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Think Like an Ecosystem: Transitioning Waste Streams to Value Streams

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Abstract. To meet the material demands of the future, transitioning waste streams to value streams is a vital step in ecological and economic sustainability. Linear production design disposes of resources before their optimal value have been realized and loses recyclable resources to waste streams. The economic infrastructure of the planet needs to be reimagined to meet human and ecological needs. The development and implementation of circular systems is key to the creation of sustainable global production. Through the analysis of the copper used in medical devices, we illustrate considerations systems engineers can take to close the waste-resource gap. Developing wasteless design mimics the resiliency seen in ecosystems and accelerates the evolution of the global economy to meet the needs of companies, the environment, and humankind.

Introduction

The Linear Growth Dilemma

The global economy functions on an assumption of continuous growth. The past century has been witness to unprecedented economic expansion with global resources being depleted at historical rates (Meadows et al, 2005). With linear expansion at the forefront of corporate initiatives, how does the economy expand infinitely on a finite planet?

The answer is a future-determining one. The economy simply cannot expand infinitely, and it will eventually hit its growth limit (Meadows et al 1972). But solutions can be found by looking into the environments in your backyard. To the alpine tundra, the riparian valley, or the coral reef. These systems have persevered through planetary ages, evolving as the earth's ecological conditions changed (Boons 2013, Gamage & Hyde 2015).

What is their secret? Ecosystems survive because they are founded on efficiency (Boons 2013); there is no such thing as waste. Every product of an ecological process is re-integrated into the natural cycle. By reflecting ecosystems in human-designed systems we can facilitate sustainable resource use. In order to preserve the global economy, the systems we create must be wasteless. In a future with higher raw material demands, converting waste streams to value streams is necessary to maintain both economic and ecological prosperity.

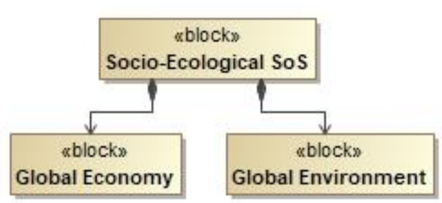

Figure 1. Statement of Socio-Ecological System of Systems as the composition of the Global Economy and the Global Environment

The environment and the economy are intrinsically linked; rather than isolated cycles they are parts of the socio-ecological whole. Figure 1 defines a Socio-Ecological system of systems that comprises the Global Economy and the Global Environment. In this simplified view, the Global Economy is defined as a system of systems as demonstrated in Figure 2. The Global Environment block represents the bioregions, ecosystems, and their parts found on Earth. As materials are not yet harvested from extra-terrestrial sources, it is logical to assert that all materials used in the production of all goods and services are sourced from the Global Environment. Therefore, all waste that is not reused is destined to flow back to the Global Environment.

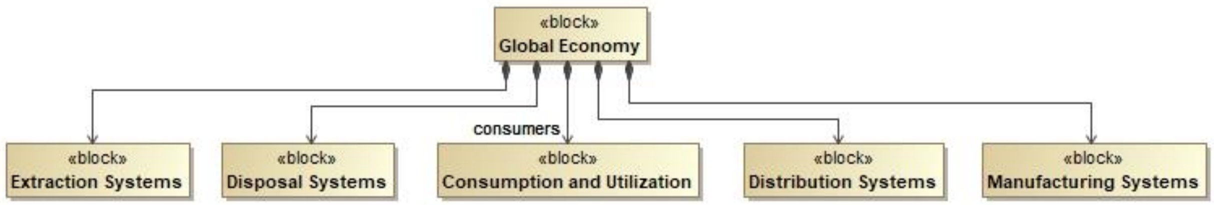

Figure 2. Definition of Global Economy as System of Systems.

The global economy produces 2.01 billion tons of waste annually (The World Bank 2022). With this number growing with the increasing population, the quantity of wasted plastic, organic material, metals, elements, and minerals is projected to increase by around 70% by 2025 (Romero-Hernandez & Romero 2018). The inefficient disposal of material contributes to the disruption of functioning ecosystems and fails to protect and maximize the investment of initial extraction. Environmental change has a direct impact on the efficiency and survival of human-made systems (Boons 2013). By limiting our perspective to only the human designed system we leave out the critical impacts of the interfaces between the environment and the economy.

