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Title: **The effect of fuzzy logic speed control on energy usage of belt conveyors**

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List of symbols

$t = Current\ time\ step$ $[-]/[s]$

$t_s = Time\ step$ length $[s]$

$t_h = Time\ horizon\ [s]$

$t_a = Time\ necessary\ to\ accelerate\ [s]$

$t_d = Time\ necessary\ to\ decelerate\ [s]$

$t_{runtime} = Run\ time\ of\ simulation\ [time\ steps]$

$t_{cycle} = Cycle\ time\ of\ input\ material\ [s]$

$t_{L_p} = Time\ the\ material\ falls\ from\ the\ primary\ belt\ conveyer\ [s]$

$L = Length\ of\ belt\ [m]$

$A = Cross\ sectional\ area\ material\ on\ belt\ conveyer\ [m^2]$

$V = Material\ volume\ [m^3]$

$a = Acceleration\ of\ belt\ [m/s^2]$

$d = Deceleration\ of\ belt\ [m/s^2]$

$v_{p/s,max} = Maximal\ speed\ of\ belt\ [m/s]$

$v = Operating\ speed\ of\ belt\ [m/s]$

$v_{ref} = Optimal\ reference\ speed\ of\ secondary\ belt\ [m/s]$

$x = Position\ of\ belt\ [m]$

Q_{in} = Mass $flow\ at\ inlet$ [kg/s]

$Q_{out} = Mass\ flow\ at\ outlet$ [kg/s]

$\rho = Density\ material\ [kg/m^3]$

$T = Torque\ on\ pulley\ [kgm^2/s^2]$

$f = Friction\ coefficient\ [-]$

$h = Height\ difference\ conveyer\ belt\ [m]$

$m'_R = Mass\ of\ idlers\ per\ meter\ [kg/m]$

$m'_G = Mass\ of\ conveyer\ belt\ per\ meter\ [kg/m]$

$m'_L = Mass\ of\ bulk\ material\ per\ meter\ [kg/m]$

$F_W = Total\ resistance\ [kgm/s^2]$

$F_H = Primary\ resistance\ [kgm/s^2]$

$F_N = Secondary\ resistance\ [kgm/s^2]$

$F_{St} = Gradient\ resistance\ [kgm/s^2]$

$F_S = Special\ resistance\ [kgm/s^2]$

$F_D = Driving\ force\ [kgm/s^2]$

$F_R = Nominal\ rupture\ force\ of\ belt\ [kgm/s\text{^}2\ ]$

$\mu = Coefficient\ of\ friction\ [-]$

$\alpha = Wrap\ of\ the\ belt\ around\ the\ pulley\ [°]$

$B = Beld\ width\ [m]$

$S_A = Minimum\, safety\ factor\ [-]$
$\delta = Gradient\ resistance\ (neglectable\ if\ < 18°)\ [°]$
$P_m = Power\ provided\ by\ motor\ [kgm^2/s^3]$
$P_W = Power\ usage\ due\ to\ friction\ [kgm^2/s^3]$
$P_a = Power\ usage\ due\ to\ acceleration\ [kgm^2/s^3]$
$P_{tot} = Total\ power\ usage\ [kgm^2/s^3]$
$W_{sc} = Work\ for\ speed\ controlled\ conveyer\ [kgm^2/s^2]$
$W_{nsc} = Work\ for\ non-controlled\ conveyer\ [kgm^2/s^2]$
$a_a = Acceleration\ of\ belt\ [m/s^2]$
$a_d = Deceleration\ of\ belt\ [m/s^2]$
$g = Gravitational\ acceleration\ [m/s^2]$
$b_n = Fuzzy\ boundary\ [-]$
$r_n = Range\ between\ fuzzy\ boundaries\ [-]$
$z = Confidence\ coefficient$
$\mu_{energysavings} = Estimated\ average\ of\ energy\ savings$
$\sigma_{energysavings} = Standard\ deviation\ of\ energy\ savings$
$\mu_{stresscycles} = Estimated\ average\ of\ stress\ cycles$
$\sigma_{stresscycles} = Standard\ deviation\ of\ stress\ cycles$
$U = Upper\ limit\ of\ confidence\ interval$
$L = Lower\ limit\ of\ confidence\ interval$
$B_n = Number\ of\ fuzzy\ boundaries$
$ES_{Low} = Lower\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ energy\ savings\ [\%]$
$ES_{Mean} = Estimated\ mean\ energy\ savings\ [\%]$
$ES_{Up} = Upper\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ energy\ savings\ [\%]$
$SC_{Low} = Lower\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles$
$SC_{Mean} = Estimated\ mean\ of\ number\ of\ stress\ cycles$
$SC_{Up} = Upper\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles$
$Scenario = Input\ scenario\ [integer]$
$Amplitude = Amplitude\ of\ input\ feed$
$Runs = Number\ of\ runs\ to\ be\ performed\ [-]$
$Animation = Animation\ at\ the\ end\ of\ the\ simulation\ [boolean]$

Summary

This report describes simulates a belt conveyor which is controlled using fuzzy logic speed control. The setup of the belt is visualized in Figure 1. The primary belt consists of a belt operating at constant, nominal speed. The secondary belt' speed is adjusted based on the input of the primary belt, such that it anticipates the feed coming from the primary belt.

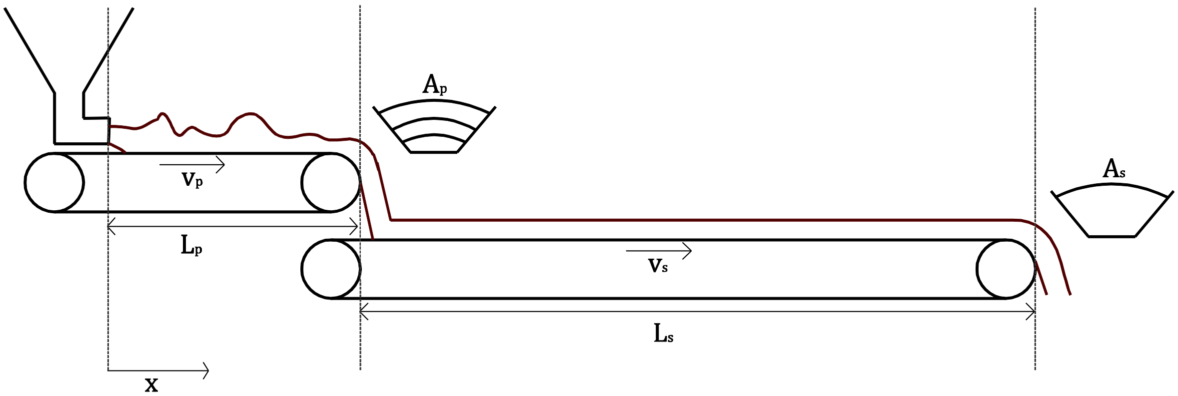

Figure 1 Belt conveyor setup

The belt conveyor friction forces have been modeled using DIN 22101 (e.V., 2002). To get an idea of the forces necessary for acceleration/deceleration the acceleration profile of He, Pang, and Lodewijks (2016) has been used. This acceleration profile gives a low jerk when accelerating the belt.

Using the input feed the speed of the secondary belt is controlled. To filter out small distortions in the signal the reference speed is tactically chosen during the time the material is on the primary belt. As a next step, the reference speed is fuzzified using predefined boundaries. This way, the signal is simplified into several ranges which decreases the amount of stress cycles. A stress cycle consists of the belt accelerating from one constant speed to a higher constant speed. The fuzzy boundaries can be strategically chosen such that the belt runs at non resonant frequencies.

The simulation is performed with several input scenarios. A constant signal, a periodically changing signal, a sinusoidal signal and a random signal. The different scenarios give an idea of the implication of fuzzy speed control on energy savings and stress cycles.

The output of the simulation is an overview of the input, speed, energy usage, stress cycles and energy savings of the secondary belt. A stress cycle consist of the belt accelerating from one constant speed to another constant speed. Besides that, a 95% confidence interval of the true mean of the number of stress cycles and energy savings is given.

The results show that in all cases fuzzy logic speed control of a belt conveyor results in saving energy. However, the amount of stress cycles increases when the number of fuzzy boundaries increases. An optimum between the number of fuzzy boundaries, stress cycles and energy savings can be found.

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1 Introduction

Energy is costly and the consumption of fossil energy has an impact on the environment. Therefore it is beneficial to look at ways to reduce the energy consumption in every way possible. A big part of the operation cost of bulk transportation is energy (40%) (Pang & Lodewijks, 2011). Belt conveyors are often used to transport bulk material and are widely used in the mining industry, power plants, bulk terminals, baggage handling systems and production lines. This report will focus on belt conveyors used for bulk material. Bulk has a lot of weight (and, as a consequence: inertia) and is a continuous product, which calls for a different control strategy than other types of (discrete) goods. Reduction of energy consumption will give a significant reduction in operation costs and therefore the industry is looking for ways to make bulk material transportation using a belt conveyor more efficient.

Improvements in energy efficiency of belt conveyors can be made using speed control when the bulk input is not constant. By varying the speed of the belt conveyor the load rate of the belt conveyor can be maximized. Thereby the average speed of the conveyor will go down which will save energy. However, the friction due to the load will increase, but according to DIN 22101 (e.V., 2002) and several studies (Lodewijks, Schott, & Pang; Pang & Lodewijks, 2011; Shah, Heidir, Rahmat, Danapalasingam, & Wahab, 2013; Zhang & Xia, 2010) speed control will result in energy savings. Research on belt conveyor speed control to improve energy saving has been widely performed. Continuous speed control, however, will result in many stress cycles of the belt and other components. A stress cycle consists of accelerating the belt from one constant speed to another. Stress cycles result in a lower lifetime of the transport equipment.

Fuzzy logic control has been studied to speed control belt conveyors:

- Using Fuzzy Speed Control at tactical level by Pang and Lodewijks (2011) and Ristic et al. (2012).
- Using Fuzzy Logic to tune the parameters of a traditional PID controller by Shah et al. (2013).

The last study includes the control technique in detail, using a PID controller, analyzing the signals from the sensors and controlling the speed during and after de- or acceleration. For this computer assignment only the higher, tactical level of fuzzy speed control is used and the acceleration and deceleration of the conveyor belt is assumed to have no overshoot and to be perfectly controlled.

The research question for this assignment is therefore:

- What is the effect of fuzzy logic speed control on the energy usage and number of stress cycles of a belt conveyor under different feed scenarios?

The input of a belt conveyor cannot always be measured before it enters the belt. A chute or hopper may not have the accuracy or capacity to measure the amount of material entering the belt conveyor or the material can be sticky or in another way unpredictable. Besides that, a belt conveyor can also serve several feeders. If the material input must be measured before it enters the belt, all the feeders must have the technology and space to measure the feed rate of the material input. Therefore the scenario used for this simulation consists of two belt conveyors. The primary belt is short and runs at nominal speed. At the start this belt the feed rate is measured. During the time the material is on the primary belt, a reference speed for the secondary belt is generated, such that the secondary can anticipate the material that is coming. A graphical representation of the setup is given in Figure 2.

