Original Research Article

Development of a method for shredder characterisation and dynamic control of the output material stream

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ABSTRACT

This work deals with the basis for the development of a method for the characterisation of shredders in the field of waste treatment. Therefore, many parameters of shredders have to be considered. In this work, the throughput and its inconsistency come into focus. The fluctuating mass and volume flow rates often cause problems for waste treatment plants. Mixed waste generates a fluctuating throughput despite continuous feeding, often starting at the first machine, the shredder. Dynamic control of the shredder is seen as a solution. By implementing a control loop at the shredder, fluctuations in output are to be minimised and the idea is that subsequent machines are thus ideally fed. Autocorrelation of the data of an output volume flow of the shredder exists, which indicates that a dynamic output feedback control of the shredder can work, therefore the attempt to control the shredder was made. However, the first control attempt was probably too rudimentary and the implementation of a dynamic control of the shredder did not yet bring any improvements in terms of throughput fluctuations. Nevertheless, the work provides indications and shows potential for further research approaches on control-based improvement of shredders’ throughput continuity.

KEYWORDS
mixed solid waste, shredding behaviour, waste treatment plants, control loop, fluctuation flow, digitalisation.

INTRODUCTION

Ambitious recycling targets for municipal and packaging waste are part of the European Union’s circular economy package; these targets include recycling 65% of municipal waste by 2035 [1]. Hence, better waste treatment has become more important in recent years [2,3]. In addition, heterogeneous waste streams from mixed (commercial and municipal) waste, which are highly variable in their composition and particle size [4], pose a challenge in their further processing. Shredders, which are often the first machines in mechanical waste treatment plants [5], have to deal with this heterogeneous and challenging material stream. Because there is no possibility of downscaling the properties and composition of the mixed heterogeneous waste streams, large-scale experiments have to be carried out [6]. The heterogeneous composition of

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waste streams also complicates the (real-time) modelling, in particular, the current state
detection of material flows [7]. Methods for sensor-based measurement of material flow data,
which are used for quality assurance in waste treatment, have already been published (cf. [8,9]),
further research on the use of various sensor technologies for materials characterisation has
been presented in two review papers (cf. [10,11]). Even though sensors are present in some
waste treatment plants, they provide hardly any data about the material stream (sensors for fire
protection, machine data, etc). In addition, sensors already installed in some plants for
recording volume or mass flows are still missing in other plants. In some cases, individual
machines are equipped with sensors that collect data. However, this collected information is
not used, particularly in terms of dynamically operating the machine interaction and plant
optimisation. Communication between the individual machines and thus a step towards
digitalisation-assisted plant operation is still missing, also because there is currently hardly any
real-time information on the load of conveyor belts or the quantities fed to the individual
machines, whose performance depends on these quantities [12,7].

A shredder changes the parameter particle size of the input material (for example: mixed
solid waste) for the downstream process. In this process step, waste is shredded and transferred
to a specific particle size range, resulting in a material stream suitable for transport, screening
and sorting. The selection of the shredder for the respective area of application usually depends
on the input material and its properties [13]. The particular shredder and its settings or
parameters (cutting gap, shaft rotation speed, knives, etc.) affect the output stream in its particle
size distribution [14], throughput capacity, and uniformity [15,16]. Insufficient attention is
paid to the aspect towards more steady throughput, especially the volume flow. Fluctuations in
the material flow can be caused by irregular material discharge of individual machines or
discontinuous feeding and can affect the performance of subsequent machines, as well as the
quality of the output material from a machine or a plant [17]. For example, a high occupancy
rate of a conveyor belt has a negative impact on the performance of a subsequent sorting
machine [17]. Data from a pilot-scale processing line — Technical Line 4.0 consisting of
shredder, drum screen and an additional machine that recorded volume and mass flow — with
mixed solid waste show an overview of the origin and causes of fluctuations [12]. The study
[18] also deals, among other things, with the influence of throughput fluctuations on sensor
based sorting machine performance in order to enable more optimised design and operation of
sorting plants. However, the authors [18] recommend further investigation of the fluctuations,
since the share of acceleration belt area that is covered by material was low (<50%) in the tests
carried out. Investigations using higher loading densities should therefore be carried out. The study
[19] states that a prerequisites for a good sorting sequence is a continuous material
volume flow, this also serves to avoid subsequent overfilling and underfilling conditions. The
aspect of smoothing material stream fluctuations and thus conveying conditions has not been
given enough attention so far. However, appropriate steps would make considerable capacity
potential available in existing treatment plants and, at the same time, improve the quality [15].
Coarse shredders are usually set based on statistical insights in waste treatment plants.
Parameters such as shaft rotation speed already pursue dynamic approaches: Programs include
certain dynamic behaviour like reversing at regular intervals if, for example, particles get stuck.
Nevertheless, the dynamic adjustment of the shredder, e.g., in terms of target shaft rotation
speed and controlling the current material flow, has not yet been implemented [6].

