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Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing

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Abstract

At the current alarming growth rate of the world's consumption, the linear economy model of creating products, using these products, and then disposing of them, with no consideration of the environmental, societal and economic impacts and consequences, is a flawed manufacturing approach that is unsustainable. Therefore, envisioning a future where nothing is wasted; a future where every "waste" becomes an asset, and no value goes unrecovered; a future where all products at the end of their primary use are recovered and either reused, remanufactured, or recycled for multiple generations, has become more than a reality, but a necessity. This emerging concept of circular economy, although gaining attention, lacks a technological perspective for effective implementation. This paper presents the principles of sustainable manufacturing to serve as the basis, and to provide the technological elements to ensure the creation of a circular economy. 6R-based technological elements are identified and shown as essential ingredients for achieving economic growth, environmental protection and societal benefits. Also presented is a case study with application that shows the life cycle cost benefits. An outlook for future research is then presented.

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1. Introduction

In recent years, the concept of *circular economy* (CE) has gained significant momentum worldwide, as the traditionally-known linear economy, based on the "take – make – dispose" model, continues to fall short of being able to meet the sustainability challenges of a world that concurrently requires sustained economic growth, environmental protection, and societal wellbeing. While the socio-political dimensions and opportunities of circular economy are being pursued and promoted across the globe for national economic growth and prosperity, the technological challenges involved in making the circular economy work and grow are not being well thought-out or planned because of the overwhelming shadow of the political agenda being pushed to the highest level with no technological considerations. This agenda largely ignores, or,

at best, overlooks, the specific societal and economic needs to achieve success with circular economy from a technological perspective. While on the surface the circular economy appears to be a new wave of hope for economic growth, regardless of the economic growth levels dictating whether these nations are developed or developing or fast emerging countries, it needs to be recognized that the driving force for circular economy is the technological capability for sustainable value creation.

Sustainable value creation has multiple forms and means, and in the manufacturing context, it is of strategic significance to understand that manufacturing is the engine for wealth generation for any nation. Developed and developing nations have shown the pivotal role of manufacturing in job creation, societal well-being, and national economic advancement. Societal well-being and economic growth heavily depend on the level and quality of education and training. Thus,

educational institutions will continue to face significant challenges in developing and implementing suitable educational programs at all levels, while the industry would be forced to embrace the need for the pivotal role of continuing education and training programs, all aimed at sustainable value creation and economic advancement with improved societal benefits and environmental protection.

1.1. The Circular Economy and Its Impact

The planet earth has only limited and finite resources, and with the continually depleting resources at an alarming rate, and the difficulty and concern with replacing natural materials with synthetic substances, the world is in serious trouble as we continue to use and abuse the “perceived to-be-abundant” earthly resources for never-ending human needs through extraction, processing, manufacturing and use activities, with a vast majority of end-of-life products/materials continue to be heading to landfills. The conceptual message of circular economy is very powerful as it is based on *reducing wasteful resources through effective design and implementation of products and processes for improved resource-efficiency* with circular material flow involving *recovery, reuse, recycling and remanufacturing* of products. The circular economy thus becomes not an option, but inevitable for continued economic prosperity and ecological balance to maintain the biodiversity with human life and economic growth.

It is hard to track the origin of the concept of circular economy. However, it is generally known that the early work of two British researchers, Pearce and Turner in 1990 set the stage for developing the conceptual framework for circular economy as they proposed the transformation of the “resource-products-pollution” mode to “resource-products-regenerated resources” [1], even though the concepts of circular economy are well-founded with strategic directions in countries such as China lately [2]. Concepts of circular economy have ecological roots, and regenerative/restorative nature of the circular economy is well within the regeneration paradigm proposed by the well-known work, Cradle to Cradle by McDonough and Braungart promoting the evolution from eco-efficiency to eco-effectiveness [3]. This can only be accomplished by design of products and processes with consideration of product life beyond its designed life, virtually going into second, third, and multiple lives for materials used in products. To achieve this is a significant technological challenge, and it is much more than a socio-political projection or agenda as it truly requires new technologies and innovations at product, process and system levels in manufacturing with a paradigm shift towards sustainable value creation for humanity.

Historically, circular economy has heavily relied upon the principles of 3Rs: *Reduce, Reuse and Recycle*. It is aimed at optimum production by utilizing reduced natural resources, producing minimum pollutions, emissions and wastes by utilizing the 3R principles [4]. The 3Rs are essentially the foundation for green manufacturing derived in the 1990s from lean manufacturing, which is based on 1R (Reduce) introduced in the 1980s. The current trend shows that achieving sustainable value in manufacturing requires transformation from lean to green to sustainable manufacturing [5].

