chain of event for a conveying cycle would be initially $0kPa$ difference and when the pump is turned on a large pressure difference build up due to air compressibility. When this transient passes the pressure difference quickly converges towards an equilibrium and remains at that equilibria with only small ringing effects over time. Thus no incentive for further analysis of filter performance was deemed to exist for this thesis.

Discussion

The system in an application will have multiple benefits compared to an traditional static system. One of the main being the reliability of operation to be expected after the initialisation phase has passed. This reliability of operation is due to the level sensors, emergency mechanism and evolutionary learning from earlier cycles. For the traditional conveyor a source of machine downtime is failure of the filter caused by overfilling with material. This is a problem mostly prominent when maximum capacity of the system is desired and will in reality forces the operator to use a certain level of margin to compensate for uncertainties in the conveying process. This margin can in essence be removed when using a level sensor and thus batch size will always be approximately the maximum size without risk of filter failure. Another risk of down-time is pipe blockage, although normally complete stops will not form in a well designed system. Instead blockages would form either due to a poorly designed pipe system, environmental disturbances or shifting material properties. The approach of using an emergency valve that stopped the addition of new material to the pipeline and allow the pump to decrease load in order to be able still provide air flow worked in certain cases. The main factor determining the success rate of the emergency function was the material itself, if the stop was caused by a sudden blockage caused by jamming of a plug with hard components such as rye flour and pipe the operation was in most cases not successful. On the other hand if the problem arose more gradually due to for example too heavy loading with material in the pipeline, the operation in most cases were able to avert the risk of a complete stop.

Given that today no emergency function exists the possibility of averting some of the possible stops must be seen as an improvement, noting also that if the system is running in a controlled manner the sudden type of stop should only be possible if major external disturbances occur. Therefore the main usage of the the emergency function should be in the start up phase of optimisation when material properties are unknown or changing. It is also notable that all the parents that form the base for the current cycles will have been selected on the basis of measured performance in the system and the longer the run-time the further the selection will have advanced and thus a larger set of solutions will have been selected from to form the best performance base for the current cycles parents. Thus it will be so that each machine will have a set of parameters based on the limitations of that specific machine and not a theoretical or approximation of the control parameters.

Another large benefit of the optimisation is that due to that the system can without risk be operated closer to maximum performance, the system can therefore be used more efficiently or in new applications. The saving can be realised as a smaller conveyor doing the same job or using the same setup and use intermittent operation, if a smaller conveyor is used the footprint from production will be smaller. New applications will be possible since the system will be able to adapt to the surroundings.

In a modern factory capacity demands are often described as compliance with takt time. These demands could then form the boundaries for a successful cycle whilst allowing the optimisation for either robustness or efficiency, the time left after each cycle could be spent idle. Thus the process can avoid unnecessary optimisation in capacity if the rest of the factory does not benefit from the added capacity. This could be realised as a specific demand on capacity to optimise so that the capacity criteria is fulfilled and then optimise for another criteria. A large benefit of such an approach is that it allows for a more efficient setup which will have less energy flowing through it that probably will lead to less stress on components giving longer lifetime and time between maintenance. Alternatively robustness could be optimised to avoid stops due to material changes or a combination of the two to suit the application.

A mayor question regarding this thesis is how to relate the measured performance improvements to what could be expected to be achieved by an operator? This is of-course a question without a definitive answer since it will depend on the operators level of skill and time assigned for the task. A skilled operator that has long experience will of course use that experience and achieve good performance of the system within a relatively short time-span with high probability. If the operator instead is a novice the time required will probably increase significantly. The novice operator will also face the problem of identifying behaviour that may lead to problems in the long run such as robustness issues due to too heavy plugs forming that he or she has not encountered before. Another factor is that even though an optimisation has been carried out at some point in time it is not certain that this point of optimal operation will remain at the same location, there are a broad variety of reasons that can lead to changes in the system performance such as humidity,temperature, wear on equipment etc. The benefit of using a constantly running auto-tuner here becomes apparent as time progresses it will continuously strive to improve performance and counteract disturbances, whilst a human operator would at some point in time settle for good enough or not be available when a disturbance occurs. Thus the time required for optimisation is not as simple as it also incorporates but also how often machines are to be re-tuned.