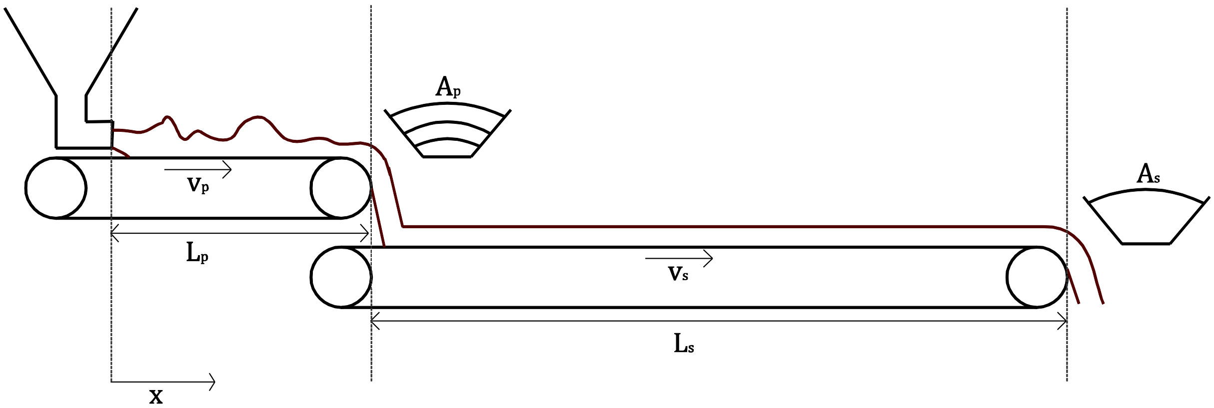


Figure 2 Belt conveyor setup

$L_p = Length\ of\ primary\ belt\ [m]$

$L_s = Length\ of\ secondary\ belt\ [m]$

$v_p = Operational\ speed\ primary\ belt\ [m/s]$

$v_s = Operational\ speed\ secondary\ belt\ [m/s]$

$A_p = Cross\ sectional\ area\ material\ on\ primary\ belt\ [m^2]$

$A_s = Cross\ sectional\ area\ material\ on\ secondary\ belt\ [m^2]$

$x = Position\ measured\ from\ sensor\ [m]$

Setting up the simulation model of a fuzzy logic speed belt conveyor consisted of the following steps:

1. Modelling the dynamics and friction coefficient of the belt conveyor using DIN 22101 (e.V., 2002) and the acceleration and deceleration profiles of He, Pang, and Lodewijks (2016). This information is used to calculate the power consumed by a belt conveyor operating under constant and variable speed.
2. Defining various input scenarios to represent the different kinds of bulk material input.
3. Define an algorithm using fuzzy logic speed control to determine the speed of the secondary belt conveyor based on the input of the primary belt conveyor.
4. Simulate the controlled and uncontrolled belt conveyor for a number of runs using a random input feed (Monte Carlo simulation).
5. Calculate the mean values and confidence intervals of the energy savings and number of stress cycles due to fuzzy logic speed control.

In chapter 2 the power used by a belt conveyor is calculated using DIN 22101 (e.V., 2002), the standard for calculating the power requirements of the belt conveyor. This subject is followed by giving the acceleration and deceleration profiles to get an idea of the force and time used accelerate and decelerate. Then the material input is given, followed by the composition of the belt. In chapter 3 the algorithm used to determine the reference speed is discussed and the assumptions for the speed simulation of the belt given. Chapter 4 focusses on the in- and output of the simulation. Chapter 5 presents the results of the simulation discusses the results briefly chapter 0ends with recommendations and conclusions drawn from the results.

2 Belt conveyor

To get an idea of the acceleration and deceleration rate and the amount of power used at constant speed, the dynamics of the belt conveyors are described in a simplified form using DIN 22101 (e.V., 2002). The deceleration and acceleration paths must be determined to get an idea of the amount of energy used or saved to alter the speed of the (loaded) belt.

2.1 Power calculation

First, the power necessary to overcome the friction is calculated. Because the total power consumption is determined by both friction and acceleration, this part is only sufficient for calculating power consumption at constant speed.

The total resistance is formulated as:

$$F_W = F_H + F_N + F_{St} + F_S$$

$F_w = Total\ resistance\ [kgm/s^2]$
$F_H = Primary\ resistance\ [kgm/s^2]$
$F_N = Secondary\ resistance\ [kgm/s^2]$
$F_{St} = Gradient\ resistance\ [kgm/s^2]$
$F_S = Special\ resistance\ [kgm/s^2]$

The primary resistance is depending on belt length:

$$F_H = L \cdot f \cdot g(m'_R + (2 \cdot m'_G + m'_L)\cos(\delta))$$

$L = Length\ of\ belt\ [m]$
$f = Friction\ coefficient\ [-]$
$g = Gravitational\ acceleration\ [m/s^2]$
$m'_R = Mass\ of\ idlers\ per\ meter\ (feed\ and\ return\ side)\ [kg/m]$
$m'_G = Mass\ of\ conveyer\ belt\ per\ meter\ [kg/m]$
$m'_L = Mass\ of\ bulk\ material\ per\ meter\ [kg/m]$
$\delta = Gradient\ resistance\ (neglectable\ if\ < 18°)\ [°]$

The friction coefficient f has a major impact on the estimate of the primary resistances. The friction coefficient should therefore be established as precisely as possible for all parts of the belt conveyor. The coefficient depends on the internal friction of the bulk material, running resistance of carrying idlers and the indentation rolling resistance. For this assignment the standard value of 0.020 has been taken into account.

The secondary resistance include friction resistances and steady-state resistances which arise only in some places of the belt conveyor. They can be calculated in detail using the chute and idler configuration but can also be calculated more general when the belt is longer than 80 meters and has just one feeding point:

$$F_N = (C - 1)F_H$$

The constant C can be found in the Table 1.

Table 1 Constant C as a function of belt length, source DIN 22101

L	**80**	**100**	**150**	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**	**1500**	**≥2000**
C	1.92	1.78	1.58	1.45	1.31	1.25	1.20	1.17	1.14	1.12	1.10	1.09	1.06	1.05

Gradient resistance is the force necessary to lift the load if there is a height difference in the belt conveyor:

$$F_{St} = L \cdot h \cdot g(2 \cdot m'_G + m'_L)$$

$h = Height\ difference\ conveyer\ belt\ [m]$

For this simulation special resistances are not taken into account because the simulated belts have a standard design.

The power necessary to overcome friction under constant velocity is equal to:

$$P_W(t) = F_W(t) \cdot v(t)$$

$P_W = Power\ due\ to\ friction\ [kgm^2/s^3]$
$v = Operating\ speed\ of\ belt\ [m/s]$

The power usage when accelerating is equal to:

$$P_a(t) = F_a(t) \cdot v(t)$$

$P_a = Power\ usage\ due\ to\ acceleration\ [kgm^2/s^3]$
$F_a = Force\ necessery\ to\ accelerate\ the\ belt\ [kgm/s^2]$

F_a will be determined in paragraph 2.2 . Acceleration power is equal to 0 when speed is constant, so the total power necessary for overcoming the friction and acceleration is:

$$P_{tot} = (F_a + F_W) \cdot v$$

$P_{tot} = Total\ power\ [kgm^2/s^3]$

The acceleration and friction force depend on the load on the belt. To calculate the load on the secondary belt constant material flow at time step t_{L_p} is used:

$$Q_{in}(t_{L_p}) = A_p\left(t_{L_p}\right) v_p\left(t_{L_p}\right) = A_s\left(t_{L_p}\right) v_s\left(t_{L_p}\right)$$

Q_{in} = Mass $flow\ at\ inlet$ [kg/s]

$A = Cross\ sectional\ area\ belt\ conveyer\ [m^2]$

$t_{L_p} = Time\ the\ material\ falls\ from\ the\ primary\ belt\ conveyer\ [s]$

The only unknown is A_s. This can be calculated by:

$$A_s\left(t_{L_p}\right) = \frac{A_p\left(t_{L_p}\right) v_p\left(t_{L_p}\right)}{v_s\left(t_{L_p}\right)}$$

These cross-sections are stored at discrete points with interval t_s. The speed of the belt determines the how many time steps (or cross sections) are on the physical belt. Therefore we should know the corresponding positions of the cross sections. This can be done by integrating the speed signal:

$$x(t) = \frac{1}{s} \cdot v(t)$$

$x = Position\ of\ belt\ [m]$

In essence, integrating a signal is adding up all previous signal values multiplied by the time interval t_s. Now that $x(t)$ and $A_s(t)$ are known (with A_s being the surface of the cross section at the start of the secondary belt) we can calculate the surface at the exit. With the corresponding speed, the output at time t can then be calculated:

$$Q_{out}(t) = A_s\big(t(x(t) - L_s)\big) \cdot v(t)$$

Q_{out} = Mass $flow\ at\ outlet$ [kg/s]

The input is equal to:

$$Q_{in}(t) = A_p(t) \cdot v(t)$$

The mass on the belt is found by integrating the difference in input and output:

$$m'_L(t) = \frac{1}{s} \cdot \frac{Q_{in}(t) - Q_{out}(t)}{L_s}$$

Figure 3 shows three diagrams. To understand these diagrams they are explained below. All diagrams refer to the second belt.

- Diagram 1: This diagram shows the input of material on the secondary belt during the course of the simulation run (which is a 1000 seconds in this case). The input of material only starts after a period of time because it first needs to pass the primary belt.
- Diagram 2: This diagram shows the output of material (unloading) from the secondary belt during the course of the simulation run. The output of material starts after a period of time because it first needs to pass the primary and secondary belt.
- Diagram 3: This diagram shows the total mass of material on the secondary belt during the course of the simulation. As can be seen the belt is loaded during the first time period (it starts empty). In the end it is unloaded, the mass on the belt is zero at the end of the simulation. The red line indicates the maximal possible loading of the secondary belt.

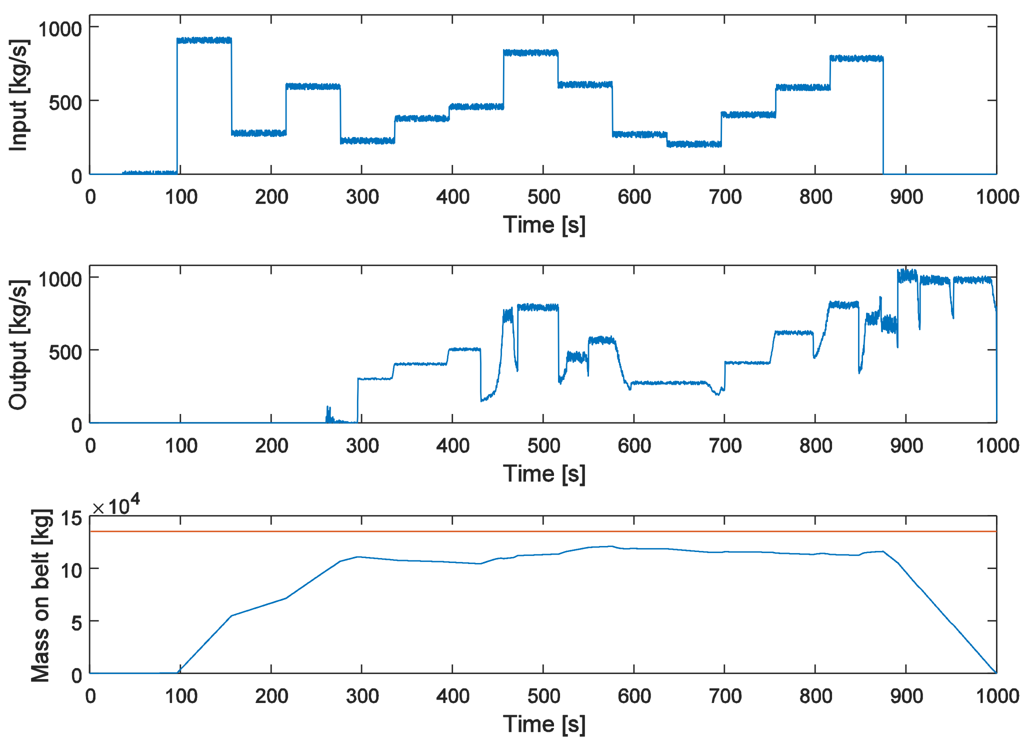


Figure 3 Input, output and mass on the secondary conveyor during a simulation run

It is important to know the mass on the secondary belt at all times, because the mass needs to be accelerated and causes friction, which translates into power consumption.