Recently adopted 12th five-year plan (2011-15) for China’s economic and social development promotes the continuous implementation of CE in industrial sectors [6]. A more recent report produced by Ellen MacArthur Foundation, in conjunction with McKinsey Center for Business and Environment and SUN – Stiftungsfonds für Umweltökonomie und Nachhaltigkeit GmbH (Foundation for Environmental Economics and Sustainability), the new environmental economics branch of the Deutsche Post Foundation, strongly emphasizes the need for embarking on circular economy for Europe in order to remain competitive and productive in global manufacturing [7]. Achieving circular economy in its fullest and complete form requires in-depth understanding of the integral elements of its technological framework. This is, unfortunately, far beyond the simple socio-political projections for any strategic objective of any country or geopolitical region.

To understand and appreciate the value of circular economy, it is important to gain valuable knowledge on sustainable manufacturing and its fundamental message for accelerated growth in industrial production based on product, process and system innovations. Significant educational challenges exist for such understanding and appreciation of the current and future needs [8].

1.2. Sustainable Manufacturing at product, process and system levels

Sustainable manufacturing is essentially a complex systems problem since to achieve it, three integral interacting levels must be considered: products, processes and systems [9] --- see Fig. 1. There is no generally accepted or universal definition for sustainable manufacturing. Indeed, there are many insufficient attempts, including a partially integral approach; almost all fall short because they largely deal with products and processes, but fail to stress the **interconnectivity among the three integral elements involved in manufacturing (products, processes and systems)**, and show the **basis for sustainable value creation an economic growth**.

In reality, sustainable manufacturing does offer a new way of producing functionally superior products using sustainable technologies and advanced manufacturing methods, but only if product design, production, supply chain design and management and enterprise-level logistics can be, understood,



Fig. 1. Integrated elements of sustainable manufacturing [9]. developed and managed in a holistic and integrated way.

1.3. Principles of 6R-based Closed-loop Sustainable Manufacturing

The sustainable manufacturing approach focuses on a broader, innovation-based 6R methodology for products over *multiple life-cycles* [10]. This 6R approach offers a closed-loop, multiple product life-cycle system as the basis for sustainable manufacturing (Fig. 2) [11].

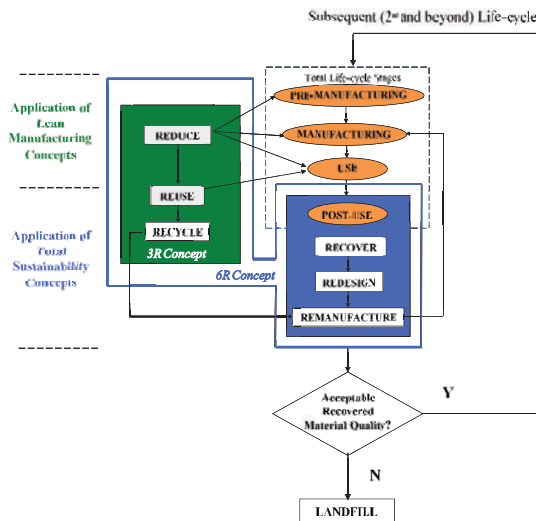


Fig. 2. Multiple product life-cycle as a basis for sustainable manufacturing [11].

In the 6R methodology, *Reduce* mainly focuses on the first three stages of the product life-cycle, and refers to the reduced use of resources in pre-manufacturing, reduced use of energy, materials and other resources during manufacturing, and the reduction of emissions and waste during the use stage. *Reuse* refers to the reuse of the product as a whole, or its components, after its first life-cycle, for subsequent life-cycles, to reduce the usage of virgin materials to produce newer products and components. *Recycle* involves the process of converting material

that would otherwise be considered waste, into new materials or products. The process of collecting products at the end of the use stage, disassembling, sorting and cleaning for utilization in subsequent life-cycles of the product is referred to as *Recover*. The *Redesign* activity involves the act of redesigning of next generation products, which would use components, materials and resources recovered from the previous life-cycle, or previous generation of products, while *Remanufacture* involves the re-processing of already used products for restoration to their original state or a like-new form through the reuse of as many parts as possible without loss of functionality.

