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Green operations of belt conveyors by means of speed control

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Abstract

Belt conveyors can be partially loaded due to the variation of bulk material flow discharged onto the conveyor. Speed control attempts to reduce the belt conveyor energy consumption and to enable the green operations of belt conveyors. Current research of speed control rarely takes the conveyor dynamics into account so that speed control lacks applicability. Based on our previous research, this paper will provide an improved three-step method to determine the minimum speed adjustment time. This method can be summarized as Estimation-Calculation-Optimization and ECO in short. The ECO method takes both the potential risks and the conveyor dynamics into account and is expected to keep belt conveyors in good dynamic behaviors in transient operations. The work will study a long inclined belt conveyor of an import dry bulk terminal, both in terms of belt conveyor energy savings and the conveyor dynamics. Based on a suggested acceleration time, a speed controller will be built and several computational simulations will be carried out to evaluate the energy savings by means of speed control. Due to speed control, the belt conveyor's filling ratio is expected to be improved in a large scale and a significant power reduction will be achieved. Consequently, both the energy cost and the carbon footprint will be considerably reduced. Then green operations of belt conveyors will be realized. Moreover, the speed control is looking forward to resulting in an appropriate dynamic performance.

Keywords: belt conveyor, energy savings, speed control, green operations, carbon footprint, ECO method

1. Introduction

Belt conveyors play a significant role in the dry bulk handling systems. In recent decades, the applications of belt conveyors are becoming longer, faster, and more efficient with higher capacity and less environmental impact [22]. According to Daniel Cluçonet [5], there are more than 2.5 million

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conveyors in operation annually in the world. Considering the extensive use of belt conveyors, the operations of belt conveyors involve a large amount of electricity. Taking the challenges associated with the environmental pollution and the electricity availability in some parts of the world into account [3, 27, 30], there is a strong demand for lowering the energy consumption of belt conveyors to reduce the cost and the carbon footprint. In the past decades, several different energy systems are designed [4, 16, 19, 25, 33, 34, 37, 38], among which speed control is an important aspect for realizing the green operations of belt conveyors.

Speed control is not a new research concept and right now there are lots of researchers and engineers studying the speed control of belt conveyors. However, these research mainly focus on the realization of soft start-up or stop operations [18, 20, 24, 26]. Hereby, differing from the traditional definition, speed control is a method of reducing energy consumption by regulating the conveyor speed to match the variable material feeding rate [15]. Generally, belt conveyors are running at designed nominal speed and in the most cases the belt conveyors are partially loaded. In such cases, the conveyor speed can be adjusted to match the material flow and the conveyor's filling ratio is expected to be significantly improved. Consequently, the belt conveyor's energy savings can be achieved. This is the so-called speed control.

The research of speed control can be dated back to the end of last century [6]. The current research of speed control mainly focuses on establishing models to predict energy saving [16, 36] and developing control strategies of speed control [37, 38, 23, 28, 29, 31, 32, 35]. However, these researches rarely take both the transient operation and the conveyor's dynamic performance into account. According to He et al. [14], transient operations are operations in which the conveyor speed changes over time for the purpose of matching the variable feeding rate of bulk solid materials. Comparing those operations in the normal start-up or stop activities, the transient operations for speed control should be given more attention since the belt conveyor is loaded with a high filling ratio due to the speed control. Moreover, the dynamics of belt conveyors in transient operations is of more complexity, especially in cases where the conveyor speed is frequently adjusted to match a variable material flow. Pang and Lodewijks [28] stated that in transient operations, a large ramp rate of conveyor speed might result in very high tension on the belt, which is the major reason of belt breaking at the splicing area. Taking the maintenance time and cost into account, the risks caused by the speed adjustment operation must be prevented. However, except for our previous work [14], there are rare researches showing information on risks in transient operations for speed control. Thus, the speed control still lacks applicability.

This paper is one step further of our previous work [14]. In our previous work [14], a three-

step method was proposed to determine the minimum acceleration time in transient operations. That work is the first research output of improving the applicability of speed control. Based on the previous work [14], the three-step method here is improved and summarized as Estimation-Calculation-Optimization and ECO for short. The ECO method takes both the risks and the conveyor dynamics in transient operations into account. Moreover, besides the minimum acceleration time, the ECO method can also be applied to determine the minimum deceleration time.

The paper’s objective is to implement the speed control for belt conveyors with considerations of the conveyor’s dynamic performance. A long inclined belt conveyor of an import dry bulk terminal is studied, both in terms of the belt conveyor’s dynamic behaviors and in terms of the belt conveyor energy savings by means of speed control. The studied belt conveyors is part of a bulk material handling chain where the material flow is varying with the variable-in-time number of available ship unloaders. The peak of the material flow feeding rate can be predicted according to the actual number of available unloaders. Then the conveyor speed can be adjusted to match the material flow. To realize a soft speed control, firstly, the ECO method is employed to determine the minimum speed adjustment time, both in acceleration and deceleration operations. The results of Calculation and Optimization come from simulations which are based on an existing finite element model (FEM) described by Lodewijks [21]. Secondly, with a suggested speed adjustment time, a speed controller is built and series of reference speeds are defined according to the variable-in-time number of available cranes. To evaluate the speed control, several computational simulations are carried out. In order to precisely evaluate the speed control, the variable efficiency of the driving system is taken into account. According to the experiment results, the belt conveyor utilization is improved by 24% from 45% to 69% due to speed control. The average electricity consumption of the studied belt conveyor is significant reduced by over 10% of that consumed by constant speed drives. Annually, the speed control could enable up to more than $\text{€}11,000$ cost saving in terms of electricity and around 90tons reduction in terms of CO_2 emission. Moreover, the employment of the ECO method ensures a soft dynamic performance in transient operations.

2. Energy model and potential energy savings

2.1. Energy model

The energy model of belt conveyors is derived from the standard DIN22101 [8] and the paper [16]. The driving force F_d exerted on the drive pulley equals the total motional resistances F_f adding the net forces F_A resulting in accelerating:

$$F_d = F_f + F_A \quad (1)$$

According to DIN22101, the total motional resistances can be calculated by:

$$F_f = CfL[m'_{roll} + (2m'_{belt} + m'_{bulk}) \cos\delta]g + Hm'_{bulk}g + F_S \quad (2)$$

where C is a factor for calculating the secondary resistances, f stands for the artificial friction coefficient, L represents the conveyor length, $m'_{roll}, m'_{belt}, m'_{bulk}$ are idlers mass, conveyor belt mass and bulk material mass per length unit, respectively, δ represents the mean angle of inclination of the installation, H is the change in elevation between head and tail pulleys, g is the gravity acceleration and F_S represents the special resistances which do not exist in all belt conveyors.

