Integrating Green and Sustainability Aspects into Life Cycle Performance Evaluation

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Abstract

Recently, an increasing number of customers of the machine tool industry have applied life cycle costing (LCC) to compare the cost-effectiveness of different investment options. These concepts have mainly been used to address maintenance costs since these have proven to be one of the most important cost drivers. The approach of life cycle performance (LCP) broadens LCC by considering the relationship between the costs and benefits of a machine over its entire life cycle. With the increasing importance of environmental consciousness, it has become crucial to incorporate environmental impact when evaluating machines. A framework is presented that enables the integration of green manufacturing principles into LCP-evaluation. The role of interoperability within this framework is also discussed.

Keywords

Life cycle cost, green manufacturing, monitoring

1 INTRODUCTION

Machine tool manufacturers face increased worldwide competition. This competition has necessitated the reduction of manufacturing and operation costs for each machine tool [1]. As a result, many companies have recently focused on the life cycle cost (LCC) to evaluate the machine's performance. The automotive sector in particular has identified the potential of LCC concepts and has confronted their machine suppliers with adapted warranty demands [2]. LCC is used to compare the cost-effectiveness of different business decisions or investments from the point of view of a decision maker in a company [3]. Traditionally, these concepts have included only those parts of the product life cycle where direct costs or benefits arise without much consideration of environmental impacts and its related costs. Figure 1 shows an exemplary analysis of the main cost drivers as an average result of 5 different LCC analyses of machine tools over 10 years [4].

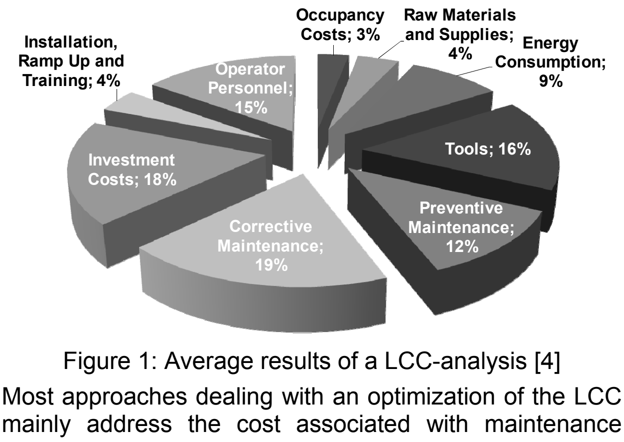

Figure 1: Average results of a LCC-analysis [4]

Most approaches dealing with an optimization of the LCC mainly address the cost associated with maintenance activities since they have proven to be the main cost drivers (see Figure 1). By using methods of life cycle performance evaluation (LCP), it is possible to estimate the trade-offs between the performance of a machine in terms of its reliability, availability, quality and the associated costs [5]. Recently, environmental consciousness has played an increasingly larger role in manufacturing due to customer demands for "green" products, increasing regulation, and increasing energy and consumables costs. Given the relatively large environmental impacts of manufacturing – manufacturing accounts for nearly 20% of global greenhouse gas emissions [6] - it has become crucial to find ways to effectively integrate green design into existing business routines for sustained success.

Increasing environment consciousness has many implications ranging from material selection to the type and amount of energy consumed. Each aspect has implications on the LCP of a specific machine tool. A successful consideration of this subject demands interdisciplinary approaches. Therefore, the objective of this paper is to combine the concept of LCP with green manufacturing. Various approaches already exist in both fields, which are initially introduced in a brief overview. Based on identified challenges, a framework is presented which enables the integration of principles and methods of green manufacturing into LCP-evaluation. Within this framework the necessary requirements and tasks that must be addressed are discussed. Finally, the role of interoperability will be presented since suitable data acquisition is the basic requirement for a successful application of the developed framework.

2 LIFE CYCLE PERFORMANCE EVALUATION

The life cycle performance (LCP) of a mechanical system such as a machine tool describes the efficiency of this system with respect to its costs from the initial investment to its disposal. In this context, efficiency means economic accessibility with regard to a high availability, output, quality and flexibility. These factors can be combined to the Overall Equipment Effectiveness (OEE), which is mainly used as a key performance indicator in the concepts of total productive maintenance (TPM) [7]. This broadens the basic idea of LCC by taking the manufacturer's, user's and service provider's processes included in the system's life cycle into consideration. So far, the main objective in this area has been the optimization of technical services such as maintenance intervals or the provision of spare parts [5]. Furthermore, methods for the assessment and control of risk of adapted warranty contracts have been developed [2, 8]. Recently, the approaches for the evaluation of single machines are transferred to the evaluation of a whole production system or a plant [9]. Figure 2 gives an overview about the concept of LCP and the aligned areas of focus.