Since there is a lot of dynamical data available in the system troubleshooting can be simplified, for example failure of the bottom hatch has occurred during test when material builds up on the sealing surfaces. The symptoms of this being that the conveyor does not reach a vacuum level below that created by airflow through the air filter. This was easily seen in the data supplied by the HIL-rig showcasing the possibilities of large data processing. This stream of data would allow for identification of a number of error codes that would require less knowledge from the operator to understand system errors and helping technical support with troubleshooting and communication . The error identification would also not be limited to analysing malfunctioning components but could also watch for signs that could indicate need for maintenance before it generates a stop.

The air filter used to separate the air and material streams was on forehand indicated by Piab to be a weak link in the chain that often would limit the system performance. In this project the filter wear has not been identified as having a negative influence on conveying, performance has not dropped significantly during run-time and has remained at the levels indicated by the data sheet D.

The reason for this result has been a source of a number of theories regarding soft-start, constant speed, level sensing and controlled environment. The soft start theory is based on that since the air flow is controlled towards an specific value there will not be an initial rush of air and less pressure waves travelling in the system during the starting phase of conveying, thus wear on the filter should be reduced. Controlled speed is based on the idea that the control of air flow gives less variations in material speed and that acceleration is the main source of separation between different size particles and creation of turbulence. The separation of particle size is unwanted because the smaller particles are easily carried in the air and are more prone to clogging up the filter openings whilst turbulence in the conveyor will also help these small particles to reach the filter. Another theory is that the level sensor stops overfilling and is therefore effectively stopping the contact between the filter and settled layer of material which would indicate that given normal operation with good safety margins in a traditional application the filter would not be a narrow sector. This is in line with Piab's impression that the customers mainly experiencing filter issues are pushing the limits of performance.

It has also been theorised that the laboratory used in this study does not show large variations in environment and thus a triggering factor for filter breakdowns may have been removed. Within the scope of this study it has not been possible to exactly pin-point what caused the lack of problems with filter performance but a combination of the factors listed above is considered as a starting point.

As the system is based upon optimisation with regards to parameters, it renders the problem of optimisation to a more abstract level for the operator. This can be seen as a positive effect on one hand since the demands formulated will mostly be directly traceable to the parameters formulated in this thesis, on the other hand the system might not be able to use earlier knowledge collected with the standard system regarding a specific material. To determine how to present this type of data is also one of the areas crucial if this technology is to made into a viable product as the difficulty has been moved from actual tuning of the system into design of the cost function for optimisation. One vision for this is to try to incorporate a language similar to the UML used in system requirements engineering based upon shall and should for design of the cost function.

Another observation is that despite using the same equipment setup for all materials all materials have been possible to convey in a good manner achieving reasonable results, this in combination with the knowledge that a conveyor in a factory often are associated with more than 1 type of material gives that there must be large gains to be made if each material could be individually optimised for. This could be realised by having multiple optimisations running simultaneously and switching between them as the material in the conveyor changes. In this way the same conveyor can support a wider range of materials whilst still not sacrificing unnecessary performance. It could also be possible to use the same conveyor setup for a wider range of materials allowing a factory to standardise their conveyor population. The benefits of such an possibility would be evident in both maintenance and purchase of the machines.

A drawback with the system developed in this paper is the dependency upon the sensors installed, the reality perceived by the system will be completely dependant upon sensor data. Thus if the sensors can be made to give a false reading and this reading indicates better performance the system can start optimising for that type of disturbance to occur. This is of-course an unwanted characteristic and in this project it was counteracted by identifying errors and counteract their cause. In a application it will be of large importance to have all the used sensor input tested such that no data indicates better performance than is true, although indicating worse performance should only be excluding that area from optimisation. Since the system is measuring variables that are not always evident to the naked eye, fault diagnosis can be hard to perform if the system does not perform as expected.

Due to the manner in which the optimisation algorithm operates and the lack of models for the influence of the control parameters there exists a possibility to make the system modular. The thought behind this is that since the optimisation algorithm is not limited to a specific number of control parameters and can easily be increased or decreased to suit the application, thus a cost effective solution can be created based on the demands. It would also be possible in a large factory were multiple conveyors are running the same material to create a network that distributes the information gathered so that the information from all conveyors are accessible for each system. In this way the optimisation process can be made drastically shorter. Such an internet of things application would offer considerably better performance but what information to share without losing the optimisation for the process at hand becomes a though question.

Another large issue that needs to be addressed in the process in creating a product of this technology is how it should be implemented. One vision is to create a optimisation system that is add on to the conveying system and runs the optimisation until the operator is content with the results and then aborts and removes the extra equipment. That equipment can therefor consist of high quality components and be expensive as it will be able to service a large number of machines. Another approach is to have complete system distributed on all locations and create a database of solutions that have been proven that can be distributed to benefit all.

