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TOTAL PRODUCTIVE MAINTENANCE: A CASE STUDY IN THE TISSUE PAPER SECTOR

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Abstract. *Implementation of a Total Productive Maintenance approach in a tissue papermaking plant operating in Italy in the tissue & towel sector is presented in this paper. The described reengineering of maintenance activities was focused on the continuous paper machine and included a thorough preliminary extraordinary maintenance program, the implementation of a daily schedule of condition monitoring activities, the development of a specific software tool for data analysis, and the introduction of revised maintenance activities based on newly developed critical check points. In particular, the problem of felt management has been addressed which has a significant economic impact on operational costs. Adopting the described paper machine maintenance management plan it has been possible to nearly double the average felt life, passing from 30 to 60 days. In this way significant economic savings are expected, up to 100.000 Euro /year, and a reduction of machine downtime results leading to an increased plant productivity.*

Keywords: *Total Productive Maintenance, Continuous Machine, Tissue Paper, Papermaking, Economics.*

1. INTRODUCTION

Competitiveness and globalization ask for efficiency increase and cost reduction through improvement of main firms performances. Especially in complex production systems, maintenance management represents one of key function for which taking a closer look at methology and procedures seem to be necessary (Raouf et al., 1998; Lee, 1995). In this scenario Total Productive Maintenance (TPM) appears as a promising and effective system framework for plant and equipment control and management (Tokutaro, 1994). TPM combines preventive maintenance with Japanese concepts of total quality control (TQC) and total employee involvement (TEI). The result is a new system for equipment maintenance that optimizes effectiveness, eliminates breakdowns, and promotes autonomous operator maintenance through day-to-day activities. Papermaking sector presents critical issues as far as maintenance is concerned, owing to the continuous nature of the process, the dedicated and customized large-sized machines utilized and the relevant costs involved in either scraps, unplanned stops and spare parts. The problem of plant maintenance in the papermaking sector is therefore frequently discussed in the literature. Apart from specific case studies reports (De Macedo, 1998; Kodmon et al., 2000), several authors studied this problem from either an organizational point of view (Bartell, 2000; Childs et al., 2000; Cooper, 1998; Trodd, 1998; Wheaton, 1996) or a technical one (Eliot, 1999; Hilden, 1996, Sweet, 1999). In the paper, introduction and implementation of a TPM approach is presented with reference to a papermaking plant operating in the tissue & towel sector representing a significant test bed when the severe running conditions are considered. At first the manufacturing system is described in the work, highlighting main process phases as well as the maintenance requirements. A critical equipment of the system is the continuous machine where the single tissue paper is produced. In this machine the "felt", i.e. the fibrous belt which supports the wet paper sheet and tranports it to the drying drum, also performing a partial water draining, represents the component which strictly affects efficiency, quality and cost of the process.

Currently the felt has in average a life of about 30 days after which it is changed as a precautionary preventive maintenance measure, even if is in good conditions, to avoid the risk of its failure during machine operation. However, felt management significantly contributes to the plant operating expenses. In the study the optimal economic life of the felt has been preliminarily evaluated determining a value around 60 days. In this way significant economic savings are expected, and a reduction of machine stoppages may be obtained leading to an additional paper production. Increase of felt life was considered to be feasible because an analysis of hystorical data showed that nearly 50% of felt replacements had taken place according to a fixed schedule without any felt damage or production quality degradation having occurred.

An integrated maintenance management program was thus developed in the optic of a TPM approach to prevent the likelihood of felt failure during the extended life span, including:

- a preliminary extraordinary maintenance program;
- setting up of a daily schedule of condition monitoring activities and developing a software tool for data analysis;
- revised maintenance activities based on newly developed critical check points.

