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Through Life Analysis for Machine Tools: from Design to Remanufacture

Robert X. Gao and Peng Wang

Department of Mechanical and Aerospace Engineering, Case Western Reserve University, Cleveland, OH, 44120, USA

Tel.: +1-216-368-6045; fax: +1-216-368-6445. *E-mail address:* Robert.Gao@case.edu

Abstract

Increasing awareness of environmental burden calls for a sensible transition of manufacturing from the traditional mode where products have only one cycle of service life after being produced to a sustainable mode where multiple cycles of service life are enabled through material recovery, reuse, and remanufacture. As both the means for product generation and a product of modern manufacturing processes, machine tools have been increasingly viewed as a critical element for improving through life and consequently, sustainability. This paper examines the life cycles of machine tools and recent advancement in extending their life cycles. A life cycle is defined as starting from the design, proceeding through the stages of manufacturing and usage, and completing by the end of the service life. Modular design techniques that facilitate the manufacture and assembly of machine tools and analytical methods for reliable machine state estimation and remaining service life prediction are presented. Extension beyond completion of the first service life is enabled by recover and recycle of material from worn/broken machines, and redesign methods that reduce the amount of new materials to be used for making the same product in the subsequent re-manufacturing processes to ultimately realize materials reuse. Opportunities and challenges for sustainable manufacturing in the context of cloud manufacturing are also highlighted.

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Keywords: sustainable manufacturing; life cycle analysis; remanufacture; cloud manufacturing

1. Introduction

Increasing awareness of environmental burden caused by production and consumption of materials and stricter regulations motivate sustainable development that not only stipulates economic growth but also enhances environmental sustainability and social stability. Manufacturing, as the core of industrial economies, is expected to be transitioned into a new mode of operation that increases economic benefits by improved efficiency in resource (e.g. material, energy) utilization while at the same time, reduced environmental burdens (e.g. toxic emission and waste generation), to achieve sustainable living [1].

The key characteristic to differentiate sustainable products from their traditional counterparts is their multiple life cycles. When a sustainable product approaches the end of its first life cycle, it enters its post-life stage that is aimed to maximize the material usage through "6R" [2]: recover, recycle, redesign, reduce, remanufacture, and reuse.

In the post-life process, recover refers to repair or retrofit of a product to extend its service life, and redesign means to use the recycled materials with upgraded configuration or functionality of the original product to meet customers' new requirements, followed by remanufacture that restores the used product to like-new conditions, for reuse in the new life cycle. In this process, waste components resulting from the recovery and remanufacture procedures enter a recycling operation that extracts high-valued materials to reduce the amount of new materials to be used in the subsequent remanufacturing. Based on the usage experience during the product's first life cycle, machining planning and operation conditions can be optimized to reduce energy consumption and extend product life, as illustrated in Fig. 1.

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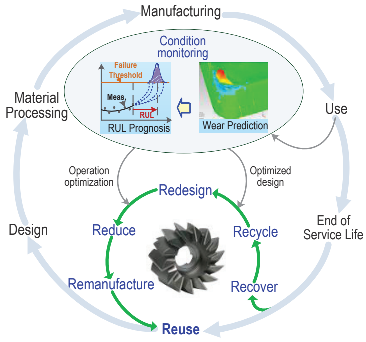

Fig. 1 Multiple life cycles of sustainable manufacturing

Extensive research has been conducted to promote the transition from traditional to sustainable manufacturing. Rusinko [3] explored the relationships between specific environmental factors (e.g. reducing energy consumption) that affect sustainability and competitive manufacturing outcomes. The study provides guidelines on prioritizing transition to sustainable manufacturing. Haapala et al. [4] pointed out directions for making the transition, from the perspective of energy consumption, airborne emission, water consumption, generation of wastewater and solid waste, and resource recovery. Goodall [5] reviewed methods to support decision-making in the process of evaluating the feasibility of remanufacturing. Du [6] performed comparative analysis of three industry models of machine tool remanufacturing in China: recycling-based, solution-based, and trade-in remanufacturing. The analysis indicated that solution-based remanufacturing model is most promising. McMillan et al. [7] investigated the theoretical potential for metal recycling, and concluded that the inherent properties of metals in general support indefinite recycling, which yield high-purity metal to offset primary production.

