Chapter 5

Condition based maintenance - industrial practice

5.1 Introduction

The aim of this chapter is to examine whether a number of common assumptions found in the literature on the way condition based maintenance systems are designed and implemented can be supported by empirical evidence. Condition based maintenance (also referred to as predictive maintenance) is a program that recommends maintenance actions based on condition monitoring information (Jardine et al., 2006). This information has to be strongly correlated with the onset of failure, and a certain threshold value should be identifiable that indicates the need for intervention (Tsang, 1995). Most of the research done in the area of condition based maintenance addresses only the technical aspects, with most of the papers covering mathematical approaches to a certain specific problem (Garg and Deshmukh, 2006). Hardly any empirical evidence was published so far on the managerial aspects of designing and implementing condition based maintenance technology. We have attempted to fill that gap to some extent.

Relevant empirical research on manufacturing and general maintenance technology has been done by Meredith (1987) and Hipkin and Lockett (1995), among others. They formulated postulates based on the existing literature and examined these in multiple case studies. We have followed the same methodology. Based on a well-known conceptual framework on the management of technology (e.g. see Carrillo and Gaimon, 2004; Gaimon, 2008; Meredith, 1987) we have developed three categories of postulates: (i) technical systems, (ii) managerial systems, (iii) workforce knowledge. It is generally accepted that in the management of technology, careful attention to each of these categories is of paramount importance (Gaimon, 2008).
Our focus on the process industry is for two reasons. Firstly, process industry firms work with high capital investments and large expenses for downtime, availability and reliability. This in turn puts pressure on the maintenance function and causes the need for advanced maintenance technology and practice (Arts et al., 1998; Ketokivi and Jokinen, 2006; Tan and Kramer, 1997). Secondly, empirical research in this area is limited to date (Van Donk and Fransoo, 2006). In line with Swanson (2003), and based on our own preliminary knowledge of this industry, it can be expected that condition based maintenance is an important maintenance concept in dealing with these high demands on availability and reliability.

This chapter proceeds with definitions, typical steps and a typology of condition based maintenance (§5.2). In §5.3 the theoretical framework with eight postulates is presented. §5.4 outlines the methodology. §5.5 and §5.6 discuss the five case companies and the results of the study. Each theoretical postulate is compared with the case data and analyzed. Some postulates were supported by the empirical findings, whereas for others, limited or no support could be found in practice. The chapter finishes with a discussion and conclusion section (§5.7).

5.2 Condition based maintenance types and processes

In the last decades a huge body of literature has emerged on different types of condition based maintenance models. There are two classes of tasks: diagnosis and prognosis (Jardine et al., 2006).

5.2.1 Definitions, typical steps and typology

The goal of diagnosis is to detect the failing component and its failure mode. Diagnosis is done after a certain measurement indicates a potential problem, being it component failure (so-called posterior event analysis) (Jardine et al., 2006) or some other abnormity (Venkatasubramanian et al., 2003a). Prognosis means predicting the remaining useful life of a component, or estimating the probability that a component can still function before failure occurs (Jardine et al., 2006). Both diagnosis and prognosis will result in a maintenance intervention, ideally with a minimal time gap between the intervention and the estimate of the time of actual failure. Machine components can then be patched, overhauled or replaced depending on the state of the component, availability of spare parts and other variables. The execution of condition based maintenance typically consists of the following four steps:
1. Data collection. The relevant data is collected (offline or online) through the use of process control systems, vibration measurements, oil sampling, and other methods. The two most common data types are failure data and process data (Veldman et al., 2011). Failure data, such as vibration indices or the amount, type and size of metal particles in lubrication oil, are direct expressions of the failure mode of a component (Jardine et al., 2006). Process data relate to the output characteristics of the component (e.g. pressure, flow, temperature) and can only be used indirectly to identify the failure mode (Tsang, 1995).

2. Data analysis. Depending on the situation, the data needs to be cleaned; for example, during startups and shutdowns the plant may exhibit erratic behavior, which is not to be misinterpreted as failure. The data can be analyzed in several ways, for example by direct comparison with a threshold or by looking at trends or other remarkable behavior. Two types of models are generally used for this purpose: analytical and statistical models (Jardine et al., 2006). Analytical models are cause-effect type of expressions of failure, whereas statistical models need historical data to calculate the probability of failure, along with its expected time to failure. Relating the process data-failure data dimension to the analytical model-statistical model dimension yields a typology of condition based maintenance types, see figure 5.1.

3. Decision making. Based on the data and the analysis, a decision is made. Such a decision may involve a change in operating routines or the direct execution of a maintenance task. It may also lead to additional data collection and analysis.

4. Implementation. When a decision has been made, an intervention is planned. After the intervention, reports can be made and stored for future maintenance actions. Evaluations are conducted when deemed necessary.

### 5.3 Postulates

#### 5.3.1 Technical system postulates

*Postulate 1. Process companies apply more diagnosis than prognosis in their condition based maintenance programs.*

Many condition based maintenance review papers describe diagnosis and prognosis applications applicable in the process industry (e.g. Heng et al., 2009; Jardine et al., 2006; Kothamasu et al., 2006; Koochaki et al., 2008;
Figure 5.1. Matrix of condition based maintenance types (Veldman et al., 2011).

