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A New Paradigm of Manufacturing: Selling Use Instead of Selling Systems

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Abstract: Current manufacturing system development for medium to large volume production follows a "cradle to grave" strategy. For each new product model, a complete new manufacturing system has to be designed and constructed with very little of the existing system being re-used. Reconfigurable manufacturing systems designed for product families are resource-effective systems that can adapt quickly to product changes and be used to manufacture products of the same family for different manufacturers. Rather than selling systems to different manufacturers, the manufacturing system builder can design, construct and manage the reconfigurable system and sell parts to the manufacturers, significantly reducing the frequent design, construction and ramp-up of the systems. On the other hand, manufacturers can lease the reconfigurable systems from the builder to reduce cost associated with facility management and over-capacity. In this context information about the use-intensity of production equipment becomes key to enable its high availability. Usage information can be applied in the fields of preventive maintenance and the re-use of modules form reconfigurable systems to allow cost-efficient adaptation and reconfiguration of production equipment between the different usage phases. An example will be used to illustrate the economical benefits of such a new paradigm in manufacturing and to point out the call for action.

1 Introduction

Dedicated manufacturing systems for medium to high volume production have traditionally been designed following the life cycle model of "cradle to grave". That is, given the design of one or two products, manufacturing systems are designed specifically for these products. For example, auto manufacturers spend over $500 million every three to four years to develop the manufacturing systems, mainly stamping and assembly systems, for the vehicle bodies of a specific model or associated variants. The manufacturing systems are usually designed from the ground up, with little or no components of the manufacturing systems being reconfigured or reused for the next model. The development of such system takes time. In addition, there are major quality and productivity problems with the such designed systems since very little knowledge learned from the operations of the prior system are transferred to the new. The quality and reliability problems take a long time to debug and ramp up. As a result, manufacturers may miss the short windows of opportunity for introduction of new products.

When demand for the product is high, the cost per part is relatively low. Dedicated manufacturing systems are cost effective as long as demand exceeds supply and they can operate at their full capacity. But with increasing pressure from global competition and over-capacity built worldwide, there may be situations in which dedicated lines do not operate at full capacity. Due to the low adaptability, dedicated systems can not respond to market changes in either volume or product variety cost effectively.

Flexible manufacturing systems (FMS) can produce a variety of products, with changeable volume and mix, on the same system. FMSs consist of expensive, general-purpose computer numerically controlled (CNC) machines and other programmable automation. Because of the single-tool operation of the CNC machines, the FMS throughput is lower than that of DML. The combination of high equipment cost and low throughput makes the cost per part relatively high. Therefore, the FMS production capacity is usually lower than that of dedicated lines and their initial cost is higher.

A new type of manufacturing system, reconfigurable manufacturing system (RMS), is now being developed to cope with the large fluctuations in product volume and mix caused by the changing market conditions [Koren, et al, 1999]. This is achieved through:

- Design of a system and its machines with configurations which may be adjusted at the system level [e.g., adding machines or changing configurations] and at the machine level [changing machine hardware and control software; e.g., adding spindles and axes, or changing tool magazines and integrating advanced controllers].

- Design of a manufacturing system around the part family, with the customized flexibility required for producing all parts of this part family. (This reduces the system cost.)

The RMS is designed to cope with situations where both productivity and the ability of the system to react to change are of vital importance. Three coordinates – **capacity, functionality, and cost** – define the difference between RMS and the traditional DML and FMS approaches. While DML and FMS are fixed in capacity-functionality, RMS capacity and functionality change over time as the system reacts to changing market circumstances (Figure 2).

	Dedicated	RMS/RMT	FMS/CNC
Machine Structure	Fixed	Adjustable	Fixed
System focus	Part	Part Family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized	General
Simultaneously Operating Tool	Yes	Yes	No

Table 1: RMS combines features of dedicated and flexible systems (Koren et al, 1999).

Independent of the types of manufacturing systems, the current practice is the same: i.e., machine tool builders or system integrators will design and construct the manufacturing systems for the manufacturers according to the product design given by the manufacturer, and then sell the system to the manufacturer. Rather than selling systems to different manufacturers, this paper proposed a "selling use" approach: the manufacturing system builder can design, construct and manage the system and sell parts to the manufacturers, significantly reducing the frequent design, construction and ramp-up of the systems. Reconfigurable manufacturing systems is especially suited for such new paradigm.

