Application of Fuzzy Logic in Belt Conveyor Monitoring and Control

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Summary

This paper discusses the application of Fuzzy Logic in belt conveyor monitoring and control. Human inspectors can provide information required for belt conveyor monitoring and control. However, this information is only useful if it is accurate and consistent. To ensure consistency the information gathered by human inspectors needs to be objectified, which can be done by using Fuzzy Logic. Based on the concept of Fuzzy Logic a belt wear index and a belt inspection frequency index are introduced. Examples of the use of these indices and procedures to determine the underlying parameters are given.

1 INTRODUCTION

On BeltCon 12 in 2003 the concept of applying strategies for automated maintenance by using intelligent monitoring systems was firstly introduced [1]. The main reason to introduce this concept was to optimise the operational performance and reliability of large-scale bulk handling systems. The definition of reliability depends on the aggregation level considered: component, equipment and system. The reliability of a bulk handling system for example can be defined as the average percentage of time the system’s continuous performance is guaranteed. In the concept of using intelligent monitoring systems to optimise reliability all three levels are important and considered. This paper focuses on monitoring a conveyor belt and thus on the components level. The other two levels are considered in a separate paper [2].

The information used for intelligent belt conveyor monitoring in principle can come from three sources: visually obtained information from human inspectors, information from sensor systems, and information available from enterprise resource planning systems (ERP), also see Figure 1. An important challenge that is faced when using all three different sources of information is to convert them into one common format on which the outcome of the monitoring process can be based.

When using human inspectors specific problems may occur. Information gathered by human inspectors is only reliable when the inspection is performed by a well-trained and experienced inspector and when an inspector inspects a specific system for a considerable time. At least two problems occur if the before mentioned conditions are not met. Firstly, if an inspector is not well trained then the information he gathers is not accurate. Secondly, if different inspectors perform adjacent inspections then there is a serious risk that the results of the inspections are inconsistent. This is caused by the fact that different people can have a different opinion on the same maintenance status of a system. The before mentioned two problems explain why many companies have poor experiences with external companies performing maintenance and inspections.

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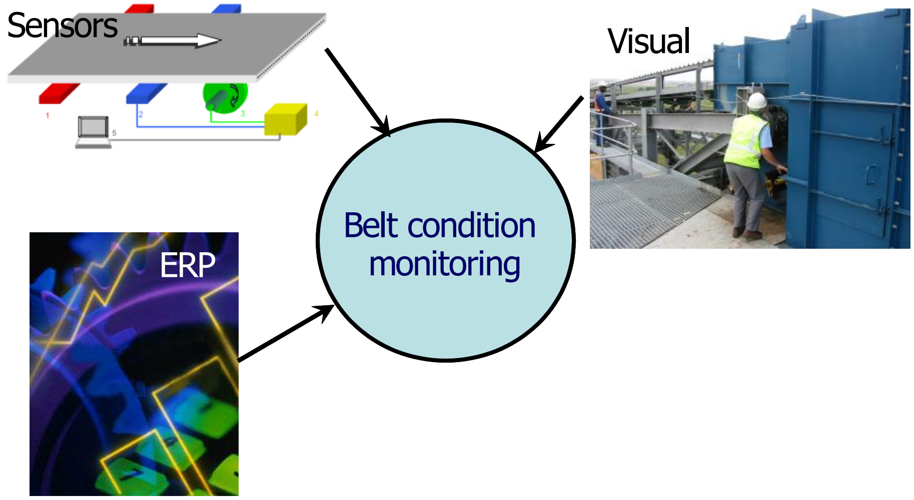

Figure 1: *Three sources of data and information [3].*

One way to address the problem of inconsistency is by objectification of the information obtained by human inspectors. These inspectors obviously need to have a minimum level of expertise to enable a meaningful inspection. Information can be objectified by using fuzzy logic. There are five main reasons to use fuzzy sets as a tool in belt conveyor monitoring:

1) objectification of inspection results; this means that the results of an inspection performed by a human inspector in terms of linguistic expressions can be translated in a number,
2) increasing the consistency of inspection results performed by different human inspectors,
3) it allows fuzzy interpretation of observations,
4) it allows combination of inspection results with information from other sources.
5) the approach using fuzzy sets gives a straight forward advice.