Now, the friction and acceleration force and the power consumption for all time steps can be calculated. Multiplying the power usage with the time step interval and summing them up gives the total power consumption (work):

$$W_{sc} = \sum_{t=1}^{t=t_{runtime}} P_{tot}(t) \cdot t_s$$

$t_s = Time\ step\ length\ [s]$
$t_{runtime} = Run\ time\ of\ simulation\ [time\ steps]$
$W_{sc} = Work\ for\ speed\ controlled\ conveyer\ [kgm^2/s^2]$

The original situation is the belt conveyor operating at constant speed. This means there is no acceleration and only the friction will be taken into account. The friction is linearly depending on the mass and therefore the average mass on the belt for the simulation time can be taken for calculating the mass causing the friction on the belt throughout the simulation:

$$m'_L = \rho \frac{\sum_{t=1}^{\mathrm{t_{runtime}}} A(t)}{\mathrm{t_{runtime}}}$$

$\rho = Density\ material\ [kg/m^3]$

The friction force and resulting total power usage (work) can be calculated. The work performed for the simulation is then:

$$W_{nsc} = \sum_{t=1}^{t=t_{runtime}} P_W \cdot t_s$$

$t_{runtime} = Run\ time\ of\ simulation\ [time\ steps]$
$W_{nsc} = Work\ for\ non - controlled\ conveyer\ [kgm^2/s^2]$

The efficiency of a speed controlled conveyor compared to an uncontrolled conveyor comes down to:

$$energy\ savings = 1 - \frac{W_{sc}}{W_{nsc}}$$

2.2 Acceleration and deceleration profile

The method of He et al. (2016) (which is based on DIN 22101 (e.V., 2002)) is used for determining the acceleration profile of the conveyor belt. His research shows that a sinusoid acceleration profile gives the smoothest transition from one speed to another, minimizing the jerk on the belt. The acceleration at a certain time in the acceleration path is described as:

$$a(t) = \frac{\pi}{2}\frac{(v_1 - v_0)}{t_a}\sin\left(\pi\frac{(t - t_0)}{t_a}\right) \quad for \quad t_0 \le t \le t_0 + t_a$$

$a = Acceleration\,of\,belt\;[m/s^2]$

$v_0 = Operating\;speed\;before\;speed\;transition\;[m/s]$

$v_1 = Operating\;speed\;after\;speed\;transition\;[m/s]$

$t = Time\;[s]$

$t_a = Time\,necessary\,to\,accelerate\;[s]$

$t_0 = Start\;time\;[s]$

The velocity profile can be found by integrating the acceleration profile:

$$v(t) = \int a(t)dt = \int \frac{\pi}{2}\frac{(v_1 - v_0)}{t_a}\sin\left(\pi\frac{(t - t_0)}{t_a}\right)dt = \frac{v_1 - v_0}{2}\left(1 - \cos\left(\pi\frac{(t - t_0)}{t_a}\right)\right) + v_0$$

The constant is determined by making the velocity at $v(0)$ be v_0. The velocity profile is described by:

$$v(t) = \frac{v_1 - v_0}{2}\left(1 - \cos\left(\pi\frac{(t - t_0)}{t_a}\right)\right) + v_0$$

A graphical representation of the velocity and acceleration of the acceleration profile is given in Figure 4.

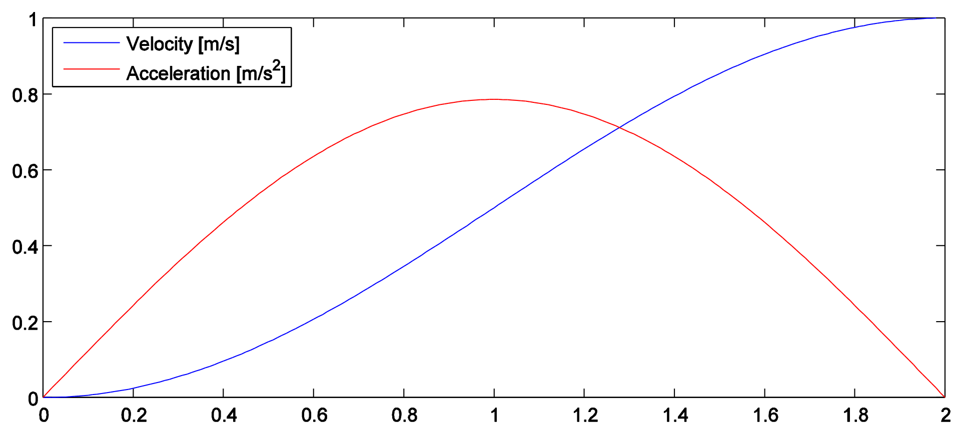


Figure 4 Example of acceleration profile for a conveyor belt

The maximum acceleration is determined by using the nominal rupture force of the belt. The maximum driving force is described using the following formula:

$$F_{D,max} = \frac{(e^{\mu\alpha} - 1)}{e^{\mu\alpha}} \frac{F_R B}{S_A}$$

$F_D = Driving\ force\ [kgm/s^2]$
$F_R = Nominal\ rupture\ force\ of\ belt\ [kgm/s\text{^}2\ ]$
$\mu = Coefficient\ of\ friction\ [-]$
$\alpha = Wrap\ of\ the\ belt\ around\ the\ pulley\ [°]$
$B = Beld\ width\ [m]$
$S_A = Minimum\ safety\ factor\ [-]$

The acceleration force is equal to:

$$F_a = L(m'_R + 2 \cdot m'_G + m'_L)\alpha$$

The power used when accelerating is equal to:

$$P_{tot} = (F_a + F_W)v$$

The driving force F_D consists of the acceleration force F_a and the force F_W necessary to overcome friction:

$$F_a + F_W \le F_{D,max}$$

The maximum acceleration is therefore:

$$\alpha_{max} = \frac{(F_{D,max} - F_W)}{L(m'_R + m'_G + m'_L)}$$

The sinusoid describing the acceleration has a maximum amplitude of:

$$a_{max} = \frac{\pi}{2} \frac{(v_1 - v_0)}{t_a}$$

The minimal time necessary to accelerate from v_0 to v_1 is:

$$t_a = \frac{\pi}{2}(v_1 - v_0) \frac{L(m'_R + m'_G + m'_L)}{(F_{D,max} - F_W)}$$

The deceleration rate is determined by friction and mass. In the real case the motor will also decelerate the conveyor belt, but this contribution has been neglected. The decelerating forces are combined in the friction force F_W. For deceleration the following formula is taken into account:

$$d = \frac{-F_W}{L(m'_R + m'_G + m'_L)}$$

$d = Deceleration\ of\ belt\ [m/s^2]$

The speed profile of deceleration is:

$$v(t) = \int d(t)\,dt = \frac{-F_W \cdot (t - t_0)}{L(m'_R + m'_G + m'_L)} + v_0$$

A graphical representation of the velocity and acceleration of the deceleration profile is given in Figure 5.

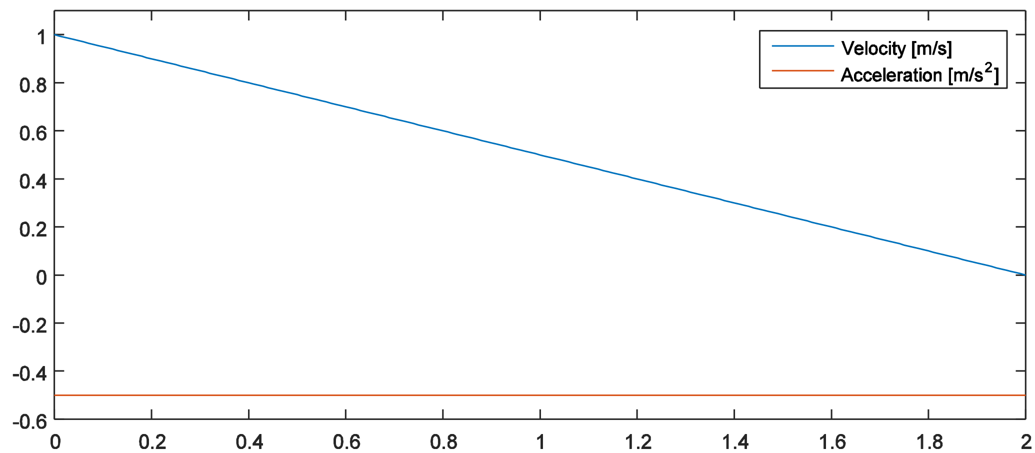


Figure 5 Example of deceleration profile for a conveyor belt

Time necessary to decelerate from v_0 to v_1 is equal to:

$$t_d = -(v_1 - v_0)\frac{L(m'_R + m'_G + m'_L)}{F_W}$$

$t_d = Time\ necessary\ to\ decelerate\ [s]$

2.3 Feeding material

The input in bulk material can take different shapes depending on the situation. To get a representation of most situations, several input scenarios are available for simulation. The input scenarios are visually given in Figure 6. The following input scenarios are taken into account:

- The first input scenario consists of a constant feed, speed control will only adjust according to this particular feed. Constant feed represents a long term stable stream of input.
- The second input consists of a periodically changing input. This represents for example, a ship unloading at a bulk conveyor with different feed rates.

- The third input represents another periodically changing feed rate: a sinusoid. This type of feed rate can be caused by, for example, a hopper wheel.
- The fourth input is completely randomized. This feed rate represents the many processes that have a very unpredictable and fast changing input rate.

All input scenarios have a slightly distorted signal to make it represent the irregularities due to the grain size of the material.