Fig. 3 shows a total life-cycle incorporated, 6R-based closed-loop system for sustainable manufacturing which would enable a “near-perpetual” material flow, while facilitating the

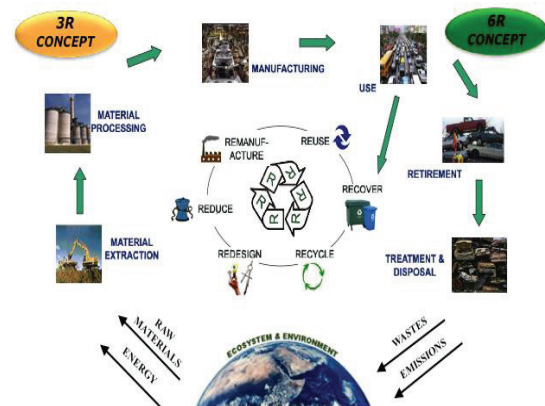


Fig. 3. 6R-based closed loop system for sustainable manufacturing [12].

optimal use of energy, raw materials and other resources, and will be expected to produce minimal wastes and emissions at the end [12]. Natural sequence of the 6R applications within the entire life-cycle is illustrated in Figure 4 with several decision points and multiple closed-loop options [13].

While resource-efficient manufacturing and generation of minimal wastes and emissions are the anticipated cornerstones

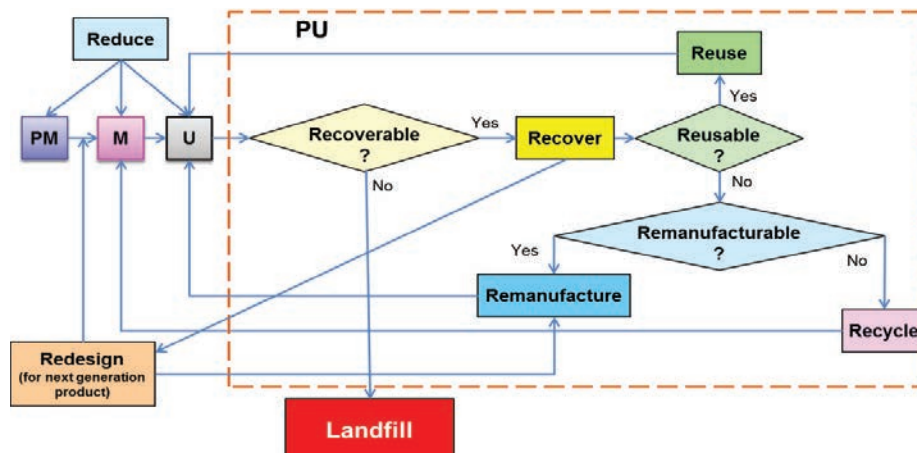


Fig. 4. Sequencing of 6R applications within the total life-cycle with decision points and multiple closed-loops [13].

of closed-loop sustainable manufacturing, comprehensively understanding the 6R-based material flow and its impact on value creation is essential to achieve economic and societal benefits with reduced adverse environmental impact.

1.4. Lack of Consideration of Sustainable Manufacturing in Circular Economy

Early work on circular economy emphasized the need for closed-loop material flow and the technology advancement, but the technological aspects of achieving such circular economy were largely left unresolved as there was a significant knowledge gap that needs to be filled in by the technical experts with successful implementation in industry. Early economic theories clearly bring out the need for developing closed-loop material flow; the means to achieve such technological advancement through innovation and creativity were only rudimentarily understood and conceptually considered. Also, there was a lack of serious or careful analysis of the various technological elements that need to be developed and integrated into the economic models to create sustainable value for the circular economy.

1.5. Paper Objectives and Content Summary

This paper is aimed at presenting the essential technological elements for developing a circular economy. In what follows, a systematic analysis of the identified 6R-based technological elements, along with a case study showing the life-cycle cost benefits, is presented with an outlook for future research to achieve a circular economy through innovation.

2. Technological Elements of Circular Economy

2.1. Identifying and Developing Technological Elements

Fig. 5 presents a simplified material flow diagram showing the interactions between the 6R activities and the four life-cycle stages (pre-manufacturing, manufacturing, use and post-use) for the first life-cycle (shown in red) and the subsequent life-cycle (shown in blue) based on 6R elements.

It is assumed that the activity *Reduce* is blended in all stages of the life-cycle, and the first necessary step in the post-use



Fig. 5. Closed-loop material flow diagram of 6R elements and the four life-cycle stages.

stage is *Recover*, from which all other four innovation-based Rs (*Reuse*, *Recycle*, *Redesign* and *Remanufacture*) originate as shown in Fig. 5.