This paper is build up as follows. Section 2 introduces the concept of Fuzzy Logic. Section 3 shows the types of damage that need to be distinguished in order to enable a detailed inspection of a conveyor belt. The belt wear index is introduced in Section 4, which also shows an example of how it can be used. Section 5 further introduces the belt inspection frequency index, also including an example. In order to enable prediction of the growth of damages of a conveyor belt a software package has been developed that can be used to simulate the future degradation of belt conveyors. This prediction can be based on the results of inspections performed by either a human inspector or automated sensor based systems. This package will be introduced in Section 6. Section 7 finally lists the conclusions and recommendations.

2 FUZZY-LOGIC

Fuzzy logic or the theory of fuzzy sets is basically a theory of graded concepts, a theory in which everything is a matter of degree. Fuzzy sets were introduced by Zadeh as a methodology of representing and manipulating data that was not precise, but rather fuzzy [4]. The first reference to the application of fuzzy logic in the field of belt conveying can be found in [5]. The application of this method is further discussed in [6]. Although the use of fuzzy logic is introduced in these references, they do not provide any practical guide lines.

The basics of Fuzzy Logic are as follows. Let X be a non-empty set. A fuzzy set A in X is characterized by its membership function:

$$A : X \to [0,1] \qquad (1)$$

and A(x) is introduced as the degree of membership of element x in fuzzy set A for each $x \in X$. The value zero is used to represent complete non-membership, the value one is used to represent complete membership, and values in between are used to represent intermediate degrees of membership. A mapping of the fuzzy set is also called the membership function of a fuzzy set. Membership functions can have different shapes, see Figure 2. The exact shape of a membership function, or the change in degree of membership with change in specific variable, depends on the variable under consideration. An example will be shown later.

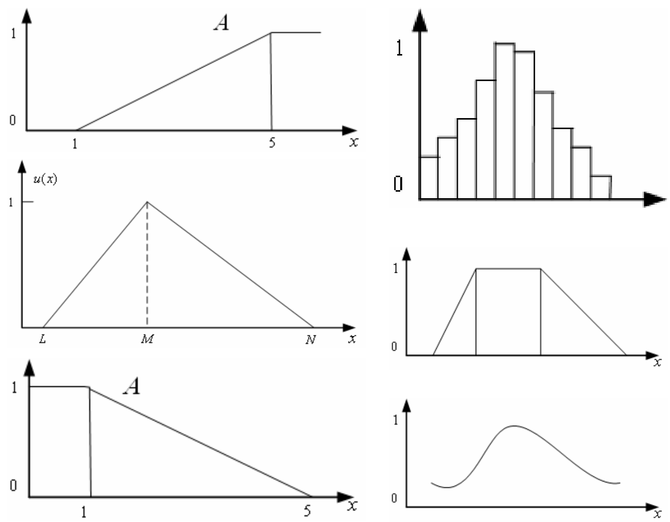

Figure 2: *Membership functions.*

3 BELT DAMAGE CHARACTERISATION

Before the damage registration by using Fuzzy Logic and the prediction of the development of damage can be discussed the belt damages have to be identified. In practice a large number of damages can be identified. We mention 15 damage types:

1. breadth tear
2. puncture
3. tongue-tear
4. longitudinal tear
5. cut
6. edge damages
7. torn out cable
8. varicose vein
9. blister
10. torn out cover
11. extreme abrasive wear
12. bare cables
13. fire damage

14. shingling
15. delamination of joint

The first four damages (breadth tear, puncture, tongue-tear and longitudinal tear) make up for about 85% of all the reported damages. The figures 3 till 6 show typical damages as can be experienced in the field.