As further described by DIN22101, the required mechanical power P_m on drive pulleys is calculated by multiplying the driving forces F_d and the conveyor speed v :

$$P_m = F_d v \quad (3)$$

Then taking the driving system efficiency η_{system} into account, the required electrical power P_e is

$$P_e = \frac{P_m}{\eta_{system}} \quad (4)$$

2.2. Potential Energy savings

It is assumed that the design capacity of a belt conveyor is Q_{nom} at the nominal speed v_{nom} . If it is further assumed that the belt conveyor is a general-purpose conveyor and that the actual material feeding rate Q is less than the design capacity, then if the belt conveyor is running in a steady operating condition with the nominal speed v_{nom} , the bulk material mass $m'_{bulk,con}$ on the conveyor per length unit is

$$m'_{bulk,con} = \frac{Q}{3.6v_{nom}} \quad (5)$$

and the electrical power is

$$P_{e,con} = \left\{ \frac{CfL [m'_{roll} + (2m'_{belt} + m'_{bulk,con}) \cos\delta]g + Hm'_{bulk,con}g}{\eta_{system,con}} \right\} v_{nom} \quad (6)$$

where $\eta_{system,con}$ is the driving system efficiency at the nominal speed v_{nom} and in Equation 6 the special resistance is omitted.

If the belt conveyor is running in a steady operating condition with a non-nominal speed v_{var} , then the bulk material mass $m'_{bulk,var}$ on the belt per length unit is

$$m'_{bulk,var} = \frac{Q}{3.6v_{var}} \quad (7)$$

and the consumed electrical power is

$$P_{e,var} = \left\{ \frac{CfL \left[m'_{roll} + (2m'_{belt} + m'_{bulk,var}) \cos\delta \right] g + Hm'_{bulk,var}g}{\eta_{system,var}} \right\} v_{var} \quad (8)$$

where $\eta_{system,var}$ is the driving system efficiency at the speed v_{var} .

Then comparing Equations 6 and 8 yields the power saving by means of speed control

$$\Delta P_e = P_{e,con} - P_{e,var} \quad (9)$$

and the saving ratio is

$$R_{P_e} = \frac{\Delta P_e}{P_{e,con}} \times 100\% = \left(1 - \frac{P_{e,var}}{P_{e,con}} \right) \times 100\% \quad (10)$$

If it is further assumed that the driving system efficiency at nominal speed equals that at non-nominal speed, then in the case of a horizontal belt conveyor, Equation 10 can be recast by

$$R_{P_e} = \frac{(m'_{roll} + 2m'_{belt})(v_{nom} - v_{var})}{(m'_{roll} + 2m'_{belt} + m'_{bulk,con})v_{nom}} \times 100\% \quad (11)$$

or

$$R_{P_e} = \frac{R_m(1 - R_v)}{R_m + R_Q(1 - R_m)} \times 100\% \quad (12)$$

where

$$\begin{aligned} R_m &= \frac{m'_{roll} + 2m'_{belt}}{m'_{roll} + 2m'_{belt} + m'_{bulk,nom}} \times 100\% \\ R_v &= \frac{v_{var}}{v_{nom}} \times 100\% \\ R_Q &= \frac{Q}{Q_{nom}} \times 100\% \end{aligned}$$

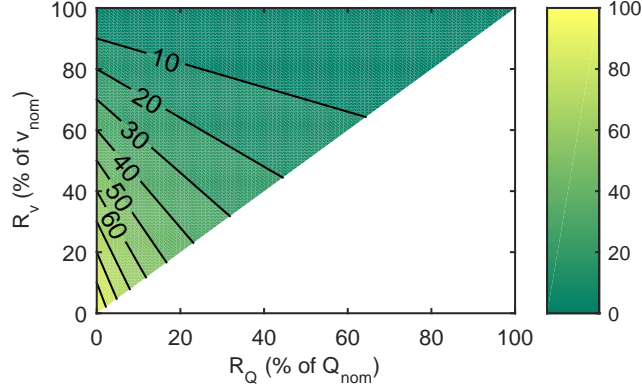


Figure 1: Proportion of energy savings by means of speed control. An assumption is made that the efficiency of driving systems is a constant over variable speeds and variable loads.

Figure 1 illustrates the power saving ratio according to Equation 12 with respect to a constant mass ratio $R_m = 20\%$ and variable speeds from 0 to 100% of the nominal speed. For example, if the material feeding ratio is 50%, then the maximum power saving percentage can be up to 16.67% if the speed equals 50% of the nominal speed. Note that the belt conveyor is not allowed to work in the conditions represented by the white area in Figure 1 since in such conditions the belt conveyor might be overloaded.

Another importation notation is that the result in Figure 1 normally is larger than the measured since in practice the efficiency of the whole system decreases with a decrease of the magnitude of the speed or the load. Taking the variable values of system efficiency into account, Equation 12 then can be recast by

$$R_{P_e} = \left(1 - \frac{R_m R_v + R_Q (1 - R_m) \eta_{system,con}}{R_m + R_Q (1 - R_m) \eta_{system,var}} \right) \times 100\% \quad (13)$$

and according to the data of variable efficiency of the whole system (including transformer, frequency converters, motors and air conditioning) supported by ABB [1], Figure 2 illustrates the proportion of energy savings by means of speed control.

Based on the standard DIN22101 [8] and the paper [16], this section reviewed the belt conveyor energy model and analyzed the potential energy saving by means of the speed control. However as discussed before, the research of speed control is still at a developing stage since the current research rarely takes the conveyor's dynamics into account and there is a lack of work describing the transient operations. On the basis of [13, 14], a method called ECO is put forward in the next section to decide the demanded speed adjustment time and to help to design a speed controller.

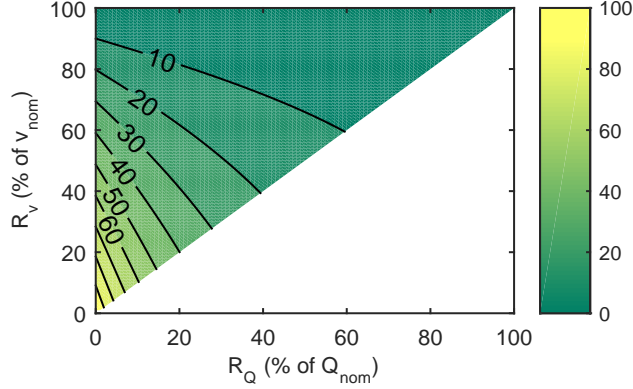


Figure 2: Proportion of energy savings by means of speed control. Variable values of driving system efficiency is taken into account. The data of efficiency of the whole system is from ABB [1].

3. Deciding speed adjustment time

The conveyor speed is adjusted to match a variable material flow for the purpose of reducing the energy consumption. Pang and Lodewijks [28] suggested that selecting an appropriate acceleration time was of significant importance since poor transient operations might result in very high tension on the belt. Taking both the potential risks and the dynamics in transient operations into account, this section discusses the ECO method in detail which consists of three steps: Estimation, Calculation and Optimization. Differing from the previous work [14], this work considers more risks in transient operations and both the acceleration and deceleration operations are taken into account.