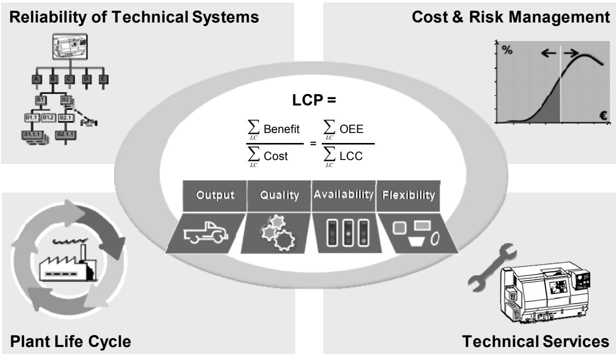

Figure 2: The concept of LCP (after [10])

The necessary basis for those applications is the analysis of the reliability and the calculation of the service life of the components within a technical system. This information also enables the calculation of specific key parameters such as the Mean Time Between Failure (MTBF), the Mean Time To Repair (MTTR) or the technical availability. These are the common metrics that are normally incorporated into contracts based on LCC [11]. On the one hand, knowing the reliability parameters helps the customers of the machine building industry to increase the level of certainty in planning the production, preventive maintenance activities, and the storage or the provision of spare parts. On the other hand, most LCC-based contracts incorporate a transfer of risk from the customer to the manufacturer who is now responsible for predicting the reliability and the associated cost [12]. By taking over those risks, small- to medium-sized manufacturers may endanger their business models. Therefore, new approaches are necessary which suitably subdivide the risks between the manufacturers and their customers [13]. In the machine tool industry in particular, manufacturers only have a limited knowledge of the reliability behavior of their own products in the field. Thus, most manufacturers are neither able to determine the required key figures or to price the contractually fixed warranty in an appropriate way [8]. The application of the methods of LCP can support manufacturers in this process and contribute significantly to a reduction of those risks. But, the availability of necessary data sources from the field (such as load profiles and times to failure data) remains a major challenge.

The issue of sustainability and energy costs is addressed briefly in most LCC concepts. But, this issue is mostly neglected or only broadly applied due to the complexity of its measurement and assessment as well as the major role of the maintenance cost. Since manufacturing processes are energy intensive and energy costs will rise in the future, the evaluation of energy consumption as well as the impact of the manufacturing processes on the environment is considered as a future success factor in terms of a holistic LCP-evaluation of a machine tool. This requires the integration of green manufacturing principles into LCP-evaluation.

3 GREEN MANUFACTURING

Sustainable development has become increasingly important as manufacturers attempt to balance economic growth with social awareness and the minimization of their environmental footprint. So, the three sustainability pillars include the economy, environment and society, but this paper will focus on the economic and environmental factors only.

LCC and LCP-evaluation are two methodologies that measure the economic implications of owning a machine tool (though LCP-evaluation, as previously described, extends to the inclusion of machine tool availability and flexibility). Alternatively, the environmental factor of sustainability can be seen through environmentally conscious manufacturing, which "addresses the dilemma of maintaining a progressive worldwide economy without continuing to damage our environment" [14]. In this steady transition to the incorporation of green practices, the following principles have been associated with the greening of manufacturing: the reduction of material and energy usage, waste management, recycling and remanufacturing, as well as the move away from the use of toxic materials. These principles are similar to those suggested by [15]. Some of these principles have been exemplified by current manufacturing standards. Waste management, for example, is evident in the emphasis of waste reduction in lean manufacturing and waste minimization and reuse in the concept of industrial ecology. Continuous improvement, though, on all levels is crucial to successfully integrating "greenness" in manufacturing.

Life cycle assessment (LCA) is a quantitative tool often used to provide an indication of how well a product or process is performing on an environmental-level. A thorough LCA includes the following steps: goal definition, scope definition, inventory, and impact assessment [16]. The identification of metrics in the goal definition is important in realizing the goals of the LCA. Manufacturing metrics include: energy and other resource usage (as suggested by [17]), processing times, material removal rate, and mass or volume of material removed. The scope of analysis may vary as well ranging from the enterprise or supply chain down to the individual machine tool.