Figure 3 reflects the linear utilization schema where waste produced by the global economy flows back to the environment where it is neither reclaimed nor reused. By considering the environment as a stakeholder in our system development processes, it is possible to transform this linear flow into a sustainable circular flow by reprocessing and reusing the waste produced throughout the lifecycle of engineered systems. Reprocessing materials in many cases is less expensive and requires less energy than extracting new material (Gamage & Hyde 2012). By recognizing all waste streams eventually return to the environment as shown in Figure 3, systems engineers may expand the scope of their system boundary analyses to include the environment as an interfacing item and to identify the impact of the waste that results during each phase of a system's life cycle, including production, commissioning, utilization, maintenance, and decommissioning (Boons 2002). By considering the environment as a stakeholder, the scope of risk assessments should be expanded to explicitly assess environmental consequences of system designs.

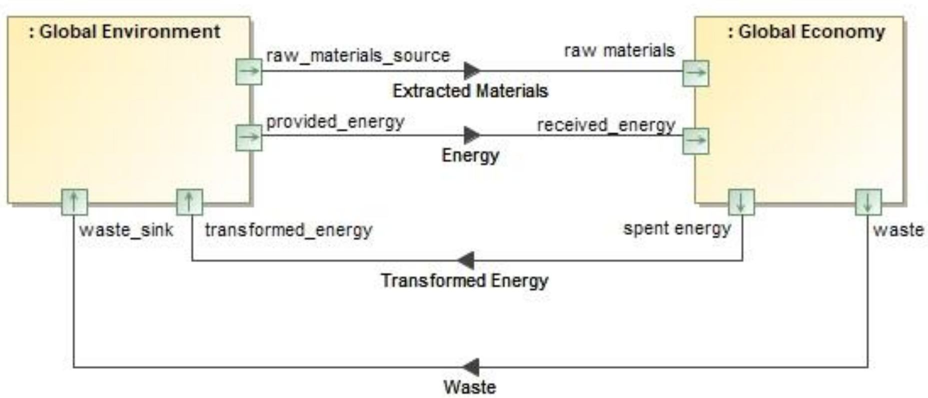

Figure 3. Major categories of interfaces between the environment and global economy.

Ecological-inspired design integrates human-demand into natural flows and sustainable cycling of resources through the environment (Gamage & Hyde 2012). Companies have the opportunity to increase value and resilience in their production cycles, and for stakeholders including the environment (Bocken et al 2019). Transitioning to circular economies presents uncertainty, as it breaks away from the business models primarily used in the global economy. But it has the potential to evolve the infrastructure of commerce and create sustainable systems by optimizing revenue, shortening production cycles, and reinforcing economic resilience (Bocken et al 2018).

When designing production cycles with society, environment, and economy in mind (Bocken et al 2019) the definition of waste needs to be reevaluated. The economy and the environment must find a way to exist and still maintain ecosystem integrity through eliminating the need to deposit waste back into the environment (Geissdoerfer et al 2017). By closing the gap between waste streams and value streams, production design can not only be more efficient but can regenerate the ecosystems they rely on for raw materials (Genovese et al 2017).

Through discussion of the concept of waste, circular production design, and a case study using a medical device example that evaluates the impact of transitioning copper waste streams to value streams, we present a set of considerations that will aid Systems Engineers in integrating value streams into production systems.

Waste Streams

The accepted standard for production and product design is linear. Resources are extracted as raw material from a natural environment, products are manufactured, the products are consumed, and then deposited back into the environment as waste. Waste is created and disposed of throughout this process, at the point of harvest and manufacture as well as at the end of the product's life. With every 20 tons of waste, there is an estimated 5 tons of waste produced during its manufacturing, and 20 tons eroduced at the point of resource harvest (Meadows et al 2005).

In order to sustain the current demands of global production, ecosystem productivity is often exploited to meet economic needs. Though this is apparent across industries, elements and minerals present a particular point of concern because of their high demand in the modern economy for the construction of electronics (Northey et al 2014). Element and mineral sources have slower rates of replenishment contributing to the added strain placed on the limited viable sources (the harvest point of a resource) (Meadows et al 2005). While the limits of sinks (the destination of waste) are often considered, the limits of sources have a greater influence on the longevity of viable production (Meadows et al 2013). When resources are harvested without sufficient time for the source to replenish, the usability of raw-material production is at stake (Boons 2013). With extended strain, these sources produce degraded and limited raw materials, which will impact the future cost of material extraction and refinement.

Increasing the sustainability of raw-material harvest should not be the only focus in reducing environmental impact. Redesigning production can further increase the sustainability of manufacturing (Bocken et al 2019). These flows from sources to sinks, as shown in Figure 3, represent a linear model with a definite beginning and end. With production inevitably designed to produce waste and the majority of products being designed to end in landfills, resources are being returned to the environment long before their full value has been realized. This is strongly apparent in electronic waste streams, as the products contain metals, elements, and minerals. Not only are these materials relatively scarce but they also cause damage when introduced back into environments as waste (Bertram et al 2002).