3.1. Estimation

Taking the potential risks in transient operations into account, an estimator is built in the Estimation step to compute the permitted maximum acceleration and initialize the acceleration time. The acceleration operation includes risks of belt over-tension, belt slippage and motor overheating. In the deceleration operation, more attention should be drawn towards the risk of pushing motor into the regenerating operation.

3.1.1. Acceleration operation

Belt over-tension. With respect to the risk of belt over-tension, the belt tension must be maintained in a certain level. In cases where head pulleys are the drive pulleys and the system is not regenerative, the maximum belt tension generally occurs right before the drive pulley. In an acceleration operation, the belt tension T_1 before the drive pulley can be approximated by

$$T_1 = T_2 + F_d \quad (14)$$

where T_2 is the belt tension after the drive pulley if it is assumed that the take-up is located right after the drive pulley.

According to DIN22101 [8], the permitted belt tension before the drive pulley can be estimated by

$$T_{1,max} = \frac{k_N B}{S_{A,min}} \quad (15)$$

of which k_N is the belt tension rating, B is the belt width and $S_{A,min}$ is the demanded minimum safety factor in transient operations.

In the case of a belt conveyor tensioned by a single sheaved gravity take-up device with mass M , the belt tension T_2 equals

$$T_2 = \frac{1}{2} M g \quad (16)$$

which neglects the acceleration of the take-up device.

Combining Equations 15 and 16 with 14 yields the permitted driving force

$$F_{d,max,tension} = \frac{k_N B}{S_{A,min}} - \frac{1}{2} M g \quad (17)$$

with respect to the belt over-tension risk.

Belt slippage. Belt slippage is another major risk in acceleration operations. As stated by Kuhnert and Schulz [17], if the driving force exerted on the drive pulley is larger than the permitted, the belt will slip around the drive pulley. If the belt slippage occurs to such an extent that it slows down or even stops the conveyor then blockage of the belt's feeder chute or material spillage may occur. Furthermore, a serious belt slippage might result in wearing the belt's bottom cover and reducing the belt's service life. Therefore, the risk of belt slipping should be given much attention in transient operations. To define the permitted driving force with respect to the belt slippage risk, the frictional coefficient μ between the belt and the drive pulley, the wrap angle α of belt around the drive pulley, and the belt tension T_2 should be taken into account:

$$F_{d,max,slip} = T_2 (e^{\mu\alpha} - 1) \quad (18)$$

where $F_{d,max,slip}$ is the maximum driving force with respect to the belt slippage risk.

Motor over-heating. The rated motor torque is the maximum continuous torque available at the design speed that allows the motor to do work without overheating. In practical acceleration operations, the maximum service torque is allowed to be slightly larger than the rated for few seconds. The ratio of the maximum service torque and the rated torque is defined as service factor (i_{sf}), and for example, the standard service factor for an open drip-proof motor is 1.15 [9]. Then in the acceleration operation, the permitted motor service torque is

$$\tau_{motor,max} = i_{sf}\tau_{motor,nom} \quad (19)$$

and the maximum driving force $F_{d,max,heat}$ onto the drive pulley is

$$F_{d,max,heat} = i_{rf} \frac{\tau_{motor,max}}{R_d} = \frac{i_{rf}i_{sf}\tau_{motor,nom}}{R_d} \quad (20)$$

in which i_{rf} is the gearbox reduction ratio and R_d is the drive pulley's radius. It is important to note that Equation 20 neglects the impact of the inertia of the transmission and the drive pulley.

Then taking these three risks in acceleration operations into account, the permitted maximum driving force $F_{d,max}$ in transient operations is

$$F_{d,max} = \min(F_{d,max,tension}, F_{d,max,slip}, F_{d,max,heat}) \quad (21)$$

As described by Newton's Second Law, the acceleration is the net result of any and all forces acting on belt conveyors. Then in acceleration operations, the permitted acceleration is

$$a_{max,ac} = \frac{F_{A,max}}{m} = \frac{F_{d,max} - F_f}{m} \quad (22)$$

where $F_{A,max}$ is the maximum acceleration force and m is the total motional mass of a belt conveyor. In the speed control of belt conveyors, the belt conveyor should complete the acceleration operation before the coming of the large material flow. Differing from the acceleration operation, the deceleration operation starts after the arriving of the low material flow. Therefore the total motional mass of a belt conveyor is variable in transient operations. However, if the pulley's inertia is neglected, the total mass of the bulk solid on the belt conveyor, either in the transient operation or in a steady operating condition, is no larger than the value of $Lm'_{bulk,nom}$. Hence, it is eligible to view the total mass as a constant

$$m = L(m'_{roll} + 2m'_{belt} + m'_{bulk,nom}) \quad (23)$$

in the procedure of determining the maximum acceleration as in Equation 22.

3.1.2. Deceleration operation

In a soft deceleration operation, the driving force exerted on drive pulleys decreases gradually and the conveyor speed is reduced smoothly. Differing from the acceleration operation, the deceleration operation mainly considers the risk of pushing motor into the regenerative operation. When engineers design a conveyor system, the function of driving system is determined by the conveyor working condition and the configuration of the belt conveyor system. In the case of horizontal belt conveyors, the motor's driving system normally does not include the generating function unless a regenerative braking is required. Then taking the risk of pushing motor into the regenerative operation into account, the maximum deceleration is

$$a_{max,de} = \frac{-F_f}{m} \quad (24)$$

3.1.3. Speed adjustment time

The mechanical jerk is the first derivative of acceleration with respect to time. The conveyor's dynamic performance, especially the mechanical jerk, is dependent on the acceleration curves in the transient operations. In soft acceleration and deceleration operations, the mechanical jerk must be restricted since the excessive jerk results in considerable belt tension fluctuations. According to DIN22101 [8], the belt tension is responsible for the belt sag ratio and as noted by CEMA [2], the bulk material may be spilled away from belt when the belt sag ratio is more than 3 percent. In addition, the material spillage might be resulted from excessive belt speed deviations which also might be caused by big mechanical jerks. In order to reduce the mechanical jerk and enable a soft-start operation, Harrison [12] recommended a sinusoidal acceleration profile which is employed by this paper.