Figure 3: *Breadth tear (and extreme abrasive wear).*

Figure 4: *Puncture.*

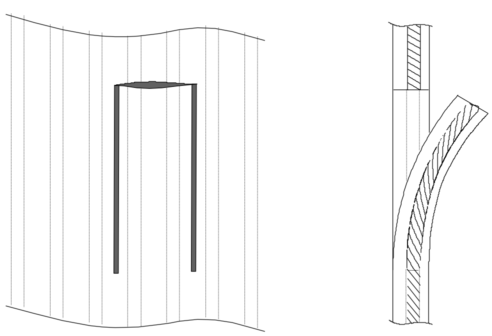

Figure 5: *Tongue-tear.*

Figure 6: *Belt with a longitudinal tear.*

4 BELT WEAR INDEX

The reliability of a belt conveyor system can be quantified by using a reliability number, which is an aggregated measure of damage. This number is based on the assessment of the impact of wear and damage on the belt conveyor's performance. The reliability number can be used to determine what actions need to be taken: do nothing, repair the system or replace components. An example of a reliability number is the wear index.

Fuzzy sets can be used well for defining a belt wear index. The main purpose of a belt index is to determine whether or not certain damage needs to be repaired, and in addition whether or not the current inspection intervals are appropriate or not. Assume the four following fuzzy sets [7]:

- location factor (concentration factor) LF,
- intensity factor (type of damage) IF,
- extension factor (size of damage) EF, and
- accumulation factor (growth of damage) AF.

The membership functions of the location factor LF, the intensity factor IF and the extension factor EF are given in the Figures 7, 8 and 9. The membership functions express the degree of contribution (or membership) to the change that damage needs to be repaired.

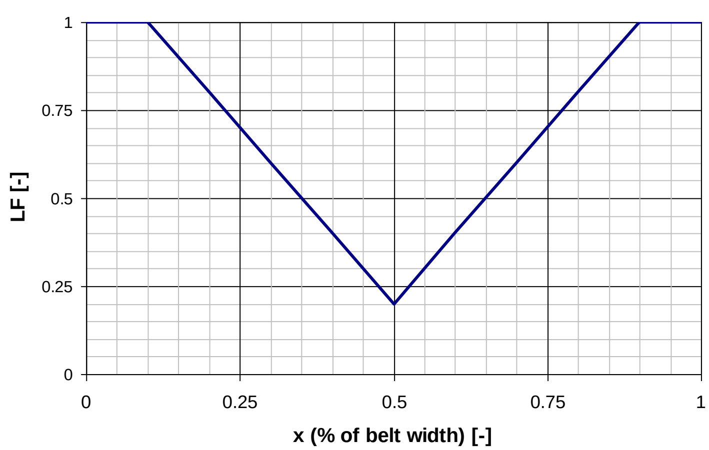

Figure 7: *Membership function of the location factor.*

Figure 7 shows that the location factor is 1 at the edges of the belt and minimal in the belt's centre. The reason for this is that it is more likely for edge damage to lead to transverse belt rupture than for damage in the centre of the belt

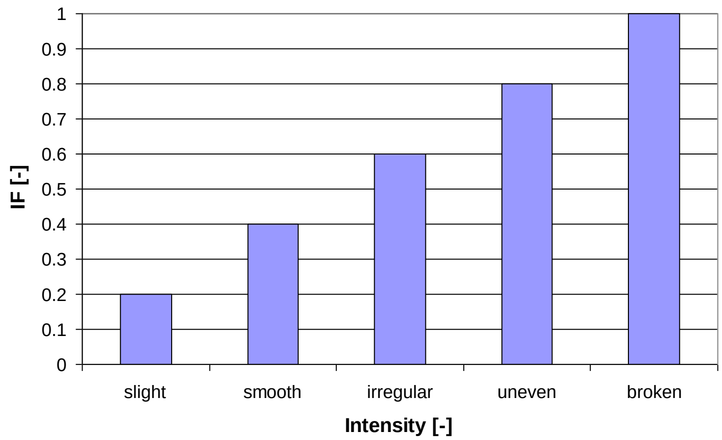

Figure 8: *Membership function of the intensity factor.*

Figure 8 shows the variation in membership of the intensity factor. In essence the more irregular the damage the higher the degree of membership.

