

Concept for Recycling-Oriented Design in the Development of Cutting Machine Equipment

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Abstract: - Based on research on existing norms and regulations, scientific articles, industry practices, and the author's personal experience as a designer, key concepts have been identified as essential for developing recycling-oriented design. Among these, material-specific recycling, modular product systems, and standardization stand out. The article presents a concept for developing fixtures in which, at each stage of product development, additional methods are applied alongside classical methods. These methods determine which specific analyses and actions need to be included in order to achieve a product that is recyclable and aligned with the principles of the circular economy.

Key-Words: - recycling-oriented design, Circular Economy, EU regulations, material-specific recycling, specialized machines

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1 Introduction

Modern products are characterized by significantly shorter life cycles. In the past, household appliances were typically used for 10–12 years or more, whereas today many products, including automobiles, are often replaced after only two or three years in order to obtain a newer model. At the same time, the Earth's resources are limited, which directly affects their prices. To maintain their competitiveness, European companies must develop strategies to adapt to increasing costs of energy and raw materials. In response to these challenges, the European Commission has introduced a number of regulations and policies aimed at improving resource efficiency and reducing environmental impact.

This situation has a significant impact on the mechanical engineering sector, where energy and material costs strongly influence the final product price. German industry is strongly oriented toward the development of customer-specific solutions [12, 15]. Products are characterized by a high degree of customization, and this customer orientation represents one of the key strengths of German industry.

2 Problem Formulation

Modern products are characterized by short life cycles, high material and energy costs, and significant customization, particularly in the German industry. In the production of machine tools, this necessitates strategies for efficient resource use. Design for recycling reduces material costs and dependence on fluctuating raw material prices, facilitates disassembly and material reuse, and is often required in European procurement projects for machines and equipment.

What are the best methods that should be considered in the design of recyclable constructions based on the author's review of regulations, technical guidelines, and best practices in reuse, remanufacturing, and the circular economy?

2.1 Regulatory Framework

The Ecodesign for Sustainable Products Regulation (ESPR, EU 2024/1781), require manufacturers to demonstrate that their products are designed for recyclability, reparability, and ease of dismantling. Recycling-oriented design is therefore no longer optional, but a legal obligation. Annex I of the regulation defines product parameters relevant to sustainability and circularity, including the use of recycled materials, design for component reuse, upgradeability, remanufacturing, and refurbishment.

2.2 Technical Guidelines and Design Education

The **VDI Guideline 2221** provides detailed guidance for recycling-oriented design of technical products. It supports engineers and designers with information and decision-making tools to systematically improve recyclability. Key principles for resource efficiency include [2,3]:

- Reduced material use through optimized material efficiency and minimized manufacturing waste.
- Material substitution to lower environmental impact.
- Recycling via the reintegration of production scrap, end-of-life products, or product components.

2.3 Best Practices in Machine Reuse and Remanufacturing

My investigation examines how companies address recycling challenges, which approaches are most effective. Cutting machine producer have offered Machine refurbishment for years, replacing and modernizing worn components or those for which superior alternatives exist[6,7]. Some packaging machinery manufacturers actively buy back machines, refurbish them, and resell them, achieving 60–90% of the original price depending on the level of renewal [11].

Experience shows that initial machine designs often do not facilitate later upgrades or refurbishment[14]. This highlights the importance of considering refurbishment and adaptation during the initial design phase.

When a machine tool is decommissioned, its components can be utilized in three main ways:

- **Direct reuse:** Fully functional components meeting technical and safety requirements can be immediately reused without rework. — hydraulic units, screws, standard mechanical parts
- **Remanufacturing:** Components are refurbished or technically restored to achieve performance comparable to new parts. Examples include spindles, hydraulic power units, and tool holders.

3. **Material-specific recycling:** Components that cannot be reused or remanufactured are dismantled and sorted by material. Metals (steel, cast iron, aluminium, copper, brass) are remelted and reused in production, with aluminium reaching up to 95% recyclability. Some plastics can be mechanically recycled, while others are used for energy recovery.

By implementing these strategies, companies maximize the value of their machines, reduce waste, and support circular economy principles.

2.4 Design Principles for the Circular Economy

In machinery and plant engineering, where products often remain in service for decades and involve high capital investment, early integration of circular design principles is both ecologically and economically advantageous [8, 11, 12]. Key principles include:

- **Modularity:** Enable targeted replacement or upgrading of components, extending the overall lifespan of equipment.
- **Standardization:** Use standardized components and interfaces to simplify handling, spare part procurement, and system compatibility.