Figure 3 illustrates the sinusoidal acceleration profiles and the speed curves in transient operations. The mathematical expression of the acceleration and speed is:

$$a(t) = \frac{\pi \Delta v}{2 t_a} \sin \frac{\pi t}{t_a} \quad (25)$$

$$v(t) = v_0 + \frac{\Delta v}{2} \left(1 - \cos \frac{\pi t}{t_a} \right) \quad (26)$$

where Δv is the speed adjustment range, t_a is the speed adjustment time, t is the instantaneous

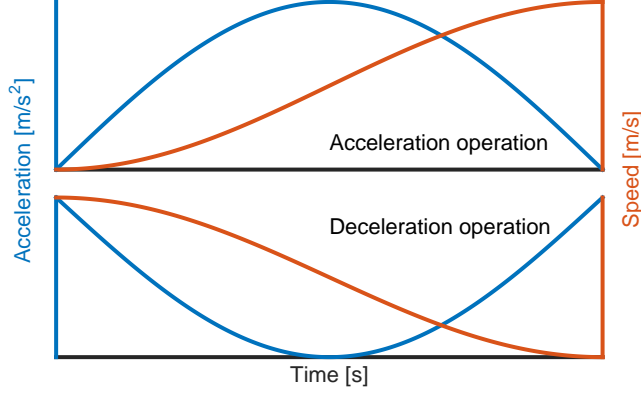


Figure 3: Acceleration profiles and speed curves in transient operations, both in acceleration and deceleration operations

time ($0 \leq t \leq t_a$), and v_0 is the original speed before the transient operation. According to Equation 25, the maximum acceleration occurs at $t = t_a/2$ and

$$a_{max} = a \left(\frac{t_a}{2} \right) = \frac{\pi}{2} \frac{\Delta v}{t_a} \quad (27)$$

Then in transient operations with sinusoidal acceleration profiles, the required minimum acceleration times are:

$$\begin{aligned} t_{ac,min} &= \frac{\pi}{2} \frac{\Delta V}{a_{max,ac}} \\ t_{de,min} &= \frac{\pi}{2} \frac{\Delta V}{a_{max,de}} \end{aligned} \quad (28)$$

where the subscripts *ac* and *de* represent the operations of the acceleration and deceleration, respectively.

3.2. Calculation

In the Estimation step, an estimator is built to approximate the permitted acceleration and the demanded adjustment time in consideration of the potential risks. To detect whether the risks occur in transient operations, simulations are carried out in the Calculation step to analyze the conveyor's dynamic behaviors. The simulation takes the effect of belt dynamics and hysteresis into account on the basis of an existing finite element model, which is presented by Lodewijks [21] in detail .

Figure 4 illustrates a typical long belt conveyor. The mark 'a' presents the conveyor belt which is supported by numbers of rotating idler rollers (b). To overcome the frictional resistances, the conveyor is driven by a head pulley (c) and to produce a large pre-tension, a sliding pulley (d) is

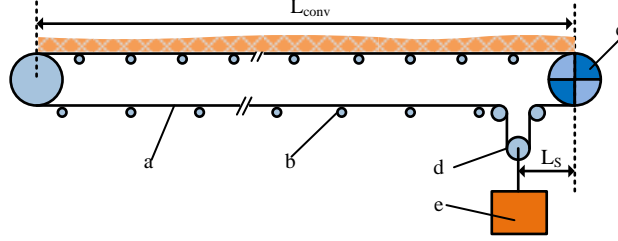


Figure 4: Typical belt conveyor geometry (Courtesy of [21])

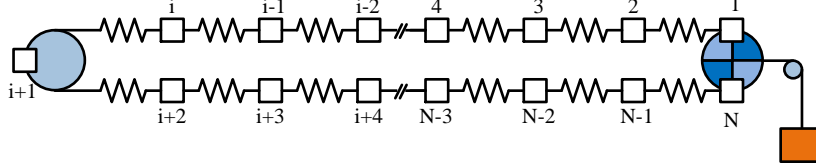


Figure 5: Lump-mass spring-dampened finite element method

used and tied to a gravity take-up device (e). Figure 5 illustrates the belt finite element model. The belt is divided into a number of finite elements: $N-1$ segments with N nodes. On the carrying side, the node is integrated with mass belt, idler and bulk material. On the return side, the lump-mass of node equals the sum of belt and idler masses. It is worth noting that the $(i + 1)^{th}$ node includes the mass of the tail pulley.

In Figure 4, the mark ' L_S ' presents the horizontal distance between the drive pulley and the take-up pulley, and the mark ' L_{conv} ' stands for the distance between the drive and tail pulley. In the case of the conveyor with a take-up pulley installed nearby the head pulley, the value of L_S is far less than L_{conv} . Hence in Figure 5, it is eligible to combine the drive pulley and the take-up pulley into one. If we further suppose that the belt is laid in x -direction and the belt only moves towards one direction, Figure 6 illustrates the simplified belt conveyor system. In this system, the conveyor driving system and the tension system are replaced by two forces, which are marked as ' F_d ' and ' $1/2Mg$ ', respectively.

3.3. Optimization

With respect to belt viscous-elastic properties, belt performance is complex and uncertain. Due to the fact that in the Estimation step, the belt is viewed as a rigid object which neglects the effect of

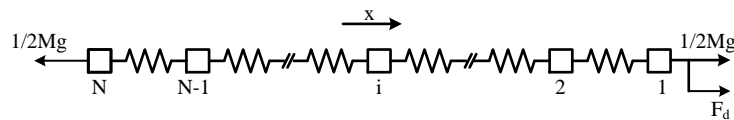


Figure 6: One dimensional model of belt conveyor system

Table 1: Failure risks and their solutions

Failure risks	Suggested solutions
Belt over-tension at the splicing area	Replace a new belt with higher tension rating Extend the speed adjustment time or apply a softer acceleration profile
Belt slippage around the drive pulley	Decrease the mass of take-up devices Increase the mass of take-up device Increase the wrap angle or replace a new pulley with a higher friction resistance coefficient Extend the speed adjustment time and reduce the driving force
Motor overheat	Extend the speed adjustment time and reduce the driving force Reduce the frequency of speed regulation process Replace a new motor with higher torque rating Install a cooling device
Material spillage from belt	Reduce the mechanical jerk by extending speed adjustment time or applying a softer deceleration profile
Pushing motor into the regenerative operation	Apply a softer acceleration profile or extend speed adjustment time

belt dynamics and hysteresis, the conveyors' dynamic performance in the Calculation step might be poor since the transient operation with the estimated acceleration time might result in, for instance, the risk of belt over-tension. As suggested by [13], further studies should be carried out to improve the conveyor's dynamic performance in transient operations. Some solutions are summarized in Table 1, including replacing a new belt with higher tension rating, optimizing the mass of the take-up device, applying a softer deceleration profile and increasing the speed adjustment time. With respect to the fact that changing the construction or components of an existing conveyor is not practical to some extent, the general method of improvement is to extend the speed adjustment time. Then the third step, Optimization, is carried out to find the minimum speed adjustment time. The optimization is also realized by using finite-element-model-based simulations.

