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Technological Innovations and Obsolescence: Leveling the Playing Field for Remanufacturing

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***Abstract*—In a linear economy, manufacturing is less costly and more profitable than remanufacturing because of reduced private costs of utilization and production. However, manufacturing also involves higher resource extraction and waste as externalized costs than remanufacturing. We use a vintage capital framework to assess technological innovations in remanufacturing and their potential benefits to society and human occupations. Our study shows that replacing manufacturing with remanufacturing technologies creates positive static and dynamic circular economy externalities. These externalities can be quantified to assess improvements in social outcomes. A smartphone remanufacturing innovation case study is presented as an illustration of the article's main ideas. Future research should investigate additional specific cases to develop a comprehensive methodology for assessing the impact of remanufacturing innovations on social outcomes. This will provide valuable insights into the broader implications of remanufacturing practices.**

***Keywords*—manufacturing, externalities, occupational meaning, circular economy, sustainability, national accounting systems.**

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I. Introduction

Technological innovations in durable goods often lead to increased productivity when considering a narrow definition and accounting framework. However, national accounting frameworks like the Systems of National Accounts typically do not fully measure the productivity of natural resources, stock changes, pollution, human well-being, or occupational meaning [1]. In addition, these omissions create an upward bias in total factor productivity (TFP) gains attributed to technological innovations, as it fails to account for the losses incurred through extraction and environmental damage caused by accelerated obsolescence. Therefore, it follows that reconsidering the limitations that current accounting systems impose on technological innovations in manufacturing and remanufacturing is essential to achieving sustainability goals.

This paper uses a vintage capital theoretical approach and model production function to quantitatively demonstrate the feasibility and benefits of remanufacturing, considering principles of circular economy [2], [3], sustainability, and occupational science [4], to explore the limitations of current national accounting systems and opportunities for alternatives.

There is extensive literature on technological innovations and economic growth that tries to capture the effects of technological progress on growth dynamics in accordance with Solow's [5] observation that innovations must be embodied in new vintages of capital before they can be effective. This vintage capital theory is supported by the empirical observation that capital prices decline steadily and rapidly compared to what would be expected without technological progress and embodiment [6]. Additionally, economic growth based on vintage capital replacement is characterized by accelerated depreciation due to obsolescence and gestation lags [7]. Of course, there are several tradeoffs to consider.

On one hand, technological innovations and remanufacturing have the potential to reduce negative environmental impacts by optimizing the use of resources (such as materials, energy, and information) and minimizing waste and pollution. However, these innovations can also result in wasted resources and diminished well-being when older products are discarded. Furthermore, remanufacturing often involves increased capital and labor costs for technological upgrades [8], [9]. This raises the question of whether there are alternatives to national accounting frameworks that can facilitate the transition towards remanufacturing and address the limited current focus on capital and labor productivity gains and losses in relation to natural resource extraction, environmental and human ecosystem protection, and occupational meaning [10].

In other words, when national accounting frameworks primarily emphasize indicators like gross domestic product (GDP) growth and monetary value, they tend to overlook the positive environmental and human impacts of remanufacturing and the resource efficiency it offers. Remanufactured goods are often treated as used products rather than valuable resources with embedded labor, materials, information, and capital. The current framework encourages the production of durable goods that contribute to environmental damage in a linear economy characterized by extraction, processing, and disposal. This phenomenon is compounded by the fact that durable goods become obsolete at a faster rate due to technological progress, leading to their depreciation [6], [7].

Additionally, it is interesting to note that the combination of vintage capital and innovations can create macroeconomic volatility due to “replacement echoes” – the ability of an economy to reproduce its history in cycles [11], [12]. This phenomenon refers to the economy's tendency to cyclically reproduce intense investment periods because of waves of obsolescence. In other words, when vintage capital is present, technological innovations can recreate past cycles of substantial investment unless mitigated by limiting factors. Limiting or stabilizing factors may be imposed with the help of effective fiscal policy [13], for example, by using taxes. Moreover, including all durables and materials in assessments of remanufacturing could lead to improved guidelines to develop stabilizing factors, green accounting systems, environmental protection measures, and the promotion of humane technological innovations [14] that prioritize the well-being of labor and non-labor human occupations that align with sustainability goals [15]–[17].

II. OBJECTIVES

The objective of this study is to evaluate the potential impacts of replacing manufacturing technologies with remanufacturing technologies on positive static and dynamic circular economy externalities. It also examines how national accounting systems frame and may limit the realized benefits of remanufacturing and explores alternative approaches such as green accounting systems. Additionally, the study considers the potential effectiveness of green policy instruments such as taxes, regulations, and nudges in promoting remanufacturing.