The step of taking this technology from the laboratory to the factory will raise some ethical aspects on if such technology should be released on all markets and applications. If the technology is used to be able to remove humans from the optimisation process for dangerous materials there is a lot to be gained in terms of workplace safety, these materials where the handling is still not automated are also often difficult to convey and thus this system could allow for this development whilst it is dust free so that the operation does not pose unnecessary risks. Another application is the replacement of existent equipment which would allow for energy savings from more optimum usage of the conveyor equipment, this is not considered as a hard question since this is a normal commercial process. The third aspect is replacement of cheap labour caused by low running costs for an optimised solution, this is a much harder question but due to the complexity of the systems components and usage it is likely that a smaller amount of qualified jobs will be created locally. In this case the question is harder to answer since different jobs are hard to compare and might have different consequences in different situations.

Another issue is the stochastic operation of the optimisation algorithm that does not allow for a definitive answer regarding performance or stability of the process. The performance of the algorithm would therefore be a knowledge based upon experience of actual optimisations combined with understanding of the conveying process itself. Thus to convey this knowledge simply with empirical evidence will be a communication problem.

The performance of the algorithm will also be completely dependant upon the amount of input information available, the smaller the area to be searched the faster convergence towards the optimum solution given that the area designated is correct.

Here the customer also has a role to play as defining what is desired from his process, if a complete material library is desired they might also be required to contribute to this library. Even if this library exists a decision of how much to trust that information will always be necessary.

The method devised was during the starting phase of the project closely followed as material from pneumatic conveying was reviewed and a course in basic vacuum conveying for new Piab employes attended. This gave a reasonably good understanding of the problem both theoretically and practically which contributed to the success of the project.

The design and testing of the HIL rig for the laboratory test was initially performed according to the plan and the functional test were approved but new problems arouse when new materials were introduced. One of the larger issues was the level sensors operation with very fine powders that tended to build up on the sensors, a number of solutions were attempted and a suitable answer for the laboratory tests found. Thus the method was not followed as improvements were made to the equipment during the testing phase, this was however not deemed to have an influence on the system performance.

Conclusions

6.1 Material characterisation and simulations

As can be observed in chapter 4.1 the simulations predicted capacity performance improvement in all the simulations carried out. This is of-course given optimal conditions and repeatability of cycles, given that normally cycles will be dependent upon uncontrollable environment parameters the simulation will be approximately an ideal case. Concerning the average time required to optimise to within reasonable performance, this is of course dependant upon the given material as can be seen in the results from chapter 4.1 and what is deemed as reasonable.

Generally most of the bad performance cycles are suppressed within 10-15 generations. The average performance usually start to stagnate after approximately 20 generations, thus setting the limit for when optimisation is said to have reached a reasonable level. Given that a normal cycle time in an application lies within 20-30 seconds [7], this would lead to an optimisation time between 1 and 2 hours before acceptable performance with low risk of disturbance to be expected.

6.2 Optimisation procedure

The optimisation procedure produced clear capacity performance improvements for all materials tested compared to an evenly distributed set of solutions. The time-span indicated by the simulations were confirmed in the test except for those cases were the optimisation goal was unfavorably formulated and thus did not meet the criteria for reasonable performance. The reason for this being that an optimisation towards one goal did not sufficiently capture all the characteristics of the desired solution, by adding optimisation goals it becomes possible to achieve good performance but information regarding the desired end goal becomes crucial.

Adapting the optimisation criterion of the system for a given material was crucial in achieving good performance. Most materials tested were possible to achieve good conveying performance using the cost function based solely on capacity and still achieve good results. Although some materials required additional cost function input information to produce adequate results. In the test carried out two unique sets of problems in optimisation were encountered, firstly the rye flour posed robustness issues and secondly confectioners sugar exhibited inconsistent performance.

The robustness issue with rye flour were effectively counteracted by increasing the importance of suppressing the robustness criterion consisting of pressure variations in the optimisation, thus leading to the system conveying at a leaner phase. Another benefit of the leaner phase was more stable performance over multiple cycles.

Confectioners sugar showed good performance running with only capacity optimisation if only maximum capacity is considered but large variations in performance made the optimisation unsuitable for an industrial application. By applying a degree of efficiency in the cost function the system produced result in running conditions that promotes small deviations in speed of the material and consistency in material in pipeline over time. This due to that the acceleration of plugs is a large part of the energy consumption and thus if the system is to be as efficient as possible both constant speed and material content is desirable. Early tests of the optimisation algorithm indicated problems with individual cycles that due to external disturbances, history dependency of the system or any other cause achieves a performance rating that is not representable for the system settings it represents.