4. Case study

4.1. Over-viewing

A long inclined belt conveyor in an import dry bulk terminal is what we are studying. The terminal is located at Rotterdam in the Netherlands and handles millions of tons of coal and iron ore yearly. A simplified terminal is as shown in Figure 7 [15] and 010-020-030 is one of the belt conveyor transport chains. The primary function of this terminal is as follows. The material in ships can be unloaded by four cranes in parallel and discharged onto the 010 belt. Then the material flow

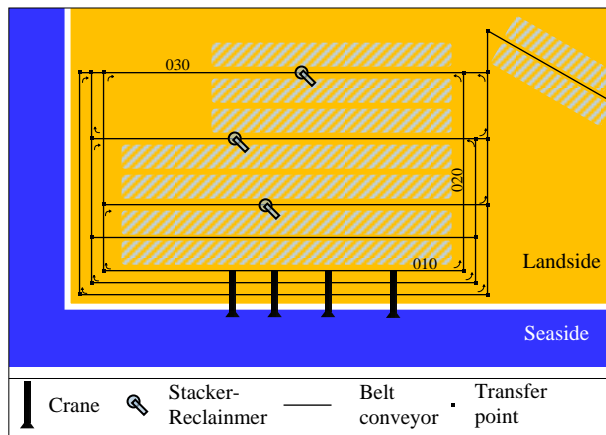


Figure 7: Import terminal layout (Courtesy of [15])

on the 010 belt is in turn deposited onto the 020 and 030 belt conveyors, successively. Finally, the material is discharged from the 030 belt and stored at a stockyard by stackers.

In the case of operations with a conventional strategy, the belt conveyors in the 010-020-030 network are running at designed nominal speed. In practice, with respect to the crane-scheduling problem, the number of available cranes is variable-in-time during ship unloading. As a consequence, the material flow on the 010-020-030 chain can be considerably lower than the design capacity. Based on the number of simultaneously operating cranes, the ship unloading capacity during this time interval however can be determined and the peak of material feeding rate onto belt conveyors can be approximated. Accordingly, the conveyors' speed can be reduced to match the number of cranes and then the utilization of belt conveyors is improved. In such a way, the energy saving of belt conveyors are enabled as a result.

As an example, the 020 belt conveyor is studied, which has the largest useful conveying length in the 010-020-030 chain. The 020 conveyor has a conveying length of $660m$ and a lifting height of $16.1m$, with a conveying capacity $6000t/h$ at the nominal speed $4.5m/s$. It is driven by three $355kW$ frequency controlled drive units. The detail of the 020 conveyor's parameters is shown in Table 2.

4.2. Determining the minimum speed adjustment time

Acceleration operation

According to the requirement of the terminal, the minimum speed of the 020 conveyor is set to $2m/s$. Then considering the number of available cranes, the conveyor speed can vary from $2m/s$ to $4.5m/s$. Taking the largest speed adjustment range into account. Firstly, an estimator is built and according to the data in Table 2, the maximum driving forces are $464.7kN$, $338.2kN$, $235.9kN$ with respect to the risks of belt over-tension, belt slippage, and motor over-heating, respectively.

Table 2: 020 belt conveyor parameters

Parameters	Symbol	Value	Unit	Parameters	Symbol	Value	Unit
Max conveying capacity	Q_m	6,000	t/h	Special resistances	F_s	0	N
Material cross section	A	0.1607	m^2	Head pulley friction coefficient	μ	0.3	-
Nominal belt speed	v	4.5	m/s	Angle of wrap	α	340	$^\circ$
Belt width	B	1,800	mm	Tension weight	m_T	14,000	kg
Trough angle	λ	40	$^\circ$	Chose belt	-	ST1600	-
Maximum belt load	m'_{bulk}	370	kg/m	Chose belt strength	k_N	1600	N/mm
Conveying length	L	660	m	Belt weight	m'_{belt}	48.6	kg/m
Conveying height	H	16.1	m	Belt Modulus	k	115000	N/mm
Idler spacing	l_o	1.25	m	Belt damping factor	E	0.35	-
Return idler spacing	l_u	5	m	Radius of drive pulley	R_d	0.5	m
Idler weight	$m'_{ider,c}$	44.64	kg/m	Motor nominal torque	$\tau_{motor,nom}$	2279*3	Nm
	$m'_{ider,r}$	11.16	kg/m	Number of driving units	-	3	-
	m'_{ider}	55.8	kg/m	Motor service factor	i_{sf}	1.15	-
Friction coefficient	f	0.025	-	Gearbox reduction factor	i_{rf}	18	-

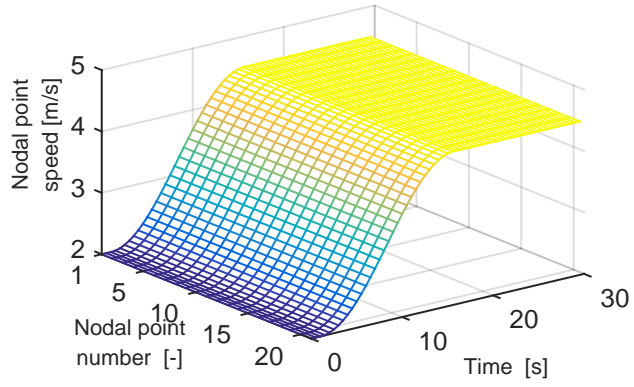
Table 3: Further simulation results with variable acceleration times

Acceleration time (s)	14.75	14.80
Required maximum driving force (kN)	236.03	235.72

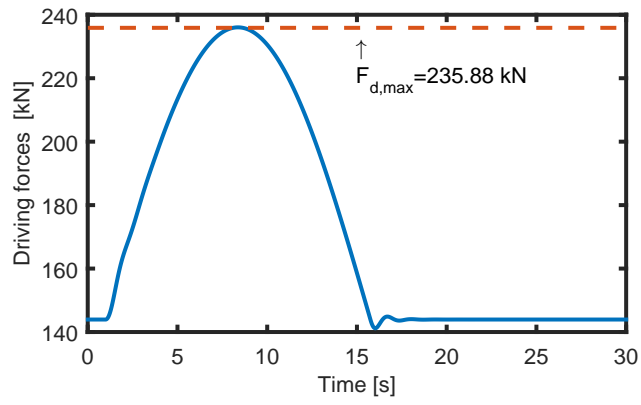
Accordingly, the conveyor requires at least 14.75s to increase speed from 2m/s to 4.5m/s with more consideration of the risk of motor over-heating. Secondly, a simulation is carried out to calculate the conveyor's dynamics whose results are shown in Figure 8. However, Figure 8(b) shows in the time period between 8.1s and 8.7s, the driving force exceeds 235.88kN. That means this acceleration operation increases the risk of motor over-heating. Thirdly, as discussed before, any and all risks must be prevented in transient operation so that the optimization is required to be carried out with further simulations. Taking the motor overheat risk into account, data in Table 3 shows that for this acceleration activity, the optimized acceleration time is around 14.80s with maximum driving force 235.72kN.