When linear systems are the norm, resources are lost to waste streams and reintroduced into the environment to disrupt the natural ecological cycling of material. When pollutants enter ecosystems, they further diminish the health and prosperity of raw-material production (Boons 2013). If the environment cannot handle the levels of contamination, it is at risk of irreparable degradation leading to a complete loss in a raw-material source (Meadows et al 2005). Beyond impacting general environmental and social prosperity, it increases the complexity a producer faces in sourcing raw materials. Though globally there has been attention drawn towards analyzing the efficiency of waste streams, the vast number of materials being moved through economies is done without optimization of their potential value. Innovation through the transition of waste streams to value streams presents a viable solution (Meadows et al 2013), but transitioning waste streams to value streams requires an innovative approach. Boon describes three of the main barriers in building ecologically inspired systems (2002):

1. Technical impossibilities
2. Gaps in knowledge about the ecological impacts of productions
3. The challenges in integrating the cooperation of autonomous actors involved in systems development

Specifically in transitioning waste streams to value streams, Romero-Hernandez and Romero identify the three main hurdles in closing the waste to resource loop (2018):

1. Lack of clear starting point
2. Lack of innovative ideas
3. Lack of top-down leadership

Across waste stream types there is a lack of infrastructure available to manage closed loop cycling of resources (Betram et al 2002). Developing a systems-based framework to address common barriers is needed to accelerate the shift to circular design within any production process. To approach this transition, an understanding of the potential of circular economies and waste streams as value streams is needed.

Closing the Waste and Resource Loop

The Future is Circular

When waste is properly managed, and its value optimized, the health of the environment is cultivated. This leads to increased economic efficiency and quality of life (Meadows et al 2005, Boons 2013, Bocken et al 2019). By creating a circular system, the cycling of resources through a system reduces the need for raw material inputs and increases revenue potential (Genovese et al 2017, Bocken et al 2019). Sustainable design innovates the effectiveness of production systems and cuts down production costs (Boons et al 2019, Bocken et al 2018). Production and sale cycling times are lowered by eliminating the raw-material harvest and refining stages (Bocken et al 2019). Through reintegrating waste streams to value streams, the cost of the product is also reduced (Romero-Hernandez & Romero 2018).

A circular system is more resilient. When waste is moved through production systems designed for closed cycling, the design mimics the movements of resources through natural systems (Meadows et al 2005, Gamage & Hyde 2012). Like in an ecosystem, a circularly designed system defines no by-product as waste. Rather as resources ready to be recycled, reformed, and put through the system again. When waste streams become value streams, the system becomes self-sufficient causing a cascade of resiliency-based benefits. By implementing a circular design, industrial symbiosis is achieved. This is when waste materials from one process become the raw material for another, or the by-product from one industry can be repurposed into the production of a different industry (Bocken et al 2019). Through the development of integrated system design, innovation and economic expansion does not need to be limited when energy-use is sourced sustainably, and when waste is redefined as a resource (Gamage & Hyde 2012).

Copper in Medical Device Wiring

Globally copper is used at a rate of 26.7 million tons per year (International Copper Association 2021). As a key material in the construction of electronics, copper is a high-demand resource in the modern technological economy (Northey et al 2014). As a main component in electronics, copper is vital for the transition of the global infrastructure to sustainable technologies such as electric vehicles and solar panels. Though copper has high value, it is being lost through poorly designed waste management (Bertram et al 2002). While 95% of copper has the potential to be recycled, only around 40% of global copper is recaptured before entering landfill where it becomes inaccessible (Wang et al 2021). Around 48% of copper is lost to waste streams in Europe (Bertram et al 2003, Soulier et al 2018), and a staggering 67% of copper is lost to waste streams in the United States (Wang 2021).

Copper is mined primarily in South America and then sent to refineries primarily in China to be processed for use in manufacturing (Kapur et al 2006). The environments where copper is mined are highly impacted by extraction. Mining destroys the physical environment and releases pollutants causing extensive ecosystem damage. After their prescribed use, products containing copper are either disposed of in landfill or incinerated causing harmful levels of pollutants to enter the environment and degrade ecosystem functionality further (Reijnders 2003).

While high-quality copper ore is the goal of extraction, as reserves decrease mining will be forced to focus on lower-quality ore requiring extensive refinement before it can be used. This requires mines to expand causing increased environmental damage surrounding extraction sites. These factors will cause the cost of copper to increase, imposing strain on copper dependent industries (Northey et al 2014).