This was partly counteracted by implementing the re-visitation which in essence is re-initialisation of the population every 10th generation.The result of this was that these abnormalities were suppressed by the start of each 10th generation as can be seen in Fig.(4.22) were at the end of the first 10 generations bad performance parents become visible and therafter quickly suppressed. The other part of the elimination of this phenomena was to improve the sensors and how data was collected, for example was a cleaning jet of air added to improve the reliability of the level sensors by blowing away material buildup. The time required for optimisation on the actual system is very similar to that produced in the simulations given that the cost function is adequate for the material and excluding individual disturbance cycles. This holds true for the performance of the system but the time required for the control parameters to achieve steady operation with small deviations is highly material dependant and might not occur even if the performance is highly tuned. A high dependency on a certain control parameter will lead to fast convergence due to large influence on selection criteria, the opposite also holds true and thus a parameter with little to none influence will not be affected by the selection process.

This phenomena can be illustrated with plastic pellets that shows good performance development shown in Fig.(4.7), thus a high level of convergence of control parameters is expected. By studying Fig.(4.9) there is a clear convergence for the parameters carriage air valve and the air flow but not for the linear opening that still at the end of the optimisation has a large variation. This is due to the low internal friction and low bridging tendencies that leads to the low influence of the sending station geometry, thus as the optimisation progresses the starting set will be maintained. This can be viewed as positive effect if that parameter would suddenly be of importance the entire range would be used as it starts to influence the selection, on the other hand it gives large usage of the actuator controlling that parameter whilst still not improving performance.

The optimising algorithm implemented is based upon evaluating the performance after each individual cycle and implement identified improvements at the end of a generation, thus the parents control parameters will only be updated after one generation has passed. This leads to that changes in the conveying process that happens within a time-line that in this time-frame can be considered short will not be counteracted until this time has passed. On the other hand if the change is gradual and slowly occurring the optimisation algorithm will adapt to the changes as they occur, this phenomena occurred for a large proportion of the materials used in the study as the amount of material was limited and degradation was clearly visible during run-time. The system then gradually adapted to these changes without large negative influence on performance.

In this study the same equipment was used for all test except for the feature of fluidisation that was turned on or off when deemed necessary to achieve stable sending or emptying conditions. This gives that for a specific material and a given conveying distance some modification of the system would have enabled better performance. The algorithm developed during this study does not take this into account, neither does it incorporate any sanity check regarding the results achieved as it was desired to use as little input information as possible. Thus the algorithm will not evaluate the installation or chosen components. The optimisation will instead optimise the system to achieve the best performance in terms of performance parameters given the limitations presented by the system.

Future Work

This thesis only studied the first initial steps of optimisation, the tuning towards a optima and performance within the proximity of a optima. As a result of this fact further studies to evaluate the performance in long-time tests are advised in order to fully determine what level of tuning can be achieved and identify any unforeseen problems running for a prolonged period of time close to an optima. Questions to study could be the level of convergence and drift in solution over time amongst others.

The flow controller itself and its application could form source for more in-depth studies and further development. It was theorised that the system could benefit from two stages of air flow settings within a cycle. The first being establishment of the transport phase and the second being the run-time flow. The establishment stage could be realised as either a ramp up to run-time flow or a constant value or any other starting sequence, time and eventual flow value would be control parameters for the optimisation.

For low speed applications where the friction will highly affect the performance an anti-friction strategy could prove beneficial. An approach suggested is to introduce a super-imposed dither signal that gives flow variations that allows for compensation of friction in moving plugs whilst still not resulting in a increased average material speed.

Since the optimisation algorithm is not limited to a specific number of control parameters modular system was envisioned. A modular system would offer large benefits since the required control parameters needed to achieve good performance vary greatly with the material conveyed. If a control parameter with no influence is used it will continuously be running the entire starting range of settings as was observed in section 4.2. This behaviour results in high actuator usage and a system easily adding and removing control parameters is therefore advantageous as it can remove actuators that does not add value, this could be realised through using a decentralised system with all control parameters as external actuator nodes. The main obstacles for realising such a system are to design a network layout that enables adaptable size, to design the actuator and sensor nodes and adaptation of the optimisation algorithm. The first and second step should not be the complex part of the solution as this has been realised before and can rely on trusted technologies. The last issue being adaptation of the optimisation algorithm will require both theoretical and practical work as how to determine the correct population size and mutation factor for a given number of control parameters. This becomes a trade-off that also need to allow for a large variation in material conveyed adding to the complexity.