Veldman et al., 2011; Venkatasubramanian, 2005; Venkatasubramanian et al., 2003a,b,c). Examples are oil analysis, vibration analysis, thermographic analysis and the use of process monitoring. However, it was recognized that prognosis was far less developed and used in practice than diagnosis (Heng et al., 2009; Jardine et al., 2006; McKone and Weiss, 2002), and nearly all publications on actual industry cases appear to describe diagnosis rather than prognosis (Garg and Deshmukh, 2006). Reasons for this could include the stochastic nature of the manufacturing system, complexity of the available models (often developed in academia) and a limited use of operating and reliability data (Heng et al., 2009; Jardine et al., 2006).

_**Postulate 2. Process companies make extensive use of information systems and specialized software in their condition based maintenance programs.**_

Process companies are reported to rely on specialized software to diagnose failure, predict remaining useful life or the probability of failure within a certain time interval (Campos, 2009; Jardine et al., 1997; Kothamasu et al., 2006; Lin et al., 2004; Tsang et al., 2006). Mobley (2002) stated that the software program provided with each condition based maintenance system is the heart of a successful program. In the process industry, companies also make use of their own process control and monitoring systems for condition based maintenance (Mobley, 2002; Sharif and Grosvenor, 1998; Tsang, 1995). Garg and Deshmukh (2006) described that maintenance information systems, widely used for maintenance execution processes, are not used in practice for condition based maintenance tasks.

### 5.3.2 Managerial system postulates

**Postulate 3. Process companies make use of third parties for specialized condition based maintenance tasks.**
A recent trend in maintenance management is the outsourcing of activities (Garg and Deshmukh, 2006; Hui and Tsang, 2004; Murthy et al., 2002; Persona et al., 2007; Pinjala et al., 2006; Pintelon and Gelders, 1992; Pintelon et al., 2006; Tarakci et al., 2009; Tsang, 2002), although this is not always without risk. Tsang (2002), for example, noted that the loss of plant knowledge and skills is a significant issue. Companies may choose to outsource for various reasons, such as lack of resources, skills, facilities and capacity. In the process industry, diagnosis or prognosis tasks are often outside the scope of the maintenance department due to the specificity of the techniques or knowledge needed. Also many original equipment manufacturers include condition based maintenance tasks in their service offering. It is for those reasons that many companies outsource (at least part of) their condition based maintenance tasks (Carnero, 2006; Persona et al., 2007).

Postulate 4. Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.
Whereas we expect that process companies outsource specialized condition based maintenance tasks, they generally carry out much of the remaining work. Recent maintenance literature clearly shows that the maintenance department cannot function in isolation of other functions. In particular the tight linkages with the operations function are described as very important (Al-Najjar and Alsyouf, 2004; Alsyouf, 2007; Jonsson, 1999, 2000). The reason is quite straightforward: a manufacturing firm can produce according to its goals (e.g. high quality, low cost, short lead times etc.) in a predictable way, only to the extent the plant allows it. This requires well-maintained plants with high levels of reliability and availability. In the development of the relationship between maintenance and operations, the position of the maintenance department in the organization and the assignment of responsibilities for condition based maintenance tasks are important (Carnero, 2004; De Groote, 1995; Pinjala et al., 2006; Pintelon and Gelders, 1992; Swanson, 1997; Tsang, 2002). The level of (de)centralization is debated in the literature (e.g. Pintelon et al., 2006). Beebe (2004) strongly suggested the use of team structures to retain ownership of the plant and plant knowledge. This practice is also proposed by Mobley (2002). For obvious reasons a key feature of such autonomous units may be the tight linkages with other departments such as operations (McKone and Weiss, 2002; Swanson, 2003; Waeyenbergh and Pintelon, 2002).

Postulate 5. Process companies make use of strict procedures to execute their condition based maintenance program.
As the need for predictability and plant availability grows, planning and
scheduling maintenance tasks become more important through a more prevalent use of preventive and predictive maintenance (Pintelon et al., 2006). Aided by maintenance information and ERP systems, detailed procedures are set up that cover the entire process from work order to the evaluation of the task that is carried out eventually. Many authors propose a procedural approach to condition based maintenance (e.g. Carnero, 2004, 2006; Mobley, 2002; Muller et al., 2008a,b). According to Mobley (2002) condition based maintenance programs rely on procedures that define the methods, schedule, and execute data acquisition, analysis, and reporting. This is especially relevant from a quality management perspective (Vanneste and Van Wassenhove, 1995).

Postulate 6. Process companies use employee training for the correct execution of their condition based maintenance program.

As maintenance tasks are often complex and place high demands on workforce knowledge, training becomes an essential managerial tool (Hipkin and Lockett, 1995; Garg and Deshmukh, 2006; Swanson, 1997; Tsang, 2002). The same holds for condition based maintenance tasks (Carnero, 2006; Tsang, 1995). As the technical complexity of the plant and the level of sophistication of diagnosis and prognosis tools increases, the need for appropriate training increases as well. According to Mobley (2002) training is a critical success factor for predictive maintenance, and the training program should be extensive, and not be limited to a few days.

5.3.3 Workforce knowledge postulates

Postulate 7. Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.