III. METHODOLOGY

We use a vintage capital model production function [12] and expand on this previous work using a vintage capital theoretical approach to account for static and dynamic circular economy externalities. We assume remanufacturing encompasses all durables and associated flows. We apply the theoretically expanded model to a smartphone industry remanufacturing innovation case study to explore and discuss potential impacts on human well-being and occupational meaning.

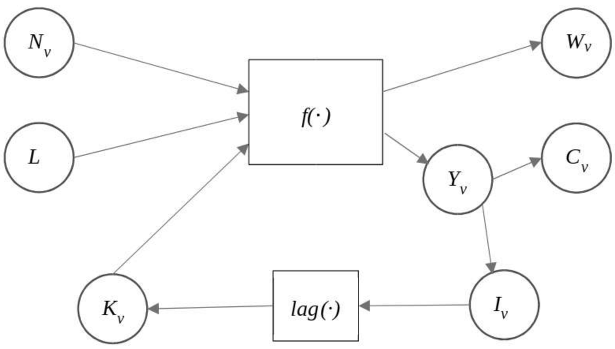

Fig. 1: The vintage capital model production function

Figure 1 provides a conceptual diagram of the vintage capital model production function and relationships among relevant variables. Production depends on capital K_v, labor L, and natural resources extraction N_v. The index v represents the innovation cycles that lead to new vintages (generations) of durable goods. Y_v represents the physical output, while W_v represents the environmental burden. The environmental burden captures all waste, pollution, and detrimental effects of productivist industrial processes on human well-being, including disruption of labor and nonlabor human occupations [15]–[17]. Therefore, the environmental burden, W_v, represents all negative externalities to the natural and human ecosystems. Output Y_v has two components: consumption C_v and investment I_v. Capital K_v of vintage v becomes obsolete at the end of each innovation cycle, contributing to W_v. New capital K_{v+1} of vintage v+1 is built during vintage cycle v with investment I_v and is deployed at the beginning of the next innovation cycle.

Subscripts m and r are used to differentiate between manufacturing and remanufacturing variables. Following the discussion in the first section, and ceteris paribus, we simplify the analysis with the following hypotheses:

$N_{vm} > N_{vr}$ (1) $W_{vm} > W_{vr}$ (2)

$I_{vm} > I_{vr}$ (3) $C_{vm} > C_{vr}$ (4)

Inequality (1) represents lower amounts of natural resources extraction under remanufacturing. Inequality (2) represents the smaller environmental burden of remanufacturing. Inequality (3) represents the increased physical costs of building-up capital (investment) under remanufacturing. Finally, inequality (4) represents that increased investment needs in remanufacturing come at least partially at the expense of consumer goods production.

IV. Results and Discussion

A. Remanufacturing, National Accounting, and Green Accounting

Remanufacturing in a vintage capital theoretical framework (Figure 1) can be seen as the embodiment, at every vintage cycle, of materials, energy, and information required by the upgrading of older vintages of durable goods. Solow observes that these factors should be included in national accounts' investment and capital formation categories [8], [13]. Remanufacturing activities in a circular economy are, however, harder to objectify and measure than linear economy activities based on productivist manufacturing business models due to the higher complexity of the tasks involved and the exclusively human (at least for now) craftsmanship necessary to perform many of its tasks. We present this as the first limitation to including remanufacturing in national accounting systems.

As a second limitation, circular economy activities such as remanufacturing create complex chains of positive externalities that are harder to measure than the negative externalities created by linear economic activities. This point is discussed extensively in [18], which identifies three types of positive externalities related to circular economy activities: (1) systemic static externalities, (2) idiosyncratic dynamic externalities, and (3) systemic dynamic externalities. All these positive externalities of remanufacturing tend to be undermeasured in legacy national accounting systems, and as such, they put remanufacturing in a disadvantaged position compared to manufacturing.

Finally, as a third challenge, legacy national accounting systems do not consider the gains or losses in human well-being and occupational meaning due to the productivist linear economy business models very commonly used in manufacturing, an essential social problem brought to light recently by phenomena such as the Great Resignation or Big Quit [19] and the quiet quitting [20]. Although the loss of occupational meaning due to technological disruptions is a relatively recent concept developed by occupational scientists [21]–[23], the notion has been known at least since the writings of Karl Marx on work and alienation [24]. Remanufacturing involves a stronger component of occupational meaning, possibly leading to higher occupational engagement levels [25] through human craftsmanship.

