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Design for longevity in industrial products: a pedagogical case study on steel moulds for injection mould manufacturing

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Abstract: This paper aims to demonstrate the life cycle costing and environmental impacts of different R-strategy scenarios, with a focus on steel moulds. Reuse primarily focuses on remanufacturing steel moulds and exploring the most environmentally optimal strategy, serving as a supplier in a circular economy. The scope of this case study does not include recycling scenarios. The study uses a pedagogical case study in collaboration with The LEGO Group. One approach is to map the CO_2-eq footprint of steel mould consumption to prepare for a digital architecture based on material consumption and circular strategies.

Introduction

The application of repair technologies for metalwork, such as welding, laser cladding, and powder metallurgy, is well-known. The literature on lifetime extension is sparse. Hatcher et al. (2011) and Govindan et al. (2017) highlight a lack of research on remanufacturing and closed-loop supply chains outside established industries, such as automotive and electronics, noting a shortage of quantitative methods for optimising operations.

This paper explores opportunities for mould manufacturers to extend the lifetime of steel injection moulds to optimise material efficiency. The study is a collaboration within the MADE FAST project, motivated by the exploration of optimal strategies for science-based targets and data-driven emissions reduction. It focuses on the circular opportunities in mould manufacturing, as an area where the moulding industry holds control over what and how much material is used in mould fabrication. The objective is to demonstrate the life cycle costing and environmental impacts in different R-strategy scenarios focusing on steel moulds. One approach is to map the CO_2-eq footprint of steel mould consumption to prepare for a digital architecture based on material consumption and circular potential data. Concurrent with the case, the partner conducted a pilot study to explore the reuse of mould components, selecting those based on cost and weight. This study builds on the pilot project to provide the company with a data basis, including CO_2. The analysis builds on real-life issues and serves as a pedagogical case study conducted at the LEGO Group manufacturing facility, with an injection mould as the research context. Injection moulds are designed and ordered in various configurations and purposes, ranging from high-volume to low-volume production, and from standard to unique designs, with differing shapes, complexities, and sizes. The object of the case study is the mould box design platform used in the company's internal manufacturing operations, which produces 70% of the injection-moulded goods for the case company. From a cost perspective, an estimated benefit is that when a steel mould foundation is reused one to two times, it results in a 12% savings in mould manufacturing costs, and the new mould cost is reduced due to the reuse of components with depreciated value.

Method and data

Data collection methods include gathering product-specific data using a Bill of Materials, conducting interviews with company employees at both operational and strategic levels, providing guided tours led by company experts who demonstrate the sustainable lifetime extension initiative, and documenting these activities with video and photographs. Additionally, informal meeting summaries were collected from February to November 2024.

Developing a CO_2 tool

A collection of the parts and components that constitute an injection mould, typically used for procurement, order, and assembly, is known as the Bill of Materials (BOM). Each part or component, along with its accompanying data, is available in the BOM, typically including material, weight, quantity, part ID, and part name or description. In this case, the BOM's extension includes volume and generic data on CO_2-equivalents embodied in the material weight. The BOM must expand on data points for all subassemblies and components of a single material. This is necessary to gather generic data on embodied CO_2-eq for the mould parts. The CO_2 tool is set up in Microsoft Excel, providing a basis for exploring and comparing reuse scenarios for injection steel moulds. Generic environmental data is applied as part of building a tool for CO_2-based scenarios. The partner company does not have detailed data points to describe different steel materials used for moulds. Therefore, the next best course of action is to integrate proxy data on CO_2-eq from Ansys Granta Edupack, as detailed in Table 1, "Data basis on mould components applied for the CO_2 tool development".

Volume	[mm^3]	Extracted from the CAD software.
Density	[kg/mm^3]	Collected from the material datasheet from the supplier.
		When the supplier is unknown, a similar material is looked up in the Ansys® Granta material library. Density is collected from the material library for the representative material.
Embedded CO_2	[kg/kg]	The material library chooses a material corresponding to the one listed in the BOM. The CO_2-eq data accounts for potential emissions from mining, material refining, transport, and material processing until the block is delivered as a raw block.
Weight	[kg]	Density is multiplied by the volume.