It is often argued that knowledge management is essential for the management of technology (e.g. Gaimon, 2008). Sufficient workforce knowledge is a prerequisite for improving plant performance and making appropriate investments (Carrillo and Gaimon, 2004; Ferdows, 2006). The three most important domains (or ‘departments’) in a maintenance organization are maintenance engineering, process engineering and operations, representing, respectively, ‘knowledge of the technical system and how it can fail’, ‘knowledge of how the production process is designed’ and ‘knowledge of how the production process functions’ (Al-Najjar and Alsyouf, 2000; Buchanan and Bessant, 1985; Crespo Marquez and Gupta, 2006; Hipkin and De Cock, 2000; Hipkin and Lockett, 1995; Hipkin, 2001; Øien, 1998; Swanson, 1997; Waeyenbergh and Pintelon, 2002). Investigations into the role of domain-related knowledge have also been done in the condition based maintenance field. Wang et al. (2000) modeled the use of maintenance expert judgment in the mod-
eling of condition based maintenance for water pumps at a large soft-drinks manufacturing plant. Klingenberg and De Boer (2008) explained what types of information can be used in the condition based maintenance of punching/blanking technology in sheet metal using a hybrid solution of artificial neural networks and expert systems. Hoof and Laird (2003) identified the types of knowledge needed in the diagnosis of large generators. Riis et al. (1997) developed a ‘situational maintenance model’ and state that for both diagnosis and prognosis process knowledge is needed (in addition to the other two types). In a series of reviews on diagnostic and prognostic models applicable to the process industry, Venkatasubramanian et al. (2003a,b,c) and Venkatasubramanian (2005) clearly showed the relevance of the three types of knowledge in a wide range of models.

Postulate 8. The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.

In order to benefit optimally from the available knowledge, integration of the knowledge is required (Carlile and Rebentisch, 2003; Grant, 1996). As the condition based maintenance tasks are often conducted by the maintenance engineer, it is essential for him/her to integrate the knowledge of the three domains. In some cases this could be done by simply adding the production process parameters into the diagnostic and prognostic models, but in many other cases extensive communication is needed between maintenance engineering, process engineering and operators to truly understand figures and trends (Hipkin and Lockett, 1995; Sharif and Grosvenor, 1998). Many neural networks, expert systems and so on are designed to facilitate knowledge integration (e.g. Muller et al., 2008b) but their applicability may be limited due to the complexity of the underlying models, as we explained in the first postulate.

5.4 Methodology

In order to examine the postulates, we have conducted a multiple case study, which is appropriate since our primary aim is theory-building from an exploratory perspective (McCutcheon and Meredith, 1993). The research is exploratory since we have no solid ideas on the exact behavior and causal relationships of the concepts in practice, but rather aim at developing knowledge that can serve as a stepping stone towards such conceptual models. Hence the use of a multiple case study (Dul and Hak, 2008; Eisenhardt and Graebner, 2007). The postulates help us in guiding the research process, and, eventually, in the development of hypotheses that can be tested statistically with a large sample. As the postulates do not contain explanatory
statements, we prefer to avoid the word ‘test’.

Our focus is on the process industry for reasons explained before. A specific selection of case companies was made based on three criteria. Such an approach to sampling is important in case research (Eisenhardt and Graebner, 2007; Siggelkow, 2007). The criteria are:

1. Company size, whereby companies were selected with a minimum number of employees of 50. This is based on the assumption that larger firms have more possibilities for the development of advanced maintenance techniques, such as condition based maintenance (Carnero, 2006).

2. The degree to which the companies consider plant maintenance as an important part for achieving excellent overall performance. This was measured by interviewing key personnel prior to the actual case study.

3. In addition, a selection was made of unrelated companies (not part of the same conglomerate and no supply relationship), in order to avoid any ‘double dipping’. This (together with criteria 1 and 2) resulted in a set of four companies (which we label Gas, Elec1, Aramid and Chem). An opportunity arose to also investigate a fifth company (Elec2), which is related to another company (Elec1). This was taken into account when assessing the results.

At the case companies, interviews were conducted with representative personnel, such as maintenance managers, process engineers and maintenance engineers. Follow-up telephone interviews were used for validation and additional questions. The interview data was structured and labeled per firm to allow for cross-case analyses. Additional data sources included written documents and presentation material. Measures taken to ensure the validity and reliability are summarized in table 5.1. The case companies are described in detail in the next section.

5.5 Case firm descriptions

This section describes some general characteristics of the process industry together with the characteristics of the five case companies.

5.5.1 Process industry characteristics

According to the American Production and Inventory Control Society (APICS): “process industries or basic producer industries are manufacturers that produce products by process manufacturing”; “process manufacturing is production that adds value to by mixing, separating, forming, and/or chemical
Table 5.1. Ensuring validity and reliability in the five case studies.

<table>
<thead>
<tr>
<th>Criterium</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construct validity</td>
<td>Multiple documents, multiple informants, informants were asked to provide additional information in follow-ups</td>
</tr>
<tr>
<td>Internal validity</td>
<td>Pattern matching using cross-tabulations, careful attention for rival explanations; both theoretical as well as in interview protocol</td>
</tr>
<tr>
<td>External validity</td>
<td>Selection of case firms typical for process industry, use of authors’ expert opinions on uniqueness of case firms</td>
</tr>
<tr>
<td>Reliability</td>
<td>Structured interview protocol, careful write-up of interview data</td>
</tr>
</tbody>
</table>

reactions” (Cox III and Blackstone Jr, 1995). Process plants are typically a relatively complex network of piping, static equipment (e.g. vessels, heat exchangers), rotating equipment (e.g. pumps) and electric systems, operated by sophisticated process control systems that measure, register and control process parameters such as temperature, flow, pressure and structure of liquids, gases, pulps, powders and so on. Process control information, system outputs, failures and process disturbances are all important sources of information for diagnostic and prognostic systems, as is illustrated in figure 5.2.