With the advancement of cloud computing and IoT, cloud manufacturing, where modular and configurable services are provided across geographical barriers, has increasingly become a viable mode of production [8], as illustrated in Fig. 2.

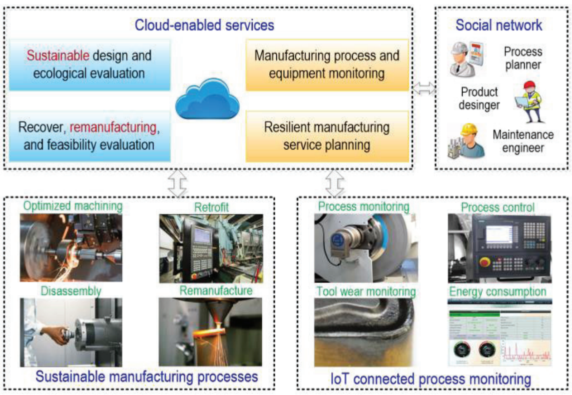

Fig. 2 Infrastructure of cloud-enabled sustainable manufacturing

2. First Life Cycle

Modular design that facilitates remanufacturing and advanced condition monitoring techniques for machine state estimation and operation optimization are discussed below.

2.1 Modular design

Reuse should be considered as characteristic or purpose when a product is designed, in order to facilitate recycle and remanufacturing when the product has reached the end of its first life cycle. This necessitates strategies that determine if certain components of a machine tool should not be designed as an integrated whole but connected by certain joint techniques to facilitate disassembly.

A framework for modular design of machine tools for remanufacturing has been developed by dividing and designing a series of general function modules, and selecting and combining these modules to meet the customer's requirements [9]. Rational module division facilitates product disassembly, recovery, and reuse. A modular design scheme is illustrated in Fig. 3. It is based on a series of design criteria for remanufacturing, from the selection of material options across evaluation environmental impact, connection of modules for ease of disassembly, decision-making on maintainability and end-of-life evaluation to economic consideration of remanufacturing. As an example, one criterion for facilitating disassembly is associated with the types and interfaces between components to be connected. The number of interfaces should be reduced, and certain connection methods, such as welding, should be avoided.

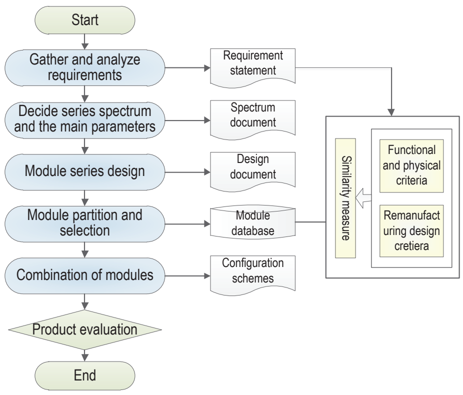

Fig. 3 Modular design for remanufacturing (adapted from [9])

Further research on modular machine design is reported in [10], which was motivated by the need for reuse and recycling of certain components. A set of five requirements on module compartmentalization have been proposed: technological stability, functional upgradability, long life, ease of quality assurance, and ease of cleaning and repair. In another effort, a mathematical model taking geometric information, connectivity of components, and attributes components as inputs and the derived modular structure as output was proposed [11]. To comparatively evaluate component connection methods, the types of parts contact, combination, and tools to be used were analyzed, and guidelines for component liaison intensity were proposed to facilitate modular design of machine tools [12].

2.2 Condition monitoring

The operational reliability of industrial machines and assets significantly influences the sustainability of manufacturing and competitiveness of the industry. Hence, ensuring reliability