Table 1. Data based on mould components applied for the CO_2 tool development.

Material Assessment

Material identifiers refer to a specific steel alloy from a particular supplier, purchased based on its quality and the insurance provided for the exact constituents in the alloy, as specified by the supplier. Considering the EU List of Critical Raw Materials, the material assessment of the injection mould visualises material content distribution with Microsoft Excel charts.

Interview to extend data collection

Interviews are used to verify the gathered and structured data, both to extract data from internal company databases for design and procurement, and to agree on the material selection approach for substituting generic data from Ansys Granta EduPack. Interviewees from the company partner include a material specialist, mould designers, supply chain management, and the sustainability team.

User test for the CO_2 tool

A test of the developed tool is performed with the intended users, including the mould design platform owner, mould developer, and the data specialist responsible for developing and converting it into a software platform. The users were shown a demonstration of the tool layout and its features and were provided with test versions of the tool. The company project responsible was facilitating user test input and discussion, and a co-facilitator and researcher kept notes. The duration was 25 minutes. A second test was performed a month later for the intended users in a revised tool version, followed up on key points from the first test.

Lifetime of a mould - state of the art

During the manufacturing stage, which utilizes an injection mould for object production, production stops if a mould component fails prematurely, thereby reducing the mould's lifetime expectancy. The stopped mould box is handled by expert service personnel for maintenance, repair, or replacement of the faulty component with a spare. When the expected lifetime of injection cycles is reached or if the quality of the objects declines, the mould box is worn out and removed from production. In this case example, the mould box order was approved to run 9 million injection cycles. The lifetime expectancy of the mould components is subordinate. The production time of a mould box lasts from a few months to several years, depending on the market demand for the object design and the concomitant mould wear. Wear affecting object quality is prevalent in tool cavities and cores.

Mould components with remaining service life are dismissed when the mould is ordinarily scrapped.

Opportunities for lifetime extensions

The mould box is designed to support the form-giving inserts for exactly the volume of objects in demand, ensuring a match between production volume and cavities, as well as the number of injection cycles. While the form-giving inserts must be remelted and cannot be reused as it is a worn part, simply replacing it and reusing the remaining mould components is not sufficient.

The product - a steel mould

The case injection mould box is a collection of metal components designed to produce plastic objects with tight surface tolerances and stress resistance.

The main categories of mould components include the essential form-giving insert, cavity and core, large plates, and function-specific subassemblies. The lifetime-determining component for the mould box is the form-giving insert, which shapes the object and is essential for defining shape, tolerances, and surface quality. The form-giving insert is the component most marked by wear and tear during cycles, as it is repeatedly closed, filled with hot plastic, opened, and released from the produced plastic object. Once worn out, the mould box is typically welded using a CO_2 burner and sent for mixed-grade metal recycling, as it is the lowest-value option for capturing metal. Figure 1 illustrates the circular scenarios explored.

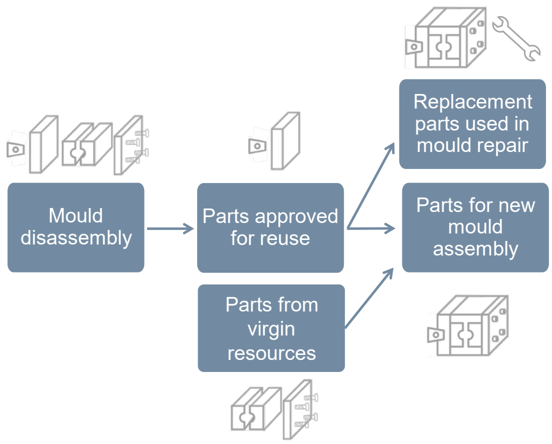

Figure 1. The exploration of longevity strategies.

According to the interviews conducted, it is evident that the remaining mould components have a longer life expectancy due to the precautionary principle of not wasting the engineering effort invested in the form-giving insert. It is worse not to meet manufacturing demand for objects due to a mould malfunction resulting from component design with too low requirements and a form-giving insert with a remaining service life than to have the mould designed to the above-required specification.