This investigation deals with the problem of the non-uniform throughput performance of
shredders. The aim was to achieve improved waste plant processing performance by controlling
the shredder's output without the need for additional machinery or facilities. This study will
present data analyses from real-scale experiments to show and quantify the possible potential
of dynamically adjusting shredder parameters to control the output stream. The concept of
implementing an output feedback control loop for the shredder originated from insights gained
during the ReWaste4.0 project (cf. [20]) (the preceding project of the ReWaste F project
cf.[21]), in which this work is included).“ The hypothesis — supported by autocorrelations
observed in the output flow (cf. Figure 1) — was that the processed waste material and the resulting volume flow of a shredder’s output is more similar than in average within a certain amount of time.

**METHOD**

First, the basis of the idea of implementing an output feedback control loop is discussed; the topic of autocorrelation must be addressed for this. A correlation between two data points (autocorrelation) is usually expressed as an autocorrelation coefficient $r_k$ (cf. eq. [22]) [23].

$$r_k = \frac{1}{N-k} \sum_{t=1}^{N-k} (x_t - \bar{x})(x_{t+k} - \bar{x})$$
$$\frac{1}{N} \sum_{t=1}^{N} (x_t - \bar{x})^2$$ (eq. 1)

These correlation coefficients applied to different lags produce a diagram, an autocorrelation function (ACF)-plot (cf. Figure 1). An ACF (ordinate) describes the correlation between data points of the time series and the time series offset by one lag (abscissa). The diagram shows that the correlations decrease with increasing lag up to approx. 175s. There is no fixed defined value for defining a strong or weak correlation. However, values between 0.3 and 0.5 usually indicate a weak correlation, values between 0.5 and 0.7 indicate a moderate correlation and values greater than 0.7 indicate a strong correlation [24]. In this example, there is a moderate correlation up to 25s and a strong correlation only up to 6s, but there is at least a weak correlation up to approx. 175s. In conclusion, the idea of an output feedback control loop is born from the existing context.

![Figure 1: ACF plot; Data from a test series of the ReWaste4.0 project from 2019; Shredder settings: shaft rotation speed 80%, cutting tools F, cutting gap closed. Mixed commercial waste was comminuted.](image)

**Experimental Setup**

Large-scale tests were conducted to collect meaningful data and information under real conditions. The material comminuted was mixed solid commercial waste from Styria, Austria. To avoid the effects of non-continuous feeding, the material was continuously fed by a crane or wheel loader; the shredder grinding chamber was always well filled. The shredder used was
a Terminator 5000 SD provided by Komptech GmbH (cf. Figure 2). The comminuted material
was transported from the shredder to a Digital Material Flow Monitoring System (DMFMS), a
mobile machine from Komptech GmbH, which records the mass and volume flow (described
in more detail by [16]). The control of the shredder throughput is to be realised based on data
generated by a volume flow sensor mounted above the discharge belt of the shredder. This
method was tested, considering its retrofitability and, thus, its implementation in existing
plants. Before the tests with the control loop started, tests to get a calibration curve were carried
out.