By systematically applying these principles, manufacturers can enhance sustainability, enable circular use, and support long-term resource efficiency [12].

3 Method for the Development of Recycling-Oriented Constructions: The Case of a Dividing Head

The dividing head is used for rotation and precise angular positioning of the workpiece and is applied in the processing of components on specialized machines, where standard commercially produced dividing devices cannot be used.

The development of a recycling-oriented design is presented using the example of a dividing heads. The development process is structured according to the stages defined in VDI 2221 and is complemented by methods for recycling-oriented design and resource optimization. For each stage, the key aspects that need to be considered during product development are discussed.

Product development begins with the clarification of the task. After confirming market interest in the dividing head, the necessary technical parameters are defined, including those that may provide a competitive advantage. A questionnaire is used to identify the customer requirements that are considered most important. The House of Quality method is then applied to identify and prioritize the key customer requirements and the corresponding technical parameters.

This phase concludes with the preparation of the technical specification for the dividing head, defining two key parameters: the diameter and the required clamping force.

In order to develop a modular system and reduce the variety of dividing heads, the maximum required clamping force is determined for each diameter. Based on these two parameters, the corresponding types of dividing heads are developed.

To ensure long-term recyclability and efficiency, the dividing head must allow for easy future upgrades. This requires analyzing potential market requirements and necessary modernizations over a 10–15 year horizon during the research phase.

Due to the development of materials and cutting tools, the machining of parts is performed over time at higher speeds and forces, which also requires a higher clamping force. The dividing head is designed to accommodate these increased forces and to allow for future upgrades requiring higher clamping forces. In the **Concept Creation** phase, the main functions that the dividing head must perform are identified (Fig. 1).

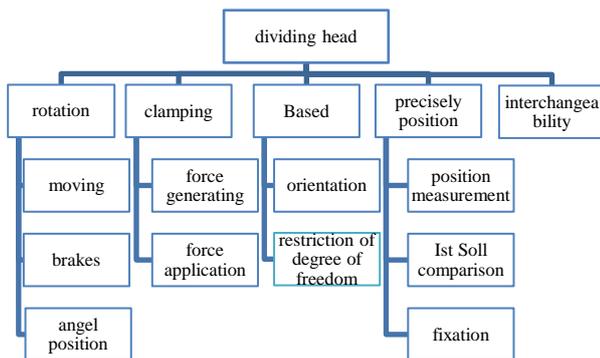


Fig.1: Main functions of dividing head

The developed dividing head is intended for specialized machines. Since these machines do not have standard T-slots, the dividing head must adapt to the specific geometry and surfaces of different machines, ensuring universality and the possibility of reuse without the need to manufacture a new device for each machine. For this reason, interchangeability has been integrated as a separate function.

This approach makes the dividing head independent of the installation situation. The design follows a modular principle, allowing individual components to be used or replaced independently. When decommissioned, the housings can be reused without additional processing.

During the concept creation phase, the most optimal variant was identified. For this purpose, the morphological box method was used. The sub-

functions of the dividing head were listed, and for each function two or three possible technical solutions were proposed.

Criteria for Selecting the Optimal Variant

The first criterion is the use of company-specific standard components – solutions already developed and applied in other products within the company. Integrating these components ensures proven design solutions and facilitates both development and maintenance.

The second criterion concerns the selection of a clamping system that allows for future upgrades. The system must be easily adaptable if the required clamping force increases over time.

The possibility of constructing subassemblies is implemented through the modular system approach. Components with a long service life, such as housings, are standardized, while components with short innovation cycles are designed to be highly flexible and easily replaceable.

Other important criteria include manufacturability, compatibility with machines, and the production capabilities of the enterprise.