Deceleration operation

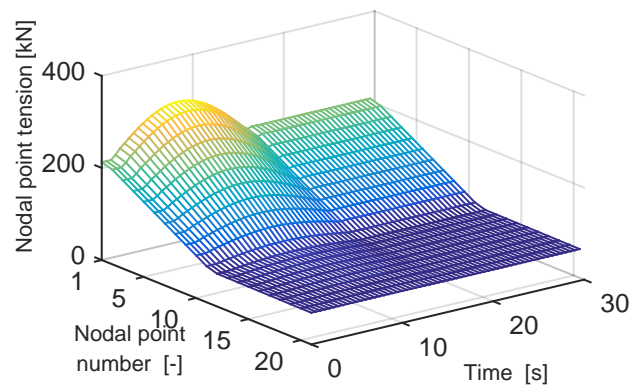
The data in table 2 suggests that the 020 belt conveyor requires at least 9.41s to reduce conveyor speed from 4.5m/s to 2m/s in consideration of the risk of pushing motors into the regenerating operation. The calculation results are shown in Figure 9. However, Figure 9(b) shows that in the period between 5.3s and 6.0s the value of driving force is negative. That means during that interval the motors have to work into the regenerating mode. Due to the fact that these applied motor drives cannot be pushed into the regenerative operation, the optimization should be carried out. The further simulation result in Figure 10 shows with the adjustment time 9.5s, the deceleration operation results in a minimum driving force 0.531kN. That means in this case the optimized



(a)



(b)



(c)

Figure 8: Acceleration operation with $\Delta v = 2.5 \text{ m/s}$ and $t_a = 14.75 \text{ s}$

minimum deceleration time approaches 9.5s.

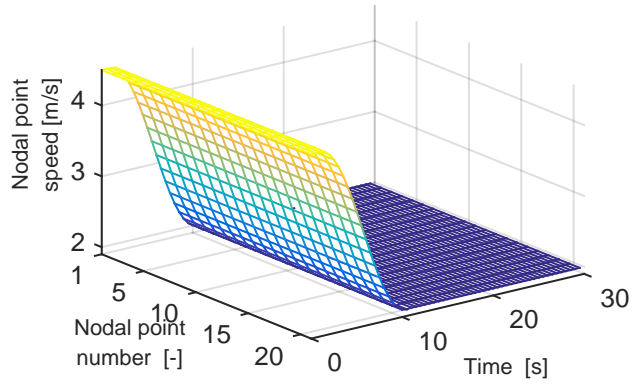
Consequently, the minimum speed adjustment time approaches to 14.80s and 9.50s, with respect to the acceleration and deceleration operations, respectively. However, in practical transient operations, the speed adjustment time is suggested to be longer than the calculated by ECO method. The major reason is that the time length of transient operations has an extremely limited impact on the total energy savings in the case of passive speed control where the adjacent speed adjustment's interval is tens of minutes or hours. Therefore, considering more on the belt conveyor's dynamics, the practical speed adjustment time would be longer than the optimized. Taking the adjustment time 30s for example, either in acceleration or deceleration operations. Figure 11 illustrates the driving forces in transient operations with $t_{ac} = t_{de} = 30s$. It shows in the acceleration operation, the peak of driving forces is only 30% more of the driving forces required in a steady operating condition. The figure further shows that either in the acceleration or deceleration operations, the dynamic driving forces virtually equal the forces computed by energy model of DIN22101 [8]. That means in the following research, the dynamic driving forces can be directly estimated by Equation 2.

4.3. Implementation of speed control

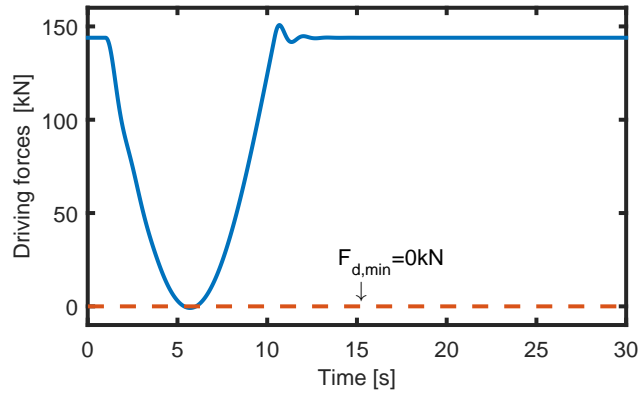
The terminal is yearly operating for 360 days at 24 hours per day and the studied belt conveyor is occupied for 40% of the total operation time of the terminal. According to the variable-in-time number of available cranes, the reference speed is classified into four levels: 2m/s, 2.3m/s, 3.4m/s and 4.5m/s. Then based on the number of available cranes in a time interval, the conveyor speed is discretely adjusted to match the peak of incoming material flow in that time interval.

The bulk material handling operation in one day is studied. The blue line in Figure 12(a) illustrates the material feeding rate onto the 020 belt conveyor in 24 hours. A model is built to simulate the speed control. Taking the transient operation into account, the red line in Figure 12 illustrates the corresponding belt speed in accordance with the peak of the material flow. Note that before the arriving of the larger level of material flow, the conveyor has already completed the acceleration operations. On the contrary, the arriving of the lower level of material flow triggers the event of deceleration operations. In addition, it is worth noting that this paper takes the variable-in-speed efficiency of the driving system into account. Based on the data supplied by ABB [1], the system efficiency can be expressed by

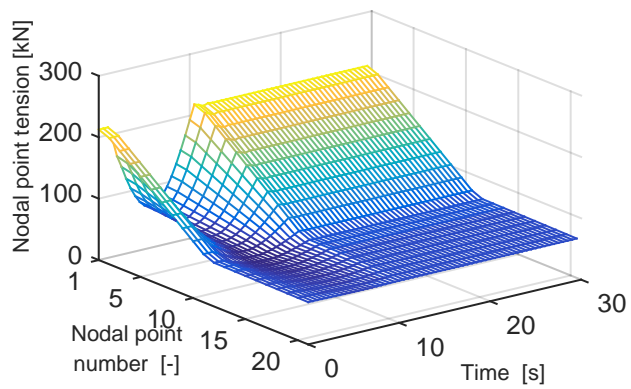
$$\eta_{system}(R_v, R_\tau) = 0.7878 + 0.1953R_v + 0.05067R_\tau - 0.1147R_v^2 + 0.048R_vR_\tau - 0.042267R_\tau^2$$



(a) Belt speed



(b) Driving force



(c) Belt tension

Figure 9: Deceleration operation with $\Delta v = -2.5\text{m/s}$ and $t_{de} = 9.41\text{s}$