The maintenance program was then satisfactorily tested over a several months period obtaining the desired increase of average felt life. In the paper a detailed description of the methodological approach which led to the development of such an effective TPM program is described. The proposed approach has been succesfully implemented in an Italian plant

2. TISSUE PAPERMAKING PROCESS

A papermaking plant operating in the tissue & towel sector is usually composed of three main sections (figure 1): the pulping mill, where a pulp slurry suspension is prepared by processing cellulose; the continuous machine, which performs sheet formation, drying and winding in large rolls; and the final rolling section, where multiple paper sheets are joined to obtain a reel of multilayer sheet. End-products such as paper towels and napkins are then obtained starting from the multilayer paper reels in a separate packaging facility. In the forming section of a continuous paper machine the pulp slurry is is uniformly distributed across the "wire" of the machine, a fabric belt running around a forming cylinder. The newly formed sheet, still very soft and wet, is then discharged from the wire, resorting to a pick-up shoe and a vacuum system, to a felt-like belt (the "clothing") which moves the sheet to the drying drum passing through the press section, where the sheet is smoothed and moisture is reduced to about 45%. Lubrication along the felt passage and felt cleaning is provided by several pressurized water jets. After leaving the felt, the paper sheet passes on steam-heated drying cylinders of the dryer section used to evaporate the rest of the moisture in the sheet. Large hoods, where hot air is blown to improve the drying process, usually enclose the drying cylinders. A proper coating is applied to the sheet in the drying area in order to help its detachment from the cylinder and provide peculiar properties or finishing to the produced paper. Several blades detach the sheet from the cylinder before it is finally wound in large reels, ready for shipment. A schematic drawing of the paper machine considered in the present study is depicted in figure 2.

3. ANALYSIS OF FELT LIFE

The felt is a 37 m long and 3 m wide multilayer fibrous belt used as a support to the paper paste during the tissue formation phase. Felt permeability also enables to drain water from the tissue reducing the humidity content of the paper paste from 90% to 45% when it passes from the forming to the drying section of the machine. Control and maintenance management of the felt is of great importance for the correct operation of this continuous running machine.

In particular, felt failure causes machine stoppage while its damage causes defects of the end product which has to be scrapped. Apart from breakages the felt has to be periodically substituted because its permeability properties gradually decrease leading to a progressive increase of consumption of natural gas utilized for paper drying.