2. The "Selling Use" approach

When selling product, an essential element of profit is the decline of marginal unit costs due to large lot sizes. The resulting resource consumption is not of too much concern. All costs of purchase, operation, maintenance and disposal of the product are at the expense of the product buyer. If the product is not in use, the product buyer as owner has to bear the idle capacity costs. The manufacturer has a reduced interest in long products life, as replacement products increase sales and profit. The buyer of a product has become its legal owner and is himself in charge of it.

In the "selling use" approach, the buyer pays only for the utilization of the product and not for the product itself. The costs of investment, operation, maintenance and disposal are managed by the utilization seller. The old style product manufacturer and seller hence develops into a utilization seller and service provider of components and products. The utilization seller is hence interested in a long-lasting and robust product that bears little costs throughout its usage. Such a product decreases resource consumption compared to a product under the selling products paradigm.

The disadvantage of selling products compared to selling use is the tendency to higher costs of underutilization and higher resource consumption. Selling use gets competitive once these costs can be avoided.

What are the criteria for a successful implementation of a "Selling Use" model for Reconfigurable Manufacturing Systems? The two key parameters that can be altered by changing the systems architecture over time are capacity and functionality. In a selling use model the Original Equipment Manufacturer's (OEM) interest as the proprietor and configurator of the equipment must be to realize a high utilization of his system as his profit is generally related to the units being produced. Hence, he is more likely to act in highly fluctuating market environments regarding the capacity and functionality required for manufacturing. In this environment the RMS can best compete with conventional DML and FMS in terms of high utilization. Fig. 1 depicts the two fundamental process chains for the "Selling the Product" vs. the "Selling Use" approach.

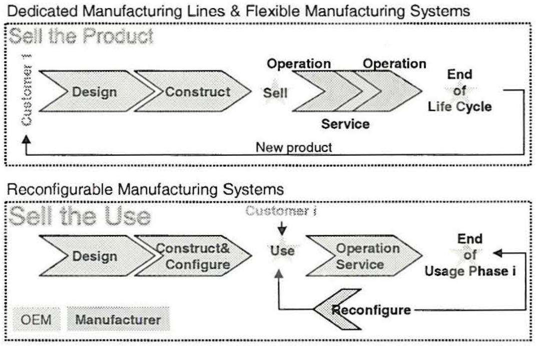


Figure 1: Selling Use vs. Selling the Product

The vital drivers for the selling use model arise from the option to use manufacturing equipment modules more than just once. The OEM as a proprietor bears the costs for the reconfiguration and is therefore tempted to re-use altered components, e.g. in other RMS.

Yet, the selling use model bears the danger of opportunistic behavior because it separates the rights to the cash flows over the Life cycle from the rights over the residual value at the End of Life Cycle. Separating the rights regarding the cash flow and residual value, the Selling use model produces incentives for asset abuse, under maintenance and opportunistic behavior at the point of the "Use-Contract" renewal. Bilateral agreements such as obligations and options can be applied to overcome some of these negative incentives, as shown in Fig. 2. Such instruments are not adequate to be used in highly fluctuating market environments where the demand for production capacity and functionality changes rapidly. Mistrust comes from a lack of knowledge about the usage of the product, i.e. the asymmetric distribution of information between the manufacturer and the OEM regarding the usage time, reliability and functionality of the product.

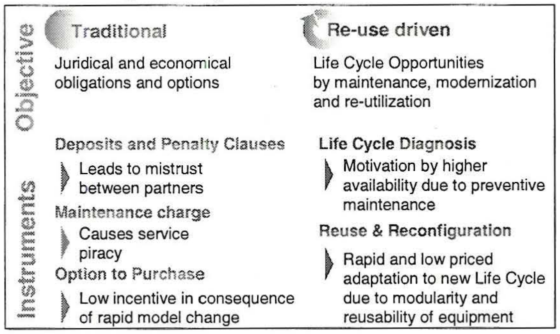


Figure 2: Methods to safeguard selling use contracts

Reconfigurable Manufacturing Systems clear the way to implement the selling use model, particularly in rapidly changing market environments. KOREN defines key characteristics for reconfigurability which are Modularity, Integrability, Customization, Convertibility and Diagnosability. Modularity, integrability and diagnosability reduce the reconfiguration time and effort whereas customization and convertibility reduce cost.

Diagnosability is critical in reducing the ramp-up time of RMS. Frequently reconfigured systems therefore depend highly on fast and efficient diagnosis during ramp-up time. In a selling use model all five RMS-characteristics have a direct influence on the cost to manipulate the capacity and functionality of the system, yet diagnosability deserves a special focus. It is the basis for the re-use driven selling use model for RMS.