Research is ongoing in relation to manufacturing and the environment [18-23]. All provide useful analyses in moving towards green manufacturing, and some common themes arise such as faster processing rates. However, although increased speeds may have an immediate decrease in energy, it is highly probable that there is a long-term effect on the machine tool, which is not yet evident and is associated with increased loads over its lifetime. So, it is important to emphasize and include metrics, such as energy consumption and processing rates, in LCP-evaluations since they will ultimately have a direct impact on the availability, maintenance, and aligned costs of machine tools.

4 FRAMEWORK

The continued development of both LCP and green manufacturing depends on the extent to which several aspects of a manufacturing system have been fully characterized and measured. For example, LCP requires a more accurate gauge of the load profile and failure modes of a system where as green manufacturing analyses require a better understanding of the various flows in a system. In order to gain this understanding, a straightforward framework must be developed to guide further implementation efforts. This framework can be described as follows:

1. Design and integrate appropriately targeted process monitoring and measurement system(s) that can obtain the relevant data identified to accurately gauge the full life cycle.
2. Characterize the manufacturing system and the role of each component in the system by utilizing the data obtained in (1).
3. Optimize the development of the component or process of interest using the models and characterizations developed in (2).

Using this framework, many different metrics can be incorporated into the LCP approach. In the machining example that follows, challenges, potential solutions, and continuing challenges will be highlighted in the implementation of the prescribed framework for maintenance, reliability, and environmental impact through electrical energy consumption.

4.1 Step (1): Measurement

The first step in the design of any process monitoring system is gaining a basic understanding of the manufacturing system so that important data items can be identified. For example, to apply the LCP approach to determine maintenance and reliability of a component of a machine tool, one needs data on the elapsed run time before a failure occurs and the loads placed on the tool that led to the failure at a minimum [5]. If the loads on a component cannot be easily or reliably obtained, then the electrical energy can serve as a useful metric representative of load. However, care must be taken to accurately gauge the electrical energy consumption due to the material removal process versus the peripheral equipment associated with a machine tool. In addition, to these data sources, other items that are useful to monitor include the failure mode and any maintenance data (e.g. components replaced and repair time). The maintenance data in particular can sometimes be of higher importance depending on the ability of a machine to monitor failure time on its own (i.e. through the NC output).

If we now focus on environmental impact, then the most direct indicator of the environmental footprint of a machine tool is the electrical energy it consumes. Electrical energy is directly linked to the CO_2 emissions of components and processes through power generation. Electrical energy measurements may also provide information on other global warming species as well as indirect water consumption in other parts of the supply chain.

The knowledge gained on the manufacturing system can now be used to select appropriate sensors for the monitoring system. Fault data can be monitored via the NC output of the machine tool. While this data source may not include the actual elapsed machining time since the previous fault, it does allow for monitoring of the current tool position, cutting speed, and feed rate meaning that the elapsed machining time can be monitored through use of software techniques tied to each of these parameters. If this method proves unfeasible, then any available maintenance data can be used to determine the elapsed machining time. No matter the data source, the NC output may be potentially modified to obtain more detailed information on fault occurrences.

Physical loads can be measured using accelerometers or force transducers appropriately located in the machining environment. Thermal loads may be monitored through a variety of thermal sensors. Thermistors have been shown to be a good choice for machining processes and tools due to their relatively fast and ideal response in the appropriate range of most machining processes, cheap cost, and simple setup [24].

Monitoring electrical energy consumption (whether for environmental reasons or for use as a load proxy) can be challenging depending on the component that one wishes to monitor. All machine tools typically require 3-phase AC power from the facility source, and thus overall electrical energy consumption can be monitored through use of a wattmeter calibrated and setup for a 3-phase, 3-load, 3-wire measurement. Once power enters the machine tool, though, it is generally used as DC power for each component within the tool. Thus, sub-metering the electrical energy throughout the machine should only require the measurement of current and voltage at the input of each component that uses DC power. Electrical power is then the product of the measured current and voltage, and electrical energy is that power integrated over a time interval. However, sub-metering in practice is not as straightforward due to the complexities of a machine tool's circuitry. A challenge, though, is that it may be difficult to know what causes a change in electrical energy consumption of any one component due to the interplay of all components within the machine tool.

Sensor integration is generally a major issue for monitoring system design. Two major challenges are the wires that are inherent with all sensors as well as the packaging that must withstand the relatively harsh conditions of a machining process. Wireless solutions and proper packaging are therefore extremely critical to ensure that any monitoring system does not interfere with the machining environment.

