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BACHELORARBEIT

Titel der Arbeit: Analyse aufkommender Methoden und Technologien zur Vorhersage von Wartungsintervallen auf Basis von Prozessdaten eines laufenden Produktionprozesses.

Titel d. A. englisch: Analysis of upcoming methods and technologies to predict maintenance intervals based on process data from a running production process.

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1. ABSTRACT

Within this bachelor thesis, some information about implementing a predictive maintenance routine in molds is given. At the beginning, it describes different tools that can be used for the maintenance of molds. This thesis develops an asset of parameters to monitor the condition of molds. Afterwards, it selects the proper tools to monitor those parameters from the so-called Predictive Maintenance Tools. Finally, with all the previous information, it creates a conceptional design of predictive maintenance intervals.

2. SUMMARY

Descriptors: Kunststoffe, Formteil, Formteilqualität, Instandhaltung, Prüfmethoden, Werkzeugschaden

Keywords: Predictive Maintenance, Mold condition Monitoring, Injection molds

The economic success of companies relies highly on effective and efficient production processes. To avoid an unexpected loss of production, companies use several different techniques to maintain their production system. Nowadays, Industry 4.0 offers many possibilities for a beneficial use of process data to get information about running production processes. One new business model that evolves from this, refers to Predictive Maintenance with the aim to predict maintenance intervals by a contemporary condition monitoring. However, the possibilities to get valuable information about the running process and the condition of injection molds are manifold and diverse.

The aim of this thesis is to analyze upcoming methods and technologies in the field of Predictive Maintenance and to create a conceptional design to predict maintenance intervals of injection molds based on process data. At the beginning, it is important to do a deep literature research to clarify the understanding of Predictive Maintenance and to contextualize the already existing approaches within the context of Industry 4.0. Before the condition of molds can be captured and monitored, the condition-related parameters have to be determined and methods to gather information about these parameters during the running process have to be evaluated. Furthermore, interdependencies between the parameters have to be analyzed and integrated into a conceptionally designed model that enables to get information about maintenance intervals and the condition of mold for the injection molding process.

At the end, an asset of maintenance tools is named which will be used for the development of a new maintenance routine based on the condition of the mold. This routine will use some of the tools that are described during the thesis to monitor crucial parameters for the condition of the mold. For the detection of each of the problems that can occur to a mold, different maintenance tools, shown in Fig. 5.1, can be used. But there are always some better options because of different factors, like detection time or price. In Figure 4.8 some different tools and their detection times are shown.

The selected tools must be able to monitor the condition of the different surfaces of the mold, as well as the vibrations which are produced in the machine due to the relative movement of the different pieces and to monitor the temperature and pressure in different parts of the mold, which can give a better idea about the situation of the mold during production time. To monitor all the described parameters the so-called Vibration Signature Analysis, Thermographic Analysis, Position Sensors and Hydrostatic Gauges to measure pressure are chosen.

3. INTRODUCTION

The maintenance stage is a fundamental part of the companies' work. This part will oversee the correct operation of the different tools used during the productive time of the company. Maintenance is therefore fundamental to get a high-quality product continuously. That is why with the growth of the industry, new techniques have been developed to improve the efficiency of maintenance, and thus avoid failures in the machines that negatively affect the production process, either through stops of the company or by failures in products.

The development of the industry has gone from maintenance methods that consisted of reacting once the failure occurred, to others where the goal is to use the different technological advances to predict when the failure will happen and react to prevent it. Therefore, the objective of this work is to adapt these new maintenance trends to the plastic injection industry and especially to be able to predict the necessity of maintenance in molds.

During the first part of this thesis, as the term maintenance is defined and a small introduction to the development of maintenance over the years is given. After finishing this part, the main maintenance methods are introduced.

Once this small introduction to maintenance is completed, it focuses on the description of the tools that can be used to monitor the current condition of the machines, and briefly explains which ones could be used to monitor the condition of molds. Then, some of the possible failures that can affect molds are mentioned and the importance of preventing each of them is described to prevent catastrophic failure in molds that would negatively affect the production process.

In the following section, the different tools previously described are related to the set of crucial parameters to monitor the situation of the molds. Finally, the chosen tools to monitor the molds are selected and briefly justify their selection.

4. STATE OF THE ART

4.1. Definition and Evolution of Maintenance

4.1.1. Definition

Maintenance is referred to as necessary actions for retaining or restoring a piece of equipment, machine or system to the specified operable condition to achieve its maximum useful life. However, for some people, maintenance describes the management, control, execution and quality of those activities, which will reasonably ensure that design, availability and performance of assets meet business objectives. [BS11]

Maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, maintenance costs can represent a high percentage of produced costs of goods. Recent surveys of maintenance effectiveness indicate that one third of maintenance costs are wasted as the result of unnecessary or improperly carried out maintenance actions. [FF15]

The losses of production time and product quality that result from inadequate maintenance management have a dramatic impact on companies to compete with others which have implemented more advanced maintenance management philosophies. [DCBP10]

The principal reason for this ineffective maintenance is the lack of data to quantify the actual need for repair or maintenance of a plant equipment. Maintenance scheduling has been predicated on statistical trend data or on the actual failure of the plant equipment. [Mob01]

4.1.2. Evolution

Much has happened in engineering since the industrial revolution around a couple of hundred years ago, but maybe the most drastic changes have taken place in the last fifty years[BS11]. Fig. 4.1, shows the evolution of maintenance during these years.

Before the Second World War, machinery was quite rugged and relatively slow running, instrumentation and control systems were very basic. Also, the demand of production efficiency was not so high and because of that, the downtime was usually not a critical issue. The machinery was inherently reliable, as we can see in the examples of machines made in that time, which are still working in some companies. During that time, there were no maintenance routine, the machines worked until they broke and then they were replaced by another one. It was the time of the so-called Corrective Maintenance as it is shown in Fig. 4.1. This is a maintenance task performed to identify, isolate, and rectify an error so that the damaged equipment, machine, or system can be restored to an operational condition. [BS11]

After the war, the times and needs changed, the industry developed a much more competitive marketplace, where the downtimes were intolerable. Machinery became lighter and ran at higher speed to satisfy the increased demand. They wore out faster and were less reliable. Because of that, the so-called Planned Preventive Maintenance was introduced as it is shown in Fig. 4.1. [Man12]

Planned Preventive Maintenance is designed to preserve and restore equipment reliability by replacing worn components before they fail. With this new system, a routine of maintenance, based on planning and controlling the work with statistical and time-based methods tools, was fixed [URL17a, SPMH10].

The times changed in the last third of the 20^{th} century because of the globalization of the marketplace, which created new needs for excellence in all activities. The World-Class Standards were understood and a dynamic system was created. With this new need for excellence, another method was introduced, the so-called Condition Based Maintenance, which is a maintenance strategy that monitors the actual condition of the equipment to decide about the necessity of maintenance actions to be done [URL17a].

The whole workforce looked for excellence by using different computer tools that were on the market, creating multi-skilled maintenance crews, which went deeper in the problems of the equipment to solve the root of the problem and not only the symptom.

Doing all this to involve all members of the organization in optimizing the outcoming pieces was called Total Productive Maintenance or Total Participation Maintenance. [URL17h] This concept was developed first in Japan and then moved to other parts of the world. A central aspect is that all workers are responsible for the up-keeping of the equipment. Furthermore, the participation of people who are not familiar with the maintenance of the equipment enriches the results because their observations are in many cases more objective. [URL17a]

In the last years, because of the third and fourth industrial revolution, there have been lots of changes in the industry. Some of them are due to changes in the materials, which are used, e.g. carbon fiber that is replacing aluminum or steel because it is lighter, stronger and more durable. Other big changes are the improving of internet and the wireless connections, which supports the interconnection between machines and the workers to make their work easier in monitoring the different parameters of a production process. [URL17a, MK08, HAA+10]

4.2. Maintenance Methods

There are different methods for traditional maintenance management. In this section, some of these traditional methods and some upcoming techniques, which can be used in maintenance management, are explained.

4.2.1. Reactive Maintenance

The so-called Reactive Maintenance is the simplest maintenance strategy, it follows the logic that whenever a machine or component breaks down, it must be fixed. It is basically the “run till it breaks” maintenance mode [Mob02]. The companies using this method, do not spend any money on maintenance until the machine breaks down. They have in general some spare parts and staff on hand to replace the failed part and to reestablish the machine activity as soon as the failure has happened. [Mob02, SPMH10]

This maintenance method is used on parts that have minimal effect on production and no safety risks. However, it is hardly ever used as the only maintenance method for the whole plant. [Mob02]

The main advantage of this method is that no planning is required and it is easy to understand and implement [URL17h]. On the other hand, there is the unpredictability of the failures, the cost of possible production losses and breakdowns as well as the costs, which are directly associated with maintaining. With this method inventory costs must be taken into consideration, because spare parts must be kept in the inventory. [URL17h, Mob02, SPMH10, Dhi02]

4.2.2. *Preventive Maintenance*

The Preventive Maintenance technique is regularly performed on a piece of equipment to lower the likelihood of it failing or mitigating degradation. It is usually performed while the equipment is still working and relies on the availability of spare parts in the inventory.

The maintenance intervals are scheduled based on elapsed time or the usage of the machine, estimated based on industrial or plant average-life statistics. The so-called mean time to failure (MTTF) indicates that a new machine has a high probability of failure during a few weeks after installation due to problems in assembly as it is shown in the bathtub curve in Fig. 4.2. Therein the x axis shows the time and the y axis the probability of failure. After the phase of "Infant Mortality", the probability of failure is constantly low for a long period in the phase called "Use Full Life Period". After this, the probability of failure increases sharply with elapsed time in the "Wear out Period" and single components should be exchanged soon. In preventive maintenance management, machine repairs are scheduled based on the MTTF statistic before the "Wear out Period". [Mob02]

The mean time to failure is calculated as it is shown in *formula 1*, by dividing the total number of device hours by the number of failures[Sey00].

$$MTTF = \frac{TotalNumberDeviceHours}{NumberFailures} \qquad (F.\ 2.1)$$

Preventive Maintenance is more complex to coordinate than run to failure maintenance because the maintenance schedule must be planned. The implementation of preventive maintenance varies vastly, some programs are highly limited and consist of only lubrication and minor adjustments[URL17h]. Others even include rebuilds for critical parts of the machine. All preventive maintenance management programs assume that the machine is going to break at some point in time. The task of the preventive maintenance management is to predict when it normally breaks and maintain it before it happens to avoid a loss in production time. [URL17h, Mob02]

One of the main advantages of this method compared to simpler strategies is Planning. Because of the plannability the companies do not have to deal with maintenance overhead costs. With the planning, the maintenance activities can be done during the production downtime to reduce the costs due to nonproductive times. Also, safety is improved because the equipment breaks down less often. [URL17h]