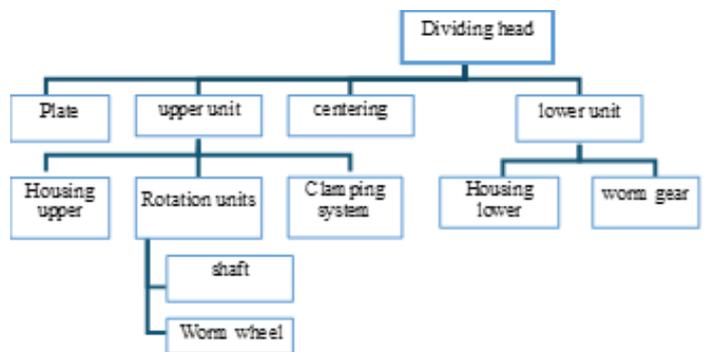


Fig.2: Assembly graph

In the assembly graph (Fig. 2) and Sketch (Fig. 3) of the selected optimal variant, the individual design groups are illustrated. The main structure consists of a lower and an upper housing, within which the corresponding subassemblies are arranged. The plate forms a separate structural element, ensuring the system’s independence from the machine and its fixtures. Depending on the specific situation, the lower housing can either be reused directly or disassembled and integrated into another design.

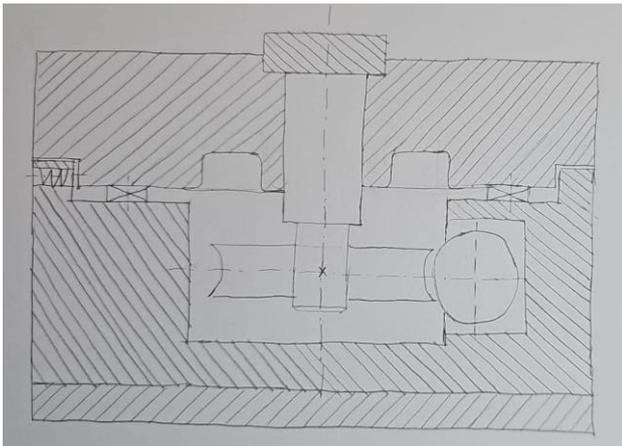


Fig.3: Principle Sketch of a Dividing Head

When selecting materials for individual components, multiple criteria are considered, grouped into four main areas. The first area covers mechanical properties, which determine strength, hardness, and load-bearing capacity. Next are surface and technological aspects, such as machinability, formability, and heat treatment capabilities. Economic and environmental factors, including cost, availability, and recyclability, are also important.

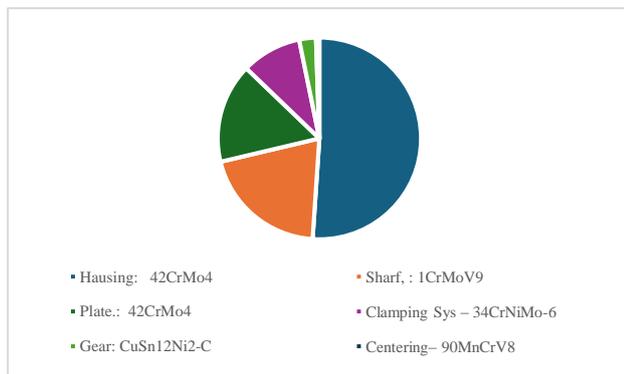


Fig.4: Distribution of Materials Used in Dividing Head

Material selection plays a key role in the circular economy, as the choice depends on how individual components are used—whether they can be directly reused or require recycling through remelting. For example, the adapter plate is almost always replaced when used with a different machine. Consequently, it is not reused in its original form but recycled through remelting. It is made of low-alloy steel (42CrMo4), which is highly recyclable when materials are properly separated. On the other hand, the housing serves to collect and position the individual components. These two parts can be reused directly without additional processing.

Figure 4 illustrates the individual components and the materials chosen for each

The final stages of product development include creating CAD models, performing FME calculations, developing documentation, production, and prototyping. In this process, it is important that the materials of the components are clearly marked, so that their exact composition and properties are known even years later, in case the documentation is unavailable.

4 Conclusion

The article proposes a method for designing recycling-oriented constructions. The proposed method offers the following advantages:

1. When selecting the material for a given component, consideration is given to the possibility that, after the end of its service life, it can be reused or recycled through remelting.
2. The product developed in this way, in compliance with the requirements of the circular economy and EU regulations, creates advantages when applying for European projects for the modernization of enterprises.
3. The proposed sequence introduces specific steps and aspects that should be considered in the development of recycling-oriented products, complementing the methodological guidelines of VDI 2221.
4. Based on an analysis of industrial practices, circular economy principles, relevant guidelines, and EU regulations, the most effective design approach for the cutting machine was selected, with a focus on recycling-oriented design.

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