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PAYNE COMMENTARY SERIES: **VIEWPOINT**

Innovators and the Development of Mini-Mills for Steel Recycling: Lessons for the Development of a Circular Economy from the Steel Industry

By McKenzie Jones and Sara Hastings-Simon

As the global population grows and societies become increasingly industrialized, the demand for resources is outpacing the capacity for sustainable production. Meeting this growing demand will require a change to the current linear approach to resource use - from one where resources are used and then discarded as waste to a more "circular economy" model [1]. A circular economy combines an environmental and economic outlook on resources with the goal to dramatically reduce the new resources needed. Systems would be redesigned to reduce overall material needs, starting from design that enables items to be repaired and reused, requiring new value chains and business models.

While the approach goes beyond simply recycling products at the end of life, recycling is still an important component of stock management in a circular economy and current efforts are underway to increase recycling across a number of sectors. Over the past two decades, the amount of plastic recycled has doubled, but the recycling rate still falls below a 10% threshold [2]. With an average recycling rate of ~86% across different sectors in the automotive and construction industries, steel is one of the most recycled materials in the world [3]. While the nature of the products, which generally exist in easily recoverable large quantities, contribute uniquely to a high recovery rate, the process and development of the recycling approach offers important lessons for other sectors that we explore in this case study.

Steel has the theoretical potential to be recycled infinitely. The most common steel recycling process, which today accounts for ⅔ of recycled steel in the United States [4], uses an Electric Arc Furnace (EAF) to melt the scrap metal. Once in this molten state, the liquid scrap undergoes a number of controlled processes to purify the steel. [5]. The material then undergoes a continuous cooling and casting process as it is hot and cold rolled into specified product. The output products can range from thin slabs to ingots. Not only can the input be solely scrap or scrap-substitute based, eliminating the need for additional raw materials, the EAF process significantly reduces energy and consumption and CO_2emissions compared with the use of carbon-based blast furnace ironmaking coupled with basic oxygen furnace (BOF) steelmaking [4].

Nucor case study

Initially the rates of recycling in the steel industry were relatively low, and largely related to the recycling of product within the steel mills rather than end of life material [6]. Historically the steel industry in the US was dominated by large integrated steel producers. The experience of one of the companies behind the growth in steel recycling, the Nucor Corporation, is an interesting example of innovation in both technology and business structure. As efforts are underway to dramatically increase the rate of recycling across a number of materials, these lessons can provide helpful real-world guidance in policy design and business approaches.

Nucor existed for decades in different forms before it made a name for itself in the steel industry. Nucor's connection to the steel industry came with the acquisition of Vulcraft, a steel joist and girder producer that used steel as input for manufacturing. While the corporation as a whole struggled to remain profitable, Vulcraft was successful, and the acting manager of this division, Ken Iverson, was appointed CEO of Nucor in 1962. Iverson sold off other unprofitable divisions and focused solely on the steel joist manufacturing sector. By 1968, four separate Vulcraft divisions were opened including new operations in Nebraska, Alabama, and Texas, to supply the increasing steel joist demands. Given the importance of steel as an input for the company's operations the issues Vulcraft faced regarding availability, price, and quality for steel were a problem for the company. As a result, Iverson oversaw the creation of mini-mills, smaller mills that used recycled steel to produce steel for Vulcraft's own operations. Mini-mills would ultimately become a force that revolutionized the steel industry [7].

Nucor opened its first mini-mill in Darlington, South Carolina in 1969 and employed a vertical integration business model to supply steel to the numerous Vulcraft divisions. The mini-mill produced solely what was necessary for Vulcraft to function, at competitive costs, eliminating reliance on external steel suppliers. Unlike integrated steel mills which utilized scrap to alleviate problems with overcooked steel, Nucor relied primarily on scrap as a continuous input for the EAFs. The dependence on recyclable materials eliminated mining expenses, reduced required manpower, and limited energy consumption, these three areas of cost savings gave Nucor a competitive advantage. In addition, the use of EAFs lead to a decrease in pollution and hazards compared to Open Hearth Furnaces.

Outside of production expenses, the decentralized structure of Nucor's mini-mills was one factor that enabled the corporation's rapid growth. The steel market varies greatly, from the automotive to the construction industry, and correspondingly the metal specifications regarding the quality, size, and alloying elements of steel exist in diverse ranges. Steel is not a single commodity product and the decentralized structure used by Nucor recognized and embraced this fact. Each mini-mill's location and design was strategically chosen based on the supply of scrap and products required. This greatly reduced transportation costs given that mini-mills were built in locations where there was an abundance of scrap and the scrap was used to make products that would specifically benefit the adjacent region. Iverson accredits the majority of Nucor's success to its decentralization. In allowing each branch to act as its own separate business, Nucor mini-mills were able to turn technological improvements across the different sectors [8] into an increased range of products and larger production size.

When the Nucor EAF model first emerged, numerous doubts were cast by 'Big Steel' regarding the viability of the threat Nucor and EAFs posed to the industry [5]. Given the mini-mill size and use of scrap steel, it was generally believed that the approach could never deliver "high quality" steel production. The steel industry struggled financially during this period, but integrated steel mills chose to actively focus on decreasing production costs externally rather than embrace the technology of mini-mills. The limited technology transfer was reinforced by the isolating nature of Nucor's business structure. Because mini-mills produced steel for internal company use there was limited interaction with other steel producers while the company grew production. Throughout the next couple of decades, Nucor opened and maintained numerous mini-mills and plants across the United States, greatly increasing production capacity. Although Nucor remained decentralized, technological innovations yielded at one plant spread quickly to others, and the rate of technological change was significantly faster than in large integrated steel plants.