However, there are also some disadvantages of this method. At the beginning, without a long experience on maintenance, the scheduled activities could be too much or too little [URL17h]. Usually the frequency of the maintenance activities is most likely to be too high. This frequency could be reduced without sacrificing reliability by taking care of the condition monitoring and its analysis. The decrease in maintenance frequency is offset by the additional costs associated with conducting the condition monitoring. [Mob02, URL17h, SPMH10]

4.2.3. Total Productive Maintenance

The Total Productive Maintenance (TPM) is a method for maintaining and improving the integrity of production and quality systems through the machines, equipment, processes and employees that add business value to an organization. [URL17h]

It requires the total participation of the workforce and incorporates the skills of all employees. This method focuses on improving the Overall Equipment Effectiveness (OEE) of the facility by eliminating the waste of time and resources. TPM incorporates maintenance into the everyday performance of a facility [URL17h]. OEE is calculated with *formula F.2.2* [URL17l].

$$OEE = (Availability) \times (Performance) \times (Quality) \qquad (F.\ 2.2)$$

The participation of the total workforce means that the top-level management is expected to be involved in promoting TPM and in taking decisions based on the overall equipment effectiveness of the facility. The operators must take the responsibility about the day-to-day maintenance of their machines. Furthermore, they are expected to report any early sign of deterioration. Finally, the maintenance staff is expected to train and support operators to meet their goals and perform more advanced preventive maintenance activities. [URL17h, Mob02, SPMH10]

Total productive maintenance is a globally established system, that is not focused only in maintenance. All of the improvements in maintenance techniques must be taken into consideration to avoid reactive maintenance. [URL17h, Mob02, URL17l, SPMH10]

4.2.4. Reliability Centered Maintenance

The Reliability Centered Maintenance is a high-level strategy that is implemented to optimize the maintenance program of a company. As Fig. 4.1 shows, this method appeared in the 1970's using the condition based theories. The aim is to implement a specific maintenance strategy on each equipment of the facility. The main objective of this method is to preserve the functionality of the system by identifying the failure modes that can affect the system function and select the applicable and effective tasks to control the failure modes. [URL17h, Ste99]

The Reliability Centered Maintenance recognizes that all equipment in a facility is not of equal importance to either the process or facility safety. Furthermore, the equipment design and operation varies and in conclusion, different equipment will have a higher probability to undergo failures from distinct degradation mechanisms than others. It also creates the structuring of a maintenance program recognizing that a facility does not have unlimited financial and personnel resources and that the use of both need to be prioritized and optimized. [SPMH10]

The main advantage of this method is to increase the equipment availability and reduce maintenance and resource costs. On the other hand there are also some important disadvantages like not considering the total cost of owning and maintaining an asset. [Mob02, URL17h, BS11, SPMH10, Dhi02, MK08]

4.2.5. Risk Based Maintenance

The Risk Based Maintenance method prioritizes maintenance resources towards assets that carry the most risk if they were to fail. It is a method for determining the most economical use of maintenance resources. This method is based on two phases. In the first phase, the level of risk is assessed and in the second phase the maintenance planning is fixed depending on the risk. [URL17h, URL17a]

4.2.6. *Predictive Maintenance*

The aim of Predictive Maintenance is to predict when an equipment failure might occur and prevent the occurrence of the failure by performing the maintenance. To the most workers, predictive maintenance is conducted by regular monitoring of the actual mechanical condition, operating efficiency and other indicators of the operating condition of machines and process systems. This will provide the data required to ensure the maximum interval between repairs and minimize the number and cost of unscheduled outages. [URL17h, Mob02, SPMH10]

In general, Predictive Maintenance can be defined as follows: “Measurements that detect the onset of system degradation, thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration of the component’s physical state”. [SPMH10, Mob02]

Predictive Maintenance has the aim of improving productivity, product quality, and overall effectiveness of manufacturing and production plants. As Fig. 4.3 shows, when you talk about Predictive Maintenance, it is not possible to refer only to the usage of any of the nondestructive testing techniques that are being marketed as predictive maintenance tools. These tools are effective at predicting failure and provide sufficient warning time for upcoming maintenance.

But it is a philosophy that uses the operating condition of plant equipment and systems to optimize plant operation. As it is shown in Fig. 4.3 the selection of the crucial process parameters is a decisive stage for the proper running of a Predictive Maintenance method. Therefore, a team of equipment manufacturers and condition monitoring experts must identify the best way of getting information about the condition of all relevant components. Predictive Maintenance uses the most effective tools to obtain the actual condition and schedules all the maintenance activities. [Mob02, PMDB16]

Once the method is working effectively, maintenance is only performed on machines when it is required or just before a failure is likely to occur. With this method, the time for the equipment to be maintained, the production hours lost due to maintenance and the cost derivate from spare parts and supplies are reduced. [Mob02, URL17h, SPMH10]

As it is shown in Fig. 4.4, Preventive Maintenance is less complex to coordinate than Predictive Maintenance because monitoring strategies do not have to be planned nor the results interpreted. The maintenance intervals are scheduled due to statistical reasons instead of the condition of the machine. But there are more advantages of Predictive Maintenance. [URL17h]

A well-managed Predictive Maintenance program will eliminate catastrophic failures, as well as it will be able to schedule all maintenance activities to minimize or delete overtime cost. It is also an important advantage to reduce the inventory and ordered spare parts [URL17h]. It is also possible to optimize the operation of the equipment, saving energy costs and increasing plant reliability. Another advantage is that with predictive maintenance, it is ensured that a piece of equipment requiring maintenance is only shut down right before imminent failure as it is said in Fig. 4.4 [SPMH10]. However, one disadvantage of this management method can be seen in the high capital investment that is required for diagnostic equipment and staff training. [Dhi02]

4.3. **Predictive Maintenance Tools**

Condition monitoring is the process of watching parameters of condition in machinery in order to identify a significant change which are signs of a developing fault [SPMH10]. The use of condition monitoring allows maintenance to be scheduled or other actions to be taken to prevent failure and avoid its consequences. Condition monitoring allows the detection of failure from their first symptom and before they develop into a major failure.

A variety of technologies can be, used as part of a comprehensive predictive maintenance program. Each technique has a unique data-set that assists the maintenance manager in determining the need for maintenance. [Mob02] This section provides a brief description of each of the techniques that should be included in a full-capabilities predictive maintenance program. In Tab 4.1 the different tools are related to some of the machines that can be monitored with the help of those tools. [LL11, NN16]

	Pumps	Electric Motors	Diesel Generators	Condensers	Heavy Equipment	Circuit Breakers	Valves	Heat Exchangers	Electrical	Transformers	Tanks, Piping
Visual Inspection	x	x	x	x	x	x	x	x	x	x	x
Vibration Signature Analysis	x	x	x		x						
Tribology	x	x	x		x					x	
Thermographic Inspection	x	x	x	x	x	x	x	x	x	x	
Shock Pulse											
Ultrasonic Leak Detectors											x
Electrical Insulation		x	x			x			x		
Wear and Dimensional Measurements				x			x				x
Noise Analysis	x	x	x	x			x	x		x	
Acoustic Emission Analysis	x	x	x	x			x	x		x	
Borescope Inspections	x						x				x
Eddy Current											x

Table 4.1: Maintenance tools related to distinct machines

(Tab. 4.1)

4.3.1. *Visual Inspection*

“Visual inspection is the process of examination and evaluation of systems and components by use of human sensory systems aided only by mechanical enhancements to sensory input such as magnifiers, dental picks or stethoscopes. The inspection process may be done by looking, listening, feeling, smelling, shaking, and twisting” [Mar96].

It was the first method used for maintaining, it was used almost from the beginning of the Industrial Revolution. This method is still a viable maintenance tool and should be included in all total-plant maintenance programs. Usually with this method some potential problems, that will be missed using the other maintenance techniques, will be detected. [URL17c]

4.3.2. *Vibration Signature Analysis;*

Vibration Signature Analysis is usually the primary predictive maintenance tool on rotating machinery systems, it is used for detection and diagnosis of bearing defects. In the last years a microprocessor has been used to acquire, manage, trend and evaluate the vibration energy created by those electromechanical systems. [Mob02]

Signatures are extensively used as a diagnostic tool for mechanical systems. These tools also use some signal processing techniques involving one or more methods to deal with the problem of improvement in the signal to noise ratio. These methods have been applied separately in time and frequency domains as are shown in Fig. 4.5 [JWM08, Bec08].

A time-domain analysis focuses usually on statistical characteristics of vibration signals such as peak level or standard deviation. The data is referred as a function of time. The main advantage of this format is that little data is lost prior to inspection. But there is usually too much data for an easy and clear fault diagnosis as it is shown in Fig. 4.5. [JWM08]

A frequency-domain refers to a display of the vibration data as a function of frequency. The time-domain vibration signal is usually processed into the frequency-domain by applying a Fourier transformation. With this format, the repetitive nature of vibration signal is clearly displayed as peaks in the frequency. This allows for faults to be detected early, diagnosed accurately and trended overtime as the condition deteriorates. The main disadvantage is that some amount of information may be lost during the transformation process as it is shown in Fig. 4.4. [JWM08]

Most programs limit the use of this predictive maintenance technology to simple rotating machinery and not to critical production systems that produce the plant´s capacity. But vibration monitoring it is not limited to simple rotating equipment. The microprocessor used for this can be used effectively also on all electro-mechanical equipment. [Mob02, PCKV97]

This tool can be used on different mechanical parts of the mold, for checking the correct running of the ejection system, and also for being sure that the different parts of the mold are properly located. It is important to properly configure the data base, because if it is not, this could result in catastrophic failure of critical plant machinery. [AMK16, RRT00]

4.3.3. Thermographic Inspection

Thermographic Inspection is a non-destructive maintenance technique that can be used to monitor the condition of a plant machinery, structures and systems, not just electrical but also mechanical equipment. It uses instrumentation designed to monitor the emission of the infrared energy to determine operating condition. By detecting thermal anomalies an experienced technician can locate and define a multitude of incipient problems within the plant. [Mob02, SPMH10]

The inspection method is based on the fact that most components in a system show an increase in temperature while malfunctioning. The increase in temperature in an electrical circuit could be due to loosen connections or a worn bearing in the case of mechanical equipment. [NN04]

Infrared technology is predicated on the fact that all objects with a temperature above absolute zero emit energy or radiation. Infrared radiation is one of those forms of emissions. Infrared are the shortest wavelengths of all radiated energy and are usually invisible without special instrumentation. Those instruments are able to measure emitted and also reflected energy. [CC10, SPMH10, NN04]

There are two different types of instruments which are generally used as part of a predictive maintenance program: infrared thermometers and infrared imaging [Mob02]

- I*nfrared Thermometers* are designed to provide the actual surface temperature at a single, relatively small point on a machine or surface. It is typically used to monitor bearing cap temperatures, motor winding temperatures, spot checks of process piping temperatures and similar applications. The main limitation of this method is that the temperature represents a single point on the equipment. [SPMH10]
- *Infrared Imaging* provides the means to scan the infrared emissions of complete machines in a short time. This system function like a video camera where the user can view the thermal emission profile by simply looking through the instruments optics. [SPMH10]

Those systems are in the market with a very wide price range from relatively inexpensive to quite expensive devices [SPMH10].