5.5.2 General company descriptions

Gas is an industrial renovation and maintenance consortium. Since 1997 it has been responsible for the engineering, construction and maintenance of around 20 gas production plants and gas transfer stations in one of the world’s largest gas fields. The consortium consists of an engineering firm, a construction firm and three major equipment suppliers. Currently the renovation part of the project is nearing its completion, so that the organization is moving from being engineering- and construction-focused to entirely maintenance-focused. Elec1 is a joint venture of a major chemical company and a utility company, and owns a natural gas powered co-generation plant that provides both steam and electricity to the various users at a chemical park. The largest part of the generated energy is supplied back into the public electricity network. Elec2 is also a joint venture of the same chemical and utility company, but somewhat smaller in size than company Elec1. It supplies steam and power for various chemical companies at a chemical park. It also produces several thousands of cubic meters of compressed air
Figure 5.2. Diagnostic and prognostic systems, where $u$ is the steering signal, and $y$ is the system output (partially based on Venkatasubramanian (2005)).

per hour. Aramid is one of the world leaders in aramid production. The aramid fiber is used for a wide variety of products, ranging from car tires and airbags to bullet-proof protection materials. The plant we investigated consists of two sub-plants: one for the polymerization process to make the aramid fiber, the other for the production of pulp and the conversion of fiber into end-products. The current research was carried out at the second sub-plant. Chem is an autonomous organization responsible for the maintenance, infrastructure, permits and protection of a large chemical park that is primarily owned by a major international chemical company. Several business units operate at the chemical park, producing a large variety of chemical products such as acids, fertilizers, plastics, rubber etc.

At a general level, the physical production technologies are comparable across the case firms, although the plants differ in age and level of redundancy. These factors are outside the scope of our research. Other production characteristics vary across the case firms. Gas is in the transition from being a swing-producer, to producing continuously at a significant capacity level. Elec1 and Elec2 both produce at base load levels, without many startups and shutdowns. Aramid’s production situation is different, since there is quite some variety in the requested end-product. Production runs are fully continuous and can vary from several days to several weeks. Chem produces different products in different plant, nearly always at full capacity. Table 5.2 summarizes the five companies.
Table 5.2. Case company characteristics.

<table>
<thead>
<tr>
<th>Main output</th>
<th>Gas</th>
<th>Elec1</th>
<th>Elec2</th>
<th>Aramid</th>
<th>Chem</th>
</tr>
</thead>
<tbody>
<tr>
<td># Plants</td>
<td>20 + gas</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Asset owner</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
<tr>
<td>Main equipment (per plant)</td>
<td>Compressor, low temperature separator units, glycol unit</td>
<td>Gas turbine installations</td>
<td>Gas turbine installation, steam turbine</td>
<td>Double disc refiner, cutting machines</td>
<td>Compressor trains</td>
</tr>
</tbody>
</table>

*At the end of 2008, the maintenance of the entire site was separated into an autonomous unit.

5.6 Results

5.6.1 Technical systems postulates

Postulate 1. Process companies apply more diagnosis than prognosis in their condition based maintenance program.

We can only find limited support for this postulate. Condition based maintenance is not yet a dominant maintenance concept. The practices the five case companies do use have significant similarities. Only basic condition based maintenance approaches are in place (e.g. oil analysis, vibration analysis), whereby failure data are used as the dominant data source. Explicit analytical or statistical models appear to be lacking. Two of the case companies (Gas and Aramid) are attempting to develop some clearly defined condition based maintenance cases based on process data, but success is still limited. In all the companies we saw an extensive use of process parameter monitoring, but the use of this data was intended to be either a preliminary trigger for further investigation, or to be supportive to an identification of abnormal signals derived from failure data. One of the interviewees mentioned the underlying production characteristics as one of the main reasons for this:

“We also have a fairly simple process. We cook water and make electricity. Those processes have been known for ages. Perhaps it’s different at base chemicals, where processes are less well known and where you have to mon-
itor more. (..) With a new plant you have startup problems, we don’t have that anymore. (..) Generally we don’t have a lot of problems. There aren’t too many startups and shutdowns and we are pretty well able to produce the base-load. The plant is designed for this base-load, not for extreme startups. (..) We are fleet leader when it comes to reliability. That might be due to the ideal operating conditions, but is also has to do with a good plant design.” (installation technologist Elec1)

One particularly striking result was that all the firms claimed to be struggling with prognostic condition based maintenance tasks. Measurement values were mostly compared to predefined limits and trends were estimated based on ‘gut feel’. Most of the interviewees mentioned the importance of the next maintenance stop or shutdown. When practices such as a thermographic analysis or a vibration analysis indicated a potential problem, more in-depth analyses are done and, based on the severity of the problem, it is decided whether the failing component can ‘hold’ until the next maintenance stop or shutdown. This is not without risk. One of Chem’s interviewees gave an example of a situation in which a problem with a turbine was detected:

“A while ago we experienced some difficulties with the vibrations of our low NOx turbine (of which only five exist worldwide). We saw some remarkable vibration signatures and we conducted washings every day, but the high vibrations remained. We contacted the vendor and they told us to keep on running. After careful monitoring we still didn’t trust the situation and contacted the vendor’s headquarters. They told us to stop the machine immediately, but we were too late. (..) The turbine crashed and we suffered millions of Euros of damage. After that we visited the vendor’s headquarters abroad and exchanged much information. That helped a lot but it seems that sometimes you learn by bitter experience.” (technical support engineer Chem)