The technology development was incremental, to start, and for many years Nucor focused solely on the production of construction products such as steel beams which were easier to produce from recycled inputs compared with other steel products. The production of a broader range of outputs was initially thought to be impossible given the design of the mini-mill, but the development of continuous casting technology tailored to the mini-mill environment was an important step forward that enabled mini-mills to produce higher quality output. Nucor introduced continuous casting technology into its mills in 1989, and the performance of the thin-casting technology ultimately exceeded expectations [9].

While the term mini-mill came from the original size of the plant, which was "mini" in comparison to the typical steel mill size of the day, it is now obsolete. Nucor today is a major steel producer in the United States, with a single mini-mill's capacity around 2.5 million tons annually [7]. Comparatively, integrated steel companies, on average, produce around 10 million tons annually, but the gap between Nucor and other integrated steel has shrunk significantly since the introduction of mini-mills in the late 1960s.

Lessons for a circular economy

The history of the growth of mini-mills provides important lessons for the realization of a circular economy in other sectors. It also illustrates the economic potential in design that increases circularity as the mini-mill approach enabled Nucor to become a serious competitor in the established steel industry through a process that was more economically competitive, and with a lower environmental impact.

Nucor's entry into steel production was driven not by a desire to compete with the established players within the steel market, but a need to meet the demand for steel within the company's own manufacturing business. This need created a motivation for a new entrant to pursue innovation. Success was not immediate, there was limited progress on mini-mill design in the early stages, but the critical need provided motivation for Nucor to continue technology development.

While in this case the need arose from the market conditions, policies and regulations can play a similar role in defining a broad challenge (an increase in recycling, or decrease in carbon emissions) that encourage development of step change innovation in production methods. Alternatively, government support of technology development can enable the required new technologies to be de-risked in a non-commercial environment.

The availability of steel scrap was critical to the success of the mini-mill model as Nucor could tap into an existing supply of scrap rather than having to develop a supply directly. Steel's high recycling rate is, in part, due to the chemical composition - as an iron alloy steel is magnetic and therefore much easier to sort during the recycling process. In addition, the relatively consolidated nature of how steel is used means that large quantities of scrap material can more easily be recovered as compared to materials that occur in products in smaller and more distributed amounts. Although home scrap – scrap generated within a mill – and new scrap – scrap generated in a manufacturing plant – contribute to the overall scrap yield, roughly 60% of steel recycled in the United States comes from old scrap. Obsolete scrap is primarily supplied by the automotive and construction industries [10].

The mini-mill case is an example where a supply of scrap that can be easily accessed by new entrants was available prior to the widespread adoption of the new technology, lending support to the need for the current efforts to design products in other sectors with the end-of-life in mind. It is likely that more significant efforts are required given that other materials do not have the same properties that give steel an advantage in scrap collection and recyclability.

The ultimate success of the novel mini-mill approach was not anticipated at the time by the incumbent steel producers, particularly given the concern around the ability to produce products from recycled steel that met end users requirements. The challenge was met through an iterative process that started with the most simple products needed. For these products the mini-mill based recycling methods were cost advantageous, and created a starting point to allow the company to slowly build and consistently improve and expand product outputs overtime. Vertical integration may not be applicable to all industries, but the principle of starting with the "easiest" product is broadly applicable.

The pace of change in technology in the mini-mill approach that enabled this improvement was much faster than in the traditional integrated steel mills. This success is in part due to Nucor being a growing enterprise installing new capacity during this critical period rather than managing legacy infrastructure. However, the faster pace also required a change of mindset and business model from one where steel mill infrastructure was built to last 50+ years in the case of integrated steel mills, to one where new equipment was introduced frequently.

Ultimately, once the challenges were overcome, steel recycling was able to compete because of the cost savings in the process. The reliance on scrap eliminates mining expenses and greatly decreases both transportation and energy costs, where energy cost is a very significant expense in steel production [11]. In addition, the use of scrap offers the potential for carbon reduction, particularly if electricity is generated from low carbon sources. In many cases the mining of raw materials is more expensive than recycled alternatives, creating an incentive to embrace a circular economy approach [12]. In other sectors where the cost differential is smaller the incentive will be less significant. This is particularly true where the full costs including externalities for the new material production aren't paid by producers. Policies that price pollution and input materials at their full costs or direct subsidies can overcome this cost differential barrier.

The steel mini-mill case study provides useful lessons in the effort to create a more circular economy which we summarize here. While not all factors can be replicated for other materials and sectors, they can guide policy design and inform business decisions to enable a more circular economy in other sectors.

1. An external force (in this case, limited availability of steel for their own manufacturing operations) encouraged a new player to innovate, ultimately overcoming doubts about the technology.
2. A robust supply of scrap from an established supply chain was available and readily accessible at the start of development of the recycling technology.
3. The first recycled product developed was for a use that necessitated only relatively basic product requirements, more complex materials were developed over time.
4. Innovation in technology led to shorter technology lifecycles and required a new approach to manufacturing design within an established industry.
5. Ultimately the technology for producing new products from the recycled scrap was competitive and thus successful due to cost savings.

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