4.2 Step (2): Characterization

As mentioned in Section 2, understanding the failure behavior of specific components is essential for any LCP-evaluation. The probability of failure at a specific time can be calculated by means of reliability analyses, though. Initially, the load-dependent reliability function has to be derived. The Weibull distribution [5, 25] is commonly used to describe the stochastic failure behavior of machine components and can therefore be applied to estimate their service-life for a certain probability. However, the Weibull distribution in its basic form does not account for the influence of varying loads due to machining processes with (as an example) different materials or cutting speeds, which have a major impact on the failure behavior of a component. So, the approach under consideration uses the Weibull Cumulative Damage Model in combination with the Generalized Log-Linear Model. These models were developed in the field of accelerated life tests and allow for time-variant loads to be integrated into a reliability analysis [26].

The estimation of the parameters of the load-dependent reliability function requires data on the component's lifetime and the corresponding loads before failure. Based on the estimated parameters of the combined analysis of different load profiles, it is possible to predict the service life of a similar component under the assumption of a future load profile. Figure 3 shows an exemplary result of a reliability analysis of a mechanical component of a machine tool as well as the derivation of a load dependent failure distribution function.

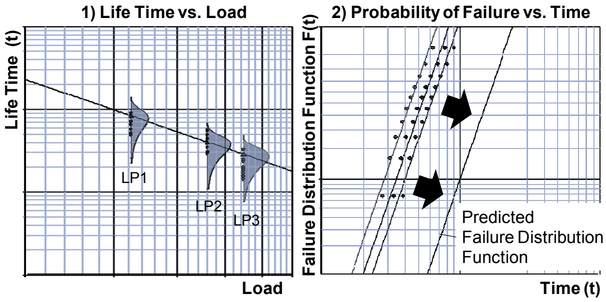

Figure 3: Derivation of a failure distribution function

The first graph of Figure 3 shows the component's lifetime in dependence of 3 analyzed load profiles (LP). The second graph of Figure 3 shows the corresponding failure distribution functions of each load profile and the derived failure distribution function based on an assumed future load profile with minor absolute values compared to the others. The parallelism of the failure distribution function is due to the load independent shape parameter of the Weibull distribution function for a specific failure mode.

Based on this information it is finally possible to calculate specific key parameters such as the MTBF, the MTTR or the technical availability which are incorporated in contracts based on life cycle cost. Furthermore, this information can be used to optimize technical services such as maintenance activities or the provision of spare parts as well as for a calculation of the aligned costs.

In order to integrate the energy cost into LCP-evaluation, it is necessary to estimate the amount of energy used by a machine during its entire life cycle. In characterizing the energy consumption of a machine tool, the processes or components should be classified as either consuming constant power over time or variable power while machining as was done by Dahmus, et al [18]. This distinction will help clarify which components or processes to focus on when optimizing.

Machine tool components that draw constant power over time include the coolant pump, computer panel, and lighting fixture (see Figure 4). These components do not require additional power as loads on the machine tool are increased while in operation. Some strategies that have been implemented by machine tool manufacturers to reduce the constant or idle power consumption include the hibernation of the computer panel while not in use for a designated period of time, or the installation of energy efficient light fixtures.

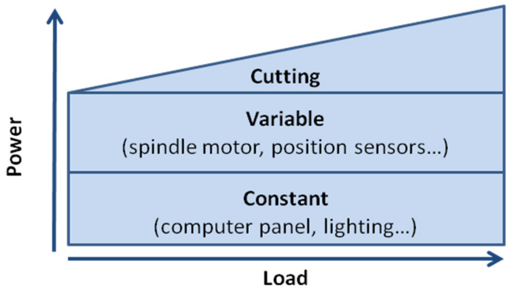

Figure 4: Breakdown of machine tool power consumption

Components such as the spindle motor, position servos, and internal cooling unit consume variable power. The power consumed by the spindle motor and position servos depend on the spindle speed and feed rate, respectively. The relationship between the power consumption of a Mori Seiki NVD 1500 and its spindle speed is linear until there is a shift in gears to rotate the spindle when the speed is set to approximately 5,000 revolutions per minute or greater [22]. The relationship between power and feed rate is also linear (see Figure 5) [27], but there is a much smaller change in overall power consumption when increasing the feed rate compared to the change in power consumption from increasing the spindle speed.