3. Diagnosability

1.1. Application in manufacturing systems

Diagnosis of the system-state is a key characteristic that deserves a special consideration in the selling use model, even beyond the ramp-up process. Whereas modularity, integrability, customization and convertibility are characteristics that are crucial in the reconfiguration of the RMS, diagnosability stays the predominant characteristic during the operation of the system. As the proprietor of the RMS the OEM's ability to control the state and availability of the system becomes a core competency. Knowledge about the usage of the system and each of its components allows its reconfiguration when the needs regarding capacity or functionality change, that is due to increasing or intensifying workloads that could possibly overstrain the system. Equally this knowledge allows the systems adaptation in case of altering system qualities due physical changes, i.e. wear.

Knowledge about the usage is therefore crucial to guarantee the required functionality and to make the re-use of components in other systems economically favorable. A change in system qualities can have its origin in the wear of the product, such as abrasion, corrosion, fatigue, ageing or staining. The selling use model aligns the interests of both parties, i.e. the OEM's and the manufacturer's. High availability is the common goal that can only be achieved by the appropriate reconfiguration and adaptation.

The risk of production standstill due to system failure caused by wear of components is shared by both parties. Postulating that risk and return will always find an equilibrium under free market conditions, the central question is which party can best provide the diagnosis of the system to guarantee the expected availability. In traditional Dedicated Manufacturing Lines (DML) the competency lies in the hands of the manufacturer. Knowledge is acquired during the relatively long utilization of a hardly changing system architecture. This type of organization seems no longer applicable in the market for RMS. Design, building and installation as well as ramp-up time and each single Life Cycle of the configured system are comparatively short. The system behavior of the RMS changes with every reconfiguration, making it difficult for the manufacturer to acquire the professional experience to conduct intensive diagnosis.

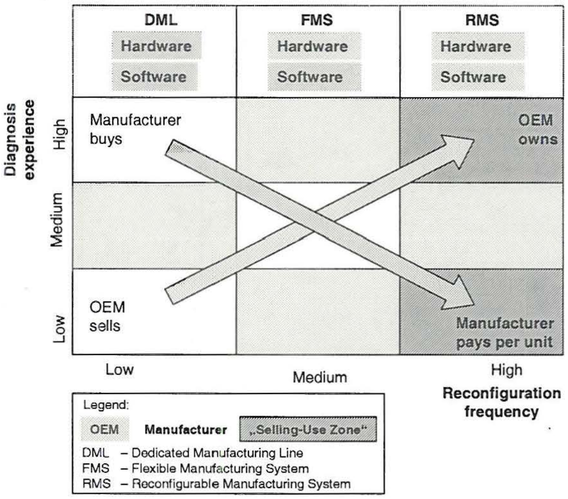


Figure 3: OEM's diagnosis experience enables the selling use model for RMS

Considering the labour intensive, i.e. cost intensive diagnosis of systems one should use the OEM's experience. This will only be possible in a selling use model, since once the product becomes the property of the manufacturer the OEM can no longer dispose components in order to optimize their utilization.

Figure 3 depicts the three common groups of manufacturing systems and classifies them regarding reconfiguration frequency and diagnosis experience. Traditional DML are likely to be serviced by the manufacturer due to the long production experience with the hardly changing systems architecture. In comparison with DML manufacturers using Flexible Manufacturing Systems (FMS) can hardly cope with the complexity of these systems when it comes to service such as preventive maintenance. OEM's have the design experience regarding these universally applicable systems. Yet, the OEM knows little or nothing about the utilization of the systems as they can be programmed to perform an almost infinite variety of processes. Generally the OEM has no access to process data, i.e. that maintenance can only be realized according to time intervals or in case of machine failure. Thus, diagnosis experience is only medium on both sides. DML and FMS are consequently not recommendable for the selling use model, simply because the OEM can not customize the manufacturing system to its individual application regarding capacity, functionality and physical condition.

Reconfigurable Manufacturing Systems (RMS) leave less time for the manufacturer to become familiar with the system's properties. The individual configuration of a RMS for very specific processes and for a comparatively very short time leaves no time for the acquisition of profound system knowledge by the manufacturer, that is the user of the RMS. The OEM is predestined to become the diagnosis specialist. As no RMS is ever likely to be identical to any other RMS, behavior and failure patterns are unlikely to be derived for the individual configured system, but rather for system components or frequently repeating design patterns. This knowledge can only be acquired by the accompaniment of the RMS over its entire Life Cycle requiring a close informational contact with all RMS utilized in the market.