Calibration curve experiment

In order to get a better understanding of data obtained from previous experiments (cf. [16])
and to create a calibration curve for the same waste used for the experiments, collected at the
same time and location, a calibration curve was created using the new data. Using this
 calibration curve, a better understanding of the correlations between the mean volume output
and shaft rotation speed should be gained. The test runs for the calibration curve were carried
out in random order at the following shaft speed settings: 50%, 60%, 70%, 80%, 90% and
100%, each for 15 minutes (so that the data collected by operating the shredder is
predominantly in a stable state: the initial oscillations are over).

Control loop experiment

First, a control loop is described in general terms, and then the experiments performed are
discussed. A control loop comprises three essential components: the process sensor, the
controller function, and the final control element. Collectively, these components automatically
modify the controller output value, matching the value of a predefined set-point (SP) by
changing a measured process variable (PV). The measured control deviation occurs as a
difference between the SP and the actual value or a proportional band (a range of values within
the PV should remain), so the response of the controller output is limited, thus reducing the
risk of an unstable control loop. The desired output value (the SP) is compared with the current
PV using a mathematical function, resulting in a measured deviation (Figure 3). The controller
uses the measured deviation to generate an electrical signal for the shaft motor to change the
shaft rotation speed. So, the process variable changes because the speed affects the
comminution process. A sensor measures the new PV, so the new value is compared with the
SP, generating a new measured deviation. So, the control loop is completed, and with good
controller tuning, the process variable remains at the SP. The control action depends on the
desired PV and the actual PV. There is a feedback loop through which a control action is exerted to keep the PV at the same value as the SP [25].

Figure 3: Flowchart: control loop of a shredder [26]

In these experiments, in order to regulate the system, the output variables of the system are measured, and the control input is adjusted. The programming of the control loop was done by Komptech GmbH. To test the application of the control loop to the shaft rotation speed of the shredder to minimise fluctuations, tests were carried out with the control loop alternating activated and deactivated (to minimise the influence of the material). The test runs lasted 15 minutes. For the tests with deactivated control loop, the shaft rotation speed was set to 70% of the maximum, this value was used as well as a start point for the tests with activated control loop. By a shaft rotation speed of 70%, a target volume of 180m$^3$/h should be reached, according to the control loop experiments (cf. section results). The idea was to select a target volume that is somewhere in the middle of the analysed speed range for static settings so that it can be regulated up and down in the dynamic setting, and thus, the two states can be compared. The tolerance range was set at first to 10%, so the control loop reacted at volume flows below 162 and above 198m$^3$/h. Then, the control loop was set to change the PV value (if necessary) every 10 seconds, with a waiting time of 5 seconds plus an observation time of 5 seconds. So, the volume flow has been observed for 5 seconds, at the end of the 5 seconds, an assessment was made based on the average volume flow. If no regulation was required, the 5 seconds start again from the beginning; if a regulation was required, then the shaft rotation speed was adjusted up or down by 20% of the speed (cf. Figure 4). However, the original step size of 10% was too small based on observations, so the next possible step based on the used software was selected (20%). A total of 18 test runs was carried out, 9 with activated and 9 with deactivated control loop.
Figure 4: Flowchart to illustrate the control loop.

Data analysis

The volume flow data, recorded by the sensor on the shredder output were stored as Dewesoft files. The files can be display and edit in Dewesoft. Selected and relevant data were further analysed using R (a statistical programming language).

RESULTS AND DISCUSSION

This chapter deals with the results. First, the results of the calibration curve tests are discussed, and then the results of the control loop come into focus.

