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Ryan Bradley
University of Kentucky, ryan.bradleyky2014@uky.edu

Ibrahim S. Jawahir
University of Kentucky, is.jawahir@uky.edu

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Designing and Redesigning Products, Processes, and Systems for a Helical Economy

Ryan Bradley*, I.S. Jawahir

Institute for Sustainable Manufacturing (ISM), University of Kentucky, Lexington, KY 40506, USA

Abstract

The Circular Economy (CE) concept has promised to unlock trillions of dollars in business value while driving a significant reduction in the world's resource consumption and anthropogenic emissions. However, CE mainly lives in ambiguity in the manufacturing domain because CE does not address the changes needed across all of the fundamental elements of manufacturing: products, processes, and systems. Conceptually, CE is grounded in the concept of closed-loop material flows that fit within ecological limits. This grounding translates into a steady state economy, a result that is not an option for the significant portion of the world living in poverty. Therefore, this paper proposes the Helical Economy (HE) concept as a novel extension to CE—one that allows for continued innovation and economic growth by leveraging an Internet of Things (IoT) infrastructure and by reimagining products, processes, and systems. This paper intends to be the conceptual overview and a framework for implementing Helical Economy in the manufacturing domain.

Keywords: Helical Economy; Sustainable Manufacturing; Manufacturing Systems; Design; Sustainability

* Corresponding author. *E-mail address:* ryan.bradleyky2014@uky.edu

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1. Introduction

The Circular Economy (CE) concept promises to simultaneously reduce anthropogenic emissions while generating business value [1]. However, CE mainly lives in ambiguity in the manufacturing domain because CE does not explicitly address the changes needed in the product, process, and system levels. Also, due to the market differentiation CE establishes, industry has seen many misrepresentations of the implementation of CE. Numerous manufacturers are relabeling business practices as being a new implementation of CE, when in reality; the practice was already in existence. Even for the new CE applications, the CE approach taken is more aligned with a waste management strategy than with a manufacturing framework [2–5]. For these reasons, CE is currently a conceptual retrofit for the linear economy. To move beyond a retrofit, CE needs to extend itself to include a system-level redesign of products, processes, and systems that decouple economic growth from resource consumption.

The paper first identifies three gaps in the current landscape of the CE concept: i) Practitioners need a framework to be able to apply in an industrial setting; ii) Degrowth and Steady State economics are not viable options for the significant portion of the world that lives in poverty. Economic growth needs to be decoupled from resource consumption through a system-level redesign of products, processes, and systems; iii) A waste management strategy is not sufficient. Omitting the Redesign and Remanufacturing elements of the 6R framework [6] can result in adverse impacts on innovation and economic growth.

The paper addresses the gaps by introducing the Helical Economy (HE) concept as a novel extension to the CE concept. HE aims to better align with manufacturing stakeholders and to be practical for both business leaders and practitioners. It does this by leveraging an Internet of Things (IoT) infrastructure and by reimagining the fundamental elements of manufacturing: products, processes, and systems. An overview and visual representation of the concept is shown, as well as a framework for implementing HE in the manufacturing domain. The paper then concludes with a discussion and a summary of plans for future work.

1.1. The Circular Economy (CE)

The Circular Economy (CE) concept, most recently championed by the Ellen MacArthur Foundation (EMF) [7–9], is defined as being “restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times.” However, CE is not a novel concept, and economists such as Skene and Murray [10] map the progression of the circular economy to previous concepts such as biomimicry [11], industrial symbiosis [12], industrial ecology [13], cradle-to-cradle [14], etc. Although not novel, CE has gained the most stakeholder support due to its appeal to both environmentally conscious and economically conscious agendas. However, this support has not directly translated into implementation since practitioners require a concrete framework that they can apply in an industrial setting.