The OEM will have to become the Life Cycle Manager of the RMS which comprises the

- requirement specific (re-)configuration of the product,
- acquisition of statistical significant usage and maintenance data,
- interpretation and aggregation of this data into adaptation knowledge and
- conduction of preferably condition based respectively time based or corrective maintenance.

As the Life Cycle Manager for the RMS, the OEM requires the right of disposition for the RMS components, to optimize their utilization during their entire Life Cycle. This demands a selling use model with the objective to reduce the costs for both parties, i.e. the OEM and the manufacturer. To understand how diagnosability becomes a new core competency of the OEM we focus on how information about the actual utilization of the RMS can be evaluated.

1.2. Deriving diagnosis information

To configure or reconfigure the RMS parameters are required. KOREN suggests possible product parameters that are workpiece size, part geometry and complexity, production volume and production rate, required processes, accuracy requirements and material property that must be taken into consideration. These product parameters address one aspect of the utilization of the manufacturing system. Described in an infinite high detail they would be an adequate mean to describe the actual utilization of the RMS.Yet, they can not comprise unplanned variations of their values nor random environmental impacts. Thus, to describe the actual utilization of the manufacturing system, additional usage data is indispensable. The provision of this usage data is the basis for the diagnosis that itself is the prerequisite for a cost efficient maintenance and profitable re-use of production equipment by the OEM.

KOREN proposes that diagnostics should be embedded into RMS on component level. Information from reconfigurable sensors is used to detect faults or quality problems during ramp-up time. As ramp-up time has a significantly higher impact on RMS than on conventional DML or FMS, new sensory measurement principles are more likely to be introduced in RMS. As sensors are embedded on component level they can be used during the entire Life Cycle of the RMS at low cost. Thus, embedded sensors should not only be used during ramp up time, but also be applied to meet the needs for maintenance and re-use of the system.

Life Cycle accompanying diagnosis requires the identification of use-intensity factors for the elements, i.e. modules of an RMS. This systematic identification of use-intensity factors and adequate sensory measurement principles is the first step in the Life Cycle Unit concept that is considered to be an enabler to conduct diagnosis during the Life Cycle of a product [1]. The Life Cycle Unit itself is conceived as a modular microsystem to provide usage data by its elements sensors (detection) and Life Cycle Board (storage, processing and transmission). Sensors and Life Cycle Board (LCB) are embedded in systems on the component level, i.e. in modules [2]. The LCU concept focuses on the provision of usage data to be applied in the diagnosis of the system's status. The objective is to support the system's adaptation, i.e. maintenance, re-use of components and its reconfiguration. Hereby the LCU concept contributes to make the selling use model profitable for the OEM.