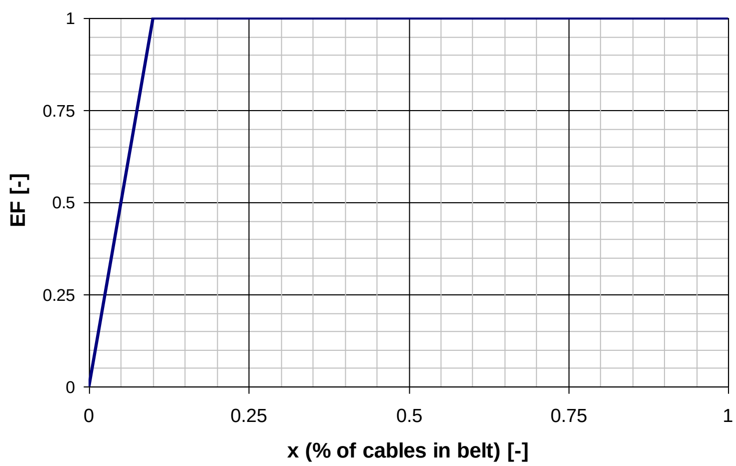

Figure 9: *Membership function of the extension factor.*

Figure 9 shows the membership function of the extension factor for a steel cord belt. Assume that damage should be repaired, or a piece of belting should be replaced, when more than 10% of the cables is broken. In that case the extension factor is 1 when more than 10% of the cables in the belt is broken.

If the location factor LF, the intensity factor IF and the extension factor EF are all damage factors then the belt wear index can be defined as follows:

$$I_r = \frac{\sum_i w_i DF_i}{\sum_i w_i} \tag{2}$$

where w_i is the weight of the i^{th} damage factor and DF_i the i^{th} damage factor.

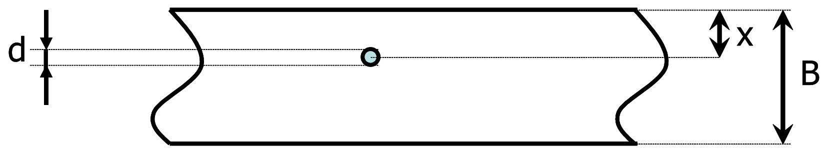

Figure 10: *Belt conveyor with damage.*

First inspection

Figure 10 shows a belt section with damage that has been inspected. Assume that the results of a first inspection are as follows: d=50 mm, B=1000 mm, x=250 mm, and that the damage has a smooth edge. From the values of d and B it can be learned that the damage involves 5% of the belt width. Assume that the weight factors w_i are as follows w_{LF}=2, w_{EF}=3, and w_{IF}=1. With these weight factors and the Figures 7 till 9 the belt index can be calculated as follows:

$$I_r = \frac{\sum_i w_i DF_i}{\sum_i w_i} = \frac{w_{LF}LF + w_{EF}EF + w_{IF}IF}{w_{LF} + w_{EF} + w_{IF}} = \frac{2*0.7+3*0.5+1*0.4}{2+3+1} = 0.55$$

The question now is what this value of the belt wear index means in terms of repairing the belt. For that purpose the belt wear index needs to be defuzzifed.