1.2. Steady-State Economics and CE

The CE concept has close ties to the degrowth and steady state economic theories of Georgescu-Roegen and Daly [15,16]. In steady-state economics, the economy must shrink or go through a period of degrowth to arrive at a state that is within ecological limits. CE’s ideal case aligns with this strategy by keeping materials in a perpetual loop of utilization and eliminating the need for virgin resources. However, the steady-state theory is not without its flaws. It assumes that the population is economically equal when entering into the steady state and that no material fluctuations will occur in population or economic growth. However, this is not practical in a world where 71% of the global population is living on less than 10 dollars per day [17]. The 71% wants a path towards the middle class, which makes stopping growth an idealistic option. A more practical and equitable solution would be decoupling resource consumption from economic growth through a system-level redesign of products, manufacturing processes, and manufacturing systems.

1.3. 6Rs of Sustainable Manufacturing and CE

The CE concept has also been linked to the 6R elements of sustainable manufacturing [18]. Looking across the "R" elements, Kirchherr et al. [19] analyzed 114 definitions of CE. A vast majority of the definitions had an overarching focus on the 3Rs (Reduce, Reuse, Recycle) with a 4th "R" (Recover) only mentioned on occasion. From this, the conclusion drawn is that most manufacturers are primarily leveraging CE as a waste management strategy rather than a manufacturing framework. CE implementations of this nature are attempting to mine short-term economic value rather than address the long-term problems through a system-level redesign. In fact, across the 114 CE definitions analyzed by Kirchherr et al., a system shift is often not highlighted as part of the description. The waste management focused strategy also causes degradation in sustainable value because there are still constraints to operate in a linear infrastructure. To go beyond a waste management strategy, the "R" elements of Redesign and Remanufacturing must be considered in combination with the prevention of degradation. These together result in upgradability [20], which is a key element of overall sustainability.

2. Designing Products, Processes, and Systems for the Helical Economy (HE)

This section presents the Helical Economy (HE) concept. HE utilizes all 6R elements, leverages an Internet of Things (IoT) infrastructure, and reimagines products, processes, and systems. The section begins with a visual representation of HE followed by a framework to be applied in the manufacturing domain.

To visualize the HE, one must expand the typical two-dimensional space often used in the linear and circular case to a three-dimensional cylindrical space:

$$r = SVC(R_{1-6}) \equiv f(Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture) : [0, 1] \quad (1)$$

$$\theta = f(t) : [\phi_k, \phi_{k+1}] \quad (2)$$

$$z = Innovation \;\&\; Economic\ Growth: [k, K] \quad (3)$$

where z is the innovation and economic growth achieved throughout time, $\theta \equiv f(t)$ is time, and $r \equiv SVC(R_{1-6})$ is the sustainable value creation achieved as a function of the 6Rs (*Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture).* r is bounded by 0, representing no value creation, and 1, the theoretical maximum sustainable value. θ is finite and bounded by the k-th generation time interval, ϕ_k, and the k+1 generation time interval ϕ_{k+1}. z has a lower bound, k, and an upper bound, K. The gray plane, k, is the ecological limit of innovation and economic growth under circular economy conditions and K is the limit under helical economy conditions. This can be graphically represented in Figure 1.

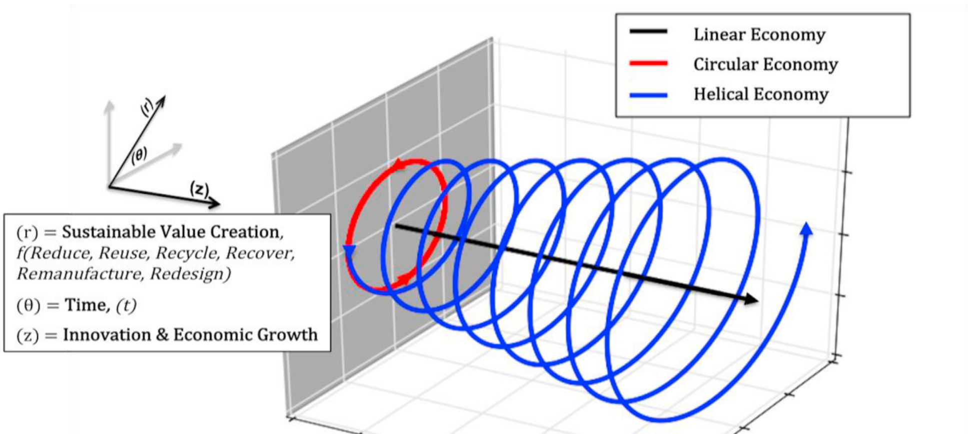

Figure 1: Visual Representation of the Helical Economy in reference to the Linear and Circular Economies

From Figure 1, the Linear Economy is shown to deliver economic growth and innovation, but at the expense of sustainable value. These unsustainable conditions will result in long-term harm to the economy, the environment, and society.