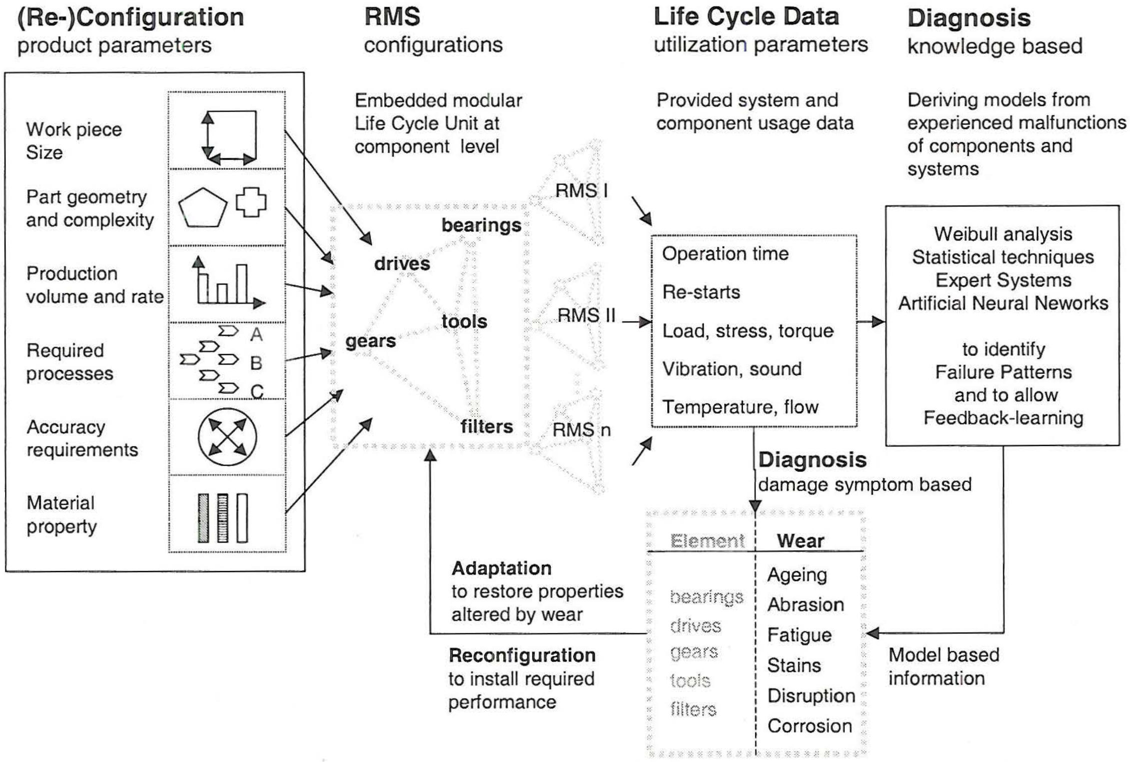


Figure 4: Diagnosis of usage data from different RMS configurations by the OEM

State of the Art methods concentrate highly on the measurement of a few parameters like structure-borne-sound (vibrations), moments or temperature form bearings, gears and drives. Measurements are primarily realized with standard "add-on" sensor systems, not with embedded modular microsystems [3]. A broader approach will have to identify and classify more relevant signals and provide this sensory data with cost-efficient systems. Furthermore statistical techniques, e.g. Weibull analysis, graph theory or techniques based on expert-knowledge or artificial neural networks have to be applied to transform sensory data into widely usable utilization knowledge.

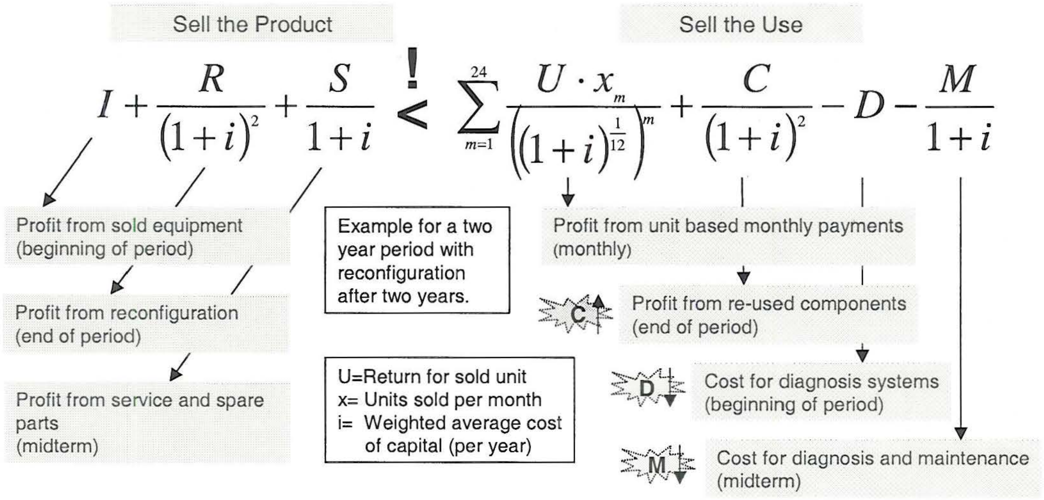
Figure 4 describes how the (re-)configuration of a RMS as well as its adaptation is being supported by Life Cycle Data. Diagnosis can be symptom based as in the case of vibration analysis on a bearing that provides data for the direct identification of wear, such as a disrupted bearing cage. Knowledge based diagnosis applies models and several utilization parameters to derive statistical information regarding the probable state of single components respectively the RMS. Symptom based and model based diagnosis support adaptation and reconfiguration. They require the implementation of embedded modular sensory systems and the Life Cycle accompanying analysis of acquired data.

4. Profitable re-use

Figure 5 below summarizes the vital issues reconfiguration, adaptation, re-use and diagnosis addressed above in a general analytic relation comparing the selling the product vs. the selling use approach for a RMS. The example compares the net profit and cost groups over a 24 month period and takes their temporal realization into account. The reconfiguration of the RMS at the end of the period is included in the example.