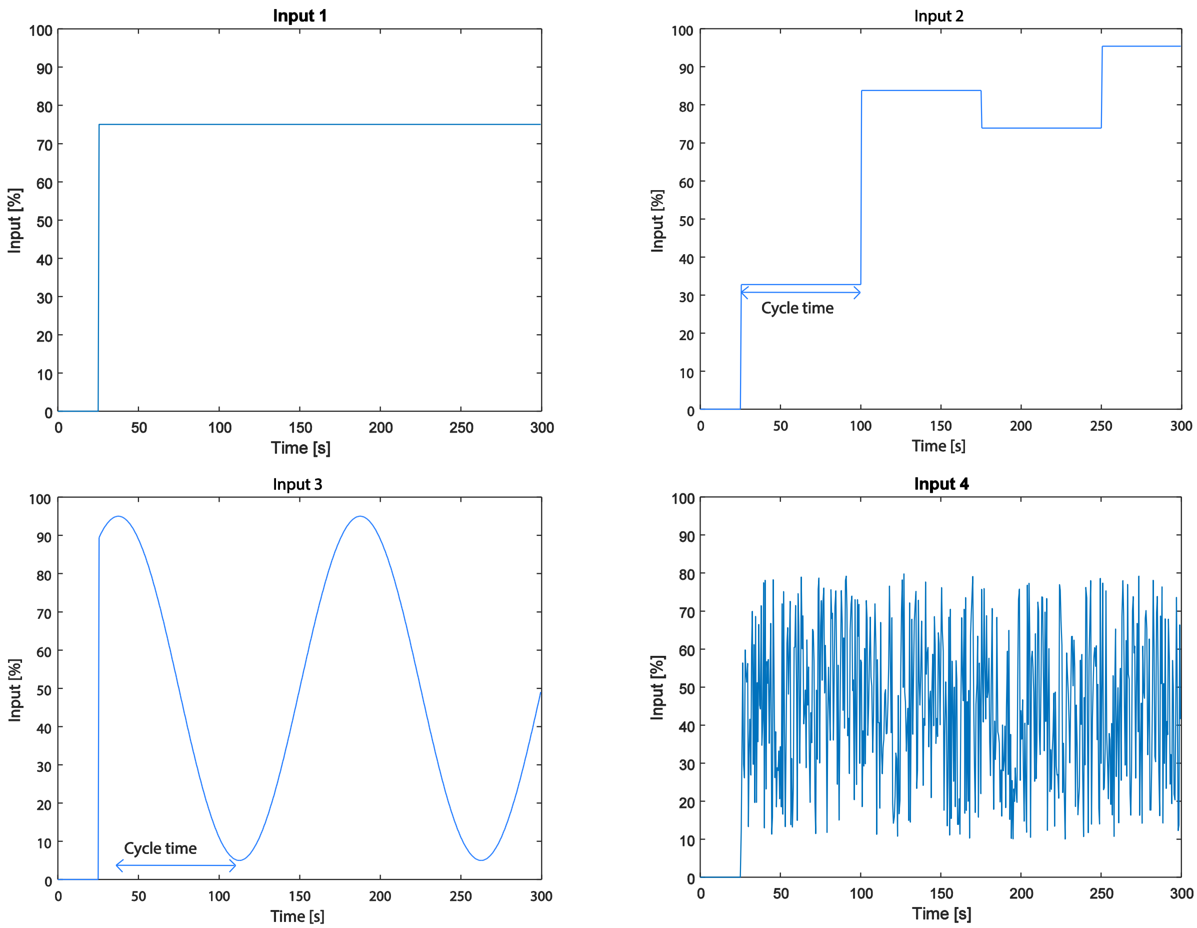


Figure 6i-iv Input scenarios used for the simulation model

The algorithm used to define the reference speed will be able to handle all four scenarios. The algorithm will be further explained in chapter 3 .

3 Reference speed algorithm

To generate the right reference speed for the secondary belt conveyor an algorithm is designed which uses the information of the material on the primary belt and fuzzy speed control. A recap of the setup is given in Figure 7.

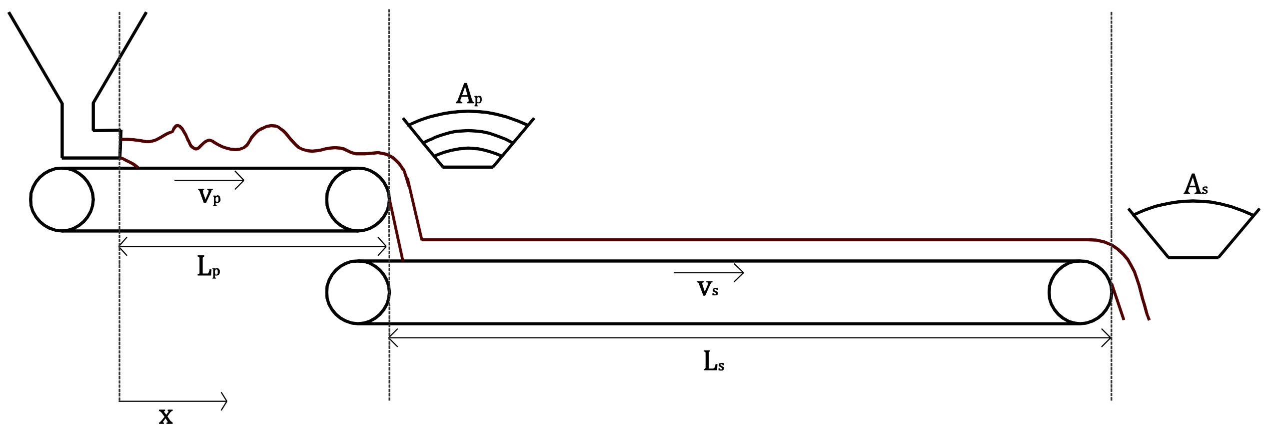


Figure 7 Setup

The length of the primary belt is calculated using the speed of the primary belt and the time necessary to accelerate a fully loaded secondary belt from standstill to maximum velocity:

$$L_p = v_p t_{a,max}$$

The prediction horizon t_h is now equal to $t_{a,max}$.

3.1 Model

A graphical representation of the model is given in Figure 8. The model has four inputs, the four scenarios given in paragraph 2.3 . A switch chooses between the input scenarios after which the buffered speed is generated in the 'Reference speed' module, this is further explained in paragraph 3.2 . After this, the fuzzification of the speed signal takes place in the 'Fuzzification' module, this is covered in paragraph 3.3 . The acceleration and decelartion profiles are calculated in the 'Acceleration/Deceleration' (see paragraph 2.2 module and from the resulting 'real' speed and acceleration combined with the input the power consumption of the belt is calculated in controlled and uncontrolled condition. This is done in the 'Power Calculation' module, the method used for this calculation is further explained in paragagh 2.1 . The results are the percentage energy saving and the number of stress cycles.

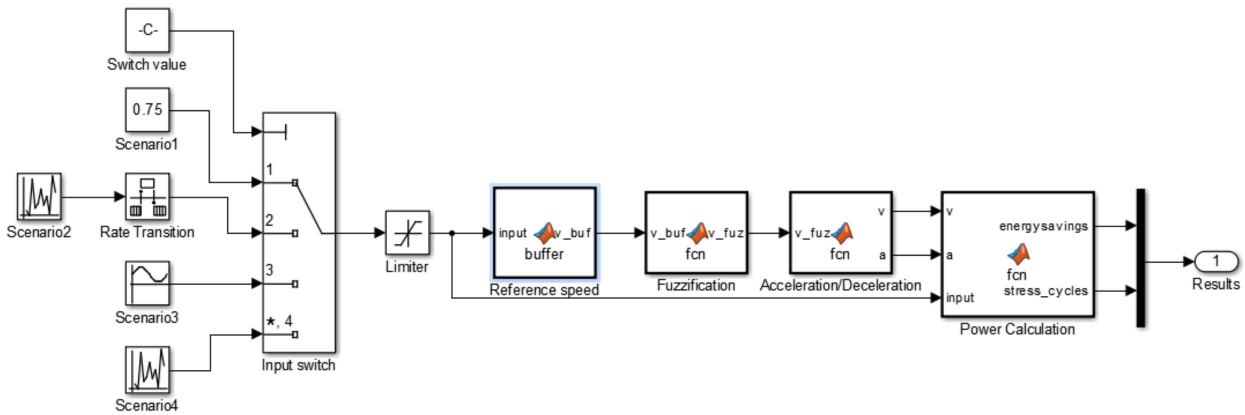


Figure 8 Graphical representation of the model used to calculate the energy savings.

3.2 Reference speed

The input rate of the bulk material (Q_{in}) is measured at the start of the primary belt ($x = 0$) by using cross section sensor. The primary belt is necessary to give the system time to measure the bulk material and adjust the speed of the (heavy and therefore slowly adjusting) secondary belt.

The mass flow can also be written as:

$$Q(t) = \frac{dV(t)}{dt} = A(t)v(t)$$

$V = Material\ volume\ [m^3]$

Since the mass flow (Q) is constant when exiting the primary belt and entering the secondary belt and the following equation holds:

$$Q_{in}(t + t_h) = \rho A_p(t + t_h)v_p(t + t_h) = \rho A_s(t + t_h)v_s(t + t_h)$$

The reference speed for the belt for this time step can already be measured during the start of the primary belt at time t. The reference speed for the secondary belt conveyor at this time step should therefore be:

$$v_{ref}(t + t_h) = \frac{Q_{in}(t)}{\rho A_s(t + t_h)} = \frac{A_p(t)v_p}{A_s(t + t_h)}$$

Since we want A_s to be maximal and constant for the secondary belt we can assume this to be constant:

$$v_{ref}(t + t_h) = \frac{A_p(t)v_p}{A_s}$$

The reference speed for the end of the time horizon can be calculated at the beginning of the time horizon, in the meantime the secondary belt conveyor can adjust accordingly. The algorithm will choose the reference speed strategically to be able to anticipate deceleration or acceleration.

A problem arises when the input is decreasing for a short time. If the belt conveyer decelerates because of this local decrease in input, it will not be able to accelerate when the input is at normal level again. This can be anticipated because (part) of the input on the primary belt is already known before it enters the secondary belt.

To handle this problem, the reference speeds are stored in an array (a buffer) for the time horizon t_h (This is essentially the input already known on the primary belt). The maximum reference speed of this array is taken as a reference speed which should be achieved after the time horizon t_h. This way, local minima (distortions) are neglected. This is visually represented in Figure 9.

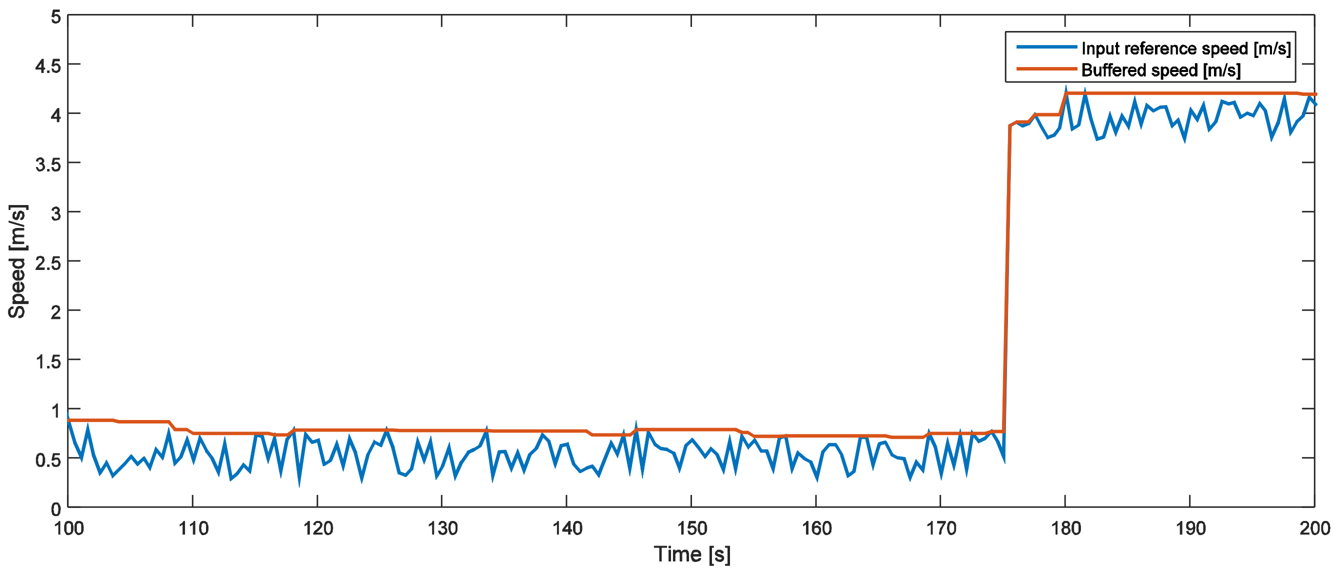


Figure 9 Input reference speed and buffered reference speed

To avoid delay in deceleration the array (buffer) is shortened to the time necessary to decelerate from the maximum reference speed to the minimum speed. This ensures enough time to decelerate timely.

$$t_{h,deceleration} = t_d = -(v_{min,buf} - v_{max,buf})\frac{L(m'_R + m'_G + m'_L)}{F_W}$$

To avoid small distortions in constant speed resulting in many speed adjustments the time horizon for deceleration has a minimal value:

$$t_{h,deceleration} < \frac{t_h}{3}$$

3.3 Fuzzification

Even though local distortions are filtered out, the buffered reference speed is still varying with small steps. This results in a lot of acceleration and deceleration of the belt. When a belt accelerate from one constant speed to another, the stress on the equipment is high. We call this a stress cycle. Stress cycles result in wear of the transport equipment due to fatigue of the materials. To lower the amount of stress cycles, fuzzy logic speed control is introduced, such that the speed is only corrected when enough difference between the current and wanted speed occurs.