Mechanical looseness occurs often due to thermal stress fatigue from overuse. An accurate temperature measurement will identify a loose condition. Also, it is possible to detect lots of problems in electrical devices like, on the fuses, bus ducts, circuit breakers or switchgears. Thanks to this method, an early detection of some improper functioning in cooling or heating systems is possible. [Mob02]

Thermography can also be used in the molding industry to check the proper temperature in the different parts of the mold to verify the correct running of the cooling system.

4.3.4. Tribology

Tribology *is* the general term that refers to the design and operating dynamics of the bearing-lubrication-rotor support structure of machinery. There are two main techniques for that: Lube Oil Analysis and Wear Particle Analysis. [Mob02, Nea95]

4.3.4.1. *Lube Oil Analysis*

Lube Oil Analysis is an analysis technique that determines the condition of lubricating oils used in mechanical and electrical equipment. It is not the key tool for determining the operating condition of machinery or detecting failure modes, but it is one of the keys to keeping machinery operating at optimal performance. Too many plants are attempting to accomplish the latter and are disappointed in the benefits that are derived. It involves monitoring and analyzing lubricant oils for characteristics as contamination, chemical content and viscosity. [Nea95, Mob02]

4.3.4.2. *Wear Particle Analysis*

Wear Particle Analysis can provide direct information about the wearing condition of the machines. There are two main methods for doing this analysis spectrographic and ferrographic. *Spectrographic analysis* is limited to particles smaller than 10 microns. F*errographic analysis* separates particles using a magnet, obviously the limitation of this method is that only magnetic particles can be removed. [Mob02, Nea95]

The applications for this analysis are quality control, reduction of lubricating oil inventories and determination of the most cost-effective interval for oil change. Millions of euros are spent annually replacing machinery which has worn out because of inability of the lubricants to perform the required task [Mob02]. The main problem for using this method in the predictive maintenance is to acquire the samples. [Mob02]

Tribology analysis can be used in the injection molding industry to monitor the current situation of the different moving parts of the mold which can be worn out because of time and use.

4.3.5. *Shock Pulse*

Shock Pulse is a technique of predictive maintenance by measuring vibration and shock pulses of bearing in motors, to identify their condition and operating life before the next overhaul procedure. But it has been a valuable tool in checking the proper lubrication of other systems [URL17f]. There is a difference between Vibration Monitoring and Shock Pulse, because when two metal surfaces contact each other while in motion, an impact occurs and a shock wave develops, which travels through the metal. The pulse is in ultrasonic range around 36KHz. Equipment such as gearboxes, lobe compressors, screw compressors and centrifuges all give off Shock Pulse signals and can be effectively monitored using Shock Pulse. This device also can save grease on the bearings that were frequently overlubricated. [URL17f, But73]

4.3.6. Ultrasonic Detectors

Ultrasonic detection is a non-destructive maintenance tool which is used to determine if and in some cases where a leak has occurred in systems which contains liquids and gases [Gal12]. With the help of some experts who are able to detect a leak by the sound of the gas going through it. But when the leak is small, the sound, which is produced, is not in a frequency that human ears are able to hear. But it can be heard thanks to the help of Ultrasonic Detectors that translate the ultrasonic hissing sound to a lower frequency which can be heard by humans through headphones.

This method provides a huge potential for extensive in situ failure analysis of materials, since it provides information on sub-macroscopic failure phenomena as well as on the overall damage accumulation. Thanks to this method experts are able to find leaks and cracks on the molds which could be critical for the running of the mold. The detection of failures with the help of this method is faster than with any other tool. [Gal12, URL17d, URL17i, URL17d, SPMH10] This method is used in the injection molding industry to monitor the filling of the cavity [TRL93].

4.3.7. *Electrical Insulation*

Electric insulation is a non-destructive maintenance tool which helps in maximizing the uptime of motors, cables and switchgears. The aim of this test is to measure the total resistance of a product's insulation by applying a determined voltage depending on the type of system it is. This tool is used to ensure that electrical devices meet codes and standards, to avoid troubles in those machines. With this it is possible to know the current situation of the different electrical components from the machine. [URL17m]

4.3.8. *Wear and Dimensional Measurements*

These non-destructive techniques can be used as maintenance tools [NN16]. These methods are performed by checking that all parts of the machine are still within the suitable measures. With those tools, the company can get information about the wear of the machine and can react properly. It can be used in all mechanical parts of the machine, because it only consists in comparing the current situation with the beginning or with the proper standard. Those measurements are more precise than the ones that can be obtained by the visual inspection, here other devices can be used like calipers, micrometers, or even some 3D-laser measurement devices. [NN16]

4.3.9. *Noise Analysis*

Noise Analysis is a non-destructive analysis used for maintenance because with the analysis of noise in the proximity of the external surface of machines it is possible to get vital information about the internal processes, and provide valuable information about a machine's running condition [JWM08].

When machines are in a good condition, their noise frequency spectrum has characteristic shapes. As faults begin to develop, the frequency spectrum changes. Each component in the frequency spectrum can be related to a specific source within the machine. This is the fundamental basis for using noise measurement and analysis in condition monitoring [JWM08]. Sometimes the signal, which is to be monitored, is submerged with some other signal and it cannot be detected by a straightforward spectral analysis. In this case, specialized signal processing techniques have to be utilized to remove the other signals. This tool can be used in all mechanical parts of the machine, and it will be very helpful for an early detection of failures.

4.3.10. *Acoustic Emission Analysis*

Acoustic Emission Analysis refers to the analysis of the transient waves generated during the rapid release of energy from localized sources within a material. The source of these emissions is closely associated with the dislocation accompanying plastic deformation and the initiation or extension of fatigue cracks in material under stress [Hel01]. The other sources of acoustic emission are melting, phase transformations, thermal stress, cool-down cracking, and the failure of bonds and fibers in composite materials. [GZS+11]

Acoustic emissions are measured by piezoelectric transducers mounted on the surface of the structure under test as shown in Fig. 4.6 and loading the structure. Sensors are coupled to the structure by adhesive bonds. The output of each piezoelectric sensor is amplified through a low-noise preamplifier, filtered to remove any extraneous noise and further processed by suitable electronic equipment which provides the information as it is shown in Fig. 4.6.

Traditionally, acoustic emissions as a technique has been restricted to the monitoring of high cost structures due to the expenses of the monitoring equipment but nowadays, it can be used for many other smaller structures like gears or other mechanical devices. [GZS+11, GLB15]

4.3.11. Borescopic Inspection

Borescopic Inspection is a non-destructive technique to monitor the current situation of a machine. The borescope is an optical device consisting of a rigid or flexible tube with an eyepiece on one end, an objective lens on the other linked together by an optical system in between. This tool is used to non-destructively inspect industrial systems and equipment to get an internal view of different parts of the machine that could not have been viewed with a normal visual inspection, like turbine engines, internal combustion engines, pipes, heat exchanger tubes, etc. [Lev05]

It can be used to inspect the different channels and cavities of the mold, looking for wear, dirt or different grooves.

4.3.12. *Eddy Current*

Eddy Current testing (ECT) is one of the electro-magnetic testing methods used in non-destructive testing, making use of electromagnetic induction to detect and characterize surface and subsurface flaws in conductive materials [GGV11, Lev05]. The principle of the eddy current technique is based on the interaction between a magnetic field source and the test material, named C in Fig. 4.7. This interaction induces eddy currents in the test piece as it is seen in Fig. 4.7. Operators can detect the presence of very small cracks by monitoring changes in the eddy current flow. [GGV11]

The two major applications of eddy current testing are surface inspection and tubing inspections. Surface inspection is used extensively in the aerospace industry, but also in the petrochemical industry. The technique is very sensitive and can detect tight cracks. Surface inspection can be performed both on ferromagnetic and non-ferromagnetic materials. [GGV11]

Tubing inspection is generally limited to non-ferromagnetic tubing and is known as conventional eddy current testing. Conventional ECT is used for inspecting steam generator tubing in nuclear plants and heat exchangers tubing in power and petrochemical industries. The technique is very sensitive to detect and size pits. Wall loss or corrosion can be detected but sizing is not accurate. [GGV11]

4.3.13. *Process Parameters*

Process Parameters monitoring is non-destructive technique consisting in checking the different parameters, which provide an actual information about the process. This method should include the checking of temperatures, pressures and all other parameters that will affect the process and that should be continuously under certain conditions, that are defined at the design time. [Mob02]

For the implementation of this maintenance tool some sensors and some tool that can manage the information are needed. The sensors will be responsible for getting the information about the parameters from the machine, and a micro-processor will enable an easier management of that information to help monitor the current condition of the machine. The sensors must give information about the current state of distinct parameters as pressure, position, speed or viscosity of fluids. [Mob02]

4.4. **Conclusion State of the Art**

Maintenance refers to keep in an appropriate condition, a machine or a process. After the Industrial Revolution, different methods have been used with the purpose of maintaining. At the beginning, it was the time of the Corrective Maintenance, which follows a “run to failure” philosophy. Afterwards came the Preventive Maintenance, which follows some statistical theories to schedule the different maintenance intervals. And recently, with the new technology developments another method has appeared, the Predictive Maintenance. This method uses different tools to monitor the condition of the machine as it is shown in Tab. 4.1. And with the help of the provided information, the maintaining intervals are scheduled.

When visual inspection is first mentioned. It is said that this tool should be included in all maintenance routines. Also, the different process parameters should be checked regularly, because they give useful information about the current state of the process. One of the tools that must be considered is the vibration signature analysis, it would be helpful for monitoring the parts of the mold in charge of ejection and of the proper alignment. The borescopic inspections, which can be used to check surfaces that are not accessible to human eye, are also described. Other tools that are used to monitor the condition of the surfaces are the ultrasonic detectors and eddy currents. Another tool that can be used to measure the wearing is the tribology analysis, which give information about the condition of lubricants and wear. An acoustic emission analysis is helpful for the condition monitoring of the mold, especially for an early detection of fatigue cracks in different parts of the mold. Testing electrical insulation would not be useful for molds, considering that there are no electrical devices in the mold.