As this example underlines, condition monitoring is often not more than a support tool when abnormal plant behavior is identified. In fact, at Elec1, Elec2, Aramid and Chem we identified an approach to condition monitoring and condition based maintenance, that appears to differ substantially from what literature generally proposes. Maintenance engineers at these companies have the habit of regularly checking various process parameters and other condition monitoring data, which, at first sight, seem relatively random. However, the selection of the process parameters that are checked is based on experience, historical grounds or recently identified problems. None of these companies had a clearly described condition based maintenance process that guides decision-making (as we defined earlier in §5.2). Instead condition
monitoring appears to be used as an additional source of information in case anywhere in the organization a (potential) mechanical problem is detected. Instead of thinking of condition monitoring and condition based maintenance as well-defined processes, it is more accurate to see condition based maintenance systems as consisting of three phases: problem identification, problem definition and decision making. The identification and definition phases appear to be black boxes; in each of the phases a systematic approach was hard to identify:

- In the problem identification black box random or periodic data inspections can lead to the identification of abnormal parameter behavior by the maintenance engineer, the operator, or the process engineer. In most cases the data is communicated with the other disciplines.

- After the problem has been identified, the maintenance engineer will look for the underlying failure mode, the operator will more closely monitor actual plant behavior and the process engineer will compare the obtained measurements with expected (or as designed) values.

- The subsequent phase is maintenance decision making. In this phase the typical maintenance activities (if necessary) are determined. Urgency of the problem, maintenance planning and criticality of the component are all important factors that influence the decision. See figure 5.3 for an illustration.

Postulate 2. Process companies make extensive use of information systems and specialized software in their condition based maintenance program.
This postulate is only moderately supported by the case data. All of the case companies make use of highly automated systems (from different suppliers) for process control. Databases and additional software are used for process monitoring at the desktop of the user (i.e. operators, process engineers, maintenance engineers). In some cases, separate systems are used for specific equipment. Gas, for example, uses specific monitoring devices for the active magnetic bearing system of the plant’s compressors. Elec1 and Elec 2 also have dedicated monitoring tools for their compressor train. Using a direct line, the original equipment manufacturer (OEM) has the ability to log in into the same system and give additional support. All the companies have installed ERP-type systems to record failures, maintenance jobs, spare part availability, etc.

Hardly any specialized condition based maintenance software was used at the case companies. The few software applications in place were mostly
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Maintenance engineer identifies abnormal parameter behavior based on random or periodic data inspection
Operator identifies abnormal parameter behavior based on his daily plant monitoring activities
Process engineer identifies abnormal parameter behavior based on random or periodic data inspection

(If deemed necessary,) the problem is communicated with the other disciplines

The problem identification black box

Q: What could the underlying failure mode be?
Q: How does the plant actually behave?
Q: How is the plant designed? What should its performance be?

The problem definition black box

Maintenance decision:
- Immediate shutdown
- More careful monitoring
- Inspect at next shutdown

Urgency
Maintenance planning
Criticality

Figure 5.3. Illustration of the two condition based maintenance black boxes.

dedicated to diagnostic tasks (see postulate 1). As mentioned, Gas is currently in the process of changing from a project execution-driven organization to a maintenance-driven organization. One of the ways of achieving this is through the development of a so-called ‘support center’, a collaborative work environment that (literally) houses all the relevant functional departments for maintenance and support activities. A specialist business intelligence company was hired to install and support hard- and software for diagnostic and prognostic activities. One of the projects is the development of a data historian to capture all the data and information from operations and maintenance processes in a user-friendly way. The aim is to support a range of diagnostic and prognostic tasks. Chem also has installed specific asset optimization software tools to support decision-making based on diagnostic and prognostic information. However, according to one of the interviewees, management support was said to be lacking so that the output of the system is not regarded as an important source for source for maintenance decisions.
The linkages of the various failure mode and effect analyses (FMEA’s) to the process data and events was said to be an additional obstacle for extensive usage of the software. At all companies except Gas on- and offline monitoring of rotating equipment vibrations are done, using portable devices or direct information from the process control systems. In case of the use of portable devices, this is supported by software tools. At Elec2, software is used for the partial discharge monitoring of generators. However, although the software vendor claims the software to have predictive capabilities, it is used for diagnostic purposes only.

Postulate 3. Process companies make use of third parties for specialized condition based maintenance tasks.
The case data confirm the postulate. The two types of third parties that contribute in condition based maintenance are (i) the OEM and (ii) the company for specialist tasks. As mentioned under postulate 2, at Gas, Elec1, Elec2 and Chem diagnosis of critical equipment (i.e. compressor trains in the first three cases and a gas turbine in the fourth) are supported by the OEM, mostly on vibration measurements. As the crash of one of Chem’s turbines indicated, support by the OEM is not a sufficient condition for effective diagnosis.

Specialist companies for specific tasks are hired for oil analyses (all case companies), thermographic analyses (Elec2 and Aramid) and vibration measurements (Aramid). The specialist company appears to be hired not only for data collection and dissemination, but also for expert judgment. When oil is analyzed, for example, the specialist company determines the threshold level and assists in the decision whether or not to repair immediately, install a temporary patch-like solution or postpone the appropriate maintenance action to the next scheduled shutdown. This can be further illustrated with the following quotes of one of Aramid’s interviewees.