There is no question on one hand that remanufacturing improves resource productivity and reduces environmental damage [26]–[28]. On the other hand, TFP, as it is currently measured, probably falls due to increased costs of investment and production, although the existing literature is unclear concerning this point. Some authors suggest that remanufacturing can potentially increase TFP [28]. In contrast, others are somewhat more cautious, showing that labor and capital costs are probably higher, and TFP is probably lower in remanufacturing [1], [2]. The latter hypothesis is used to justify inequalities (3) and (4) above.

Notice that, under the legacy system of national accounting, the following accounting identities apply:

$$\mathrm{GDP}_{vm} = C_{vm} + I_{vm} \quad \text{and} \quad \mathrm{GDP}_{vr} = C_{vr} + I_{vr}.$$

GDP_{vm} and GDP_{vr} are outputs measured as the GDP under manufacturing and remanufacturing, respectively. Due to inequalities (3) and (4), we can conclude that:

$$\mathrm{GDP}_{vm} > \mathrm{GDP}_{vr},$$

or that legacy GDP under manufacturing is always higher than that under remanufacturing. This is the usual argument governments and business leaders make to defend the linear economy status quo.

Consider now the evaluation of green production and well-being as two additional elements added to the national accounting identities above: depletion of stocks of natural resources and environmental damage. In the cases of manufacturing and remanufacturing, the Environmental Domestic Product (EDP) accounting becomes respectively:

$$\mathrm{EDP}_{vm} = C_{vm} + I_{vm} - N_{vm} - W_{vm}, \quad \text{and}$$

$$\mathrm{EDP}_{vr} = C_{vr} + I_{vr} - N_{vr} - W_{vr},$$

so, this time, we find that:

$$\mathrm{EDP}_{vm} < \mathrm{EDP}_{vr} \quad \text{when}$$

$$N_{vm} - N_{vr} + W_{vm} - W_{vr} > \mathrm{GDP}_{vm} - \mathrm{GDP}_{vr},$$

meaning that the EDP of remanufacturing will surpass the EDP of manufacturing whenever the losses due to excess of natural resources extraction and due to excess of environmental burden offset the excess of GDP under manufacturing.

To summarize, under this theoretical framework, remanufacturing GDP is always lower than manufacturing GDP, but remanufacturing EDP can be higher than manufacturing EDP, and the EDP advantage will become more significant as the negative externalities of manufacturing under a linear economy and the positive externalities of remanufacturing under a circular economy become more important.

This begs the question: why do societies still struggle to recognize that the maximization of EDP should take precedence over the maximization of GDP? One explanation is market failures [29],

[30]. Agents in a decentralized economy maximize private consumption without internalizing external costs.

Another explanation is government failures [29], [31], [32]. In this case, at least four mechanisms may play a role. Firstly, to obtain popular support, policymakers may mirror the behavior of consumerist agents instead of promoting sustainable resource use and well-being [33]. Secondly, inappropriate specification of private, public, or collective property rights may lead to individual or collective actions negatively impacting resources and well-being [33], such as rent-seeking activities. Thirdly, not only will agents in a decentralized economy not internalize environmental damage costs, but policymakers may also not have the right political incentives to do it, hence the broad use of the simpler GDP instead of the complex EDP to evaluate policies. Fourthly, government efforts may be systematically misdirected by inadequate conceptual frameworks and measurements of economic activity, such as legacy national accounting systems. A final explanation is that individuals or policymakers always choose to manufacture over remanufacture because they are caught in a prisoner's dilemma due to the lack of mutually beneficial coordination and collective action [34].

Remanufacturing becomes desirable when the agent's choices are individually and socially optimal. This scenario is achieved by changing incentives, for example, with green (Pigouvian) taxes [35], regulations, and nudges [36]. For example, green taxes internalize external costs, giving agents a coordination incentive to align individual interests with human well-being [35]. In other words, when a green tax is levied on excessive natural resources extraction and environmental damage, it provides incentives that help the transition to remanufacture to take place, be it due to its static outcomes (e.g., immediate processes changes) or its dynamic outcomes (e.g., increases in remanufacturing innovation research and development).

B. Rethinking Remanufacturing Innovations

Beyond the policy interventions mentioned in the previous subsection, another important dimension of the transition to remanufacturing in a circular economy is fostering remanufacturing innovations. Research and development efforts in this area should become a priority for the three institutional spheres of the triple helix [37].

Efforts in this area are extensively discussed in [38]. The Ellen MacArthur Foundation, for example, has spearheaded initiatives to gather knowledge in remanufacturing through events, articles, and case studies [39]. Remanufacturing innovations include the creation of reverse logistics ecosystems, developing materials better suited to remanufacturing, remanufacturing-oriented design, and sharing economy business models that integrate remanufacturing.