Through interviews with the reuse team, it was found that less-worn-out parts and plates are fit to run up to an expected 20-50 million cycles. The mould box, as a case product, is a medium-sized mould containing 755 components, weighing between 270 and 282 kg, depending on the design configuration of the particular mould box type. The partner company manufactures a significant number of moulds worldwide annually, of which 55% are platform-designed for internal standardisation. It reflects the expected volume of worn-out moulds that theoretically enter disassembly as a potential contributor to harvesting for reuse. A mould design platform includes a product portfolio of normally 11 mould designs. An exemplary mould box is drawn by the authors based on supplier sales material and patent figures and was revised by an injection mould expert with the case company. It is illustrated in Figure 2.

Figure 3 shows the material opportunities for the case mould on a weight distribution chart. The main component categories are associated with a material identifier; the largest is from the case mould, marked as tool steel grades 1.2085 and 1.2344. From the product case, the repair team identified 19 reusable components. The mould designers identified more than 59 components that hold sufficient design commonality to be reusable, including the spacers in black and small parts in dark blue and grey.

The assessment using the CO_2 tool identified reusable components based on CO_2 data in comparison to known target lists for reuse. Component categories that include parts not yet recognised by either design or disassembly teams encompass ejector base plates. Increasing the longevity of the mould box is facilitated through repair and replacement, which are simplified by the mould design, allowing for disassembly for specific purposes. Sufficiently exploiting the remaining service life of components from mould boxes taken out of production as worn out allows the manufacturing company to become its own supplier of plates and parts for new mould box assemblies and mould maintenance, facilitating component replacement. The mould is disassembled to reuse parts and then cleaned. Skilled repair personnel visually inspect each component individually to assess its potential for extended service in production. The parts are sent through the production line as if they are new parts entering quality inspection, and sometimes they are also reworked through machining. All reused parts receive the highest quality inspection of surface and shape tolerances. All reused parts that have passed quality inspection meet the same standards as new parts.

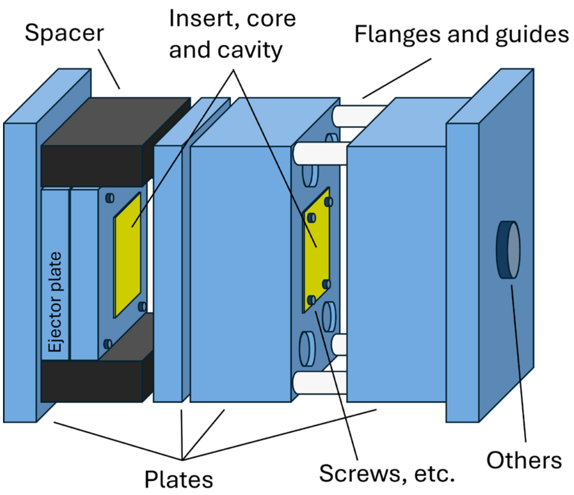

Figure 2. A representation of the main component categories of a mould box.

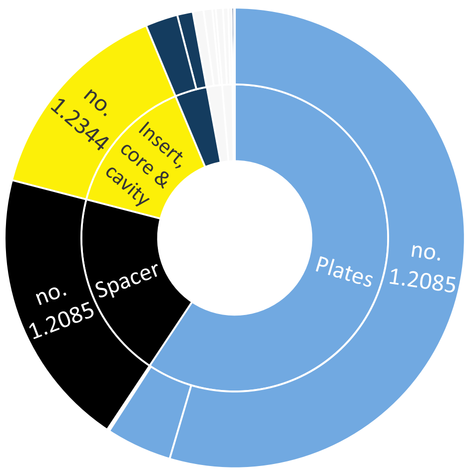

Figure 3. The weight distribution [%] and material codes of the case mould.

Results and Discussion

Expensive components include steel mould plates, which are costly to manufacture, as well as mould parts and subassemblies, which are also expensive to purchase. The interest lies primarily in the reuse of the steel mould plates, as they are the most extensive and heaviest components (Figure 3), accounting for 59% of the total expense. They are typically made from tool steel and are expected to make the most considerable contribution to the overall CO_2-eq emissions. Figure 4 shows the case result of CO_2-eq emissions on component categories, identifying potential targets for reuse, indicated by dots.