Fuzzy logic is an approach to computing based on 'degrees of truth'. This implies that the outcome is not only '0' or '1' but can be a percentage 'truth' or 'false'. The algorithm for generating the reference speed can be fuzzified by taking various speed boundaries b_n when the continuous reference speed $v_{s,ref}$ crosses a boundary, the fuzzified reference speed will be changed to the reference speed corresponding to the range r_n (range within boundaries b_n, b_{n+1}). For a fuzzy set with m intervals counts:

$$r_n \subset [b_n, b_{n+1}]$$

$$\sum_{n=1}^{m} r_n = 1$$

$$b_n \subset [0,1]$$

$$b_n = 0, \qquad b_{m+1} = 1$$

The lowest and highest boundary should be 0 and 1 respectively to cover all operation speeds. The speed is scaled as a ratio of the maximal speed:

$$v_s^* = v_s / v_{s,max}$$

When the reference speed $v_{s,ref}$ falls within a range r_n the reference speed will be equal to the higher boundary b_{n+1} to avoid spillage at all times.

Fuzzification prevents the conveyor belt from constant deceleration and acceleration. The belt conveyor' life is elongated due to the fact that it undergoes a lower amount of stress cycles.

The fuzzified reference speed can be seen in Figure 10. In the last 300 seconds, the speed changes significantly for two times. However, the reference speed is constant due to the fuzzification. This results in less stress cycles.

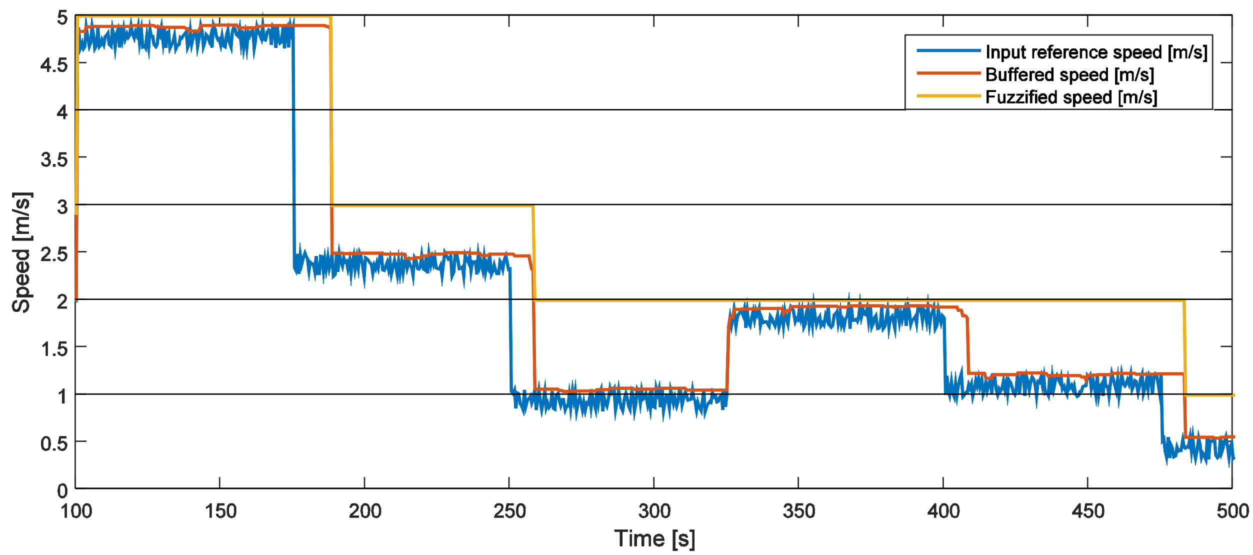


Figure 10 Input reference speed, buffered speed and fuzzified speed

The boundaries are specified as an input of the simulation model. By iteratively changing the number and positions of boundaries the amount of stress cycles and energy consumption can be optimized.

Figure 11 shows all the (intermediate) reference speeds for scenario 2. As can be seen, small distortions are removed by the buffered speed, which then are converted to the higher boundary of the fuzzified range the buffered speed is in.

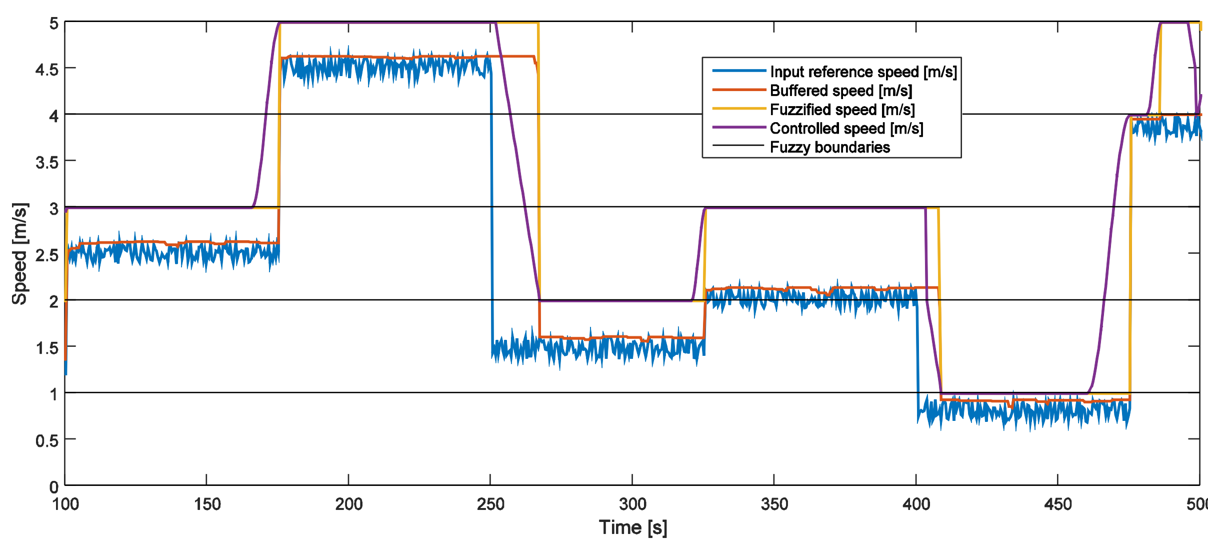


Figure 11 (Intermediate) reference speeds for scenario 2

4 Implementation

To simulate the control algorithm using the inputs defined, a model is made in Matlab. Using a Graphical User Interface (GUI) several variables can be adjusted. A visual of the initial GUI is shown in Figure 12 and the features explained afterwards.

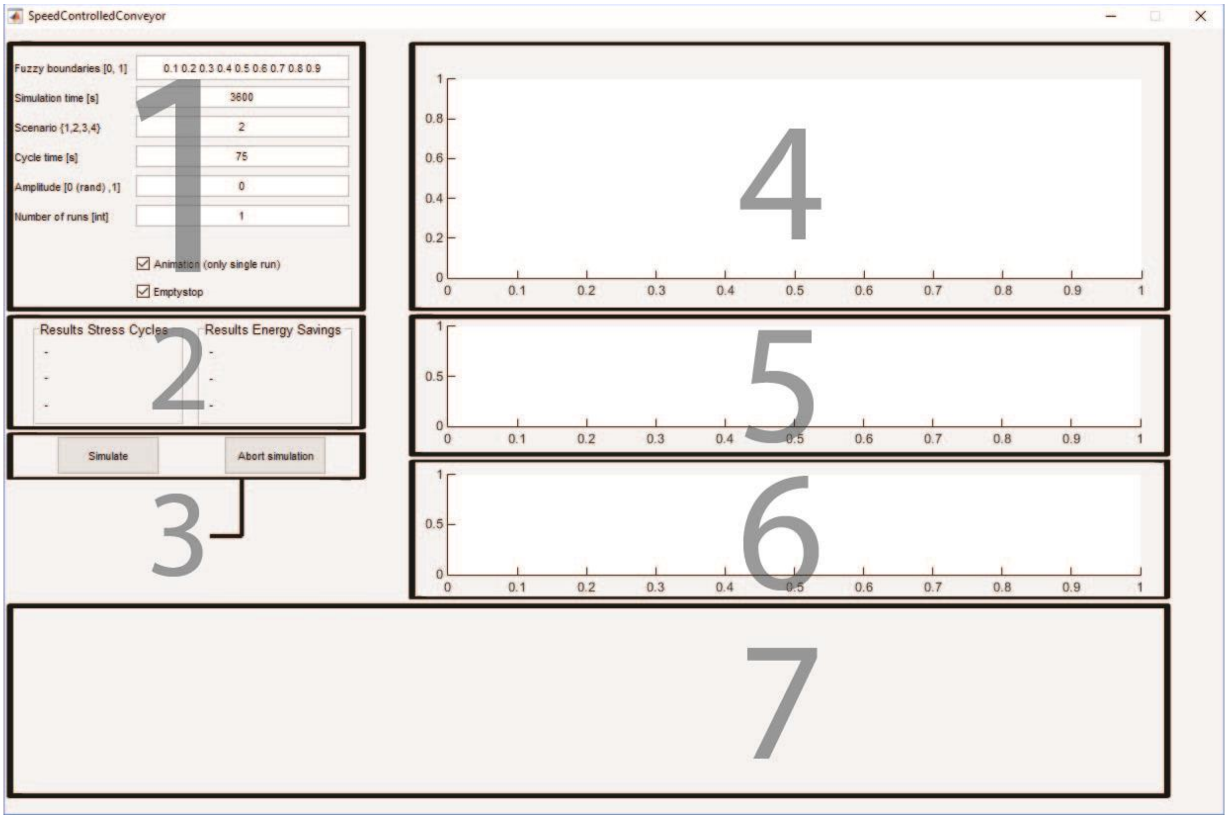


Figure 12 GUI before simulation

1. Input variables: Fuzzy boundaries, simulation time, input scenario, cycle time, amplitude and number of runs
2. Numerical results of the simulation
3. Buttons to start or abort the simulation
4. This diagram will show the input and speed of the secondary belt conveyor
5. This diagram will show the total mass on the secondary belt conveyor
6. This diagram will show the power necessary for driving the secondary belt conveyor
7. This area will show an animation of the process (if wanted)

4.1 Monte Carlo simulation

Monte Carlo simulation relies on repeating random sampling to get numerical results. This method is applied to problems where it is impossible or difficult to mathematically calculate the solution. Repeating random sampling means that an experiment is performed with a random input or a random correlation between variables. In principle, Monte Carlo simulation can be used to solve any problem having a probabilistic interpretation.