From this simplified closed-loop material flow, the technological elements or “backbone” of circular economy can be clearly defined by the 6R principles. Utilization of these elements in the application of circular economy can lead to the ultimate *end goal of sustainable value creation* in the economy, society, and the environment. This value creation, in the context of sustainability, which is often referred to as the Triple-Bottom-Line (TBL/3BL), serving as the driver for innovation (Nidumolu et al, 2009), has a significant impact on the three integral elements of sustainable manufacturing: products, processes, and systems.

Fig. 6 shows how this can be extended to multiple generations or life-cycles of a product through the activity *Redesign*. This near-perpetual material flow can be seen moving from one generation to the next. However, this figure shows that innovation with advancement is also occurring from generation to generation.

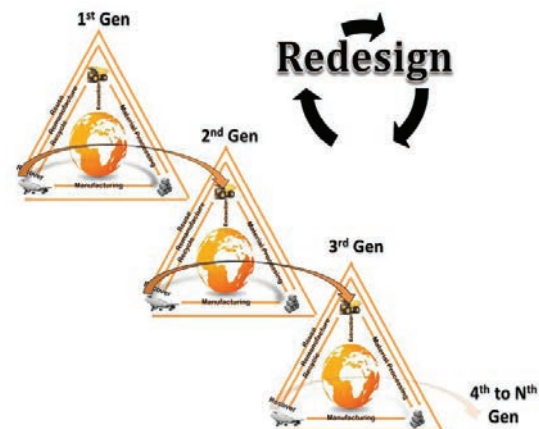


Fig. 6. Helical movement of material flow and technology advancement following *Redesign* events across multiple generations [15].

This progressively concurrent *Redesign* activity is inevitable, and for the implementation of circular economy, it requires thinking beyond a single circular loop. In fact, this can be best described as a helical movement, in both material use and technology advancement, and it is an essential element for the application of circular economy [15].

2.2. Developing Circular Economy with Technological Elements

In order to develop the circular economy with the inclusion of the 6R elements, there must be mechanisms to drive sustainable value creation. These mechanisms shown in Fig. 7 include product/process innovation, quality education and training, novel methodology, and visionary thinking. Product/process innovation includes advances in technology, as well as the optimization of current products, processes, and systems. Education and training play a vital role in achieving sustainable value creation including societal wellbeing [8].

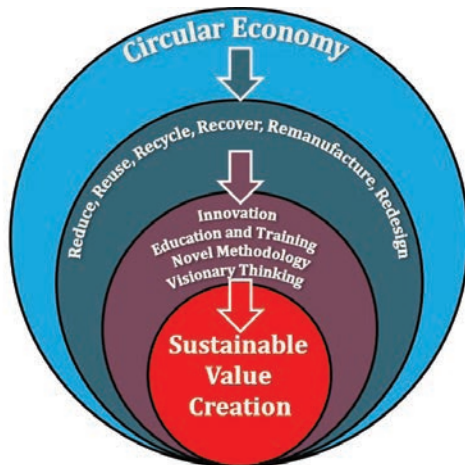


Fig. 7. Circular economy leading to sustainable value creation through its integral technological elements and the associated characteristics.

Not only is there a need for formal university education in the field, but also there is an equal need for technical school training programs that have the ability to educate and train an entirely new industry workforce for next generation manufacturing. In addition to education, there is a prerequisite demand for novel methodologies that will be the underlying infrastructure for sustainable value creation. This includes both quantitative and qualitative methodologies that can together define the direction and assessment. Another mechanism, and probably the most important, is the use of visionary thinking. Even after the map is drawn with various methodologies and educational programs that pave the way for the development of circular economy, there will still be a need for visionary thinking, which combines creativity with an established technical basis that can be a foundation for the creation of implementable solutions to “real-world” problems.

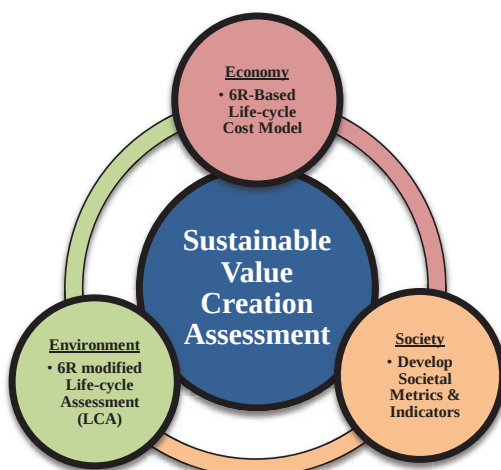


Fig. 8. Specific elements of Triple Bottom Line.