The Circular Economy is shown to exist in the two-dimensional plane at k, which is the CE's theoretical maximum value. This maximum is a function of the use of the 4R elements of Reduce, Reuse, and Recycle, and Recover, and it reflects that the omission of Redesign and Remanufacture will result in a negative impact on innovation and economic growth.

The Helical Economy is shown to add three advances to CE: HE creates more sustainable value through the utilization of all 6R elements, HE encourages continued innovation and economic growth, and HE considers the transient state away from the Linear Economy. Achieving these advances require leveraging an IoT infrastructure and redesigning at product, process, and system levels. The following sections outline the supporting HE manufacturing framework.

2.1. Internet of Things (IoT) Infrastructure

The Internet of Things (IoT) has been referred to as a means for aligning physical and information life cycles [21]. This vision suggests that this intimate connection and the information itself present a major source of value [21,22]. However, to extract this value, the IoT infrastructure has to be leveraged in a framework that presents an opportunity at realizing this value.

In context of the HE framework, the IoT system can be leveraged to widen the helix to maximum point of sustainable value creation. This requires a dynamic collection system shown in Figure 2. Data is collected via sensors and analytical models. This data is then used to train predictive models in solving for the optimum product design/configuration, the optimum process plan and tool design, and the optimum system and node configuration. To keep costs low, special attention should be paid to minimizing sensors deployed through the use of the domain expert knowledge of the physical system [23].