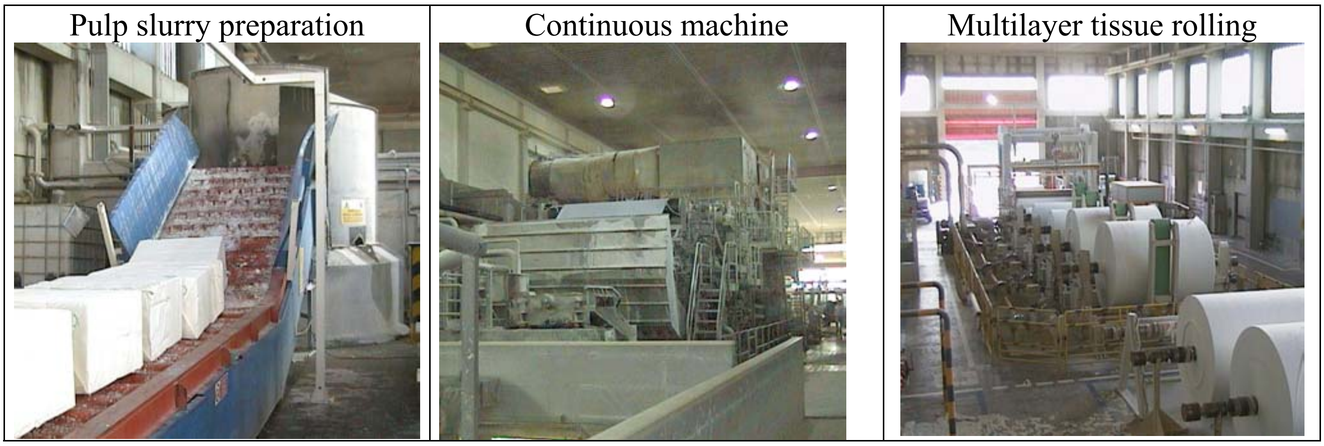

Figure 1. Papermaking plant process areas

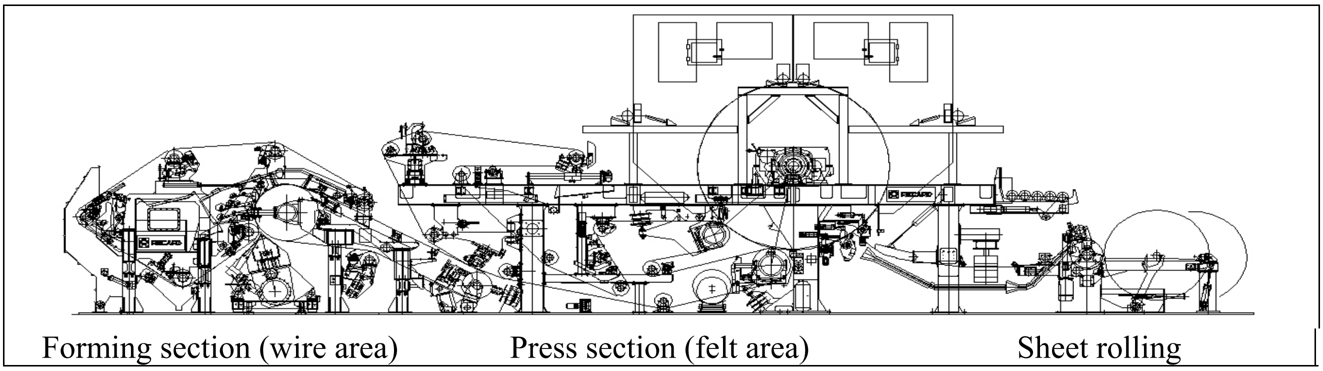

Figure 2. Scheme of the continuous machine

In the framework of the maintenance improvement program undertaken an analysis of previous felt failures and the reasons for past felt changeover was carried out at first. The analysis of historical data over a two years time span gave the results of Tab. 1 and figure 3.

Table 1. Causes of felt changeovers

Changeover cause	N. of cases	Frequency (%)
Programmed	11	50
Wrinkles	5	22.8
Wrinkles/Programmed	2	9.1
Not known	2	9.1
Failure of felt guide	1	4.5
Paper breakage due to poor felt quality	1	4.5
Total	22	100

The main cause for felt replacement simply resulted, as expected, the reach of the planned changeover interval, usually in correspondence to some other required maintenance stops. This premature replacement is justified by the avoidance of a further machine stop and to reduce the possibility of felt rupture. However, this does not necessarily implies that the felt was excessively weared when replacement took place. This conservative approach is imputable to a poor understanding of felt conditions and the absence of a condition monitoring activity. The second cause resulted the necessity of immediate replacement due to a damage of the felt surface (i.e. wrinkles, holes etc.). Such two causes in overall account for about 80% of felt substitutions. Before the start of the TPM programe the average felt life on this machine was of about 34 days.