One area strongly suggested for further exploration is the front carriage air valve that in this thesis was used as emergency valve. Influence of this valve setting was as mentioned in this thesis highly debated within the Piab organisation. The suggested approach is to move the emergency valve to a new position closer to the pump to give a shorter pipe-section to empty in case of blockage. This should improve emergency valve performance if the pipe-section on the sending station side can be cleared by the pump when the emergency function is disengaged. The front valve position should thereafter be fitted with a identical valve to that used for the rear valve in this study and the results achieved should be evaluated in comparison to that using only the rear valve. Thus a definitive answer to the influence of that parameter will have been reached and eventual performance benefits compared to the costs attributed to it.

Despite the fact that the filter in this thesis was not a limiting factor there is no debate concerning the fact that from a maintenance point of the system it will require frequent maintenance and replacement. Thus a study explicitly aimed at filter performance is proposed with the aim of determining the causes of filter failure, required warning time and predicting when in time it will occur is proposed. The study should also include how to implement the prediction into a given system and what level of certainty is to be expected.

In this thesis solely materials known to be able to transport in a vacuum conveyor were used and environmental influence was minimised. Thus the emergency function was tested only a small number of times, in order to evaluate the performance a series of robustness test would be advisable where the outcome if no action is taken is considered known. The design of these robustness tests are crucial in order to achieve a reliable result, determining ways of introducing a potential stops, classifying the severity of disturbance added and evaluating system response.

Given a system running for a longer period of time with the same material and setup, patterns will inevitably form. If an algorithm is developed that learns these patterns and warns the operator when drastic changes occur an early warning for machine breakdown have been realised that will not be connected to a specific component but the system performance. The majority of the proposed work lies within identifying these patterns and presenting the information in a suitable manner to the operator.

In this thesis the speed limitation proposed will only be estimated after a cycle is completed, thus the system will not know that the limit is exceeded until after it has happened. In order to resolve this issue, a real-time estimation of the material speed is required, this can be realised in a number of ways. The most straightforward way to find a solution to this problem would be the addition of a velocity sensor at the inlet to the conveyor as this is the point in the system were the highest material speed is expected and has the largest influence on gentleness. Possible sensors shall measure the movement speed of material entering the conveyor, for example a Doppler sensor that can be adapted to the noisy environment. Another mean of solving this issue is to introduce a upper limit to the allowed air flow, the problem being that parts of the solution area is excluded and thus also potential optima.

In the conveyor system there existed no problem in mounting the level detector indicating that the system is full of material but the sensor indicating that the system is empty was not possible to mount in the desired location. Instead it was mounted some distance up from the lowest level of the container and an extra time delay was introduced to this signal in order to reliably predict that the low level was reached. The time delay is a crude solution as it presumes all materials empties at the same rate. If a model for the prediction of empty level that use the time required for the system to go from indicating high level to indicate below low level, the level of performance could be improved as the time idle in emptying state does not add any value to the process.

Regarding the level sensors, there is also the problem of how to ensure robust operation over time, a solution was realised with incorporated a hose entering the conveyor blowing air over the sensor. This solution corrected the issues with material buildup on the sensors but were deemed unhygienic and a better solution is needed in order to take the technology to market.

The development of a UML-style language could greatly improve the user-friendly properties by introducing shall and should criteria in optimisation. The shall demands could form the criteria for allowing a child to replace a parent in the optimisation and should criteria would form the cost function basis. Given a well designed language, the requirements stated by the customer before purchase could automatically generate a cost function for that generation.

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Datasheet PiPump 200

Pump piPREMIUM 100-400

Pump piPREMIUM 100-400

- COAX® patented technology
- Side mounted for low building heights
- High vacuum flow
- Compact size and low weight
- Low noise level
- Modular design

Technical data

Description	Unit	Value
Feed pressure, max.	MPa	0.7
Feed pressure, range	MPa	0.4-0.6
Vacuum range	-kPa	60-75
Noise level	dBA	69-77
Material		Al, SS, PA, PP, NBR
Temperature range	°C	0-60
Weight	kg	6

Technical data, specific

Description	Unit	Value		
		0129190	0129191	0129192
Air consumption range	Nl/s	5-7	10-14	20-28