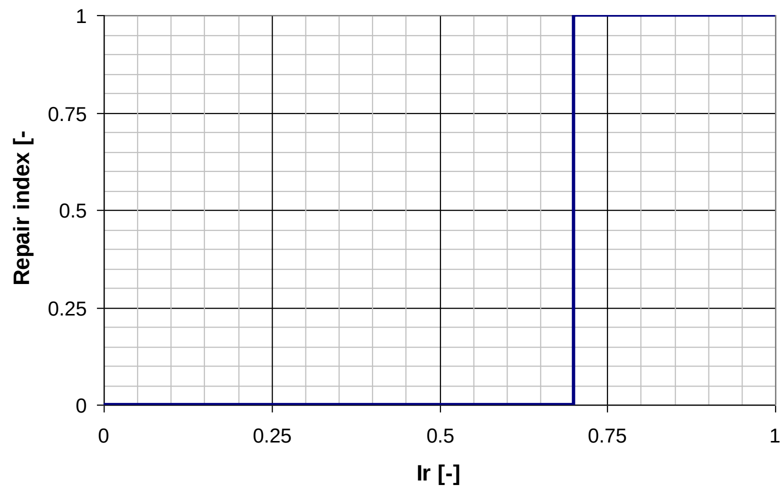

Figure 11: *Membership function of the repair index.*

Figure 11 shows the membership function of the repair index. If the repair index is 1 then the conclusion is that the damage needs to be repaired, if it is zero then the conclusion is that reparation is not necessary. From Figure 11 it can be learned that, with a belt wear index I_r of 0.55, reparation is not recommended.

Second inspection

Assume that some time later the same belt section as shown in Figure 10 is inspected again. Assume that the results of a second inspection of the same damaged area are as follows: d=80 mm, B=1000 mm, x=200 mm, and that the damage still has a smooth edge. With the weight factors and the Figures 7 till 9 the second belt index can be calculated as follows:

$$I_r = \frac{\sum_i w_i DF_i}{\sum_i w_i} = \frac{w_{LF}LF + w_{EF}EF + w_{IF}IF}{w_{LF} + w_{EF} + w_{IF}} = \frac{2*0.8 + 3*0.8 + 1*0.4}{2+3+1} = 0.73$$

From Figure 11 it can be learned that with a belt wear index of 0.73 the recommendation is to repair the belt.

Although the belt wear index gives a straight forward advice on the proper course of action, three important questions remain:

1) how to determine the membership functions LF, EF, and IF?
2) how to determine the weight factors w_{LF}, w_{EF}, and w_{IF}?
3) how to determine the membership function of the repair index I_r?

The answer to these questions is that one needs a multi-criteria approach and detailed domain knowledge. For example, the membership function of the location factor is based on the fact that damage on the belt's edge leads quicker and more often to belt failure than damage in the belt's centre. The membership function of the extension factor is based on the fact that with an increase in broken cables the safety factor of the belt decreases. The weight factors are determined by an assessment of the relative risks that a certain type of damage leads to belt failure. Finally, the membership function of the repair index is chosen such that the recommendation to repair is given if one of the individual causes requires so. As an example, if it is decided that the belt should be repaired if more than 10% of the cables are broken, as reflected by the membership function of the extension factor, then the repair index should give the recommendation to repair independent of the value of the other damage factors.

At the moment a handhold PDA based inspection tool is being developed based on fuzzy sets as illustrated above. Issues that are considered are:

- how do multiple damages affect each other and thus the belt wear index,
- if the recommendation is to replace a belt section, how to determine the length of belting that needs to be replaced taking into account the location of splices

Figure 12 shows a typical screen image of the inspection tool.

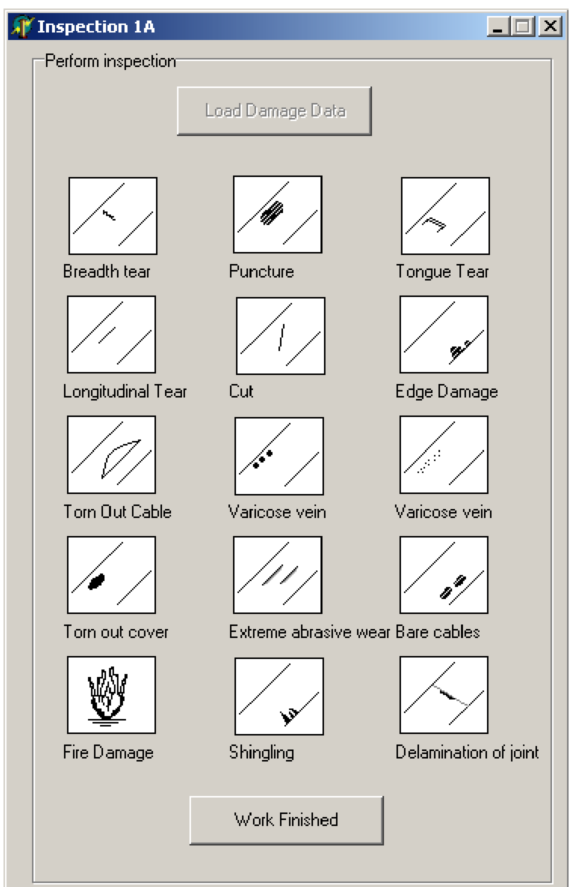

Figure 12: *Screen image of belt inspection tool.*

5 BELT INSPECTION FREQUENCY INDEX

The belt wear index of adjacent inspections can also be used to determine whether or not the current inspection intervals are appropriate. For that purpose accumulation factors can be used:

$$AF_{LF} = \frac{LF_{t+\Delta t} - LF_t}{\Delta t}$$
$$AF_{EF} = \frac{EF_{t+\Delta t} - EF_t}{\Delta t} \qquad (3)$$
$$AF_{IF} = \frac{IF_{t+\Delta t} - IF_t}{\Delta t}$$

With these accumulation factors a belt inspection frequency index I_f can be defined:

$$I_f = \frac{\sum_i w'_i AF_i}{\sum_i w'_i} \qquad (4)$$

Assume that the weight factors w'_i are as follows $w'_{LF}=4$, $w'_{EF}=8$, and $w'_{IF}=1$. With the results of inspection 1 and 2 as given in Section 4 and the assumption that these inspections were performed with a half year interval ($\Delta t=0.5$) the accumulation factors can be calculated as follows:

$$AF_{LF} = \frac{0.8-0.7}{0.5} = 0.2$$
$$AF_{EF} = \frac{0.8-0.5}{0.5} = 0.6$$
$$AF_{IF} = \frac{0.4-0.4}{0.5} = 0$$

The belt inspection frequency index then can be calculated with the weight factors w'_i:

$$I_f = \frac{\sum_i w'_i AF_i}{\sum_i w'_i} = \frac{w'_{LF} AF_{LF} + w'_{EF} AF_{EF} + w'_{IF} AF_{IF}}{w'_{LF} + w'_{EF} + w'_{IF}} = \frac{4*0.2+8*0.6+1*0}{4+8+1} = 0.43$$

To determine whether or not the inspection interval needs to be adjusted, defuzzification of the belt inspection frequency index is required.

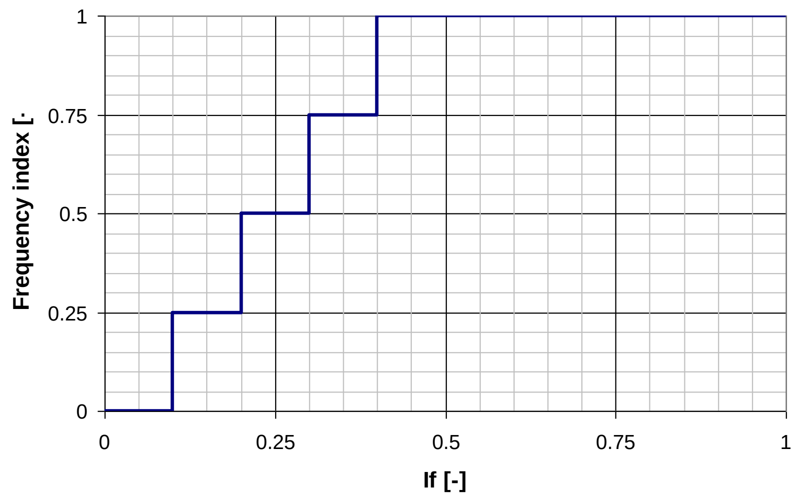

Figure 13: *Membership function of the frequency index.*

Figure 13 shows the membership function of the frequency index as a function of the belt inspection frequency index. If the different values of the frequency index mean the following:

- frequency index = 0; no change required
- frequency index = 0.25; reduce the inspection interval by 12.5%
- frequency index = 0.5; reduce the inspection interval by 25%
- frequency index = 0.75; reduce the inspection interval by 37.5%
- frequency index = 1; reduce the inspection interval by 50%

then it can be seen from Figure 13 that in case of a belt inspection frequency index of 0.43 the inspection interval should be reduced by 50%. The question is how the proper course of action, as given by the relation between the frequency index and a reduction in inspection interval, can be determined. For this purpose a logistic simulation model can be used, which will be discussed in the next section.