Monte Carlo simulation is applied to this problem, because the input is made random for scenario 2, 3 and 4. This makes it very hard to mathematically calculate the expected energy savings and number of stress cycles for a single run. Monte Carlo simulation repeats the random simulation for a number of times (these repetitions are called 'runs') so the mean of these runs converges to the true mean (the expected value which would otherwise be mathematically calculated).

To get an idea of vicinity of the estimated mean (the mean calculated by the Monte Carlo simulation) to the true mean, a confidence interval can be calculated. The confidence interval of the results is determined using the confidence multiplier of two tailed normal distributions:

$$[U, L] = \mu_{energysavings} \pm z \cdot \frac{\sigma_{energysavings}}{\sqrt{Runs}}$$

$$[U, L] = \mu_{stresscycles} \pm z \cdot \frac{\sigma_{stresscycles}}{\sqrt{Runs}}$$

$z = Confidence\ coefficient$
$\mu_{energysavings} = Estimated\ average\ of\ energy\ savings$
$\sigma_{energysavings} = Standard\ deviation\ of\ energy\ savings$
$\mu_{stresscycles} = Estimated\ average\ of\ stress\ cycles$
$\sigma_{stresscycles} = Standard\ deviation\ of\ stress\ cycles$
$U = Upper\ limit\ of\ confidence\ interval$
$L = Lower\ limit\ of\ confidence\ interval$

The confidence coefficient z is equal to 1.96 for a confidence interval of 95%. Calculating the upper and lower limit with this coefficient results in the following conclusion: 'It is 95% certain that the true mean lies within the upper and lower limit of the confidence interval'.

If the confidence interval is small, the chance that the estimated mean is very close to the true mean is high. If the confidence is big, the number of runs should be increased to get a better estimate of the true mean.

4.2 Simulation input

The settings regarding the equipment are constant for the simulation. Only scenario and strategical settings have been made variable. The constants are derived from the scenario used by He et al. (2016) and shown in Table 2.

Table 2 Constant settings for the simulation

Constants	Value
$L_s = Length\ of\ secondary\ belt\ [m]$	1200
$v_{max} = Maximal\ speed\ of\ belt\ [m/s]$	5
$f = Friction\ coefficient\ [-]$	0.018
$h = Height\ difference\ conveyer\ belt\ [m]$	0
$m'_R = Mass\ of\ idlers\ per\ meter\ [kg/m]$	14.86 + 7.72
$m'_G = Mass\ of\ conveyer\ belt\ per\ meter\ [kg/m]$	14.28
$m'_{L,max} = Maximal\ mass\ of\ bulk\ material\ per\ meter\ [kg/m]$	133.54
$F_R = Nominal\ rupture\ force\ of\ belt\ [kgm/s^2]$	500.000
$\mu = Coefficient\ of\ friction\ [-]$	0.35
$\alpha = Wrap\ of\ the\ belt\ around\ the\ pulley\ [°]$	180
$S_A = Safety\ factor\ [-]$	5.4
$B = Beld\ width\ [m]$	1.2

Some variables can be adjusted in the GUI. These are stated in Table 3.

Table 3 Adjustable variables for the simulation

Variables	Value
$b_n = Fuzzy\ boundaries\ [-]$	$\{b_n \in \mathbb{R} \mid 0 < b_n < 1\}$
$t_{runtime} = Simulation\ time\ [s]$	$\{t_{runtime} \in \mathbb{Z}\}$
$Scenario = Input\ scenario\ [integer]$	$\{1,2,3,4\}$
$t_{cycle} = Cycle\ time\ of\ input\ material\ [s]$	$\{t_{cycle} \in \mathbb{Z}\}$
$Amplitude = Amplitude\ of\ input\ feed$	$[0\ (random), 1]$
$Runs = Number\ of\ runs\ to\ be\ performed\ [-]$	$\{Runs \in \mathbb{Z}\}$
$Animation = Animation\ at\ the\ end\ of\ the\ simulation\ [boolean]$	$\{0,1\}$
$Emptystop = End\ simulation\ with\ empty\ secondary\ belt\ [boolean]$	$\{0,1\}$

The fuzzy boundaries can be adjusted to get the highest energy efficiency with the lowest amount of stress cycles. By performing several runs, the average amount of the number of stress cycles and energy efficiency can be found, this ensures the reliability of the outcomes.

4.3 Simulation output

A visual representation of the GUI containing the results is given in Figure 13.

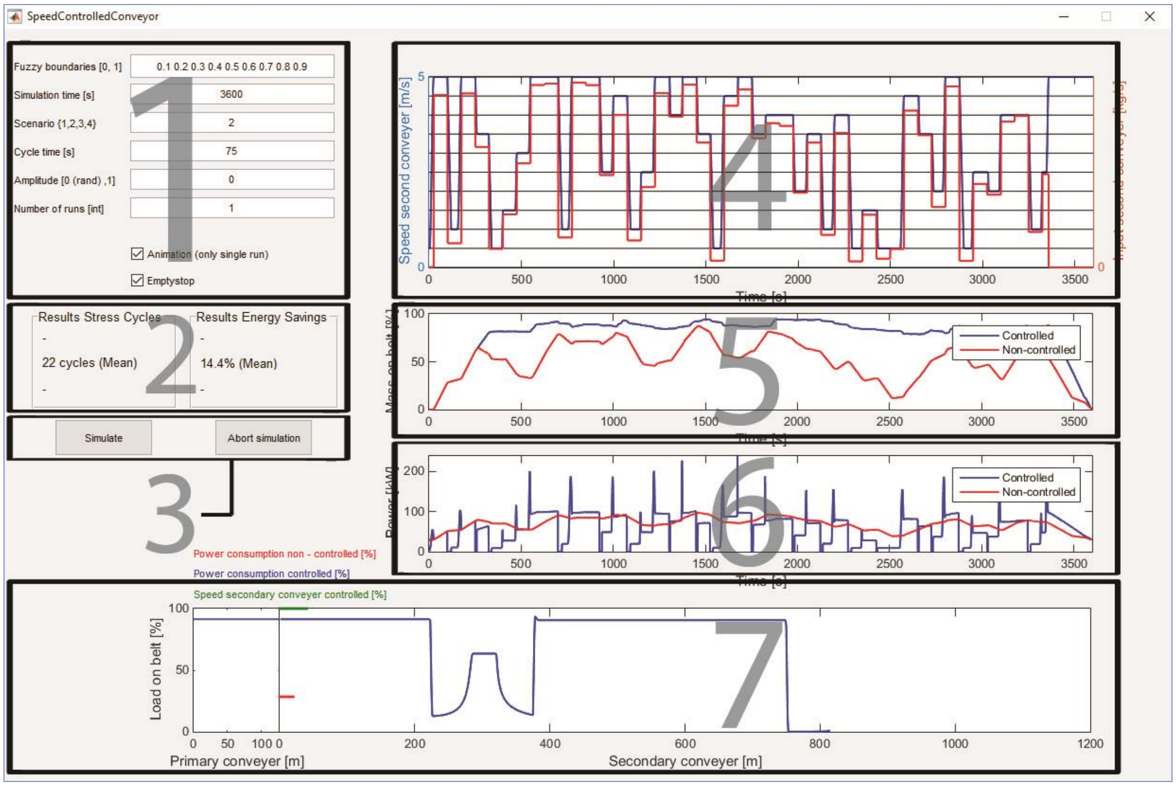


Figure 13 GUI showing the results

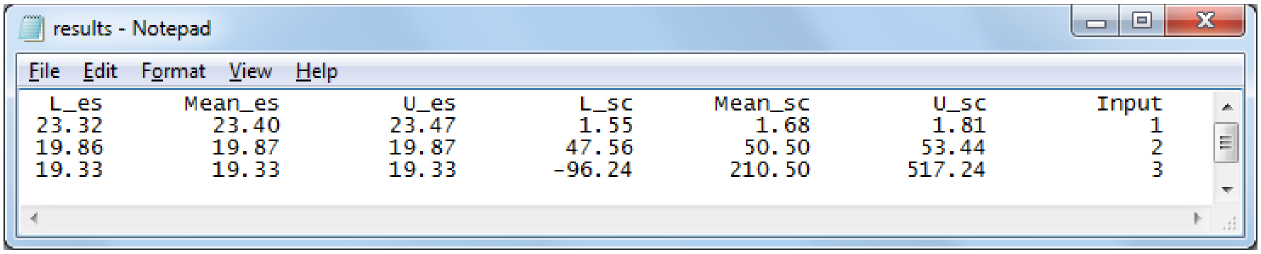
The simulation output consists of the following information:

2. Numerical results of the simulation: Upper and lower limit of the 95% confidence interval and the estimated mean of the energy savings and number of stress cycles.
4. This diagram shows the input on the secondary belt in kg per second and the speed of the secondary belt conveyor in meters per second as a function of the simulation time.
5. This diagram shows the total mass on the controlled and uncontrolled secondary belt conveyor as a function of the simulation time.
6. This diagram shows the power necessary for driving the controlled and uncontrolled secondary belt conveyer as a function of time.
7. This diagram shows the real time loading on the primary and secondary belt conveyor. Besides that it indicates the speed and power necessary for driving the belt of both the controlled and uncontrolled case.

The following results are written away to a file named ‘results.txt’ for every run:

- Energy savings with upper and lower limit 95% confidence interval
- Stress cycle with upper and lower limit 95% confidence interval
- Input scenario

A representation of this text file is given in Figure 14.



L_es	Mean_es	U_es	L_sc	Mean_sc	U_sc	Input
23.32	23.40	23.47	1.55	1.68	1.81	1
19.86	19.87	19.87	47.56	50.50	53.44	2
19.33	19.33	19.33	-96.24	210.50	517.24	3

Figure 14 Results written to text file

$L\_es = \mathit{Lower\ limit\ of}\ 95\%\ \mathit{confidence\ interval\ true\ mean\ energy\ savings}\ [\%]$

$Mean\_es = \mathit{Estimated\ mean\ energy\ savings}\ [\%]$

$U\_es = \mathit{Upper\ limit\ of}\ 95\%\ \mathit{confidence\ interval\ true\ mean\ energy\ savings}\ [\%]$

$L\_sc = \mathit{Lower\ limit\ of}\ 95\%\ \mathit{confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles}$

$Mean\_sc = \mathit{Estimated\ mean\ of\ number\ of\ stress\ cycles}$

$U\_sc = \mathit{Upper\ limit\ of}\ 95\%\ \mathit{confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles}$

$Input = \mathit{Input\ scenario\ used\ for\ the\ simulation\ run}$

5 Results

To answer the research question posed at the start of this report, the experiment is performed by varying the number of fuzzy boundaries for four scenarios. This way, the effect of fuzzy logic speed control on the energy savings and number of stress cycles under different scenarios can be determined. The number of fuzzy boundaries is varied from 1 to 9. The ranges between the fuzzy boundaries are equally divided over the speed domain.

The scenarios consist of a random input for scenarios 1,2 and 4. Scenario 3 has a maximal amplitude sine input which is constant. For the random scenarios, 50 runs are performed to get the smallest confidence interval for the true mean of the energy savings and number of stress cycles (see the introduction of this report for an explanation on stress cycles). The other settings are given in Table 4.