In the Fig. 4.8 is shown over time when the different methods detect the failure. On the y-axis is represented the functional capability of the machine, which is reduced over the time once the failure has appeared. The predictive domain is the period within that the failure must be detected and the maintenance interval is scheduled, during the failure domain it is usually too late to avoid problems in process quality. According to this figure, the most useful one is the ultrasound because the detection of the failure is the earliest, audible noise listening could be too late for the prevention of the failure because the failing piece may be too worn, and that can have affected to the process quality.

As it is mentioned before, to implement a predictive maintenance routine requires not only the selection of different predictive maintenance tools but also to develop an asset of crucial parameters to monitor the conditions of the machine. During the following sections of this thesis, the different problems that affect the molds are separated into distinct parameters. Afterwards, the tools that can monitor these parameters are selected to predict maintenance intervals of molds.

5. ANALYSIS OF MOLDS

5.1. Evaluate the conditions of the molds

In its simplest form, the injection molding process is like the operation of a hypodermic needle. A barrel contains plasticized plastic that is injected into a closed mold that contains a machined, reverse image of the desired product. This image is called cavity. The injected plastic solidified in the cavity. Afterwards, the mold is opened and the product is ejected [Bry98]. While this may seem simple, the process actually involves many individual activities and parameters that must be tightly controlled to produce a high-quality product at reasonable costs. Molds can be manufactured in many different materials like steel, copper or aluminum. Throughout this section, all the problems from the different systems of molds are going to be evaluated to give an idea of the parameters that are needed to monitor the current condition. [Bry98, Bry98, Thy01, PPT12, DKK+16, ZZH+14, Bry98, Pra14, NN95, CD93]

5.1.1. Alignment System

Within this section, all the possible problems that can happen with the instruments in charge of the proper alignment of the mold will be described. First, it is important to describe the Alignment System. This system is important for the standard operating of the mold, because molds are made of different pieces, which must be placed to achieve proper result. This system is a combination of different elements, usually screws, bolts, bushings and different rings, which will help the different plates to be properly placed. [Bry98]

There are some different methods, which ensure the proper alignment: Leader Pins and Bushings or Tapered Locks. With the Leader Pins and Bushings Method, the alignment task goes to different pins and bushings which are placed in the different plates to force them to be properly placed. In one half the pin is placed and in the other the bushings [Bry98]. In the molds, which have Tapered Locks Systems, some grooves are designed in the different plates to make the different pieces fit together in the proper position [Bry98]. Those methods could be also used together when the mold requires an extreme accuracy.

One of the first elements to be checked should be the precise alignment of the register ring. Any problem on the alignment of this element would affect the proper entering of the melted plastic in the cavity. Another important element to control is the centering bush, which will verify that the different plates, core and bottom plates, form the demanded cavity to produce the desired piece.

There are many factors that could affect the correct alignment of the pieces in the mold, but one of the most important are the thermal ones. The difference in temperature between the different pieces can produce some expansion in the pieces, which produce misalignments or even wear, if the mold is still working with these misalignments. Also on the injected parts failures can appear. [URL17b]

The thermal problems are not the only ones that can happen to molds, it is important not to forget others like: hanging, clamping and worn bushings.

Either way, any misalignment endangers the life of the mold, alignment components, delicate shutoffs, and the quality of the parts being produced. [Bry98, URL17b]

5.1.2. Filling System

The Filling System refers to all the different channels and gates through which the melted plastic flows. Usually there are two different types of channels, the sprue, which is the bigger one that brings the plastic into the mold, and the runners, that bring the melted plastic to the different parts of the cavity.

The most important failures that affect this system are: total or partial blockages of the channels. These blockages could appear due to many reasons, some of them are outlined here: Non-uniformly melted plastic, differential venting among the cavities, non-uniform cooling of the mold, hot-runner system, or hot tips, part design, particularly non-uniform wall thickness, lack of proper velocity control during filling, gates not all the same size, unbalanced flow path, laminar flow which can vary in the different channels [Bry98]

For that reason, it is necessary to inspect all channels that will provide the material to the cavities that must be filled looking for any sign of blockages. It is also important to check all the gates that allow the material to get into the cavities. Sometimes some molten plastic solidifies inside the runners or in the gates and cause blockages. [NDEH10]

Another problem which could happen to this system is that during the injection process a gate or a runner may stick to the sprue bushing and it may be difficult to release it from mold. That will bring a burr in the injected part but also a lower productivity efficiency. [Car11]

The main reasons for this are sprue taper surface not polishing enough, cutting mark around inner hole, using too soft a material, taper point area deformed or damaged after doing production for a while.

Some new injection molding machines have a heating system for the runners. For those systems, another failure for the mold could be a problem on that system, which could affect the injected polymer by contaminating it. Another problem for this could be that this system is not heating the injected plastic properly. [Bry98]

It is also important to take care of the different parameters that define the filling of the mold, pressure, temperature or injection speed of the polymer. An incorrect definition of these parameters or an alteration will cause problems to the different systems of the mold. Too high pressure or too high filling speed will produce a flashing in the cavity that will affect other systems. When those parameters are too low, it could produce an incorrect filling of the cavity or also that the polymer gets solidified earlier than in the cavity, which will produce blockages or even grooves to the surface of the channels if it is not detected early. These parameters are measured by the injection molding machine. [URL17g, BKLS17, Ber91, LWW16]

5.1.3. Cooling System

The cooling phase is considered as the most important for the injection process. It determines the rate at which the parts are produced. [Bry98] In the moment when the melted polymer is injected in the mold, the mold and the material should be at the same temperature for minimizing molding stress. Because of that, a cooling system is required. When this system is not working properly an incorrect form of the injected piece, surface cracks or different surface grooves or burrs can happen. [BD09]

In order to avoid failures in the ejected parts, a proper design of the cooling system is important, taking into consideration factors like the geometry of the part, the temperature of the mold before the process, the architecture of the cooling channels and the cooling liquid, which is usually water flowing in turbulent conditions [Bry98, NN]. Also, a correct running of the system must be guaranteed by monitoring the condition of the cooling liquid related to temperature, injection liquid speed or viscosity of the liquid.

A blockage on the cooling channels appears due to the settlement of some mineral materials on the walls of the channels. Those deposits happen because of differences in temperature and pressure [NN17b]. It is also important to take care of the corrosion of the different channels of the cooling system of the mold. Because of that a non-corrosive mixture is usually used as a cooling liquid, frequently a mixture of glycol and water [NN17a].

Another problem that affects this system is the leaking of cooling liquid of the channels. Those leaks could appear because of incorrect sealing of the different plates. This problem will not only cause many problems on the injected parts but it will also damage other parts of the mold. Stainless-steel molds are used in 10-20% of all molding jobs. These molds usually crack from corrosion not due to the molding operation but for leaks of water from the cooling system which contain chlorine which interact with the chromium, and with the help of stresses, cracks will be formed. [URL17o]

It is also important to take care of the condition of the cooling liquid flow, when it is turbulent, the heat transfer will be faster and more efficient. [MSS13, NN17a]

5.1.4. Ejection System

The Ejection System releases the injected parts once the molten plastic has solidified in the mold cavity. A good design of this system will affect the future quality and efficiency of the system. [Bry98] There are different styles of ejection systems, the most common one is with the help of pins. A stripper ring is commonly used for round parts and it is formed by a ring that has the same diameter as the part and which pushes the whole part out. The stripper can also be used as a square ring for square or rectangular parts. Stripper plates are used for larger parts and are the same size as the other mold plates. [Bry98]

It is important to guarantee the complete returning of the different pins, in the case of an incomplete returning, there will be still a part of the pin in the cavity which will be impressed in the injected part causing an important defect on the part. Another thing to take care of is the proper lubrication of the pins, bushings and other pieces in charge of the ejection of the parts from the mold. If inappropriate lubrication is used, the different parts will wear out much faster. [NN15]

With the analysis of this system, it is important not to forget the guiding system which will help to the proper ejection of the piece. This system will minimize the wear and the distortion during use, meaning that will not only protect the injected pieces but also the mold. But with the usage not only the guiding pieces but also the pins can be worn out because of the contact with the parts. [PB88]

It is also important to take care of the different parameters of filling the mold, a too high pressure at the filling time or a high filling speed will produce a flashing in the mold cavity which will result in the mold opening itself and this will damage the ejection system. It is also necessary to check out the current situation of the supporting mechanism of the mold, and also of the ejection system. An improper support will cause a faster wear in the ejection system parts.

Another possible problem to the ejection system will be an inappropriate opening of the mold which does not allow the part to fall out of the cavity. This problem must be detected and solved as fast as it occurs, because in case it is not, it will damage the surface of the cavity and other cams involved in the injection of the part. [Höö, Bry98, NN15, PB88, RRR00]

5.1.5. Wearing on the Cavity Surfaces

The wearing of the cavity surface reduces the quality of the injected part. Because of that it is important to ensure the surface is not damaged and properly polished [MCSB11, CL14].

If the mold is closed on foreign objects such as inserts, tools, nuts, screws, broken ejector pins, etc., caught between the parting line surfaces. In many cases the smallest bits of foreign objects cause the greatest damage, especially if they are caught at the cavity edge. These small bits are not detected by properly set low-pressure closing protective devices. Clamping on a tiny object, even if it is a plastic granule, concentrates the entire press clamp tonnage on this very small area—exceeding the elastic limit of any mold material regardless of quality and hardness. Other possible damage of the cavity surface can come because of the result of objects like screw drivers, knives or cutters used to assist in the removal of sticking parts, flash, short shots etc. from non-automated molds. [NN15, URL17e]

Another reason for a damaged surface is result of contact with water or non-plated surfaces. Water forms in the molds from condensation, seepage through porous metals, leaky pipe fittings and “O”-rings. Careless handling of hoses and feed lines during hook-up leaves water on the mold surface. This is not harmful if detected immediately and carefully removed. Corrosion is progressive and even if the molds are stored after being sprayed with an antioxidant, a few drops of water or condensation can cause tremendous and costly damage. Another possible reason of damage on the surface is the attack from acids after exposure to corrosive materials which may form when some thermoplastics are decomposed by over-heating. Overheating can occur in the plasticizing cylinder, the hot runner system or in the-mold cavities, as the result of too small gates, inadequate venting or cooling systems. Furthermore, is important not to forget mistakes in mold installation, continuing to produce in a malfunctioning machine, continuing to operate a mold which has started to squeak or squeal will result in damage. Damage will be done to molds that refuse to close or open normally or will not eject properly if their operation is allowed to continue without ending the problem. An alert and well-trained foreman can hear trouble starting as he passes through the molding room. The aforementioned types of mold damage are not limited to the pressroom. Tool-room technicians contribute their share by the improper assembly of molds, failure to tighten screws, leaving metal chips, grinding dust or polishing abrasive on or near sliding surfaces. But usually fatigue is the major cause of mold damage which leads to a breakdown of those mold components that are subjected to the maximum stresses while cycling correctly over long periods of time. This usually occurs, if it is going to occur at all, between 100,000 and 300,000 molding cycles. In a multiple-cavity mold, components identical to those that break first may last infinitely longer. Fatigue can manifest itself in components subject to compressive loads as well as those in torque, tension, or bending. [URL17e, Bry98]

5.1.6. Venting system

When an injection mold is closed up in preparation for receiving molten plastic, the cavity is full of air. This air needs to be removed from the cavity by using pressure, it is for that that so much of the injection pressure is needed. The air from the cavity is going to escape through these channels. If the air cannot be removed many important quality problems in the part could be caused. [Bry98]

Obstruction on them will make defects on the injected parts, because of an insufficient removing of the gas from the cavity, which will require much more injection pressure that it is defined [Gor10, Ree01].