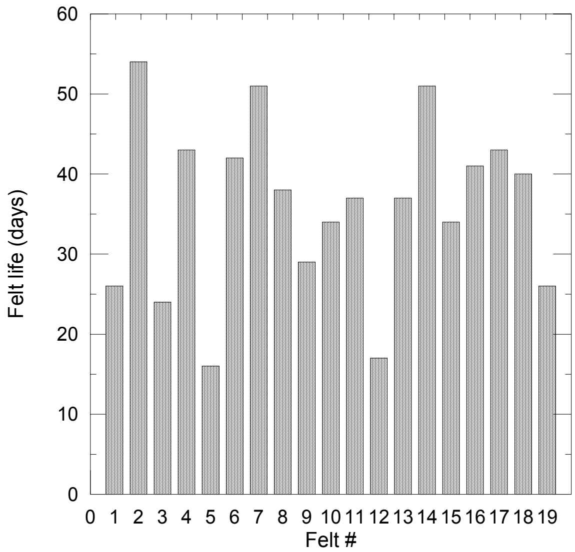

Figure 3. Historical record of felt life

4. ECONOMIC OPTIMIZATION OF FELT LIFE

Felt management represents the main operational and economic issue in a continuous paper machine. Usually felts are changed at predetermined time intervals on the basis of a programmed maintenance policy. Felt changeover requires 6 peoples and more than 5 hours work. Company management is usually conservative about felt life in order to avoid the occurrence of felt breackage during a production run which, besides a loss of produced paper, would imply much longer downtimes. This means that when the predetermined average life of 30-40 days is nearing the felt is changed as soon as possible, often in occasion of other programmed maintenance stops, even if it is apparently still in good conditions. However, apart from cutting the expenses connected to buying replacement felts, an extended felt life would greatly reduce production costs by lowering machine downtimes and associated start-up times occurring whenever a felt is changed, thus increasing annual productivity, and also reducing energy expenses for paper drying. In fact as the felt progressively loses its water draining ability an increased gas consumption for heating the drying air occurs.

A simple economic model has been therefore developed in order to determine the economic felt life and assess the possible economic benefit from increasing the felt duration respect the values currently achieved. As an economic indicator the average daily felt cost (DFC, Euro/day), computed over the felt life, has been chosen. The daily felt cost has been expressed as

$$DFC = \frac{C_F + C_G + C_{SU} + C_D}{d} \quad (1)$$

where C_F is the replacement felt cost, C_G the energy cost connected to gas consumption for paper drying, C_{SU} is the start-up cost following each felt changeover, C_D is the “dressing” cost and d (days) is the felt life. Such cost items are defined and computed as follows.

4.1. Felt cost

Typical felt cost is around 75 Euro/m^2, the actual cost thus depending on the machine size.

4.2. Energy cost

Natural gas consumption for paper tissue drying depends on the physical properties of felt (mainly the porosity) which change during the felt life owing to progressive wear, compaction and clogging. Three distinct phases may be identified: in the first period T_1 (usually 0 to 8 days starting from the changeover), a progressive felt compaction and stabilization occurs which leads to a permeability reduction. A higher than the average but decreasing gas consumption occurs. In the second period T_2 (from day 8 to approximately day 40) felt properties remain unchanged and and the minimum gas consumption rate is reached and steadily maintained. During the third period T_3 (from day 41 up to the end of felt life) gas consumption progressively grows owing to an increasing felt wear and clogging.

Energy consuption cost may be thus expressed as

$$C_G = Q_G\, P\, c_G\, d \tag{2}$$

where Q_G is the average gas consumption per ton of produced paper (m^3/t), P (t/day) is the average daily paper production, c_G (Euro/m^3) is gas cost.

Average specific gas consumption over the felt life may be computed on the basis of the specific gas consumption $q_G(t)$ during each of the three epochs of felt duration as follows.

$$Q_G = \frac{\int_{T_1} q_{G,T_1}(t)\,dt + \int_{T_2} q_{G,T_2}(t)\,dt + \int_{T_3} q_{G,T_3}(t)\,dt}{d} \tag{3}$$

Over periods T1 to T_3 the gas consumption $q_G(t)$ may be approximated respectively by the following functions: $q_{G,T1}(t) = k_1 - k_2\, d$; $q_{G,T2}(t) = k_3$; $q_{G,T3}(t) = k_4 + k_5\, d$, where $k_1..k_5$ are constant values which fit the actual gas consumption curves.

Average daily paper production is given by

$$P = 0.96\, v_P\, r_C\, l_P\, p_P\, t_P \tag{4}$$

where v_P (m/min) is the paper sheet advancement speed, r_C the sheet shortening ratio, l_P (m) the width of paper roll, p_P (g/m^2) the specific weight of paper tissue and t_P the daily production time (min). In the considered paper machine P = 87 t/day in average.

4.3. Start up cost

As soon as the felt is changed it can not attain immediatly the running speed v_P because the new felt has not yet reached the required permeability. During the start up period d_{SU} (days) the speed is kept lower, gradually increasing up to reaching the final value v_P. During the start up period, therefore, an average speed v_{SU} (m/min) may be assumed. The productivity loss resulting from the reduced speed is responsible for the start-up cost which is expressed as

$$C_{SU} = C_{DT}\, \frac{k-1}{k}\, d_{SU}\, 24 \tag{5}$$

where C_{DT} is the machine down time cost, Euro/h, accounting for the production loss and $k = v_P/v_{SU}$.