Table 4 Settings for experiment

Settings experiment	Value
$b_n = Fuzzy\ boundaries\ [-]$	$1 - 9\ boundaries$
$t_{runtime} = Simulation\ time\ [s]$	10800
$Scenario = Input\ scenario\ [integer]$	{1,2,3,4}
$t_{cycle} = Cycle\ time\ of\ input\ material\ [s]$	100
$Amplitude = Amplitude\ of\ input\ feed$	0 (except scenario 3)
$Runs = Number\ of\ runs\ to\ be\ performed\ [-]$	50
$Animation = Animation\ at\ the\ end\ of\ the\ simulation\ [boolean]$	0
$Emptystop = End\ simulation\ with\ empty\ secondary\ belt\ [boolean]$	1

This is visually represented in Figure 15.

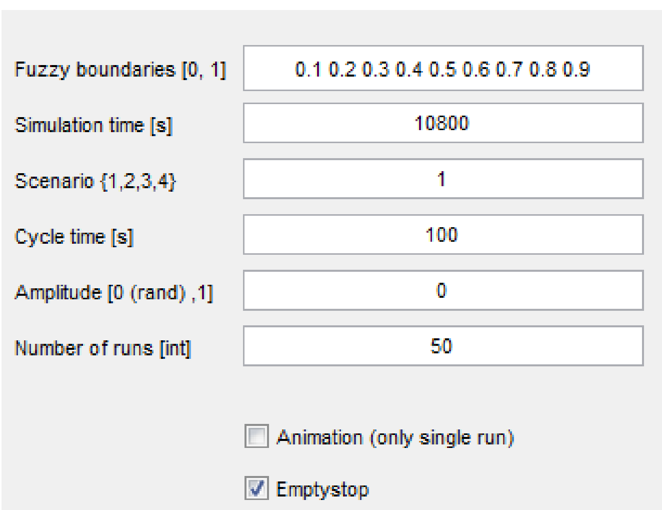


Figure 15 Settings for experiment in the GUI

In Figure 16 to Figure 19 the graphical results of a single run for the four input scenarios is given. For scenario 1,2 and 4 there have been performed 50 of these runs with random input to get a good idea of the average energy savings and number of stress cycles. The mean number of stress cycles can therefore a double instead of only an integer number.

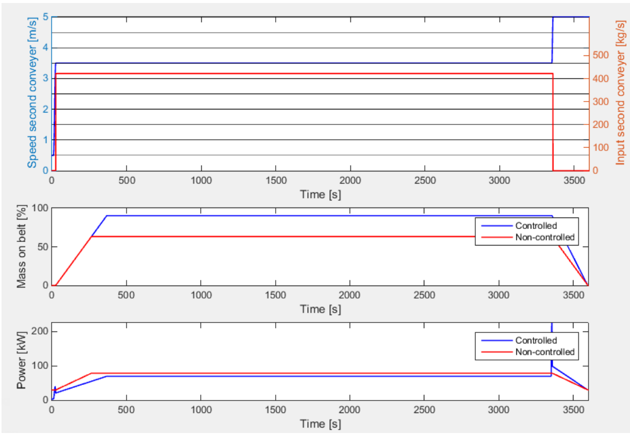


Figure 16 Graphical results scenario 1

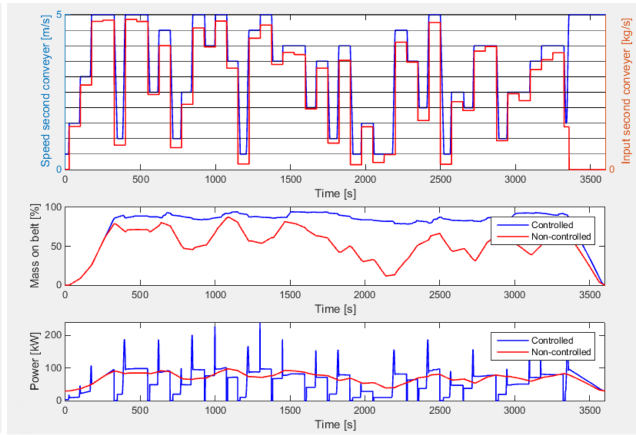


Figure 17 Graphical results scenario 2

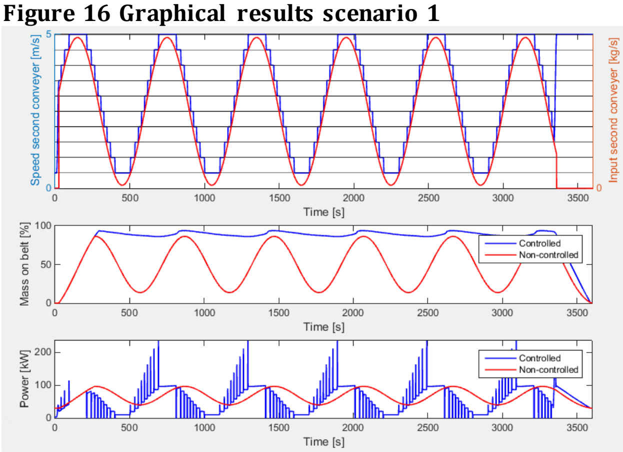


Figure 18 Graphical results scenario 3

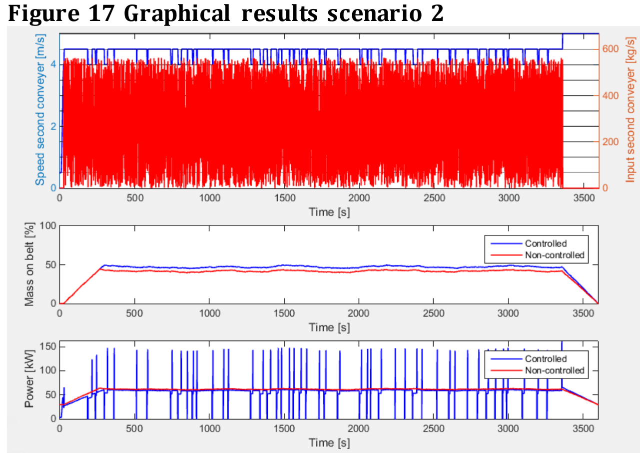


Figure 19 Graphical results scenario 4

The results of the experiment are given in Table 5 to Table 8. The results of the experiment consist of the mean energy savings and mean number of stress cycles including the borders of the 95% confidence interval for all four input scenarios. The number of fuzzy boundaries is indicated to get an idea of the effect of these boundaries on the results. A graphical representation of the results is given in

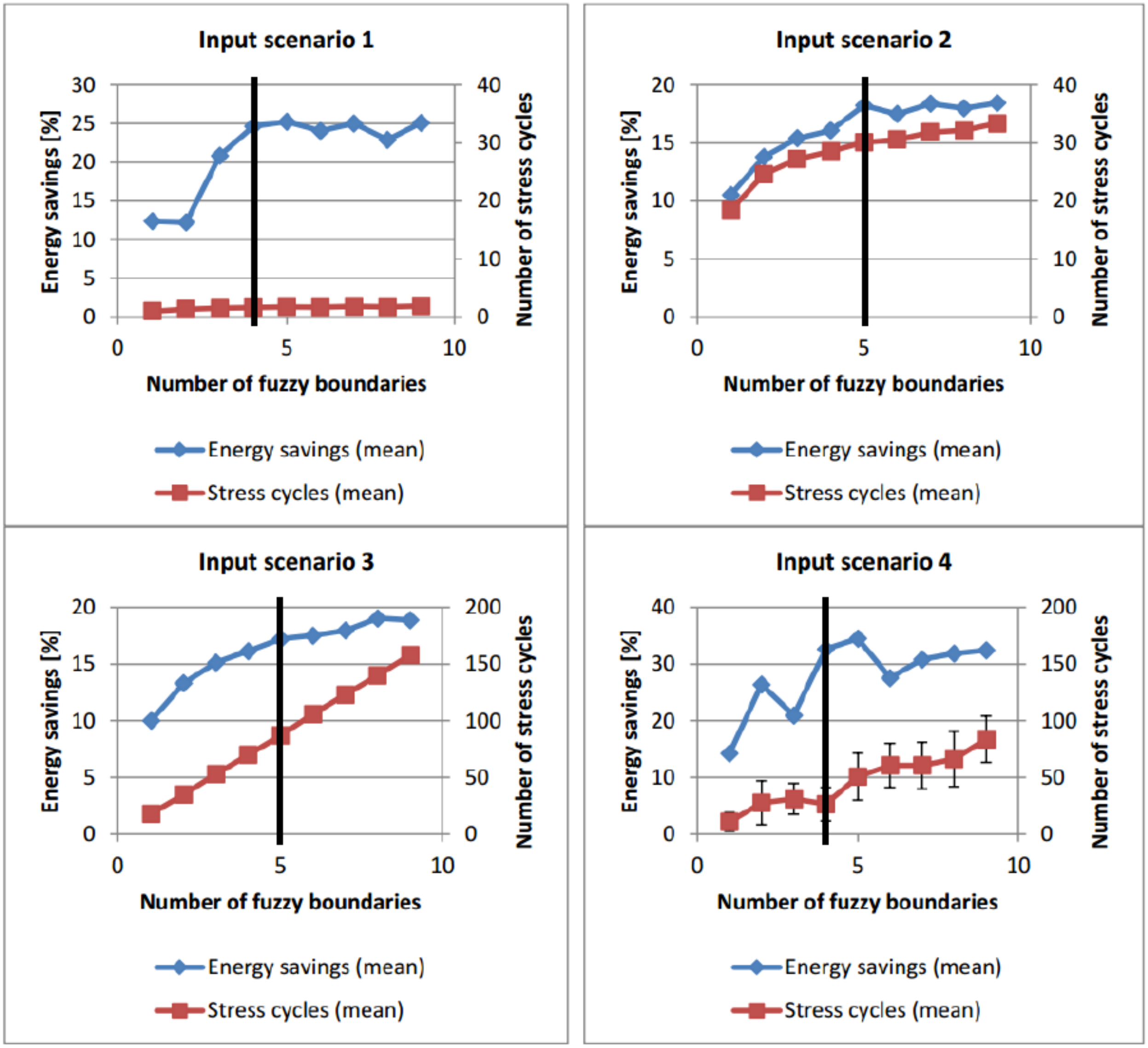


Figure 20. The 95% confidence intervals are only represented for scenario four, where the number of stress cycles is fluctuating a lot. The other confidence intervals are too small to be represented.