5.2. ***Uses of the Predictive Maintenance Tools for Monitoring the Critical Condition of Molds***

In this section, the different predictive maintenance tools described in *section 4.3* are related to the distinct parameters that monitor the problems that appear in molds during injection molding, which are described in *section 5.1.* Usually more than one tool can be used for the prediction of the maintaining necessity, but there is always one option that fits better with the necessities of the plant because of reliability, detection time or any other reason. During this section, all these solutions are explained.

First, the problems related to mold misalignment are going to be mentioned. There are distinct parameters to monitor the condition of the alignment system, position, temperature and vibrations. There are many different options for their detection. To monitor the position of the distinct plates and bushings, a visual inspection can be needed, but with the help of this inspection, the failure in the position will be detected usually in the fault domain. Another option to monitor position is by using position sensors. This tool monitors the position during the running production process, if there is any change in the detected position, the operator is notified and will react to the failure. If the failure is not corrected then the pins and bushings that are affected by the misalignment wear out faster. Another parameter that must be monitored is the temperature of the distinct parts of the mold. To monitor this parameter the infrared imaging provides information about the temperature of the different pieces of the mold which helps on the detection of any difference which is big enough to produce misalignments because of the thermal expansion.

To monitor the vibrations the operators can use vibration signature analysis. This tool monitors the vibrations produced by the machine while the process is running. Whenever there is a change in the amplitude or frequency, that will be the signal of the birth of the misalignment problem. The differences in the vibrations will affect the quality of the injected piece and also the wear of the distinct parts of the mold so it is up to the desired quality to decide when this vibration is different enough to change the worn pieces. The different vibration will become bigger with the time while the misalignment increases. With the help of this tool the failure is detected during the early stages of the predictive domain as it is shown in Fig. 4.8.

Problems related to the ejector system are going to be presented. As mentioned in *section 5.1*, the critical parameters to monitor this system are the positions of the ejector pins, false opening, flashing in cavity and vibrations. For the detection of flashing the injection pressure and temperature must be monitored. If the injection pressure is bigger than the designed pressure, that can produce flashing in the cavity. If the injection temperature is higher than the designed temperature, that increases the viscosity of the plastic liquid which also can produce flashing in the cavity. To monitor the right placement of the distinct ejector pins, some position sensors can be used. Those provide information about the placement of the ejector pins, and whenever the route is not as designed, the operator is warned. To monitor the movement of the ejector pins, vibration signature analysis can also be used. This method provides information about the frequency and amplitude of the movement. Whenever a change in those parameters occurs, the movement of the ejection system is not the same as designed and this wears down the ejection pieces. To monitor the false opening of the mold a position sensor provide the information about the placement of the ejection pins, when those are not properly placed, the operator is warned and can react to that. If the opening is big enough to allow the ejection of the injected part, then it is not a crucial failure and there is no need to schedule a maintenance interval. But whenever this opening is not big enough, the external sensors will not allow to close the mold, to avoid failures in the cavity surfaces, and because of that the maintaining interval must be scheduled just before it happens. To monitor the false opening and the position of the ejector pins, a visual inspection can be also used, but with the help of this tool the failures will be detected during the fault domain as it is shown in Fig. 4.8 and then is usually too late.

To monitor the problems related to the filling system it is important to look for leaks, blockages, problems in the heating system of the runners and filling parameters. The temperature and pressure of filling are given by the injection molding machine. If the temperature is lower than that for which it is designed, the likelihood of a blockage increases because the viscosity of the fluid becomes lower than designed. If the injection pressure is lower than the designed injection pressure, it also increases the likelihood of a blockage because the fluid flows slower. For the detection of leaks and blockages, the borescopic inspection can be used. With this optical tool, the operators can check the condition of the distinct channels, but this inspection requires a stoppage in the process. Another tool for the detection of both problems could be infrared imaging. This tool provides information about the different temperatures of the mold, while the process is running. If there is any blockage or leak, the temperature of the mold will differ from the temperature without any failure. In the case of a blockage, the areas nearby the blocked channel between the blockage and the cavity will be cooler as they are without any trouble. And the areas in the channel before the blockage will be warmer. In the case of leaks, the areas around the leak will be warmer than if there was no failure. To monitor the heating system that some molds have near the runners, the operator must pay attention to the temperature of the heating liquid. This temperature must be within the design limits to ensure that the polymer has the right properties. Another parameter to monitor is the pressure of the heating liquid, if this pressure is higher than the design pressure, it is because a blockage is taking place in any of the channels. And if the pressure is lower, it is because the heating channels are leaking. These leaks must be found as soon as possible, to prevent the corrosion of the mold due to the heating liquid. To find the leaks the operator can use a borescope or an ultrasonic detector. The ultrasonic leak detector will be faster in the detection of the leaks as Fig. 4.8, where the fastest tool for the detection of failures is considered. This tool measures the ultrasonic sounds produced by the liquid going through the leak.

To monitor the condition of the cooling system there are some parameters which are considered crucial. To check the proper condition of this system, it is important to ensure that there are no leaks, no blockages, and that the temperature is low enough to cool the injected part. To ensure that there are no leaks, an ultrasonic leak detection can be used. But this method is easier to use while the process is not running, and because of that this method can be used to find the leak whenever the operator knows that there is a leak in the channel. Another option for the detection of leaks is to use a borescope, but this method also requires, that the process is not running. Another tool that can be used for the detection of failures in the cooling channels is to monitor the pressure of the cooling liquid. This pressure will be lower whenever there are leaks in the channel and will be higher when there are blockages. This pressure monitoring can be used while the process is running. Infrared imaging can provide information about the condition of the cooling channels. The provided images will have different temperatures distribution if any failure is taking place in the cooling channels. Some areas will be cooler and others warmer depending on where the leaks or blockages take place. Also with this tool differences in temperature between adjacent pieces are detected, and leaks produced by a distinct thermal expansion between the pieces can be easily discovered. Monitoring the temperature of the cooling liquid is important to ensure that the cooling liquid still has the property to cool the injected part. When this temperature is higher, the heat transfer is slower and the cooling system might not be able to cool the part properly.

The problems that can occur in the venting system are related to blockages in the venting channels. For the detection of blockages distinct tools can be used. A borescope can be used to monitor the condition of the venting channels. This optical tool can provide information about the condition of the channels but it requires the process to stop running. Another tool which can be used for the detection of blockages is the ultrasonic inspection. This tool use two transducers, placed perpendicular to the channel one on each side, one of them sends a pulse echo and it will be reflected back by the other transducer. The presence of blockages in the venting channel is detected by changes in amplitude of the echo. This tool can be used while the process is running. To check the condition of the venting channels can also be done by monitoring the pressure in the mold cavity. When the pressure, it is higher is because there is a blockage in one of the venting channels.

To monitor the condition of the surfaces of the mold, it is crucial to obtain a good quality in the injected parts. Problems in the surfaces can be easily detected by visual inspections when the mold is opened, but this method requires the stoppage of the process. Also, a borescope can be used in the case that the surfaces are not accessible to the operator's eyes. But this tools also requires that the process is not running. These two methods are both in the fault domain in the Fig. 4.8, which means that it might be too late when the failures are detected. Another tool that can be used is to monitor the roughness of the injected parts [MCSB11]. These measurements can be done, in a previous injected part, while the process is running. The operator gets information about the quality of the injected part, and whenever this quality is not within the threshold, the surfaces of the mold must be maintained.

To prevent corrosion, it is important to try to avoid temperatures in the cavity higher than the design temperature because some acids can form after the de-composition of some polymers as mentioned in the *section 4.5,* and also the corrosion due to chlorine reaction with the steel from the mold occurs when the temperatures are high. Another parameter which can be monitored to prevent the corrosion, while the process is running, is the pH from the cooling liquid. It must be as low as possible to minimize the presence of chlorine in the cooling liquid.

All that information is summarized in Fig. 5.1 but, because of several reasons, such as investment costs or detection times, some of those tools are turned down.

5.3. **Creation of a Conceptional Design to predict Maintenance Intervals based on Determined Parameters during a Running Production Process**

After establishing relationships between the tools for an early detection of the problems and the problems throughout *section 5.2*, the optimal tools that should be used in the mold to predict the ideal maintenance intervals should be described.

Monitoring process parameters give crucial information about the current state of the different systems of the mold. The temperature, pressure and speed of the feeding polymer are monitored and should be checked regularly by the operator to ensure that the designed parameters are reached and not overtaken. By monitoring the pressure and the temperature of the cooling liquid, the detection of failures in this system is possible. As mentioned in *section 5.2* if the detected pressure is higher than the designed pressure, that is a symptom of a blockage in the cooling system, and if it is lower, that is a symptom of leaks.

One tool that should not be forgotten is the vibration analysis. It is usually used for an early detection of mechanical problems, and because of that it has been mentioned during *section 5.2*. All the different plates of the mold move at different frequencies. With the help of some piezoelectric sensors which should be located on the moving parts and also some computer programs, the operators will be able to monitor frequency and amplitude of all those movements. It will be important to monitor the movement of all the plates which are in the movable part of the mold. The computer programs which receive the measures are called spectrum analysis and can differentiate between all the vibrations that take place in the mold, and give information about the frequency and amplitude of the vibrations. If a change on these analyzed parameters takes place, the operator will know where to look and what part of the mold needs maintenance. As it is mentioned in *section 5.1*, problems related with misalignment, and guiding will be detected early on with the vibration signature analysis. Taking into consideration Fig. 4.8 with the help of this tool problems are detected much earlier than with other predictive maintenance tools. Because of that it must be included in all maintenance routines for molds.