Following the identification and definition of the scope of relevant mechanisms, there is an essential element of implementation that involves developing an assessment toolkit. This assessment will involve the creation of metrics and indicators, but attention must also be paid to the assessment methodology. In Fig. 8, possible metrics and methodologies that drive sustainable value creation assessment at product, process and system levels are shown, segmented into the three pillars of sustainability. For economy, a cost model that includes the 6R elements can be used to assess economic performance from the view of the total life-cycle. For the environment, existing methodologies such as Life-Cycle Assessment (LCA) can be expanded to incorporate the 6R elements and can be used to determine the environmental impact/burden. For the society, there is a need to develop more quantitative and scientific social metrics and indicators that can be used to assess the societal well-being. These assessments can then be fed back into the design and development stages in order to improve the sustainable value.

Developing combination of these mechanisms and assessments is the primary approach in implementing the 6R elements as the technological basis for circular economy.

3. Application of Assessment

3.1. Exploration of a single pillar (Economy)

In a generic application of such an assessment, the scope will be reduced to the evaluation of a generic material selection activity of a given generic component for the overall life-cycle cost benefit of implementing the 6R elements. Therefore, for conciseness, only the economy pillar of sustainability will be addressed in this section.

Shown in Table 1 are three generic materials and their associated cost elements per kg of material. These cost elements can then be used in conjunction with a developed 6R life-cycle cost model to evaluate the overall life-cycle cost benefit of allocation of material to the various post-recovery “R” material streams [15].

Table 1. Life-cycle cost elements for materials [15].

Cost Element	Material A	Material B	Material C
Manufacturer			
Raw Material Cost (\$/kg)	22	3	2.1
Processing and Manufacturing Cost (\$/kg)	18	3	2
Recovery Cost (\$/kg)	0.5	0.5	0.5
Remanufacturing, Recycling, Reusing Cost (\$/kg)	0.4	1	1
Remanufacturing	4.4	1	0.9
Recycling	18	3	2
Capital Recovery	-22	-3	-2.1
Environmental /Societal Relations Cost (\$/kg)	28	14	9
Customer			
Acquisition Cost (\$/kg)	Calc	Calc	Calc
Usage Cost (\$/kg)	37	37	37
Maintenance Cost (\$/kg)	42	34	31
Incentivization Factor	1	0.6	0.7

Shown in Fig. 9 is the life-cycle cost (LCC) benefit that can be reaped with each of the post-recovery material streams. Notice that this graph is not a constant relationship for all materials or all components, but is rather a snapshot for a given application. In other words, as the component or materials vary, this benefit curve will change.

From this graph, it can be seen that *Reusing* holds the highest economic benefit. This is consistent with what logic would say is true for most materials in common applications. One can also pull that *Remanufacturing* holds the second highest benefit which is also what logic would say is true for most materials in common applications. Lastly, if a material cannot be placed into such a high-value stream, then it is placed in the low-value stream of *Recycling*, where it still sees a benefit for this particular material, but it is considerably lower

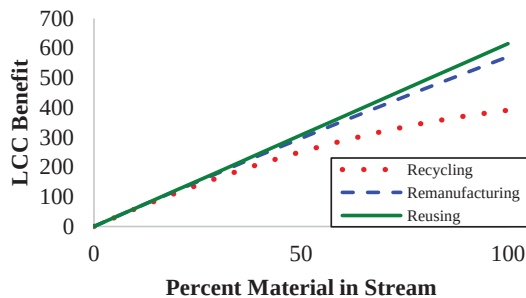


Fig. 9. LCC Benefit of the various post-recovery material streams [15].

than the high-value post-recovery streams.

3.2. Future work of the integration of all pillars (Economy, Society, and the Environment)

For the future, instead of just looking at the application from the exploration of a single pillar, the application of assessment must fully integrate the three pillars of sustainability: economy, society, and the environment. This work will focus on the integration of Life-Cycle Assessment, the 6R life-cycle cost model, and developed social metrics and indicators to provide an overall assessment of sustainable value creation.

This integration will focus not only on methodology, but also on the development of a tool that can be used in real time assessment. This tool will aim at being a full assimilation into current life-cycle management and design tools. The result of an implementation of this scale and of this calibre would mean an unprecedented ability for designers and manufacturers to know the impact of their decisions prior to even making them. This would give the manufacturing world the ultimate tool for designing sustainable products, process, and systems.

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