Table 5 Results for scenario 1

B_n	ES_{Low}	ES_{Mean}	ES_{Up}	SC_{Low}	SC_{Mean}	SC_{Up}
1	12,35	12,4	12,44	1	1	1
2	12,18	12,2	12,27	1,21	1,34	1,47
3	20,79	20,9	20,9	1,38	1,52	1,66
4	24,59	24,7	24,71	1,51	1,64	1,77
5	25,18	25,2	25,3	1,62	1,74	1,86
6	23,99	24,1	24,13	1,57	1,7	1,83
7	24,96	25	25,08	1,71	1,82	1,93
8	22,83	22,9	22,96	1,59	1,72	1,85
9	25,05	25,1	25,18	1,79	1,88	1,97

Table 6 Results for scenario 2

B_n	ES_{Low}	ES_{Mean}	ES_{Up}	SC_{Low}	SC_{Mean}	SC_{Up}
1	10,51	10,5	10,52	17,9	18,4	18,93
2	13,8	13,8	13,81	23,9	24,62	25,3
3	15,41	15,4	15,42	26,6	27,24	27,87
4	16,08	16,1	16,09	27,9	28,54	29,16
5	18,22	18,2	18,23	29,2	30,12	31,04
6	17,48	17,5	17,49	29,9	30,62	31,39
7	18,37	18,4	18,38	31,2	31,86	32,56
8	17,98	18	17,99	31,5	32,18	32,89
9	18,44	18,4	18,45	32,7	33,36	34,02

Table 7 Results for scenario 3

B_n	ES_{Low}	ES_{Mean}	ES_{Up}	SC_{Low}	SC_{Mean}	SC_{Up}
1	10,02	10	10,02	18	18	18
2	13,3	13,3	13,3	35	35	35
3	15,12	15,1	15,12	53	53	53
4	16,14	16,1	16,14	70	70	70
5	17,21	17,2	17,21	87	87	87
6	17,51	17,5	17,51	106	106	106
7	17,95	18	17,95	123	123	123
8	19,04	19	19,04	140	140	140
9	18,87	18,9	18,87	158	158	158

Table 8 Results for scenario 4

B_n	ES_{Low}	ES_{Mean}	ES_{Up}	SC_{Low}	SC_{Mean}	SC_{Up}
1	14,17	14,2	14,27	2,59	10,86	19,13
2	26,31	26,4	26,43	8,29	27,62	46,95
3	20,88	21	21,01	17,4	31,06	44,68
4	32,55	32,6	32,68	11,8	26,44	41,12
5	34,41	34,5	34,55	30	50,68	71,41
6	27,47	27,5	27,6	41,2	60,58	79,97
7	30,74	30,8	30,89	40	60,58	81,14
8	31,76	31,8	31,91	41,9	66,22	90,53
9	32,37	32,4	32,51	63,1	83,62	104,12

$B_n = Number\ of\ fuzzy\ boundaries$

$ES_{Low} = Lower\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ energy\ savings\ [\%]$

$ES_{Mean} = Estimated\ mean\ energy\ savings\ [\%]$

$ES_{Up} = Upper\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ energy\ savings\ [\%]$

$SC_{Low} = Lower\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles$

$SC_{Mean} = Estimated\ mean\ of\ number\ of\ stress\ cycles$

$SC_{Up} = Upper\ limit\ of\ 95\%\ confidence\ interval\ true\ mean\ of\ number\ of\ stress\ cycles$

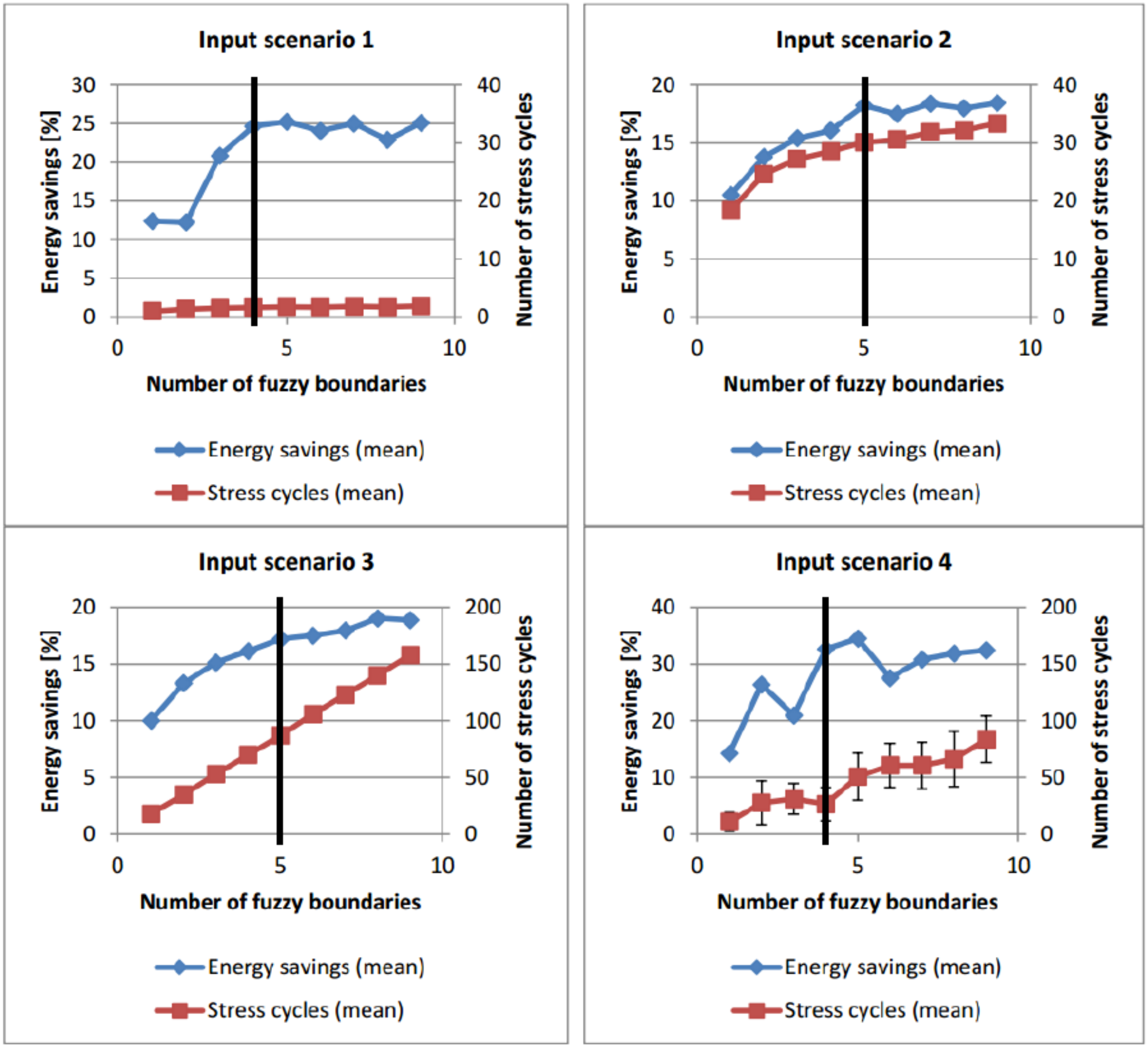


Figure 20 Graphical representation results of experiment

Both the results for energy savings end the number of stress cycles are discussed in paragraph 5.1 and 5.2 .

5.1 Energy savings

The main differences in energy savings are due to the character (periodical or constant) of the feed scenarios. Feed scenarios 2 and 3 are periodically changing and have similar energy savings. The same counts for scenario 1 and 4, which are almost constant over time. A similarity between all input scenarios is the fact that with an increasing number of fuzzy boundaries, the energy savings per extra boundary becomes less. The first two boundaries have the greatest impact on energy savings. This is interesting because the number of stress cycles increases different from the energy savings. For example: for scenario 3 the number of stress cycles increases linearly with an increasing number of fuzzy boundaries.

5.2 Stress cycles

A big difference can be found in the number of stress cycles (see the introduction for an explanation of the term 'stress cycles'). The number of stress cycles increases when the number of fuzzy boundaries increases. Small variations in input are filtered out with fuzzy logic control, however, when the number of fuzzy boundaries increases the ranges between the boundaries get slimmer and more variations in input will be anticipated on by adjusting the velocity. This increases the number of stress cycles. The four input scenarios give different numbers of stress cycles:

- Scenario 1 has an almost constant amount of stress cycles. The speed only needs adjustment to the new constant speed. The chance of the constant speed to be in the range of the maximal speed gets smaller when the number of boundaries increases. Therefore the number of stress cycles converges from 1 to 2.
- Scenario 2 has a significant increase of stress cycles. This is due to the fact that with bigger ranges (less fuzzy boundaries), the chance that the periodical change in input falls into the same range becomes bigger. This results in less stress cycles.
- Scenario 3 shows a linear increase in stress cycles. The acceleration and deceleration is performed in steps to anticipate the sinusoidal input. The more boundaries, the more steps (or stress cycles) are necessary. The number of stress cycles highly depends on the amplitude and frequency of the sinusoidal input.
- Scenario 4 shows an increasing but greatly varying amount of stress cycles. When the random signal is buffered, only the biggest values are taken into account, such that the belt does not unnecessarily decelerates. However, these biggest values are also random and can be just bigger or just smaller than a fuzzy boundary, resulting in many stress cycles. This only happens once in a few times, which is visible in the big confidence interval of the values found.

5.3 Optimal number of fuzzy boundaries

An optimal number of fuzzy boundaries can be found to get the highest energy savings at the lowest number of stress cycles. This way the machinery will endure while saving energy at the same time. The optimal number of fuzzy boundaries should be determined for every situation individually, but for the results of this experiment they are represented by the black line in Figure 20. Energy savings increase minimally after this line, while stress cycles do increase with an increasing number of fuzzy boundaries. To maintain the lowest number of stress cycles while saving enough energy savings the number of fuzzy boundaries for these scenarios should be around 4 to 5.

Conclusions and subjects for further research

In this report a simulation study to the effect of fuzzy logic speed control applied on a belt conveyor setup has been performed. The theoretical power consumption is calculated using belt conveyer dynamics as described in DIN 22101 and the acceleration and deceleration profile as described by He, Pang, and Lodewijks (2016). Four scenarios have been defined to cover most of the possible real life input scenarios. A reference speed algorithm is constructed using fuzzy logic speed control and a simulation model is built to test the effect of this algorithm on the four different input scenarios. Using Monte Carlo simulation, a confidence interval is generated for the results in energy savings and numbers of stress cycles. The simulation showed that energy savings up to 34% can be made. This, however is strongly depending on the input of the belt conveyor.

The effect of fuzzy logic speed control is highly depending on the number of fuzzy boundaries and the input scenario. The different scenarios used in this report showed similar energy savings, but increasing the number of fuzzy boundaries resulted in a different growth of stress cycles. Therefore, the boundaries should be tactically chosen to have sufficient energy savings with a low amount of stress cycles to make sure the equipment is not burdened too much. Up till a certain level, more fuzzy boundaries result in significant energy savings, but after a certain number of fuzzy boundaries, only the number of stress cycles increases.

Fuzzy logic speed control of belt conveyors can save of energy while minimizing the impact on machinery. A tradeoff between wear of belt conveyor and energy savings can be found using fuzzy logic speed control.

5.4 Subjects for further research

Open issues / subjects for further research are:

- Implementation of real time speed control. For this simulation, the acceleration and deceleration profiles have been described after the reference speed has been generated for the total simulation. This represents a real situation, but an algorithm written for real time speed control can be used for controlling a real setup.
- (Fuzzy logic) control of the acceleration rate. The acceleration rate is always maximal, this gives more stress cycles for, for example, scenario 3. When the acceleration rate is also controlled, the acceleration can be adjusted to the increase in input such that the number of stress cycles is lowered with similar energy savings.
- Inclusion of gearbox and motor efficiency. This simulation does not take into account the efficiency of the gearbox and motor. If this is linearly correlated with the speed, the outcomes for energy savings will be equal. However, in many cases the efficiency is not linearly correlated with the rotation speed of the motor/gearbox.
- Inclusion of PLC/PID control. This simulation does not take into account the control of the current and frequency of the belt conveyor motor. To implement the algorithm and get a better understanding of power usage, this should be included.

6 Bibliography

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