Vacuum flow piPREMIUM100

Feed pressure*	Air consumption	Vacuum flow (Nl/s) at different vacuum levels (-kPa)								Max vacuum
MPa	Nl/s	0	10	20	30	40	50	60	70	-kPa
0.40	5	20.0	11.6	7.6	4.8	3.2	1.6	0.40	—	60
0.50	6	22.8	13.2	8.8	5.6	3.4	2.5	1.4	0.72	70
0.60	7	24.0	14.0	10.4	6.8	3.6	2.4	2.0	1.4	75

*Feed pressure tolerance, +/- 0.01 MPa

Vacuum flow piPREMIUM200

Feed pressure*	Air consumption	Vacuum flow (Nl/s) at different vacuum levels (-kPa)								Max vacuum
MPa	Nl/s	0	10	20	30	40	50	60	70	-kPa
0.40	10	40	23.2	15.2	9.6	6.4	3.2	0.80	—	60
0.50	12	46	26	17.6	11.2	6.8	5.0	2.8	1.4	70
0.60	14	48	28	20.8	13.6	7.2	4.8	4.0	2.8	75

*Feed pressure tolerance, +/- 0.01 MPa

Vacuum flow piPREMIUM400

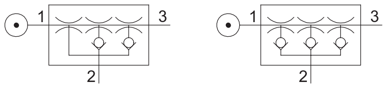
Feed pressure*	Air consumption	Vacuum flow (Nl/s) at different vacuum levels (-kPa)								Max vacuum
MPa	Nl/s	0	10	20	30	40	50	60	70	-kPa
0.40	20	64	42	30	19.2	12.8	6.4	1.6	—	60
0.50	24	73	46	35	22.4	13.6	9.9	5.6	2.9	70
0.60	28	77	48	42	27	14.4	9.6	8.0	5.6	75

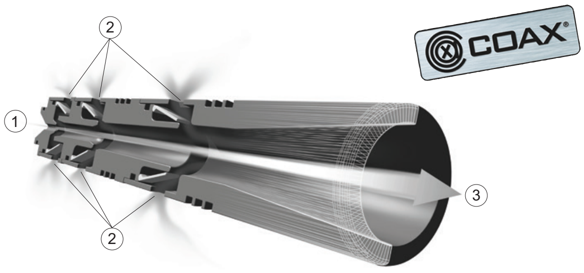
*Feed pressure tolerance, +/- 0.01 MPa

Vacuum ejector cartridge SI32-3

MANUAL COAX® CARTRIDGE MIDI

1. INSTALLATION / CONNECTIONS





RECOMMENDED HOSE DIMENSIONS IN MM [IN.] (INTERNAL DIAMETER)

Connections		COAX® cartridge	
		Pi48-2, Pi48-3	Si32-2, Si32-3 / Xi40-2, Xi40-3
1.	Compressed air	≥ 6 [0.24]	≥ 4 [0.16]
2.	Vacuum	≥ 12 [0.47]	≥ 12 [0.47]
3.	Exhaust	≥ 15 [0.59]	≥ 15 [0.59]

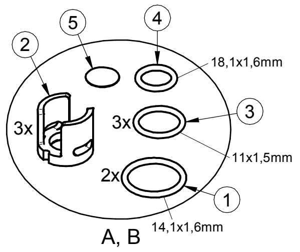
FEED PRESSURE, VACUUM LEVEL AND EXHAUST PRESSURE

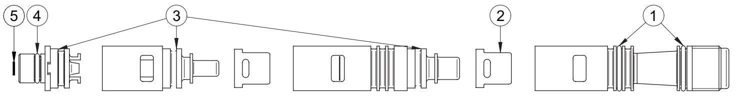
COAX® cartridge	Feed pressure MPa [psi]	Max. vacuum level -kPa [inHg]	Max. exhaust pressure MPa [psi]
Pi48-2, Pi48-3	0,31-0,6 [43.5-87]	90 [26.6]	0.14 [20.3]
Si32-2, Si32-3	0,6 [87]	75 [22.2]	0,08 [10.2]
Xi40-2, Xi40-3	0,45 [65]	75 [22.2]	0.09 [13.1]

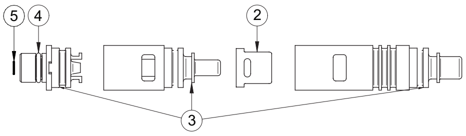
Applies to hoses up to 2 m [6.6 feet] long.