4.4 Dressing cost

This is actually the set-up cost, i.e. the cost associated to the loss of production during the felt changeover time t_{SU} (h)

$C_D = C_{DT}\, t_{SU}$ (6)

In the considered applications C_F = 11.300 Euro, C_{SU} = 5.940 Euro and C_D = 3.000 Euro. Gas consumption cost has the trend shown in figure 4, while the total daily felt management cost is shown in figure 5 with a minimum around 90-100 days. However such a life length is not attainable as it is well above the physical capabilities of currently available felts. A reasonable goal has been instead estimated in 60 days, which is significantly higher than the 35 days currently practiced. Infact the cost decrement when passing from 60 to 100 days is negligible while when passing from 30 to 60 is significant, leading to relevant savings in daily felt cost and annual expenses. Added benefits foreseen are the downtime reduction and productivity increase.

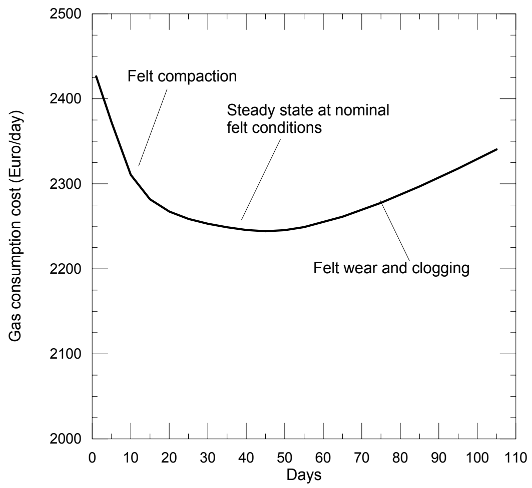

Figure 4. Trend of daily gas cost.

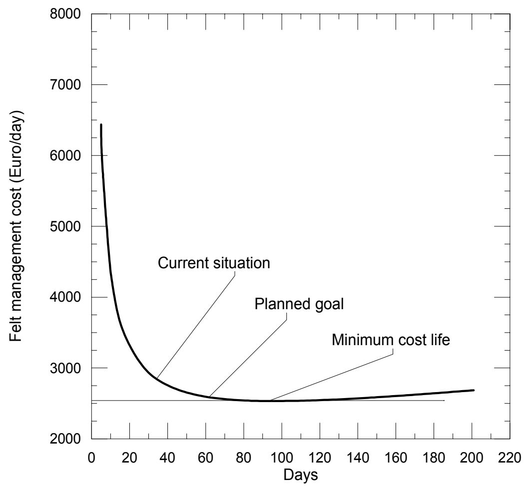

Figure 5. Trend of total felt management cost.

5. THE TPM PROGRAM DEVELOPMENT

The analysis of felt failure causes enabled to identify the following problem areas which could prevent from reaching the extended felt life goal:

- effective felt residual life is not known,
- felt surface damages, which eventually cause felt rupture or poor quality of produced paper, are due to:
  - non-uniform tensions over the felt along its length,
  - presence of paper paste residues along the felt guidepaths,
  - failure or degraded operation of felt cleaning water jets,
  - wear of felt or of the mechanical elements in contact with the felt.

These problem areas have been addressed by establishing an integrated strategy based on the three different kinds of actions as shown in figure 6:

1. Restoring the original mechanical standards through a preliminary extraordinary maintenance,
2. Development of revised maintenance and control procedures. A set of preventive maintenance measures have defined in terms of specific Critical Process Equipment (CPE) checks (oscillation of critical water jet cleaners, inspection of washing jets pipes, verification of contact pressure at the press zone, inspection of vacuum boxes, on-line measurement of felt thickness) to be carried out periodically, aimed at monitoring of weak signals from the machine and preventing the onset of physical damage to felt surface. Such checks are performed whenever the machine is stopped for other planned or on-fault maintenance actions, and their results are electronically stored and processed. For each of these CPE check a specific procedure has been written, an operator training program has been executed and specific forms to be filled by operators have been prepared along as developing a customized spreadsheet-based application for automatic management of such data collection activity.