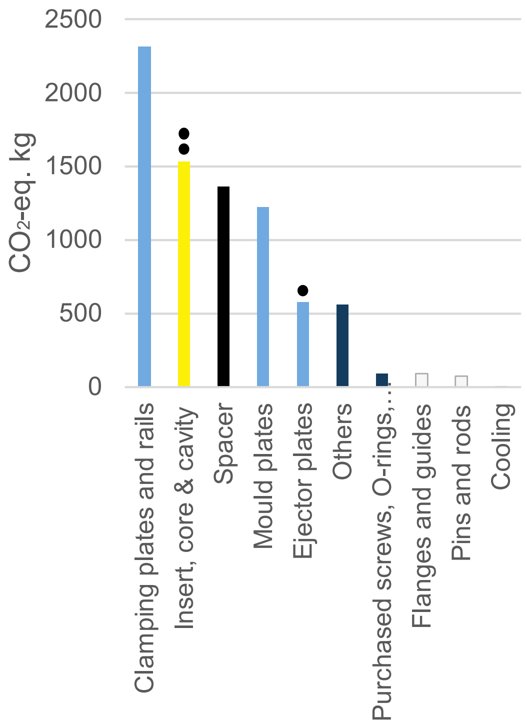

Figure 4. Categories of components in the case mould and their CO_2-eq contribution.

Disassembly is a central process for the circular economy, particularly in terms of resource utilisation and waste reduction (Vanegas et al., 2018; Cappelletti et al., 2022), which emphasises the importance of selecting a relevant End-of-Life strategy and mapping the barriers to circular reuse initiatives. Providing that the mould plate design of the case mould box is the driver of reuse, the design of mould plates varies from generation to generation due to version updates, and the plates must be forward-compatible or reworked to become compatible. Likewise, mould box designers must enable backwards compatibility for mould boxes to reuse older versions of mould plates. Generational commonality is associated with reduced manufacturing costs (Kim & Kim, 2020), a relevant point for original equipment manufacturers that utilise remanufactured components in their production. Ma et al. (2023) focus on modular design and its benefits for remanufacturing, which is used to upgrade products. In contrast, Mesa (2023) focuses on material choices in the design process. These are themes for future research.

Limitations of the study

CO_2 data is based on generic data and is not intended to provide definitive results; instead, it is indicative of emissions reductions and material choices that consider emissions as a strategic direction.

Conclusion

Few practical case examples exist, although the literature is rich in theoretical circular strategies. This study presents a real-life, yet pedagogical, case study, resulting in the case partner establishing a pilot project to test whether recovering components enables resource utilisation through reuse and remanufacturing, thereby achieving a longevity strategy in mould design and consumption (as shown in Figure 1). Following the pilot and this research project on CO_2 footprint, mould disassembly for reuse recovery has become an integrated part of manufacturing operations. Data on cost, weight, and CO_2 support it.

The lifetime extension business model targets are outlined in the newly released European standard EN 45560, which states that the reuse of products or parts retains the value of virgin resources, including materials, energy, labour, and financial capital, and avoids additional contributions to environmental impacts. The standard provides several examples, though not explicitly, to mould manufacturing and systematic data handling.

While injection moulding machinery adheres to the EU Machinery Directive 2006/42/EC, which focuses on safety, there are no specific standards in place for a greener manufacturing transition. The EU Green Deal contrasts the lack of guidelines with the Eco-design directive for energy-related products to injection mould manufacturing (EN45550-60). The directive includes reducing the use of virgin materials by extending product lifetimes (EN 45552:2020) and reusing components through remanufacturing (EN 45553), which in turn reduces the demand for new materials. In conclusion, the study demonstrated the application of data-driven environmental data to support deliberate sustainable efforts by highlighting targets for reuse and prolonged lifetime of steel mould parts based on weight, material, and CO_2-eq footprint.

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