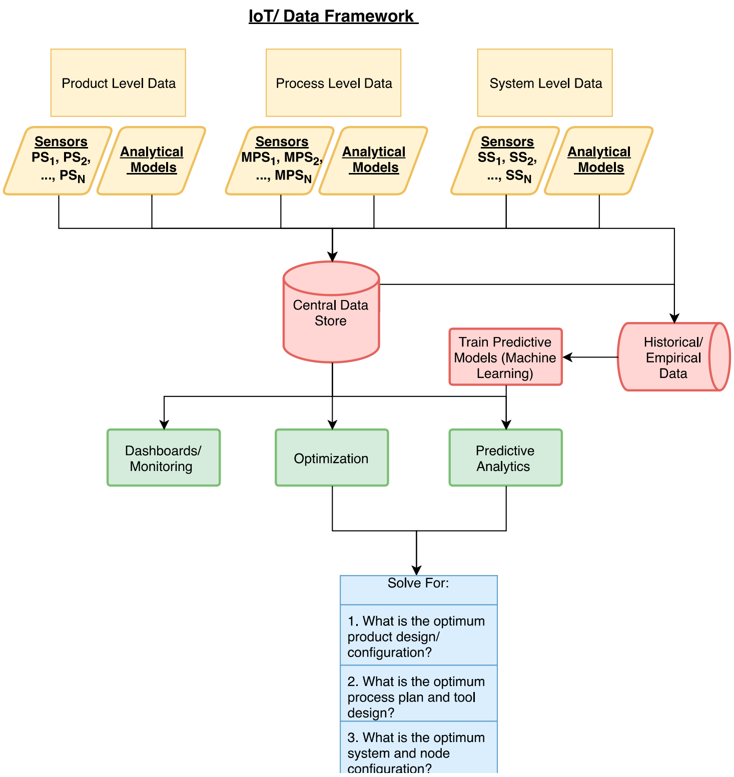

Figure 2: Conceptual Representation of Linear, Circular, and Helical Products

2.2. The Helical Product

At the product level, the linear economy has defined everything from the conceptual understanding of products; the tools and processes that have been created to develop products; and the way the system boundary is defined when approaching the design of a product. Therefore, delivering on the HE vision requires reimagining the entire production process. Looking at Figure 3, the linear product is composed of an assembly of $C_1, C_2, \ldots, C_N$ components. The product is then used and disposed of resulting in zero sustainable value creation. The circular product is still composed of the same $C_1, C_2, \ldots, C_N$ components because it is still locked into being created by the linear tools and technologies of today's manufacturing environment. However, sustainable value is extracted through the reusing of products and components and the recycling of $M_1, M_2, \ldots, M_N$ materials. Because the circular product is still locked into a linear infrastructure, there is an inherent degradation of value that occurs. Instead, HE goes beyond CE to include a redesign and reconfiguration effort. The helical product is comprised of modular components that are reconfigurable to the market demand. Post-use, the product can be reconfigured into a new product, or the material can be transferred out of the product life cycle in the form of components via parts harvesting and/or materials via recycling.

In practice, the product is connected into the IoT system and data is fed into a new suite of design tools that are developed explicitly for HE. The product must be reconfigurable and use common components and materials. Using manual or automated processes, components must be able to be rearranged into new products to meet immediate demand. The product must also be designed in parallel to the manufacturing and reverse manufacturing processes. The product must prevent degradation of value and have the ability to be upgraded through reconfiguration and remanufacturing.

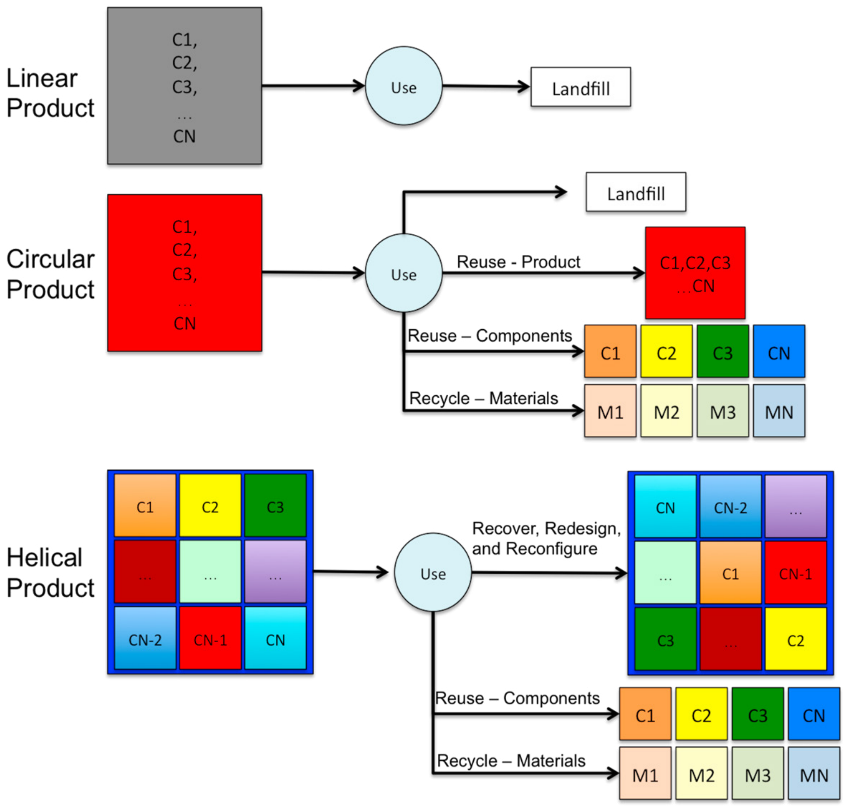

Figure 3: Conceptual Representation of Linear, Circular, and Helical Products

2.3. The Helical Manufacturing Process

At the manufacturing process level, the linear economy has dramatically defined the existing technologies that are in use today. Since the Industrial Revolution, development and investment from manufacturers have supported a one-way flow of products, from getting raw materials at their gate to delivering a finished product to their end customers. As such, the current manufacturing infrastructure and technology caters to this linear economy based one-way flow of inputs and outputs. However, why must one limit manufacturing process technology to the world of inputs and outputs? Instead, to achieve the HE vision, helical manufacturing processes must become multi-dimensional, being able to manufacture and reverse manufacture multiple products to meet the current market demand. As shown in Figure 4, helical manufacturing processes have a reverse manufacturing step in situ to that of the original manufacturing process. The material from the reverse manufacturing step is either transferred to a different process or retained and reprocessed.