Calibration Curve for Control Loop

The control loop was calibrated by establishing a clear relationship between the shaft rotation speed and the mean volume output. Figure 5 shows the mean volume flow rate over the entire time at the set shaft rotation speed. The data points show the trend of a directly proportional function, but it should be noted that there is a residual variance and that this data is a 15-minute average, which limits its practical application. Based on the data, a linear model can be calibrated for the data points, and a confidence interval can be calculated. In Figure 5, the mean data are used to calculate the linear model, using R. Despite the large confidence interval (the wide data distribution), there are not enough data points in this case to reduce the width of the interval without lowering the confidence level. However, a clear trend indicates a proportional increase in volume power as the shaft speed increases. Due to the linear model for the average volume output, the control loop was centred at 0.7. The shaft rotation speed can then be increased and decreased without reaching the limits of the shredder (by an adjustment of +/- 20%). The volume flow value of 180 m$^3$/h is calculated for the linear model for the average volume output for the chosen set point. According to the regression, a change of 20% shaft rotation speed leads to a change of 41m$^3$/h and thus 23% of the target. The effect observed with a change in shaft rotation speed of 10% was low. With a change of 20%, however, it is possible that the regulation is too high (responding at +/-10%, but the volume flow is regulated by 23%). So, a finer adjustment of the control would probably be better [26].
Figure 5: Linear model for output behaviour with confidence interval based on mean output. Shaft rotation speed in share of maximum (31 rpm) [26].

If a directly proportional linear model is assumed for the calibration, the more dominant the change in shaft speed, the more likely the output will change. This calibration model is an important part of the tuning process, so the control loop could be set up [26].

Control Loop Test

Here, the aim is to show whether a statistically significant improvement in the fluctuations is achieved in the test runs with an activated or deactivated control loop. The average of all 90/10 quantiles of all test runs (activated and deactivated control loop) is calculated. The 90/10 quantiles were tested for normal distribution using a quantile-quantile plot and the Shapiro-Wilk test and based on these, they are assumed to be normally distributed as a result. Therefore, a two-sample t-test was performed. It was analysed whether there is a significant difference between the 90/10 quantiles with activated or deactivated control loop. Figure 6 shows the results of the control loop tests, the volume data visualised as boxplots. Looking at the width of the individual boxplots, there appears to be no significant difference between the two settings with and without an active control loop. The medians are comparable, as well as the 75th and 25th percentiles [26].
The confidence interval for the difference in mean volume output contains zero; the confidence intervals overlap completely (cf. Figure 7), so the control loop does not cause any significant difference in the 90/10 quantile metric. The standard deviation of the 90/10 quantiles is smaller for the dates with an active control loop ($\sigma = 0.8$) than without a control loop ($\sigma = 1.4$), but the actual quantiles of the control loop are not significantly better. As a result, the control loop does not make any significant improvement [26].

The hypothesis of an output feedback control loop, based on the shredders volume output data and the shaft rotation speed of the shredder— for the used control loop — was not confirmed. However, such a hypothesis cannot be generally rejected either. The controller used here was very rudimentary, for example, it was inflexible in step size and based on a basic analysis. So, there is still potential for improvement: for example, a control loop could work for controllers that can be more finely adjusted, than the one used. As well further shredder settings can be considered to be dynamically controlled to create a control loop (e.g. the gap width).

Even though only one specific shredder was tested in these trials, the use of a single-shaft shredder (as used here) is common practice in waste management [27], hence the results from this work are likely to be relevant to this class of machines in general.
CONCLUSION AND OUTLOOK

Developing a method for the characterisation of shredders involves challenges. In several steps and investigations, individual parameters have to be examined and combined to form such a method. Here, in terms of the parameter: throughput and the related fluctuations, which are an important topic in waste treatment plants, the idea of smoothing them via shredder output feedback control was born. This study aimed to provide approaches to solutions that have not yet been confirmed. Experiments with an activated control loop showed no significant improvement for the 90/10 quantiles compared to those without an active control loop. The fluctuations in these data sets cannot be attributed to intermittent feeding of the shredder, as a crane operator ensured that the shredder feed hopper was always full. This work did not address some problems described by [6], such as bridging or the material and shape of the objects. As the question arises why the control loop has not brought any improvement, the next analyses are planned to be carried out. The next step will focus on a detailed time series analysis and some step testing to better understand the process characteristics. The aim is to get a refined, improved controller, to get the desired results.

Since dynamic control of the shredder in the waste management sector could lead to improved feeding of subsequent machines, as this could avoid overloading these machines, there is a need for further research studies. The dimensioning of subsequent machines could also be adapted, as they would no longer have to be designed for overloads. This step would also be financially beneficial.

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