3. Set up of management routines including the daily measurement of the relevant working parameters (gas consumption, daily production, downtime, scrap amount, production efficiency, speed loss, production time) enabling to evaluate the progressive wear of the felt and elaborate productivity statistics. A specific software application able to store and process such information for predictive purposes has been developed in MS Excel environment. The developed data analysis software tool is aimed at establishing a database of historical information about felt utilization as well as providing means to define adequate felt management strategies and proved to be an invaluable decision support instrument enabling a continuous benchmarking of machine performances respect the fixed goals.

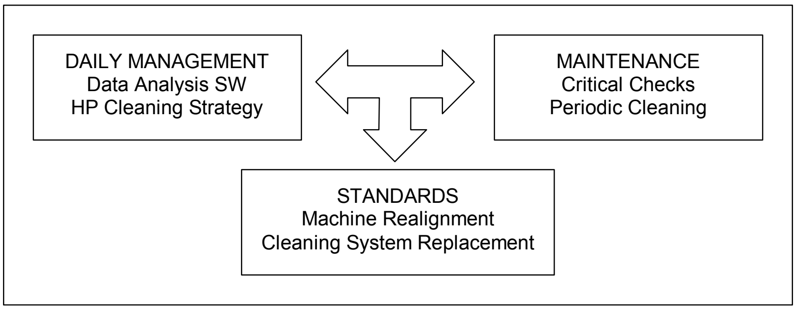

Figure 6. TPM program strategies.

Specific implementation issues have been fully illustrated in the next sections.

5.1. Non-uniform tensions over the felt along its length

Alignment of the guidepath enables to avoid unwanted variations of felt tension along its length which often result in wrinkling of the felt. Nearly all of the inspected rollers showed disalignments exceeding the manufacturer's specification range. Realignment was carried out during the extraordinary maintenance period and costed 10.800 Euro. To monitor the alignment status a routine check of the pressure profile along the felt width when it passes over the vacuum drying drum is periodically carried out by manually inserting a special pressure-sensible film in correspondence of the press-drum contact zone (figure 7). The operator inputs the resulting colour-coded information in the spreadsheet which automatically converts this information in pressure values.

Figure 7. Press-drum contact zone.

5.2. Presence of paper paste residues along the felt guidepaths

In order to guarantee that no paper paste deposit may accumulate on the guidepath, from which it can fall on the felt damaging its surface, the machine has to be cleaned several times a day. This operation can not be performed when the machine is working because paper sheet breakage would follow, but dedicate stops of the continuous machine for cleaning are unfeasible. A detailed standard operating procedure for machine rapid cleaning has been therefore developed to be carried out by two operators of each shift during the short time interval (about 5 minutes) available whenever the blade which detach the paper sheet from the heating drum is periodically changed.

5.3. Failure or degraded operation of felt cleaning water jets

Correct felt washing and lubrication is critical for the proper operation of the machine, therefore an in-depth check of the washing equipment was carried out with the following findings. Oscillation speed of the washing jets (figure 8) was not synchronized with the machine advancement speed preventing the obtainment of a uniform wetting and cleaning profile of the felt (figure 9). The cleaning brushes fitted inside the cleaning pipes weared rapidly in correspondence of the nozzles causing a disuniformity of the jet shape which eventually lead to surface damage of the felt. Furthermore, the cleaning system has to be manually operated causing safety concerns to operators and there was no automatic control of its efficiency status.

Figure 8. Washing jets.

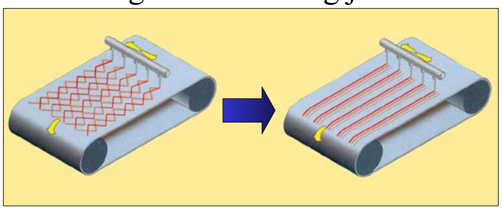

Figure 9. Washing water jet synchronization.

5.3.1. Replacement of cleaning system. The entire cleaning system has been redesigned installing new PLC controlled oscillating jet pipes free of the cited drawbacks. The cost of this operation was 63.500 Euro. Works lasted 8 days and were carried out during one of the major planned stops of the machine.