In practice, the process' machine and tooling are connected to the IoT system, which actively collects data and executes decisions on forward and reverse manufacturing activities. These decisions are made in combination with current market conditions to determine which products meet current demand. Information is also taken from other products and manufacturing tools to continuously improve product performance. Specifically, using information gathered from products in the field, near real-time sustainability performance enhancements can be made on the manufacturing floor.

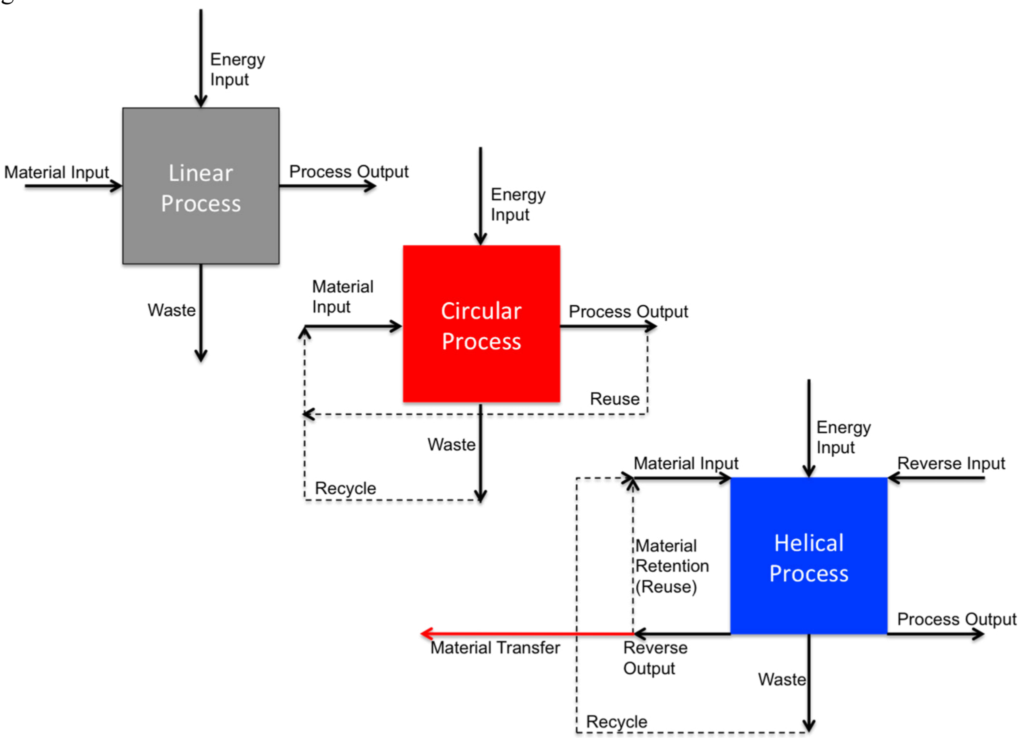

Figure 4: Conceptual Representation of Linear, Circular, and Helical Manufacturing Processes

2.4. The Helical Manufacturing System

At the system level, helical products and processes come together to form the helical manufacturing system (HMS). The HMS has to be able to respond to market demand instantaneously. With this consideration, a HMS builds on the concept of reconfigurable manufacturing systems (RMS) [24,25] to leverage the same machines for both manufacturing and reverse manufacturing processes. Manufacturing "lines" in a HMS are actually reconfigurable matrices of $S_1, S_2, \dots, S_N$ stages and $N_1, N_2, \dots, N_M$ nodes interconnected through the IoT system

(Figure 5). Products in the forward manufacturing path take advantage of the reconfigurable and flexible manufacturing stage-node combinations to support many SKUs while achieving maximum throughput. Products that enter into the reverse logistics channel are deconstructed into components and materials that are then allocated to the next best stage-node combinations that keep the components and materials at the highest possible value. Materials and components can be transferred to or from another product line at any point in the process via transfer points T_1-, $T_2, \dots, T_P$.