“We have monthly vibration measurements done by (a third party) on parts such as pumps, agitators and ventilators. (...) They send us the documents. I’m not really satisfied about these reports because it is still too ‘dirty’. I have to dig too much myself. We do have norms in these measurements, but all in all it is still an interpretation of the numbers. If something does not seem to be right, you go out and check. Sometimes the problem is complex. Then we just monitor the situation for a while.” (maintenance engineer Aramid)

“The critical values of the thermographic analyses, for example, are determined by the specialist and me. And sometimes I decide to follow his recommendation, sometimes I don’t. (...) We have done the analyses of hydraulic and lubrication oil for about 6 years. You start with a best guess and then
you adjust the norm slowly. Together (with the specialist third party) we determined the critical values. Now we get reports indicating whether we are in the green or the red zone. It also leads to the installation of certain filter systems, so now we get a signal when there is breakdown.” (maintenance engineer Aramid)

For both types of third party support, it can be concluded that a good determination of thresholds and the correct interpretation of trends are crucial factors. A short summary of the results regarding the technical systems postulates is given in table 5.3.
Table 5.3. Condition based maintenance practices at the case companies.

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Elec1</th>
<th>Elec2</th>
<th>Aramid</th>
<th>Chem</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main condition based maintenance practices</strong></td>
<td>Delta pressure, regeneration time, process monitoring, some oil analysis and vibration analysis</td>
<td>On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring</td>
<td>On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring</td>
<td>On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring</td>
<td>On- and offline oil analyses, on- and offline vibration monitoring, thermographic analyses, process monitoring</td>
</tr>
<tr>
<td><strong>Main focus</strong></td>
<td>Diagnosis</td>
<td>Diagnosis</td>
<td>Diagnosis</td>
<td>Diagnosis</td>
<td>Diagnosis</td>
</tr>
<tr>
<td></td>
<td>(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes, in the near future</td>
<td>(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes, for the support of vibration monitoring using portable devices</td>
<td>(i) Yes, automated process control systems (including systems for critical equipment monitoring); (ii) Yes, for continuous online partial discharge monitoring, and for the support of vibration monitoring using portable devices</td>
<td>(i) Yes, automated process control systems; (ii) Yes, asset optimization software, and for the support of vibration monitoring using portable devices</td>
<td>(i) Yes, automated process control systems; (ii) Yes, asset optimization software, and for the support of vibration monitoring using portable devices</td>
</tr>
<tr>
<td><strong>Use of third parties</strong></td>
<td>Yes; for offline oil analyses, and monitoring of several parameters in the compressor by the OEM</td>
<td>Yes; for offline oil analyses and vibration measurements of the main compressor train by the OEM</td>
<td>Yes; for offline oil analyses and vibration measurements of the gas turbine by the OEM</td>
<td>Yes; for offline oil analyses, vibration measurements and thermographic analyses</td>
<td>Yes; for offline oil analyses, vibration measurements and thermographic analyses</td>
</tr>
</tbody>
</table>
5.6.2 Managerial systems postulates

Postulate 4. Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.

The case data support this postulate. The five companies vary in the way (condition based) maintenance tasks are organized, but a high level of autonomy for the organizational unit responsible for condition based maintenance is clearly visible. At Gas the support center houses engineering, maintenance and operations staff from both the five consortium partners, as well as the asset owner. It is defined as a ‘collaborative work center’ and the responsibilities for condition based maintenance are going to be placed under the maintenance engineers. Elec1 and Elec2 have comparable organization structures wherein operators, maintenance engineers (at Elec1 called installation technologists), and process engineers/technologists cooperate in analyzing and optimizing the plant. At both companies, these three functions are placed into different departments, with the process technologists acting as the ‘spiders in the web’, as one of Elec2’s interviewees called it. The installation technologists (Elec1) or maintenance engineers (Elec2) are responsible for condition based maintenance tasks. At Aramid, a department called ‘asset utilization’ is created next to the operations department, to stimulate the coordination of activities between the functions maintenance engineering, process technology and operations engineering (which is responsible for specific plant performance issues, such as emissions and energy consumption). Again the maintenance engineer is responsible for condition based maintenance. Chem is also called the ‘manufacturing centre’ that supports the operation of the nine plant units at the chemical park. Every plant unit has a separate production organization. The manufacturing centre is a support centre that houses functions as maintenance, projects and operations support. The maintenance function is organized in so-called ‘shops’ that are organized geographically (i.e. north, south and mid). Next to these shops, there is a technical support department (‘short term technical decisions’) and a reliability engineering department (‘long term decisions’). The improvement function resides within ‘machine teams’, hosting the traditional maintenance-related disciplines as well as operations. Thus, operations is a ‘client’ strictly speaking, but in reality the operations function is an inherent part of the improvement team structure. The technical support engineer is responsible for condition based maintenance tasks.

Although the responsibilities for the condition based maintenance task are always assigned to what can generally be called the ‘maintenance engineer(s)’, it is the high degree of cooperation with the other two functions (i.e. process engineering and operations) that is critical to the effective use of condition monitoring for diagnosis. The way this cooperation is structured
differs. The three single-plant maintainers (Elec1, Elec2 and Aramid) rely on short communication lines in which operations is either directly integrated in the organization structure (Elec1 and Elec2), or closely related to the maintenance department (Aramid). One interviewee mentioned:

“You apply condition based maintenance where you find it necessary with respect to the process or the (technical system). A good product requires cooperation, especially in the triangle operations, maintenance engineering and process technologists. That (cooperation) is good at (our company). Everyone has his own (contribution). We need these (agreements) to manufacture a good product, at low costs.” (maintenance engineer Aramid)

The two multi-plant maintainers (Gas and Chem) try to coordinate activities in a somewhat different fashion. At Gas detailed plans are in being developed that formally establish roles and responsibilities, so that a type of professional bureaucracy appears (during the research project, the support center was still in full development, so that the actual working principles are unknown at the time of writing). Chem organizes improvement in small machine teams, with short and direct lines between team members. To conclude, a common feature of all the firms’ organization is that the close relationship between operations, maintenance engineering and process engineering (or comparable functions) is recognized and expressed in the organization structure.