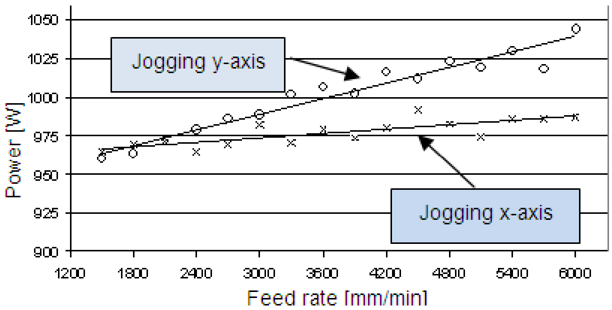

Figure 5: Power consumed to jog x- and y-axes [27]

The power of the internal cooling unit of precision machine tools is a more challenging component to characterize. The function of the internal cooling unit is to counter the thermal loads inherent in operation of machine tools to maintain positional precision and accuracy. The power consumption of the internal cooling unit of the NVD 1500 is cyclical with a cycle time of 43 seconds and amplitude of 25 W [27]. As loads on the machine tool are increased and the temperature of the machine tool rises, the pump of the internal cooling unit must work harder to maintain a desired temperature range of critical components. Without the installation of a wattmeter directly on the pump of the internal cooling unit, the power consumed by the pump will be masked by the power consumed by the machining operations.

Once the constant and variable power consumption of processes/components are characterized, the last portion to take into consideration is the power consumed by the mere act of cutting. In manual mills, this portion of the power consumption tends to dominate the overall power consumption because manual mills do not have as many peripherals as automated machine tools [18]. The cutting power consumption is also variable since it is dependent not only on process parameters that relate to the material removal rate but also on type of cutting tool and the specific properties of the part being produced (such as the material being cut).

4.3 Step (3): Optimization

The information from the reliability analysis and prediction enables the calculation of the maintenance related LCC of a specific machine tool. From the manufacturers perspective it is now possible to price their offers, optimize its contents, and determine warranty limits in order to fulfill their customer's requirements. Both the manufacturers and their customers can now develop further approaches that aim to minimize long-term costs. These approaches can optimize preventive maintenance intervals by determining the optimal probability or the corresponding remaining service life for which an unscheduled failure is to be prevented by replacing the component. Furthermore, the necessary resources regarding maintenance personnel can be planned and optimized in terms of reaching a specified availability level within a service contract. Since manufacturers are facing considerable uncertainty regarding possible expenses incorporated in these contracts the framework can support them in gathering the necessary information and adjusting their maintenance activities. By using the information from the load-dependent reliability analysis in combination with economical aspects such as storage cost, it is possible to develop efficient strategies for the provision of spare parts that allow for high spare part availability with minimal overall cost [5]. Additionally, this knowledge can be used for a continual improvement process. Frequent failure modes can be identified and prevented by redesigning the components. Likewise, the optimal setting for sensors can be modified to improve the accuracy of process monitoring as described in step 1 of the framework. This finally allows for a more precise evaluation of the machine's reliability and LCP-evaluation.

For a given manufacturing process, it is understood that overall energy consumption is reduced by faster processing times or larger material removal rates [19]. Thus, when optimizing it is not sufficient to solely analyze spindle speed and feed rate with respect to power consumption since power increases with increased loads. Rather, the analysis should extend its scope to include specific energies for a particular machining operation. This allows analysis of the trade off between decreased processing time and increased power consumption.

In optimizing the process parameters for minimum energy reduction, the feed per tooth, spindle speed, and feed rate were varied in [23, 27]. Initial experiments showed that changes in the feed per tooth, spindle speed, or feed rate while machining with the same cutting tool resulted in poor surface quality or a dramatic increase in tool wear as the energy consumption decreased with lower processing times. High speed cutting was then analyzed such that the cutting tool was changed from a 2-flute uncoated carbide end mill to a 4-flute TiN coated end mill so that faster processing times could be achieved while staying within the recommended spindle speeds and feeds for a particular cutter (see Figure 6). This tool change resulted in a significant reduction in energy consumption with minimal wear on the tool and good surface quality.

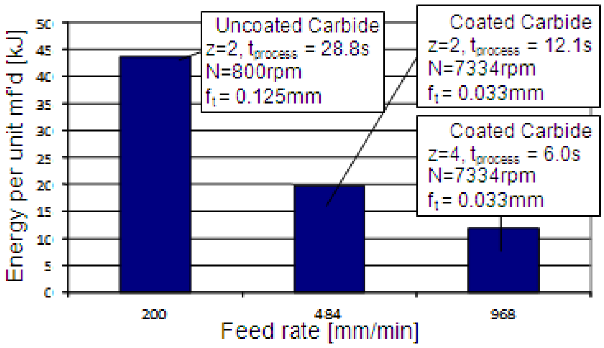

Figure 6: Specific energies for part manufacture while varying the cutting tool [23]

When optimizing the process parameters with regard to optimal energy consumption, the impacts of these changes on the reliability of specific components should be analyzed as well. Varying spindle speeds or feed rates change the load profile. Therefore, the failure behavior of certain components may vary. This again has an influence on the LCC. The overall effectiveness of this optimization can be evaluated by a trade off analysis with regard to varying LCC of different machine settings.