In practice, the system is controlled through the IoT system of interconnected products, processes, and system nodes. The decisions to move from a stage, node, and/or transfer point are determined based on the objective of maintaining maximum sustainable value.

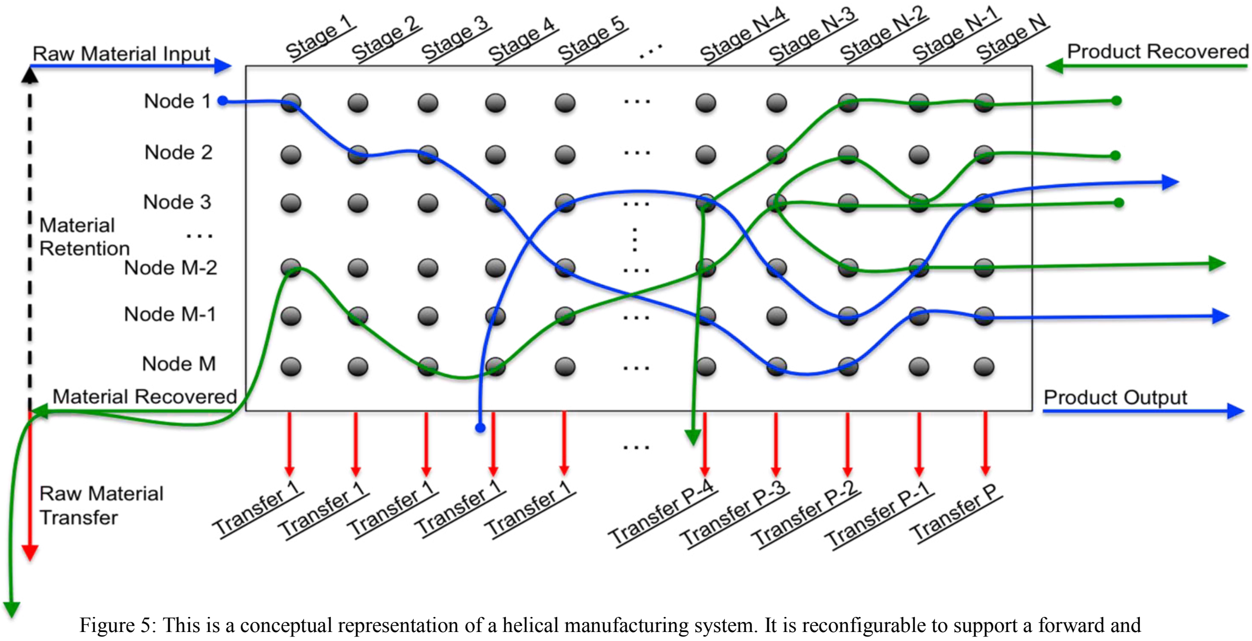

Figure 5: This is a conceptual representation of a helical manufacturing system. It is reconfigurable to support a forward and reverse material flow where the path is determined by the optimal combination of *N* stages, *M* nodes, and *P* transfer points.

3. Discussion and Future Work

This paper has introduced the new Helical Economy (HE) framework as an extension to the Circular Economy (CE). A visual representation was shown to highlight the advances made by HE: increased sustainable value through the utilization of all 6R elements, increased innovation and economic growth, and consideration for the transient state. These advances enable HE to support economic mobility of the developing world, population growth, and the eradication of obsolescence. The HE framework was then presented for implementing the IoT infrastructure and the system-level redesign at product, process, and system levels. Although largely conceptual, the reimagined products, processes, and systems overhaul the linear economy infrastructure in place today. Without replacing this infrastructure, the linear tools and infrastructure of today will continue creating linear products.

To expand this work, an analysis is underway across a diverse set of industries. This will reveal any special considerations to be taken into account in the formal HE methodology. Another expansion of this work is the formulation of analytical models for product, process, and system levels to be used in optimization modeling and simulation. These models will be used to develop a toolkit that can be used to move any given application towards a Helical Economy.

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