2. SPARE PARTS AND ACCESSORIES

	Description	Art. No.
A	Spare part kit COAX® cartridge MIDI, Nitrile	0109531
B	Spare part kit COAX® cartridge MIDI, Viton®	0124897
	Silencer COAX® cartridge MIDI	0111976





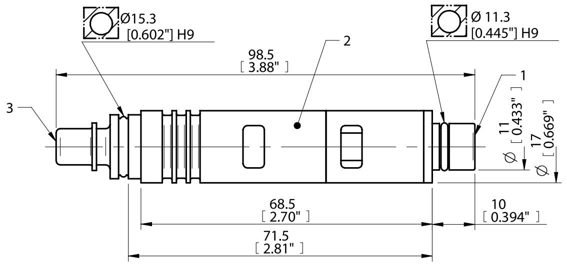


3. CLEANING

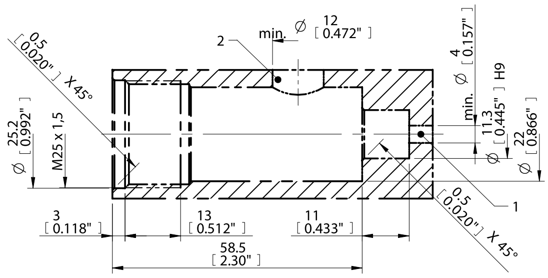
Rinse in water or use compressed air to blow off. Let dry before reinstalling.

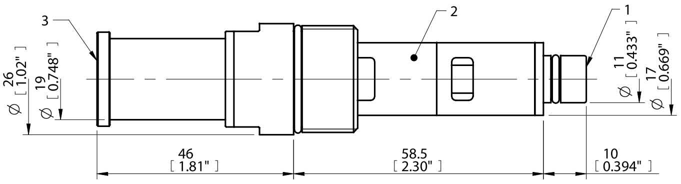
4. DIMENSIONS

Pi48-2
Si32-2
Xi40-2

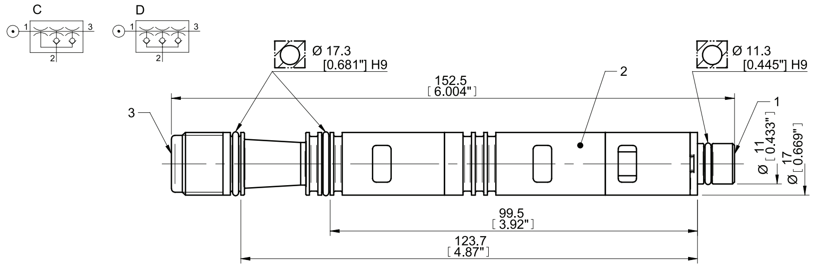


Pi48-2 C incl holding cap
Si32-2 C incl holding cap
Xi40-2 C incl holding cap

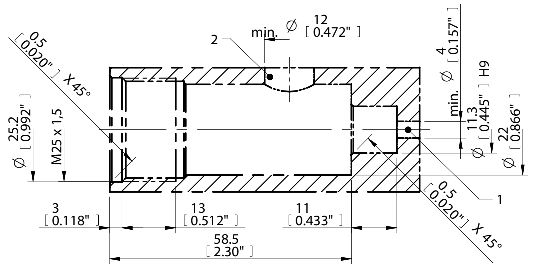


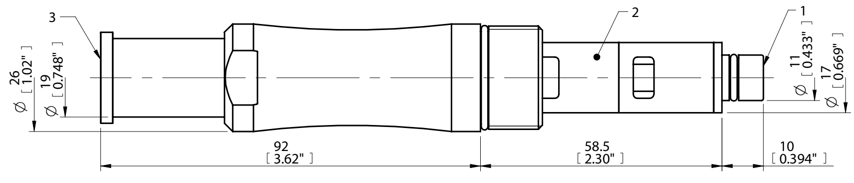


Pi48-3
Si32-3
Xi40-3



Pi48-3 C incl holding cap
Si32-3 C incl holding cap
Xi40-3 C incl holding cap





Art. No. 0113954, Rev.8
Piab AB, 2014-06 / Printed in Sweden

ARX models of air-flow

ARX483

Discrete-time ARX model: A(z)y(t) = B(z)u(t) + e(t)

$A(z) = 1 - 0.9229z^{-1} + 0.0001433z^{-2} + 0.5715z^{-3} - 0.4709z^{-4}$

$B(z) = 39.41z^{-3} - 35.45z^{-4} + 0.003414z^{-5} + 15.36z^{-6} - 12.59z^{-7} - 0.008808z^{-8} + 8.873z^{-9} - 7.373z^{-10}$