6 LOGISTIC CONTROL OF BELT MONITORING & INSPECTION

In 2003 the section Transport Engineering and Logistics started a research project with RWE power to investigate how maintenance strategies affect the operational costs of a large scale belt conveyor system [8] & [9]. One of the results of this project was a logistic model that can be used for the prediction of damage generation and the growth of existing damage on belt conveyors, also see Figure 14 & 15. The program is fully discussed in [10]

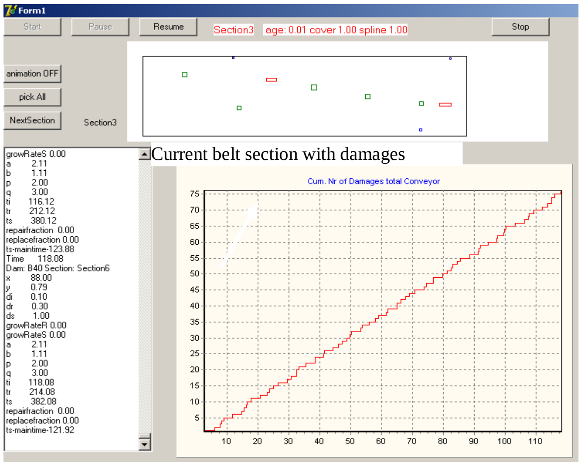

Figure 14: *Screen image of model during run.*

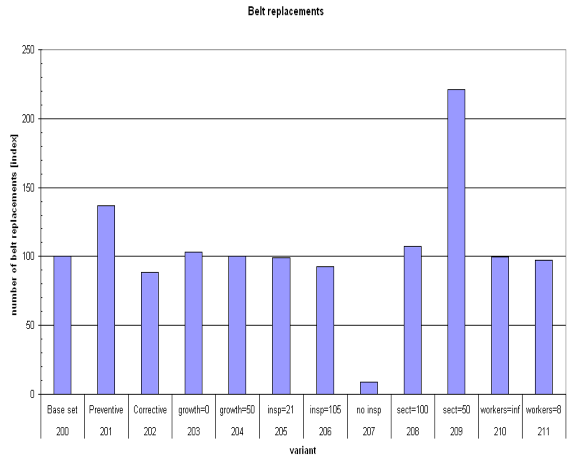

Figure 15: *Preliminary results of the prototype model [11]: Number of belt replacements for different strategies.*

The extent of damage of a belt conveyor affects the reliability of the system. Maintenance however partly determines the operational costs. The model can be been used to determine the relation between maintenance strategies and repair and replacement costs. The same model can be used to determine the proper threshold values for the belt wear index and the belt inspection frequency index as discussed in the previous section. For more information it is referred to [10].

7 CONCLUSIONS

This paper introduced a belt wear index and a belt inspection frequency index as a tool to objectify information provided by human inspectors. Both indices are based on the concept of Fuzzy Logic. Based on the examples of the use of these indices and the procedures to determine the underlying parameters, the following conclusions can be drawn:

1) The belt wear index and the belt inspection frequency index can be used to objectify inspection results by translating the results of an inspection in terms of linguistic expressions in numbers.
2) Both indices increase the consistency of inspection results performed by different human inspectors by allowing a fuzzy interpretation of the observations of inspectors.
3) Since the belt wear index is a performance number it allows combination of visually obtained inspection results with information from another source also expressed in a performance number.
4) The approach introduced in this paper results in straight forward advices by defuzzification of the belt wear index and the belt inspection frequency index.
5) The practical value of the wear index depends on correctness of the advice that results from its use. In depth domain knowledge and knowledge of multi-criteria analysis methods is required to determine proper membership functions and weight factors.
6) The effect of the use of the belt wear index and belt inspection frequency index on the overall belt conveyors reliability should be analyzed by using a proper logistic simulation model.

8 REFERENCES

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