5.3.2. Preventive maintenance strategy. As far as preventive maintenance is concerned, instead, the operator is asked to verify, approximately every 4 months, the actual oscillation velocity, the period of oscillation and the deadtime at end of stroke of the cleaning jet pipes. Every two months a further inspection is carried out including monitoring of correct nozzles-felt distance, wear of internal cleaning brushes, stroke length, and nozzles cleaning status.

5.3.3. Revised felt washing process control. Furthermore as part of the daily management activities a standardized procedure for the indirect adjustment of the water jet pressure in the cleaning equipment has been established based on the feedback control of the pressure in the vacuum boxes. In the past, in fact, regulation of such a sensitive equipment was carried out by each shift operator in an arbitrary fashion relying on their personal experience.

5.4. Wear of felt and mechanical elements

This issue concerns the preventive maintenance program and the daily management routine. It concentrates on felt thickness and the efficiency of the vacuum boxes and pick up shoe which are critical for correct water draining from the felt and are subject to frequent clogging. An automatic generation of the pressure profile has been applied in this latter case too. Wear monitoring of the vacuum boxes surface at contact wih the felt is also carried out and the results are stored on the developed spreadsheet application.

Finally, an on-line check of felt thickness has been introduced to be executed three times a week. This measurement is carried out resorting to a specific hand-held tool and is aimed at evaluating the actual felt void volume which depends from felt thickness (progressively reduced owing to wear phenomena) and is directly proportional to the amount of water it can drain from the paper sheet. Felt thickness is therefore one of the main indicator of the felt approaching the end of its useful life. In this case too the data collection and processing is automatically carried out (figure 10).

Referring to the daily management routine, apart from elaborating useful statistics for the machine productivity parameters the management software computes and displays the daily values of several performace measures such as the speed loss (respect the nominal value owing to a reduced ability of the felt to drain water) and felt thickness (figure 10) or gas consumption (figure 11). In particular the latter indicator proved to be highly representative of the system performances. In fact when the felt progressively wears its capability of draining water reduces, owing to excessive compaction and clogging, leading to an increase of drying air temperature to comply with paper tissue humidity specifications. This in turn increases gas consumption. The software tool enables the analysis of felt thickness and gas consumption trends in order to determine the critical thickness. A comparative analysis may be also carried out among felts supplied buy different manufacturers. A database of felt performances may be built. A database of felt substitutions is also managed enabling to visualize life length statistics and frequency of replacement causes. Finally the proper technical and dimensional characteristics of the felts to be utilized have been defined in greater detail resorting to the performance monitoring activity carried out with felt from different manufacturers.

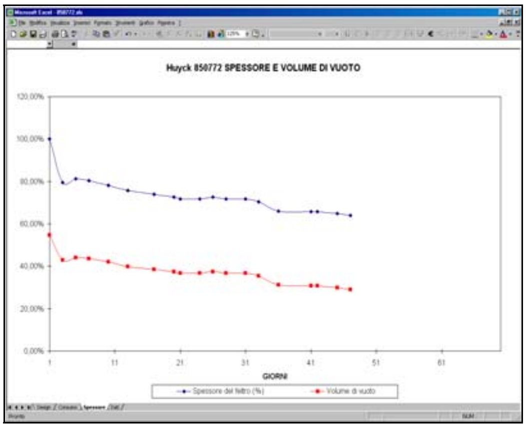

Figure 10. Trend of felt thickness and voidage vs time.

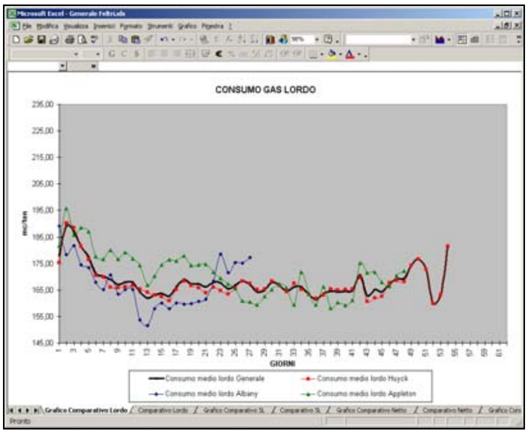

Figure 11. Comparison of gas consumption trends for different felts.