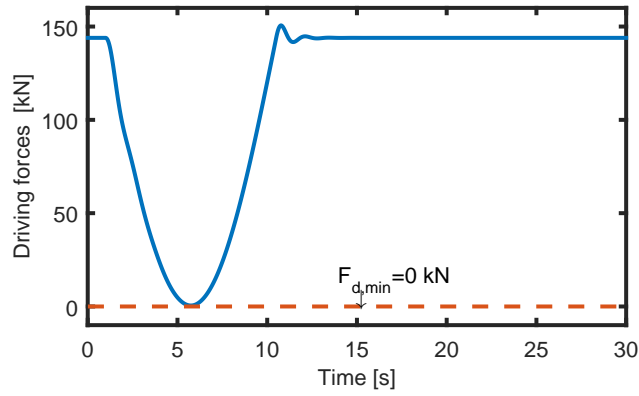
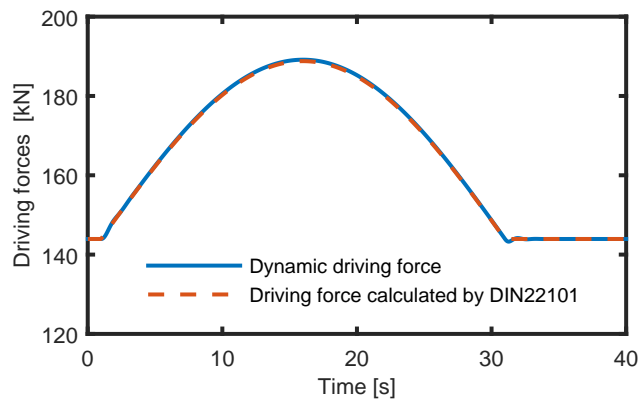
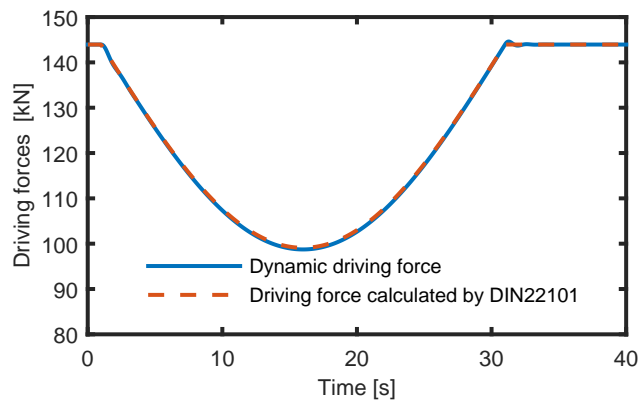


Figure 10: Driving force in deceleration operation with $\Delta v = -2.5\text{m/s}$ and $t_{de} = 9.50\text{s}$

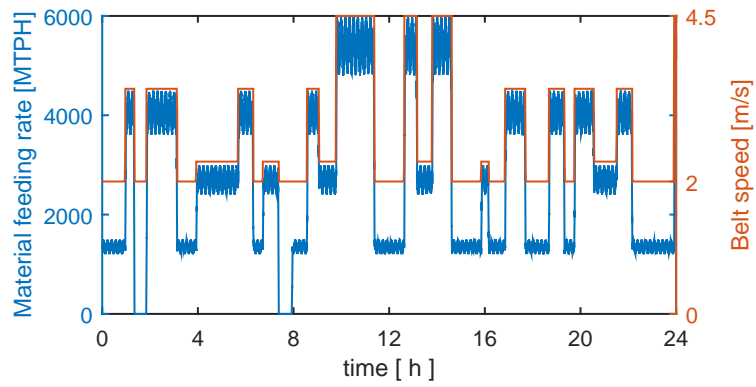


(a) Acceleration operation

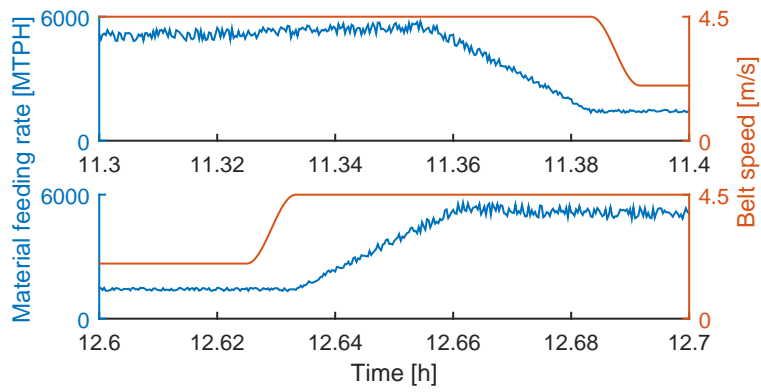


(b) Deceleration operation

Figure 11: Driving forces with $t_{ac} = t_{de} = 30\text{s}$



(a) Overall



(b) In a certain interval

Figure 12: Material feeding rate and the corresponding speed of 020 belt conveyor

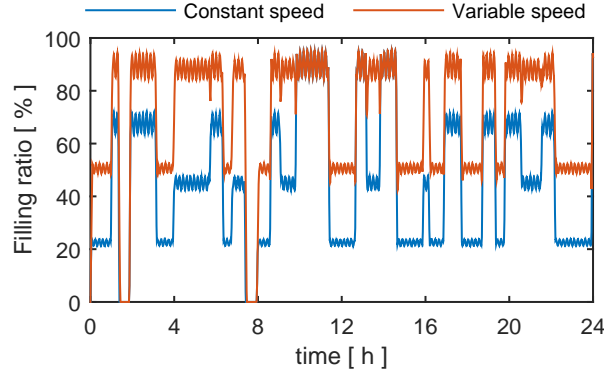


Figure 13: Filling ratio

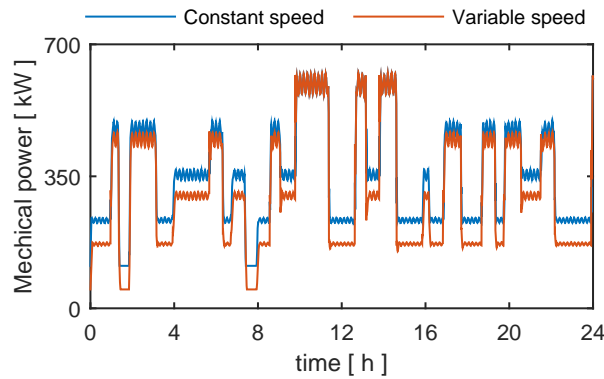


Figure 14: Instantaneous mechanical power on the drive pulleys

where R_τ is the proportion of motors' nominal torque.

The general results of simulations are given in Figure 13 to Figure 16. Overall, the operation at nominal speed consumes more energy than that at variable speed. Figure 13 presents and compares the filling ratio of the 020 conveyor over 24 hours. As the figure shows in the case of the constant speed operation, the profile of the filling ratio is similar with the shape of the material feeding rate shown in Figure 12. Furthermore, comparing the two curves in Figure 13 yields that due to the variable speed drives, the conveyor's filling ratio is improved to 69.4% from 44.8% on the average.