The seller of the RMS realizes his profits by the sale of equipment and service at the beginning, throughout and at the end of the period. The seller of the use of the RMS realizes none of these profits from sale and service. His remuneration is a monthly payment related to the usage of the RMS. In the example the number of produced units was taken as a measure to determine the calculation basis for the OEM's profit.

Diagnosis was identified as a crucial factor during the entire Life Cycle of the RMS to allow condition based maintenance and the re-use of modules. The extra costs for the implementation of embedded sensory systems on component level and the Life Cycle accompanying diagnosis of the RMS are being assigned to the OEM. Likewise he is the beneficiary of the residual value of re-used components at the end of the period. The example limits its complexity to the factors that are being determined by the quality and extend of diagnosis of the system during the usage. That means that varied economical conditions like taxation or operating expenses due to changing economies of scale or scope are not being considered. It is being assumed, that these operational effects can be measured by means of managerial accounting and thus will find a bilateral equilibrium in a free market economy.



$$I+\frac{R}{(1+i)^2}+\frac{S}{1+i} \overset{!}{<} \sum_{m=1}^{24}\frac{U\cdot x_m}{\left((1+i)^{\frac{1}{12}}\right)^m}+\frac{C}{(1+i)^2}-D-\frac{M}{1+i}$$

Figure 5: Sell the RMS vs. sell the use of the RMS for a two year period

The focus lies on the profit from re-used components (C), the initial cost for the accompanying diagnosis system (D) and the cost for diagnosis and maintenance (M). Improved condition based maintenance during the usage period is monetarily accounted for by the profit from re-used components. Improved determination of the residual value of RMS modules using Life Cycle Data allows a better allocation of the modules.

Profit from re-used components is being reduced to the residual value and the costs for adaptation.

Equ. 1 $$C = R - K$$

C: Profit from re-used components
R: Residual value
K: Costs for adaptation

The residual value of the components is being determined by physical wear and economical devaluation.

Equ. 2 $$R = I \cdot A \cdot E$$

Equ. 3 $$A = \prod_{w=1}^{n} A_w \qquad \text{with } A \in (0;1)$$

Equ. 4 $$A_w = e^{-\left(\frac{t}{T}\right)^b} \qquad \text{with } A_w \in (0;1)$$

Equ. 5 $$E = 1 - \frac{t}{T_E} \qquad \text{with } E \in (0;1]$$

I: initial Investment
A: Total wear indicator, that is the probability of survival for the component
A_w: Probability of survival regarding the component and a single wear-class
w: wear-class (ageing, abrasion, fatigue, creep, stains, deformation, disruption, loss or corrosion)
b: Shape parameter
T: Scale parameter
t: Time
E: Economic devaluation
T_E: Length of economic devaluation

The Weibull distribution (Equ. 4) can be used to model systems with decreasing failure rate, constant failure rate, or increasing failure rate. This versatility is one reason for the wide use of the Weibull distribution in reliability. The evaluation of shape and scale parameters depend on the extend and quality of the diagnosability of the system. The length of economic devaluation (Equ. 5) is being determined by the speed of technical development and decreasing market prices. The determination and utilization of the residual value requires processes that generate costs in inspection, disassembly, assembly, refurbishment as well as in the filed of logistics and opportunity cost.

Equ. 6 $$K = K_I + K_D + K_M + K_A + K_L + K_O$$

K_I: Cost for inspection
K_D: Cost for disassembly
K_M: Cost for assembly
K_A: Cost for refurbishment
K_L: Cost for logistics
K_O: Opportunity cost

Cost for inspection, disassembly and assembly, such as labour cost, are highly dependent on the quality and accessibility of diagnosis data. Cost for refurbishment, such as machining hours, spare parts and labour cost correlate directly with the decisions made during inspection. Cost for logistics and the opportunity cost of unused equipment represent further calculative cost. These basic relations help to clarify the challenges and define the call for action to make the Selling use approach profitable for Reconfigurable Manufacturing Systems:

- Identification of a wider spectrum of wear parameters for components and selection of appropriate sensors.
- Realization of cost-efficient embedded modular microsystems on component level in RMS modules as presented with the Life Cycle Unit concept. Factor (D) will decrease as micro-integration becomes state of the art.
- Stimulation of knowledge based diagnosis considering the prospect of a statistical significant data basis provided by diagnosable RMS. With such a generic database on failure modes and processing parameters reliability predictions can be made on other RMS modules and similar systems. Thus, the factor (M) will decrease with the realization of wide knowledge for the RMS.
- Life Cycle Management of used modules to maximize the profit (C) from re-used components considering the residual value and costs for adaptation.

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