Infrared Imaging is another helpful tool that should be included in all mold maintenance routines. With the information obtained through this method attached to the obtained through other methods, the operator knows the current situation of the mold. This method should be used to obtain information about the condition of the cooling system, but also any problem in the filling system can be detected with the thermographic analysis. If a part of the mold is warmer or cooler than it should be, then a problem is taking place either in the cooling system or there is a blockage in the filling system. After the detection of the improper temperature in the mold, the operator must decide, considering the current information from the process parameters, what measures must be taken to identify the cause of failure and correct it. Those measures can be to use a borescope, while the process is not running, to inspect the sprue and runners of the mold or the cooling channels. It is also possible that the required action is to inspect the sealed condition of the cooling system looking for leaks with an Ultrasonic Leak Analysis or any other action that can be related to those two systems. The thermographic inspection must also be included in all maintenance routines, because it is a helpful tool for the monitoring of the condition of the mold.

It is also important to perform regular inspections on the mold surfaces, either in the cavity or in the different channels. Surfaces can be damaged in many ways as is explained in the *section 5.1*. As it is mentioned before, to ensure the right condition of mold surfaces it is crucial to obtain good quality on the injected parts. These inspections can be done either by the human eye when the mold is opened or maybe they require other inspection tools like borescopes if it is not possible for the human eye to properly see some surfaces inside of the mold. These failures in the surface should be detected early to prevent failures in the injected parts. But both methods require that the process is not running, and because of that the method that should be used to monitor the condition of cavity surfaces is to measure the roughness of the injected parts. The roughness of the parts increase with the number of cycles. The roughness should be measured, using a profilometer, every certain amount of cycles depending on both the mold material and the injected material. These measurements give an idea about the current condition of the cavity surfaces, and provide useful information to the operator to predict the maintaining intervals.

Another system that should be used is a system to measure the current situation of the venting channels. As mentioned, this system provides a constant pressure to an empty mold and afterwards can measure it with a gauge, and can give the operator an idea about the condition of the venting channels. If there is any blockage, the provided pressure increases. Subsequently, a maintenance process must be scheduled.

These different tools shown in table 5.1, are considered crucial for all predictive maintenance routine that want to be implemented to molds. With the described tools, the operators are able to monitor the condition of the mold, and could react earlier to some of the most important problems which occurs to molds.

	Alignment System	Ejection System	Cooling System	Wear	Filling System	Venting System
Vibration Signature Analysis	x	x				
Thermographic Inspection			x		x	
Roughness Measurements				x		
Borescope Inspections			x	x	x	x
Process Parameters					x	
Pressure Measurements			x			x
Position Monitoring		x				

Table 5.1: Selected tools to monitor the different mold systems (Tab. 5.1)

6. CONCLUSIONS AND PERSPECTIVES

Different maintenance methods have been developed throughout history. Beginning with the corrective maintenance at the beginning of the industrial revolution up until the predictive maintenance which is based on taking advantage of the most recent technological developments to monitor the condition of the machines. The objective of the thesis is to design a predictive maintenance routine for injection molds.

To define a predictive maintenance routine, it is necessary to determine an asset of parameters which can be monitored and to describe the current condition of the mold while the process is running. To determine these parameters, it was required to research literature on the different problems that affect the compounds of molds and to reduce those problems to diverse parameters that can be measured using distinct tools. The developed asset of parameters includes, vibrations from the mold plates, which provides information about the condition of the alignment system. Also, some position information about critical parts of the ejection system, which ensures that the ejection movements are following the right route. Furthermore, distinct pressure and temperature information from the filling of the polymer and the cooling liquid, information on the current state of the venting channels and lastly some information on the condition of the cavity surfaces were all researched and included.

Another literature research was required to describe different maintenance tools, each of them allows the detection of a certain parameter. Once the parameters were described, it was necessary for the parameters and the distinct tools to be related. Some of those parameters can be monitored throughout different tools, but some of the tools are preferably used because the detection time is earlier or the required investment is lower.

During this thesis, some tools have been selected to monitor the condition of molds, they require the use of distinct technologies, that can measure amplitude and frequency of vibrations, can develop an infrared image of the mold, and sensors that can monitor position, pressure and temperature. Whenever those parameters are not within the design limits, a maintenance interval must be scheduled. To monitor the cavity surface condition, it is easier to measure the roughness of the injected part and if it is not within the limits then a maintaining interval is scheduled.

In future researches, these technologies should be implemented in an injection molding process to be able to define a threshold, where despite having an incipient failure, the process can still continue obtaining the desired results. This threshold varies depending on mold characteristics, desired quality and injected polymer.

In the future new technologies to characterize the mold parameters will be developed, and the existing one will be re-developed to obtain more critical information earlier. Also, some of the existing tools are not worth implementing right now because such little information is obtained for such a big investment, it may become cheaper and then it will be worth implementing. Also new technologies and sensors will be developed, and with them the exact situation of the surfaces of the molds will be able to be known earlier and without opening them. Other sensors will be developed or redeveloped to fit with the necessities of size, temperature resistance, etc. that will allow better options for the condition monitoring of molds.

7 ABBREVIATIONS

Abbreviations	Meaning
OEE	Overall Equipment Effectiveness
MTTF	Mean Time to Failure
TPM	Total Productive Maintenance
ECT	Eddy Current Testing

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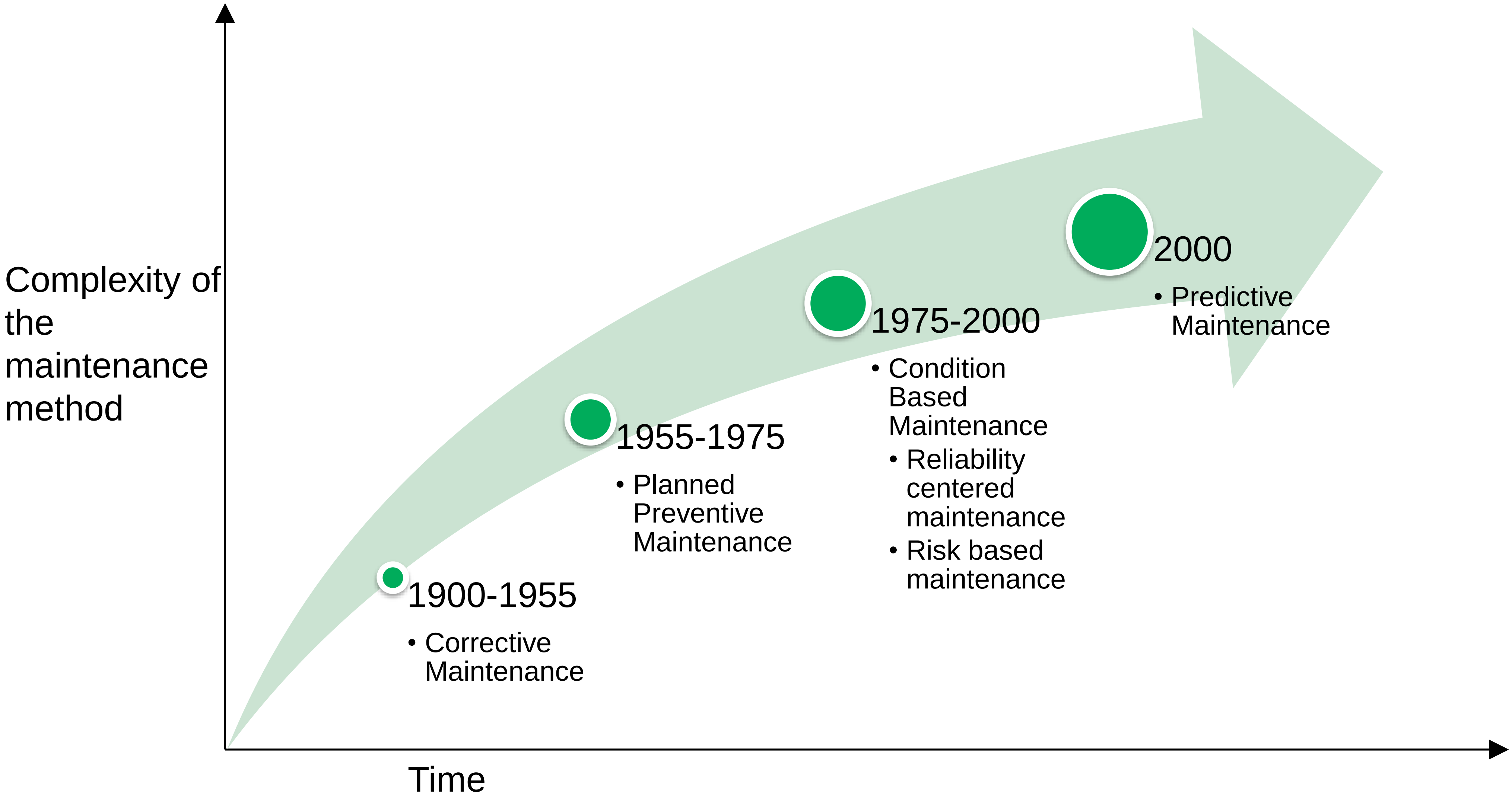
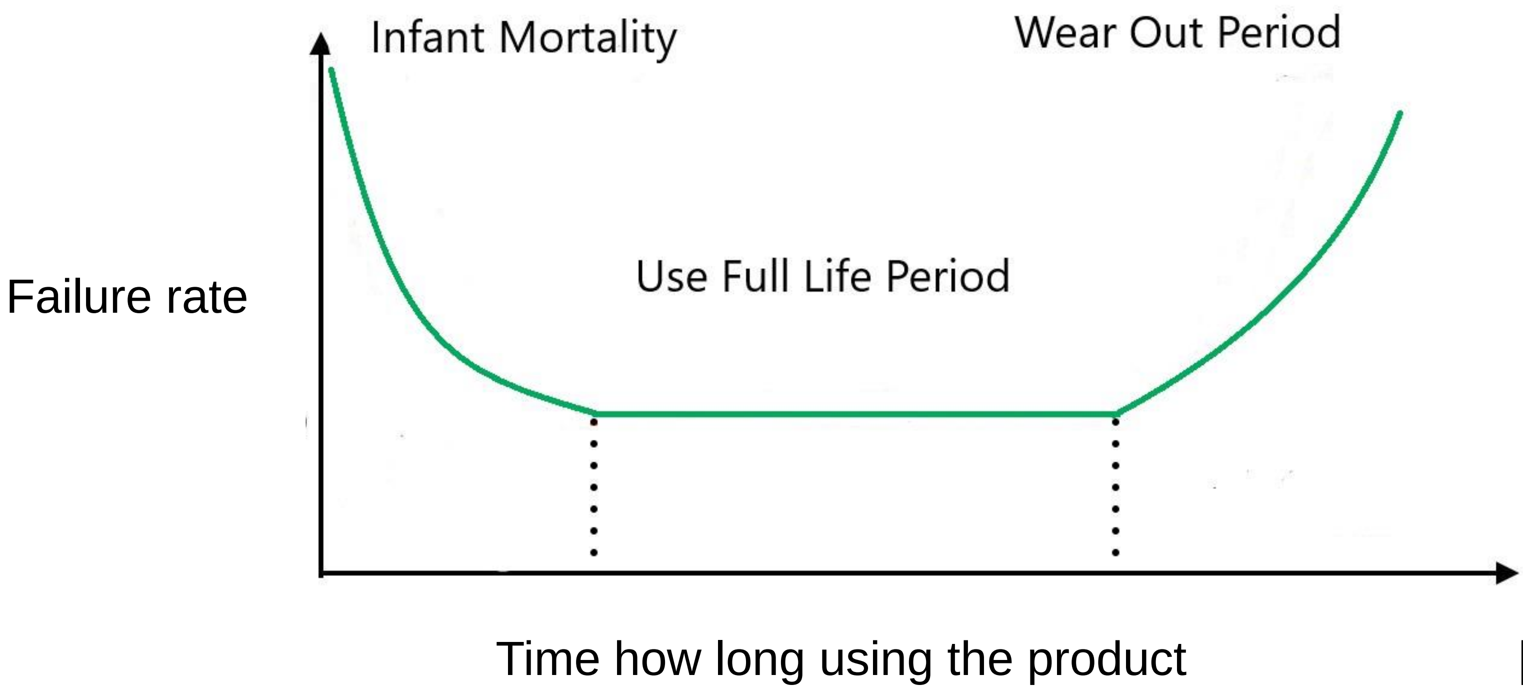
Evolution of Maintenance (Fig 4.1)