6. RESULTS

The above described TPM program required about one year to be fully implemented and its performances results based on monitoring of 7 new felts are here presented. Figure 12 shows the resulting record of felt life confirming the significant increase in felt life obtained with the described programme while figure 13 shows the trend of felt average life. Currently the felt average life is 62 days compared to 34 before the start of this program, consistent with the initial goal. A maximum felt life of 71 days has also been recorded. The investment of about 74.300 Euro was repaid in less than one year thanks to the savings obtained. In fact an increase of 28 days in the average felt life leads to confirm the expected annual savings in the order of 98.100 Euro (Tab. 2).

Table 2. Results and benefits of the felt life extension

	BEFORE	AFTER
Average felt life (days)	34	62
Daily felt cost (Euro/d)	2867	2592
N. of felt replacements ($year^{-1}$)	11	6
Total felt changeover downtime (h/year)	55	30
Total annual cost (Euro/year)	1.031.800	933.700
OBTAINED RESULTS		
Daily felt cost saving (Euro/d)	275	
Annual savings (Euro/year)	98.100	
Investment (Euro)	74.300	
Pay back time (months)	9	
Productivity increase (t/year)	200	

7. CONCLUSIONS

An integrated set of actions in the framework of a TPM approach to plant maintenance has been developed and satisfactorily applied to a continuous machine in the papermaking sector enabling a significant extension of the felt life. The program was aimed at removing or controlling all those factors which could damage the felt causing its premature deterioration as well as monitoring and analysing all the weak signals (i.e. felt thickness, gas consumption etc.) which are representative of the felt approaching the end of its useful life. As a result a nearly doubled felt life was obtained with consequent significant economic savings, reduced downtime and increased machine productivity. The action plan encompassed all aspects of machine operation and maintenance, starting from structural changes, including substitution of machine components and restoring of mechanical specifications, passing through a reengineering of daily maintenance practices and the development of a dedicated condition monitoring software tool able to process the collected data in order to offer a complete picture of system status for decision making purposes. This program succesfully demonstrated the potential of an integrated approach to machine maintenance and is currently applied in a major paper manufacturer in Italy.

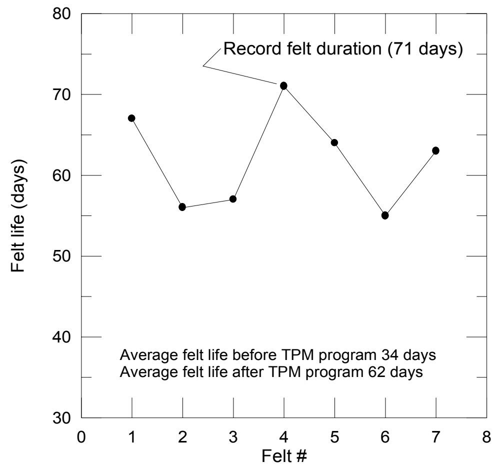

Figure 12. Felt life after the TPM program implementation

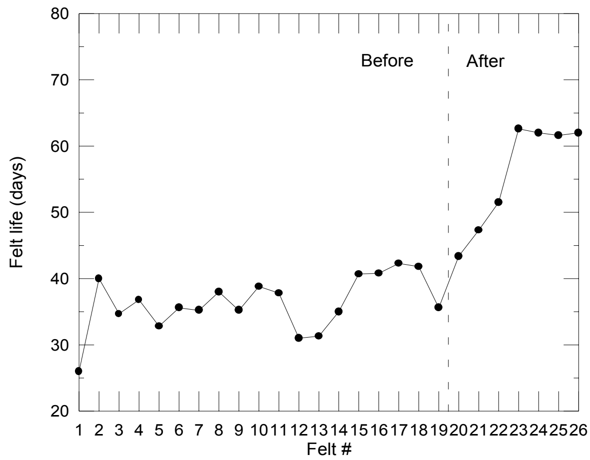

Figure 13. Moving average of felt life before and after the TPM program implementation

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