Figure 14 illustrates the required mechanical power on drive pulleys. The figure shows in the traditional mode with constant speed drives, the average mechanical power is 353kW with the maximum 623kW. However, due to the strategy of speed control, the mechanical power is considerably reduced to 308kW on the average, although the maximum is also 623kW. In terms of the electric power, Figure 15 illustrates the instantaneous consumption with the consideration of the variable values of efficiency of the whole system. As the figure shows, the average electric power consumption is up to 393kW in cases where the 020 conveyor runs at nominal speed. In the case of the 020 conveyor running at a lower speed, the average consumption can be reduced by 48kW, up to 12%

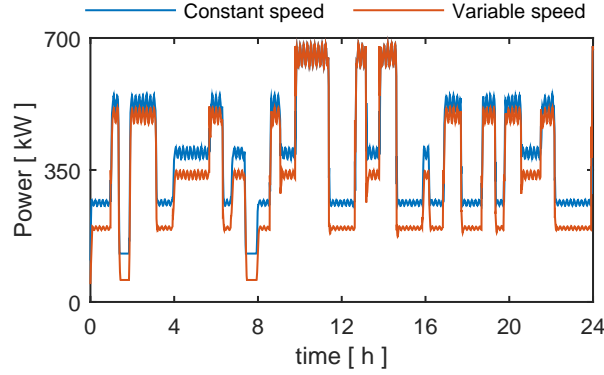


Figure 15: Instantaneous electric power consumption

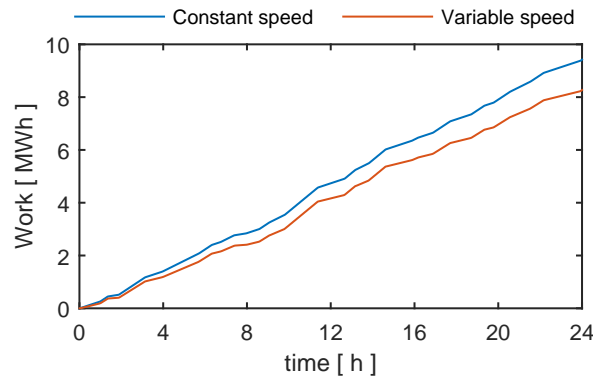


Figure 16: Accumulating power consumption in 24 hours

of that consumed by constant speed drives.

Figure 16 compares the accumulative electric energy consumption of the 020 conveyor in the 24 hours' operation. The figure shows in the constant-speed mode, the total energy consumption is up to $9.4MWh$. The comparison however illustrates that due to the reduction of the conveyor speed, the energy saving is enabled by the amount of $1.2MWh$.

Table 4 summarizes the results and illustrates the economic analysis of speed control. As prior mentioned, the belt conveyor is operated for 144 days yearly (40% of the total operational time of the terminal). From the data it can be learned that in the given example, the speed control on this studied belt conveyor yearly can result in over $160MWh$ electrical saving and around 90 tons of CO_2 reduction. According to the latest data from Eurostat [10], the Netherlands electricity price for industrial consumers during the second half of 2015 averaged $\text{€}0.0712$ per kWh. That implies for this given belt conveyor working in a given condition, speed control can yearly reduce the cost $\text{€}11,000$ in terms of electricity. Furthermore, if the social cost of CO_2 is taken into account, more than $\text{€}1,500$ cost can be reduced annually. In total, the cost savings of varying the belt speed with a varying material feed in this specific case is above $\text{€}13,000$.

Table 4: Economic analysis of speed control of 020 belt conveyor

	Constant speed	Variable speed
Average material feeding rate [MTPH]	2560	2560
Average belt filling ratio [%]	44.8	69.4
Average mechanical power consumption [kW]	352.5	308.1
Average electrical power consumption [kW]	392.5	344.6
Total electrical power consumption in 24 hours [MWh]	9.655	8.270
Predicted annual electrical consumption [MWh/yr]	1,356	1,191
Predicted annual electrical cost [i₄œ/yr]	96,500	84,800
Predicted annual electrical cost savings [i₄œ/yr]		11,700
Predicted annual CO ₂ emission [Tons/yr] ^a	714.6	627.7
Predicted annual CO ₂ emission reduction [Tons/yr]		86.9
Predicted annual reduction of the social cost of CO ₂ [i₄œ/yr] ^b		1,560
Total annual savings [i₄œ/yr]		13,260

^aThe CO₂ emission factor used is 0.527 kg/kWh [7].

^bThe global damages from CO₂ emission is around i₄œ18 per metric ton [11].

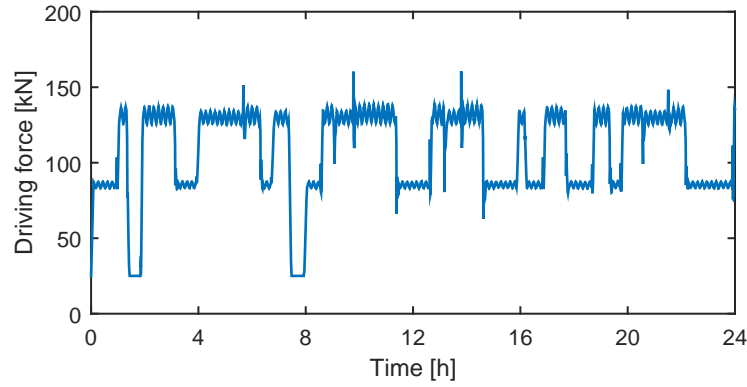


Figure 17: 020 belt conveyor driving forces

In addition, the dynamics of mechanical driving forces are illustrated in Figure 17. As described in Section 4.2, in transient operations of this belt conveyor, the risk of motor over-heating should be given more attention and the permitted driving force is around 230kN with respect to the risks in transient operations. This figure affirms that in the operation with variable speed drives, the belt conveyor works in a good condition and all mentioned potential risks are prevented since the driving force is always in a safe magnitude. Therefore, a soft and safe speed control with a good dynamic performance is realized by employing the ECO method.

5. Conclusion and suggestion

This paper studied the speed control of belt conveyors both in terms of the dynamic behaviors and the energy savings. A long inclined belt conveyor in an import terminal was studied. The computational experiments results showed that the improved ECO method was feasible to determine the minimum speed adjustment time, both in acceleration and deceleration operations. Furthermore,

the implementation of speed control resulted in a large amount of energy savings with a significant improvement of belt filling rate. The result data implied for a given belt conveyor working in a given condition, speed control annually reduced the cost $\text{€}11,000$ in terms of electricity and the emission 90tons in terms of CO_2 . Moreover, the dynamic analysis of driving forces showed that the belt conveyor remained good dynamic behaviors even though in transient operations and all potential risks were prevented. Differing from the previous research of speed control, the major contribution of this work is that the implementation of speed control took both the energy savings and the conveyor's dynamic behaviors in transient operations into account.

This implementation of speed control was supported by a model of simulation so that it is suggested to make a laboratory model which can be used to implement a speed controller before the controller is implemented in a field test. In addition, this paper only took the driving system's variable efficiency into account so that it is also recommended that the future research considers the variable frictional coefficient versus the variable speeds and variable masses loaded.

Acknowledgments

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