Postulate 5. Process companies make use of strict procedures to execute their condition based maintenance program.

This postulate cannot be substantiated by the empirical findings. All of the companies make use of ISO9000 type of systems, but none of them use a clearly defined procedure for condition based maintenance. As one interviewee explained:

“We have all the ISO certifications. Condition based maintenance however is very hard to put down into procedures. It is not something you can make a protocol for. Perhaps it is not really a process but more of a support tool. Data analysis can initiate follow-up actions, for example.” (installation technician Elec1)

During the interviews, the respondents were consistently asked whether structures and protocols existed for their condition based maintenance tasks. For example, it was asked whether the interviewee could indicate which components are monitored and whether this has been written down in a list. None of the respondents could provide such a list. The following quote is
exemplary for the perception of procedures in the context of condition based maintenance:

“We haven’t formalized our condition based maintenance tasks. I just know what to look at. I know what the important parameters are.” (maintenance manager Elec2)

As we explained in the first postulate and as we described in figure 5.3, diagnosis (and to a very limited extent prognosis) activities are done in a rather unsystematic way, and are not yet an integrated part of maintenance strategy at the case firms. The fact that the process companies do not use any strict procedures underlines this.

**Postulate 6. Process companies make use of employee training for the correct execution of condition based maintenance program.**

The empirical findings do not support this postulate. Besides the employees’ regular education (maintenance engineers often hold mechanical engineering degrees, whereas process engineers and operators often have chemical engineering degrees) and on-the-job training (e.g. reliability engineering and operator training) no training is provided for condition based maintenance. Some interviewees indicated that journals and the internet should be sufficient for their tasks. A summary of the managerial systems postulates is provided given in table 5.4.
Table 5.4. Managerial systems at the five case study companies.

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Elec1</th>
<th>Elec2</th>
<th>Aramid</th>
<th>Chem</th>
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</thead>
<tbody>
<tr>
<td><strong>Autonomy of the</strong></td>
<td>Maintenance</td>
<td>Installation</td>
<td>Maintenance</td>
<td>Maintenance</td>
<td>Technical</td>
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<td><strong>condition based</strong></td>
<td>engineering</td>
<td>technology</td>
<td>engineering</td>
<td>engineering is</td>
<td>support</td>
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<tr>
<td><strong>maintenance unit</strong></td>
<td>is embedded</td>
<td>is embedded in</td>
<td>is embedded in</td>
<td>embedded in the</td>
<td>engineering</td>
</tr>
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<td></td>
<td>in a</td>
<td>the triangle-</td>
<td>the triangle-</td>
<td>asset utilization</td>
<td>is embedded</td>
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<tr>
<td></td>
<td>collaborative</td>
<td>shaped structure</td>
<td>shaped structure</td>
<td>group consisting</td>
<td>in the</td>
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<td></td>
<td>work</td>
<td>of operations,</td>
<td>of operations,</td>
<td>of maintenance</td>
<td>manufacturing</td>
</tr>
<tr>
<td></td>
<td>environment,</td>
<td>installation</td>
<td>installation</td>
<td>engineering,</td>
<td>center,</td>
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<td>with</td>
<td>technology and</td>
<td>technology and</td>
<td>process technology</td>
<td>including</td>
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<td>representatives</td>
<td>process</td>
<td>process</td>
<td>and operations</td>
<td>maintenance,</td>
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<td>from all the</td>
<td>technology</td>
<td>technology</td>
<td>engineering (</td>
<td>technical</td>
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<td></td>
<td>relevant</td>
<td>and</td>
<td>and</td>
<td>operations is</td>
<td>support and</td>
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<td></td>
<td>disciplines</td>
<td>process</td>
<td>process</td>
<td>a separate</td>
<td>process control.</td>
</tr>
<tr>
<td><strong>Use of strict</strong></td>
<td>No / not</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>procedures</strong></td>
<td>yet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Use of employee</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>training</strong></td>
<td></td>
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</tbody>
</table>
5.6.3 Workforce knowledge postulates

Postulate 7. Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.
This postulate is partly supported by the empirical findings. The postulate suggests that within the case companies, the availability of domain-related knowledge is actively managed. The active role of company personnel (e.g. maintenance managers) was not directly identified. Moreover, the lack of employee training suggests (at least partly) that knowledge creation is not explicitly managed. However, in the previous postulates it was shown in several ways that the three relevant knowledge domains are present in the case companies, and that information systems and organizational structures are important facilitators for knowledge use. In addition, none of the interviewees felt a particular type of knowledge to be absent, although this does not necessarily imply that improvements cannot be made in the condition based maintenance process. In the following postulate we will elaborate somewhat more on these issues.