The vintage capital theory provides us with a useful insight that facilitates remanufacturing innovative thinking and that we summarize through the following proposition:

Proposition 1: any activity that reembodies materials, energy, or information into a durable good to upgrade its technological vintage is a remanufacturing activity.

C. The Fairphone Case Study: Commitment to System Upgrading as a Remanufacturing Innovation

Proposition 1 tells us that remanufacturing does not necessarily involve physical attributes of a durable good, as in the case of digital equipment operating system (OS) upgrading. Although upgrading is a relatively common activity in the digital age, it is not always the case that it is part of enterprises' business models in the durable goods industry. Smartphones, for example, are known to have short lifespans, not because of hardware failures but because their OS become obsolete [40].

Fairphone, a Dutch designer and producer of smartphones, has been broadly studied for its modular design and ethical and participatory business model [41]–[46]. Previous research has not addressed a less evident but significant remanufacturing innovation: it offers OS upgrades to its customers for as long as it is commercially and technically feasible. In the case of the Fairphone 2 model, this innovation resulted in seven years of OS upgrades, which made this device the only known smartphone to have operated under six versions of the Android OS, from version 5 to version 10 [47], [48].

Proposition 1 tells us that Fairphone has integrated remanufacturing into its durable goods production business model since OS upgrades are activities that reembody information into a durable good to upgrade its technological vintage. Unlike other enterprises in the technology sector, Fairphone credibly committed to providing this remanufacturing activity for unusually long periods, a significant contribution to the transition towards a circular economy: as stated by the Fraunhofer Institute, "keeping phones for 5 years cuts yearly impact on global warming by around 31%" [49].

Remanufacturing through OS upgrades can be costly. Firstly, engineers and designers must make the hardware compatible with future upgrades. This technical exercise increases a new device's research and development costs and business risks. Secondly, each OS upgrade involves significant remanufacturing costs of coding, testing, distribution, and technical assistance during the life of the device. This is why producers of digital devices typically operate under a business model based on OS obsolescence.

How can remanufacturing activities and establishing a level playing field for sustainability-focused enterprises like Fairphone be achieved? It is theorized that stabilizing factors or policy instruments like green taxes, regulations, and nudges are crucial in creating an environment that fosters environmentally responsible practices. For instance, a potential hypothesis suggests that designing production and sales taxes in a way that correlates inversely with the lifespan of a device could provide financial incentives for longer-lasting products. The hypothesis further proposes that regulations mandating operating system upgrades would ensure the longevity and functionality of devices. Additionally, enacting "right to remanufacture" bills is expected to establish legal frameworks that support and promote remanufacturing initiatives. Furthermore, the hypothesis suggests that implementing nudges, such as green labels, sustainability rankings, advertisement restrictions, and mandatory customer warnings, could effectively raise consumer awareness regarding the environmental impact of operating system obsolescence, thereby encouraging the adoption of more sustainable choices and helping to reduce possible consumer bias against remanufactured goods [50].

V. Conclusion and Recommendations

This article discusses a theoretically expanded vintage capital production function model and framework, and briefly addresses limitations in current national accounting systems to propose an alternative approach to the evaluation of the potential impacts of replacing manufacturing technologies with remanufacturing technologies on positive circular economy outcomes.

One major limitation is that governments rely on insufficiently developed national accounting systems that fail to integrate principles of social and environmental sustainability, circular economy, and occupational science when measuring production, human well-being, and occupational meaning. This hinders their ability to accurately assess the true impact of different economic activities.

To overcome these limitations, the development and use of the EDP with a focus on industry applications like remanufacturing and labor and non-labor occupational well-being are crucial. These can contribute to the design of better systems of private, public, and collective property rights for natural resources management and facilitate the transition from a linear to a circular economy.

Additionally, research and development efforts across triple helix institutions need to be intensified to foster technological innovations in remanufacturing. A case study in the smartphone industry exemplifies how integrating remanufacturing innovations into a company's business model can effectively contribute to the circular economy. However, to incentivize further adoption of remanufacturing, it is essential to level the playing field.

While this analysis offers valuable insights, it has some limitations. It relies on a single case study and lacks a comprehensive exploration of consumer attitudes and behaviors toward, for example, adopting remanufactured goods. To improve this work, a more rigorous comparative analysis of vintage capital theory and circular economy theory is needed. This analysis will help identify complementary aspects and opportunities for leveraging their strengths to optimize remanufacturing processes, reduce associated costs, and further develop the vintage capital theoretical framework and production model. Future research should focus on applying this framework and model to additional specific cases and investigate communities' roles in driving remanufacturing. The goal is to develop a comprehensive and repeatable methodology for assessing consumers' roles and potential impacts of remanufacturing innovations on human well-being and occupational meaning.

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