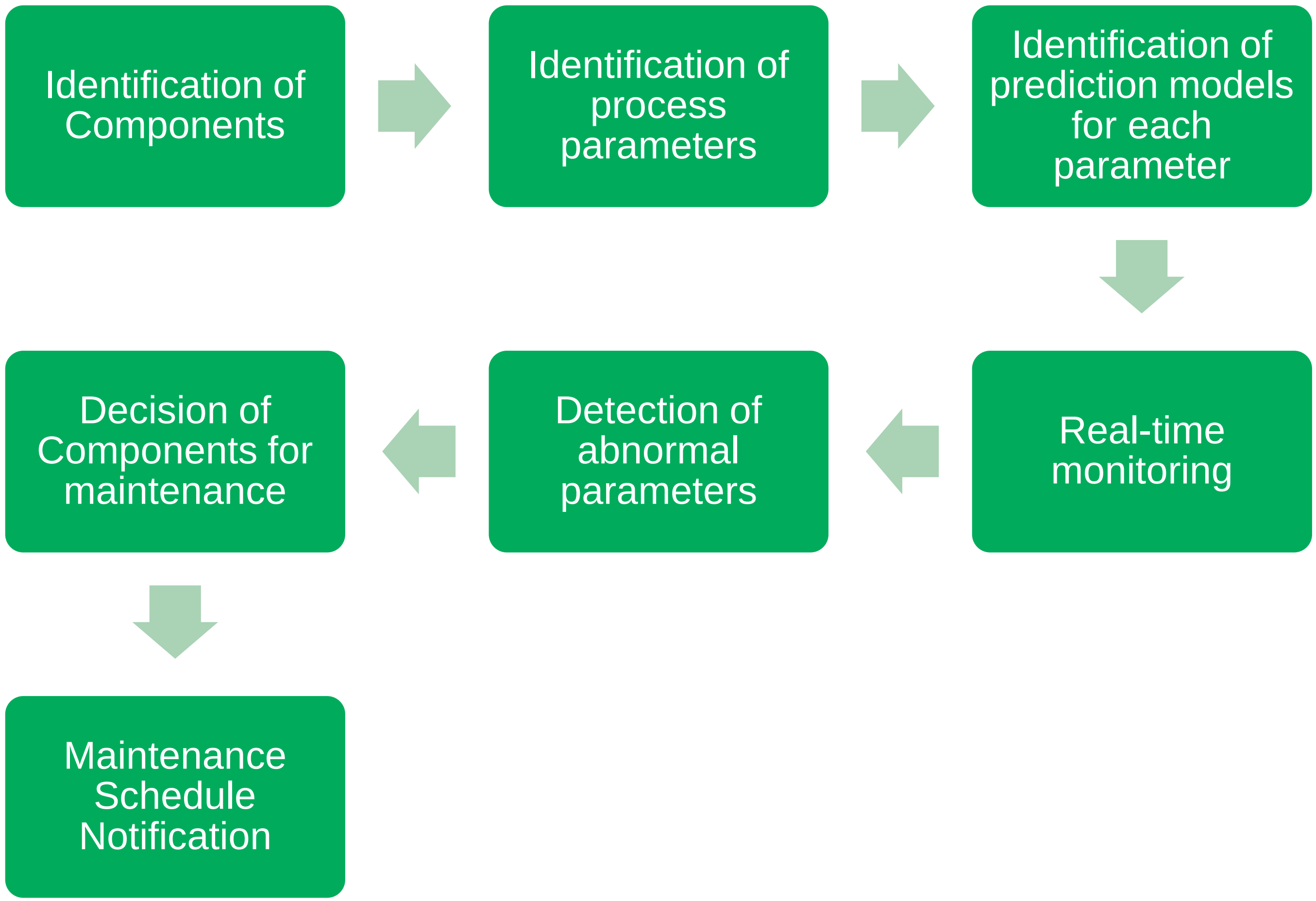


Bathtub Curve (Fig. 4.2)



[SPMH10]

Predictive Maintenance Approach (Fig 4.3)



[PMDB16]

Comparative between Preventive and Predictive Maintenance (Fig. 4.4)