5 INTEROPERABILITY

The continued development of LCP-evaluation and the incorporation of environmental aspects into LCP both require the use of several types of sensors to provide all of the necessary data sources for analysis. However, multi-sensor approaches are challenging to implement because of the need to reduce the large information flow to those signals of greatest importance, the substantial training and setup required for these systems to function properly, and the lack of commonly adopted protocols to operate each sensor type [28]. More importantly for LCP-evaluation is the fact that each data flow must be correlated to each other data flow to properly characterize any machining process. As an example, consider the difficulty in correlating the data flows from the load and energy sensors described in Section 4.1 to the actual process time and ultimately failure mode. Without a method of coordinating the load and energy data flows, assigning even a common time stamp becomes challenging. These problems become exacerbated at higher levels of integration where several machine tools are trying to work in concert such as with a production line. In short, it is difficult to communicate and coordinate information and data among various machines or sensor types [29].

Given the challenges faced by multi-sensor solutions for LCP-evaluation, interoperability is a key enabler to implementing the framework described in Section 3. Interoperability is the ability of two or more systems to exchange information and use the information that has been exchanged [28]. Through interoperability, standardization is possible such that any two sensors will be able to seamlessly communicate and work together with the ability to reduce information flows, reduce setup and training costs, and provide common protocols for operation. Furthermore, interoperability enables straightforward data correlation by a multi-sensor system.

One exemplary interoperability solution is MTConnect™. MTConnect™ is a free, open-source, XML-based data exchange standard for manufacturing equipment that was developed by the Association for Manufacturing Technology (AMT). It is an extensible, lightweight standard designed to enable "plug-in" architectures that allow for application-focused development. In addition, MTConnect™ provides a hierarchical structure that allows connectivity throughout a workshop environment and provides connectivity to other software solutions, standards, and legacy equipment. Figure 7 details the integration of the MTConnect™ standard in a manufacturing system.

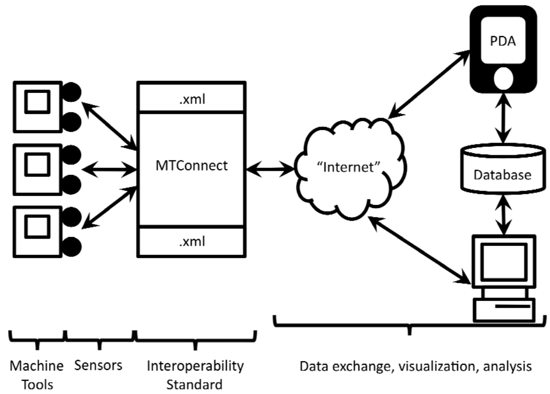

Figure 7: Integration of MTConnect™ (after [29])

A key feature of the MTConnect™ standard that is displayed in Figure 7 is that the standard is XML-based and thus uniquely able to offer connectivity to the Internet. This feature could potentially offer LCP-evaluation further benefits by providing a convenient means to continually capture data and information from machine tools that can be used to refine the metrics developed as described in Section 4.2. Furthermore, MTConnect™ and other interoperability standards provide means to enable digital factory concepts that connect designers to manufacturing facilities from the enterprise to process level while offering a feedback mechanism to better simulate, optimize, and control product and process development early in the design process [29]. This ability can provide extensive environmental and fiscal benefits by giving designers more flexibility and power to positively affect the final design of a product or process.

6 SUMMARY AND OUTLOOK

The presented framework enables the integration of green manufacturing principles into LCP-evaluation. The information needed for evaluating a system's performance in terms of reliability, maintainability, and energy consumption, as well as methods to obtain the information have been shown. Furthermore, suitable methods and metrics have been discussed. The proposed framework supplements the LCP approach by analyzing the amount of energy consumed by a machine, and thus it will help to achieve higher accuracy for any prediction purpose. Major challenges still remain in successfully implementing process monitoring and interoperability for this framework. Future work will focus on the application and further development of the framework as well as in the advancement of data and interoperability solutions.

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