Sample time: 0.01 seconds
Parameterization:
Polynomial orders: na=4 nb=8 nk=3
Number of free coefficients: 12

Fit to estimation data: 82.11 % (prediction focus)

arx7103

Discrete-time ARX model: A(z)y(t) = B(z)u(t) + e(t)

$A(z) = 1 - 0.9584z^{-1} + 0.0006141z^{-2} + 0.6817z^{-3} - 0.6079z^{-4} - 0.0005303z^{-5} + 0.252z^{-6} - 0.1926z^{-7}$

$B(z) = 39.44z^{-3} - 37.46z^{-4} + 0.008418z^{-5} + 20.43z^{-6} - 17.4z^{-7} - 0.01867z^{-8} + 16.28z^{-9} - 14.04z^{-10} - 0.001676z^{-11} + 0.896z^{-12}$

Sample time: 0.01 seconds
Parameterization:
Polynomial orders: na=7 nb=10 nk=3
Number of free coefficients: 17
Fit to estimation data: 82.58% (prediction focus)

Filter

Testat filter

0125174 Pleated rod filter Ø125 L=360 cpl ATEX Antistat PRI-HSL 360/NDU A

Benämning/Betekn.	**Matartryck**	**Luftförbr**	**Max Vak.**	**VL00**	**VL10**	**VL20**	Linjär 0-10 k
Si32-3	0,50	1,50	70	5,7	3,3	2,2	
Si32-3	0,60	1,75	75	6,0	3,5	2,6	
piBASIC600 (Si32-3x21)	0,50	Cartridge dat	COAX	95,8	61,1	46,2	-3,47
piBASIC600 (Si32-3x21)	0,60	Cartridge dat	COAX	100,8	65,4	54,6	-3,54
piBASIC400 (Si32-3x16)	0,50	Cartridge dat	COAX	77,5	47,5	35,2	-3,00
piBASIC400 (Si32-3x16)	0,60	Cartridge dat	COAX	81,6	51,4	41,6	-3,02
piBASIC200 (Si32-3x8)	0,50	Cartridge dat	COAX	45,6	26,4	17,6	-1,92
piBASIC200 (Si32-3x8)	0,60	Cartridge dat	COAX	48,0	28,0	20,8	-2,00
piBASIC100 (Si32-3x4)	0,50	Cartridge dat	COAX	22,8	13,2	8,8	-0,96
piBASIC100 (Si32-3x4)	0,60	Cartridge dat	COAX	24,0	14,0	10,4	-1,00

0125173	Pleated rod filter Ø125 L=220 cpl ATEX			Antistat PRI-HSL 220/NDU A			
piBASIC100 (Si32-3x4)	0,50	Cartridge dat	COAX	22,8	13,2	8,8	-0,96
piBASIC100 (Si32-3x4)	0,60	Cartridge dat	COAX	24,0	14,0	10,4	-1,00
0125174	Pleated rod filter Ø125 L=360 cpl ATEX			Antistat PRI-HSL 360/NDU A			
piBASIC100 (Si32-3x4)	0,50	Cartridge dat	COAX	22,8	13,2	8,8	-0,96
piBASIC100 (Si32-3x4)	0,60	Cartridge dat	COAX	24,0	14,0	10,4	-1,00

						Barometerstånd		Vakuumnivå
	Linjär 10-20		p6	p12	p6-p12	pb	p12	pb-p12
m	k	m	[bar öt]	[bar öt]	[bar]	[mbar abs]	[mbar abs]	[kPa]
95,76	-1,49	76,00	5,7	5	0,7	1009	907	10,2
100,80	-1,08	76,20	6,8	6	0,8	1009	901	10,8
77,52	-1,23	59,80	5,4	5	0,4	993	913	8,0
81,60	-0,98	61,20	6,45	6	0,45	993	908	8,5
45,60	-0,88	35,20	5,15	5	0,15	994	949	4,5
48,00	-0,72	35,20	6,2	6	0,2	994	946	4,8
22,80	-0,44	17,60	5,1	5	0,1	993	967	2,6
24,00	-0,36	17,60	6,15	6	0,15	993	965	2,8
22,80	-0,44	17,60	5,1	5	0,1	993	967	2,6
24,00	-0,36	17,60	6,15	6	0,15	993	965	2,8
22,80	-0,44	17,60	5,1	5	0,1	993	977	1,6
24,00	-0,36	17,60	6,15	6	0,15	993	975	1,8

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