Preventive Maintenance

Main objective

Statistical methods schedule the maintaining intervals

Pros

Less complex to coordinate

Cons

Some **useful life** from the maintained pieces can be **wasted**

Predictive maintenance

Main objective

Condition based maintaining intervals

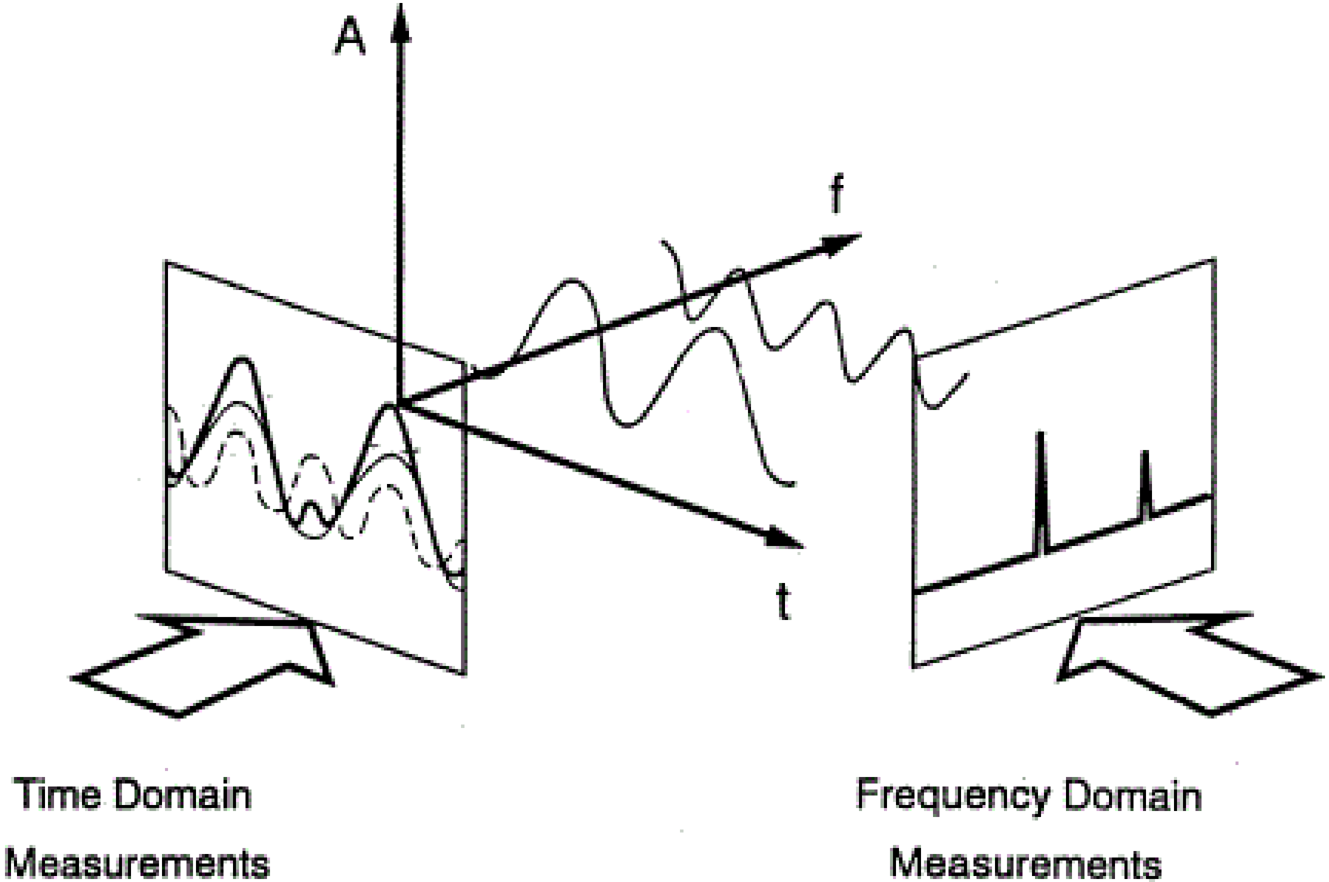
Pros

Maintenance is done **when required**

Cons

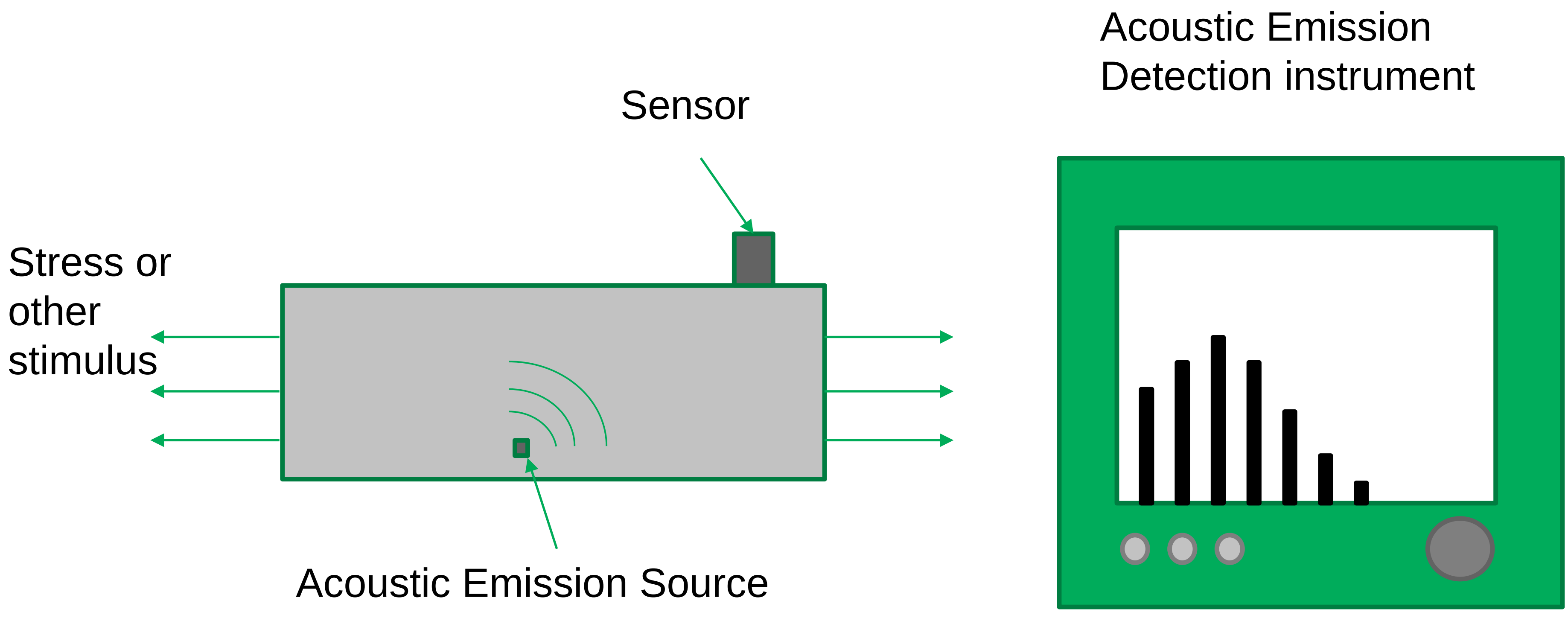
High initial **capital investment**

Vibration Signature Analysis: Time and frequency domain (Fig. 4.5)



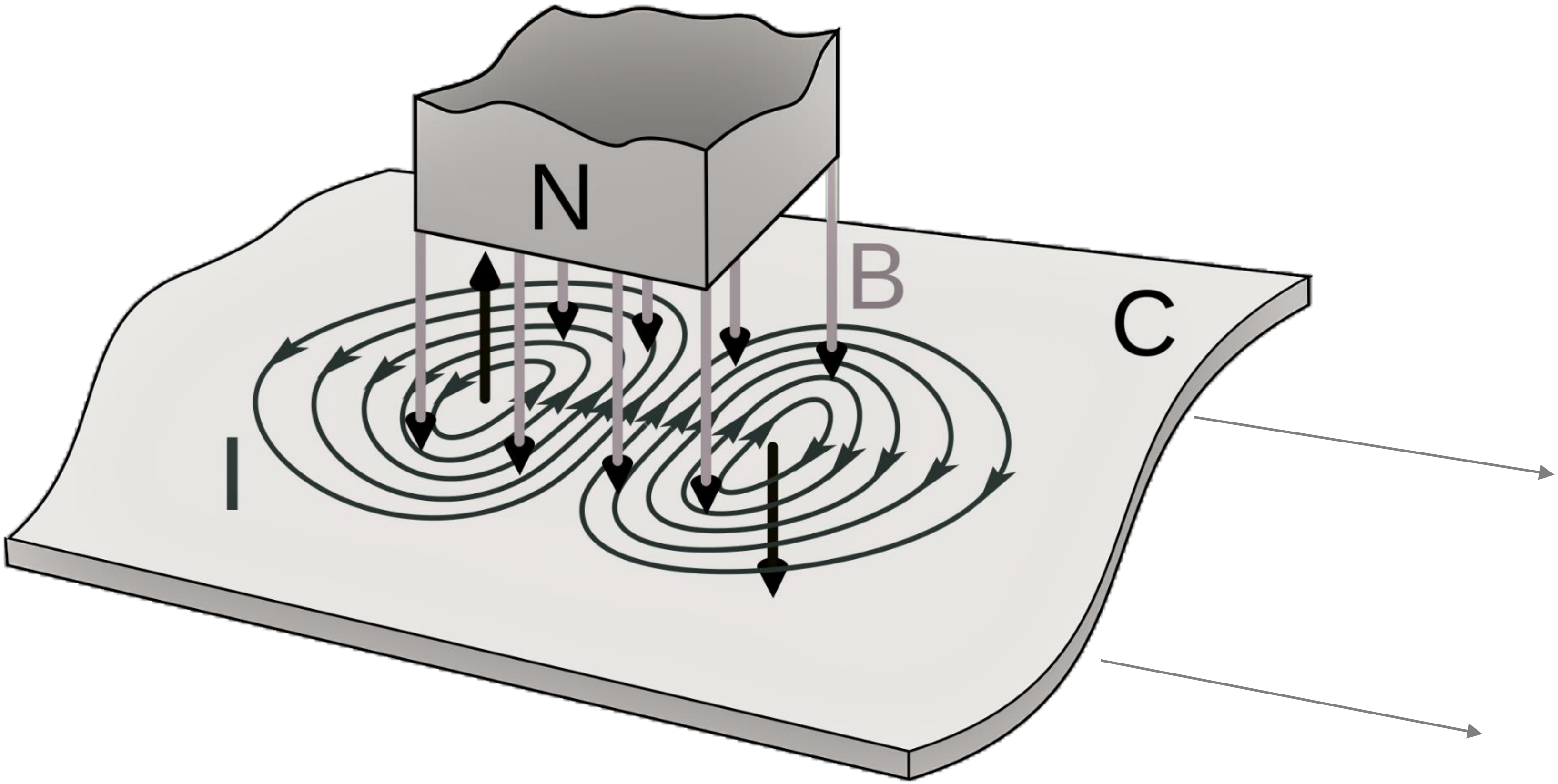
[Bec08]

Principle of Acoustic Emission (Fig 4.6)



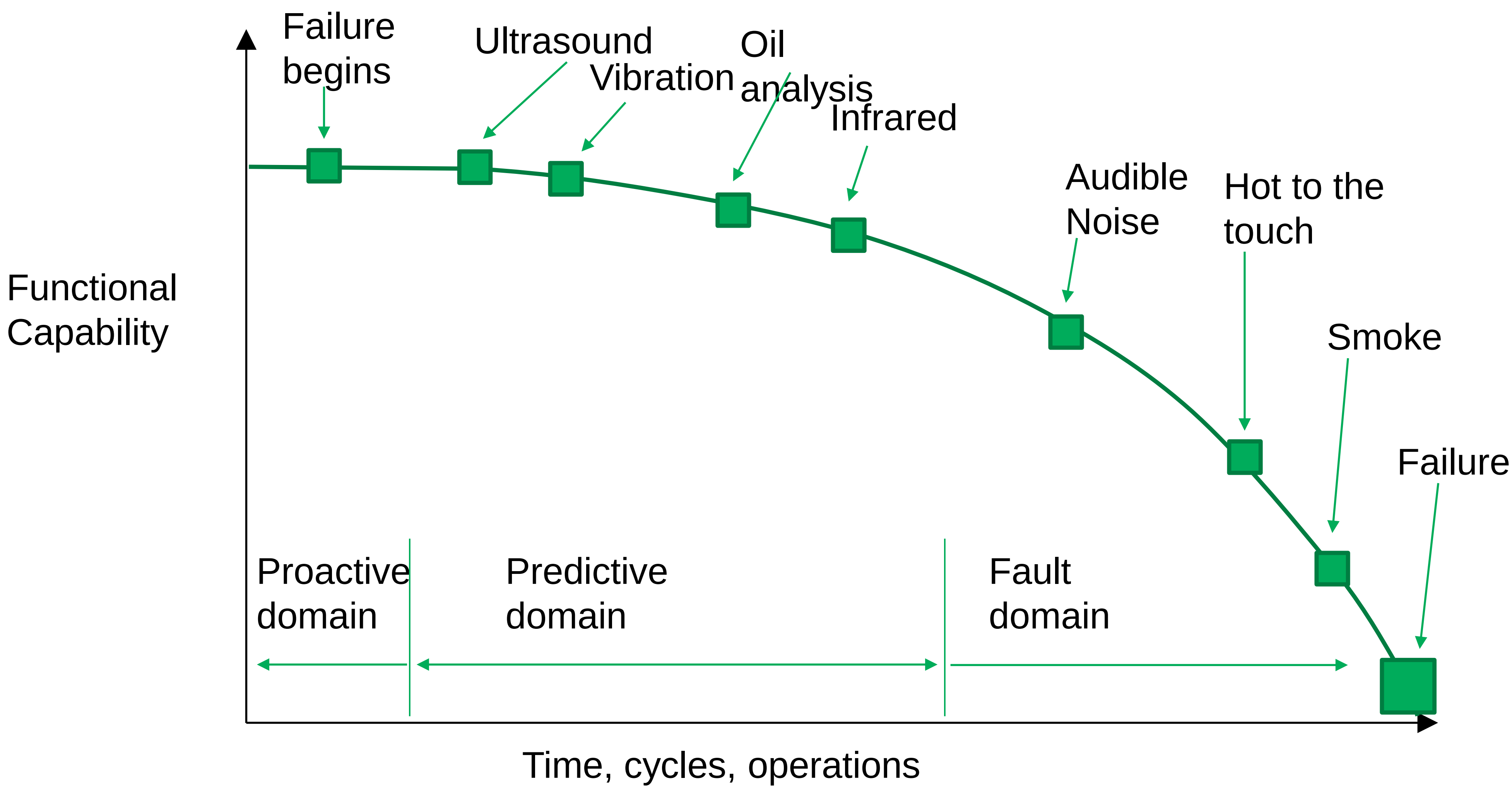
[Hel01]

Principle of Eddy Currents (Fig 4.7)



[URL17p]

Relation between the detection of the failure and the time (Fig 4.8)



Maintenance Tools Applications in Molds (Fig. 5.1)

Alignment System
- Visual Inspection
- Vibration Signature Analysis
- Thermographic Inspection
- Position monitoring
- Borescope Inspections

Ejection System
- Visual Inspection
- Vibration Signature Analysis
- Borescope Inspections
- Position monitoring

Cooling System
- Visual Inspection
- Thermographic Inspection
- Ultrasonic Leak Detectors
- Borescope Inspections
- Process parameters

Wear
- Visual Inspection
- Borescope Inspections
- Liquid parameters
- Roughness measurements

Filling system
- Visual Inspection
- Thermographic Inspection
- Ultrasonic Leak Detectors
- Borescope Inspections
- Process Parameters

Venting System
- Visual Inspection
- Ultrasonic detection
- Borescope Inspections
- Process parameters