Postulate 8. The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.
This postulate is supported when it comes to the diagnosis part. Since none of the companies explicitly attempted to actively predict failure, nothing can be said on the criticality of knowledge integration for that task. All of the interviewees stated that when certain knowledge was needed (in other words, when a problem is discovered in the data or in the plant itself), it could be found quickly and easily. At every company, knowledge of technical systems design, failure and operating conditions are aligned and easily integrated. Some supportive statements are the following:

“You have to remember that the operator is my ears and eyes.” (technical support engineer Chem)

“The operations department monitors the process parameters of course. They can, for example, monitor the temperature of a bearing, and view its trend. When something is not right, they can contact us. They will explain what they see, and we can do more analyses. There is much overlap, but the disciplines are clearly distinguishable. If the process deviates from the specifications, then we can find each other quickly.” (installation technologist Elec1)

With its support center Gas aims at moving towards prognostic condition based maintenance, recognizing the apparent need for knowledge integration:
Table 5.5. Summary of results.

<table>
<thead>
<tr>
<th>Postulate #</th>
<th>Statement</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Process companies apply more diagnosis than prognosis in their condition based maintenance program.</td>
<td>Limited support</td>
</tr>
<tr>
<td>(2)</td>
<td>Process companies make extensive use of information systems and specialized software in their condition based maintenance program.</td>
<td>Limited support</td>
</tr>
<tr>
<td>(3)</td>
<td>Process companies make use of third parties for specialized condition based maintenance tasks.</td>
<td>Supported</td>
</tr>
<tr>
<td>(4)</td>
<td>Process companies create autonomous organizational units in which the actual condition based maintenance tasks take place.</td>
<td>Supported</td>
</tr>
<tr>
<td>(5)</td>
<td>Process companies make use of strict procedures to execute their condition based maintenance program.</td>
<td>Not supported</td>
</tr>
<tr>
<td>(6)</td>
<td>Process companies make use of employee training for the correct execution of condition based maintenance program.</td>
<td>Not supported</td>
</tr>
<tr>
<td>(7)</td>
<td>Process companies make sure sufficient domain-related knowledge is available for their condition based maintenance program.</td>
<td>Limited support</td>
</tr>
<tr>
<td>(8)</td>
<td>The integration of the domain-related types of workforce knowledge is critical for the success of diagnosis and prognosis tasks.</td>
<td>Supported (i.e. the diagnosis part)</td>
</tr>
</tbody>
</table>

“The collaborative work center focuses on new ways of working that break with traditionally ‘siloed’ departments through the integration of people, processes and technology. (..) Improvements in complex operations performance as a whole must be addressed with a holistic view, with due respect to the interaction between processes, technology and people. (..) The main objective of the support center is to optimize the use of data and develop monitoring-and event prediction tools, with the prime aim of increasing the availability/reliability and production performance of the production facilities.” (operational excellence charter support center - overall activities)

Finally, we summarize the results regarding the eight postulates in table 5.5.
5.7 Discussion and conclusion

The wealth of condition based maintenance literature indicates that it is a popular topic, and it also suggests that the concept is relevant for industry. Although we do not question the relevance for industry, this study shows that several assumptions found in the literature cannot be substantiated in the current multiple case study. The case firms, all production plants in the process industry in The Netherlands, appear to have a generally unsystematic approach to condition based maintenance, with most of the attention paid to diagnosis. In the diagnosis system, on the one hand, the disciplines are able to integrate knowledge from their respective domains and solve problems, but, on the other hand, it is unclear how problems are identified and how decisions are made. Such a reactive approach might be sufficient in situations where reliability and availability targets are easily met, but might still lead to unnecessary breakdowns or maintenance interventions.

When it comes to prognosis, the findings show that some firms estimate the remaining useful life (or the probability that the installation will hold until the next shutdown) using intuition and gut feeling, and that other firms do not attempt any predictions at all. The result is a situation that is very much similar to the design of the diagnostic system we identified at the firms. However, we also saw some attempts at two companies (Gas and Chem) to use more structured approaches towards prognosis through the use of collaborative work environments and advanced types of software, respectively. Apparently these firms recognize the need for structure when the condition based maintenance models become more complex.

Several limitations can be identified in the current study. First of all, we have to recognize that plant and human safety are the most important goals for process industry firms, and this might affect condition based maintenance practice, particularly prognosis. For example, when prognostic models indicate (within a certain confidence interval) that failure will happen at time $t$, firms might still decide to opt for earlier shutdown when there is a potential effect of failure on safety aspects. In that sense, (plant-wide) optimization becomes difficult. Secondly, the findings are all from process industry firms. Other industries will differ in terms of operations strategy, dominating technologies, organizational arrangements and availability of software and hardware, thereby affecting the preferred maintenance approaches. However, even for those industries the results may still be useful since they indicate that various types of difficulties appear in the adoption and use of maintenance technology. For instance, the importance of actively managing process engineering, maintenance engineering and operations knowledge for condition based maintenance in the process industry, may have its peer in
other manufacturing industries.

Several avenues for future research exist. The results of this in-depth multiple case study could be further supported by case studies at firms with different organization structures and size. Similar research questions could also be posed in other industries, as we indicated above. Furthermore it would also be interesting research to identify the key success factors for firms actually implementing and using prognostic condition based maintenance.

In summary, this study provided an empirical perspective on condition based maintenance technology. We hope that our findings will help managers improve the success rate of their maintenance technology efforts. We would like to encourage scholars to further investigate the actual use of condition based maintenance in various industrial settings, thereby helping industry achieve its operational goals.