By developing circular systems for the copper industry, the resiliency of copper-based economies increases. Fortunately, copper can be recycled indefinitely without losing its quality. Newly mined copper and copper recovered from waste streams have no quality difference. With the demand for copper increasing but exploration not yielding adequate new sources, there is a substantial reserve we have yet to optimize (Kapur et al 2006). The copper currently circulating the economy has the potential to fill the need-gap of future copper (Copper Alliance 2021). Current reserves are projected to be sufficient for the next twenty years, but beyond this there is uncertainty about the availability of new sources (Northey et al 2014). An ideal material to be used in a circularly designed production cycle, copper waste streams can easily be transitioned to value streams (International Copper Association 2021).

With the future of copper reserves uncertain, companies need to expand their scope of viable sources to avoid the costs associated with limited supply. By developing infrastructure to transition copper waste streams to value streams copper is kept in the economy. This eliminates the need for mining raw-material and lowers the impact copper waste has on the environment when poorly managed. Restored ecosystems cause a spill-over of social and economic benefits associated with higher quality and abundant environmental reserves (Reijnders 2003). Companies implementing circular copper production cycles lower their costs, increase their revenue, and shorten manufacturing times (Romero-Hernandez & Romero 2018).

Case Study. The following discussion focuses on a case study from the medical device industry. In this case study, we analyzed copper use in an electrosurgical system, which is commonly used in surgical procedures. Specifically, we focused on the largest market, bipolar vessel sealing devices, as they are commonly used in laparotomy and laparoscopic surgical procedures (Massarweh 2006). Figure 4 shows the components which comprise this system. The handpiece, electrode and distal wires are attached to the generator via a cable, composed of braided and sheathed copper wires. Of the components shown, only the generator is designed explicitly for reuse. By design, the handpiece, electrode(s) and electrical connectors are meant to be discarded after a single-patient use.

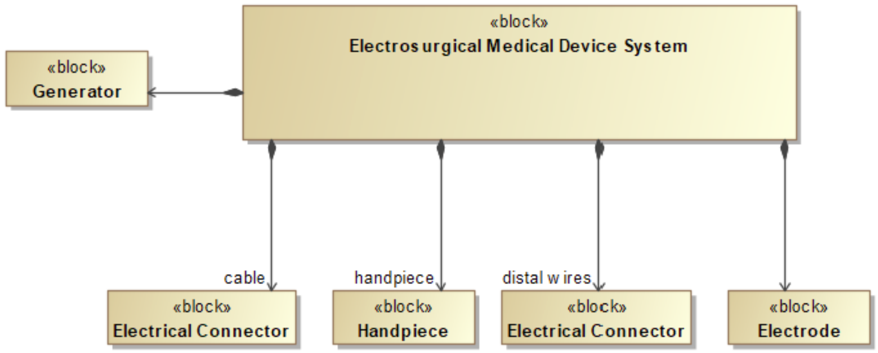

Figure 4. Typical composition of an electrosurgical medical device system.

In 2022, it is estimated that over 4.8 million single-use disposable electrosurgical devices will be used (Grandview Research). Most electrosurgical devices are discarded as biohazard, which introduces a large amount of reusable copper into biohazardous waste. Over 40 tons of copper from cable connectors will be incinerated or interred in landfills in 2022 (EPA 2022). The anticipated market increase for electrosurgical devices is 5.73% through 2030 (Strategic Market Research, 2021), at which point surgical cable connectors containing a cumulative 500 tons of copper will be discarded.

Although the quantity of copper used in electrosurgical devices is a fraction of a percent of the total global copper consumption per year, there are significant cost implications of discarding copper in surgical devices. As the copper reserves decrease, the price of copper is expected to increase. The average price of copper from 2019 to 2021 was $6500 (USD) per ton (Macrotrends) and bipolar medical device manufacturers spent less than $300,000 (USD) to support the production of the 4.8 million devices used in 2022. Goldman Sachs anticipates the price of copper will increase to $15,000 (USD) per ton by 2025, which is a CAPR of 39.7% (Bloomberg, 2022). By 2025, the medical device industry should expect to spend over $900,000 USD to support the market demand; more than triple the spend from last year. By 2030, this price could be over $6.5 million USD.

Medical device manufacturers can decrease raw material cost by considering reuse, repurposing, or recycling of surgical cable connectors. This not only saves significant cost to the device manufacturer and preserves their supply chain, but also aids in preserving the copper reserves which in turn will combat the global price of copper. Figure 5 illustrates the flow of copper throughout the lifecycle of an electrosurgical (ES) device as it may be imagined using circular design principles.

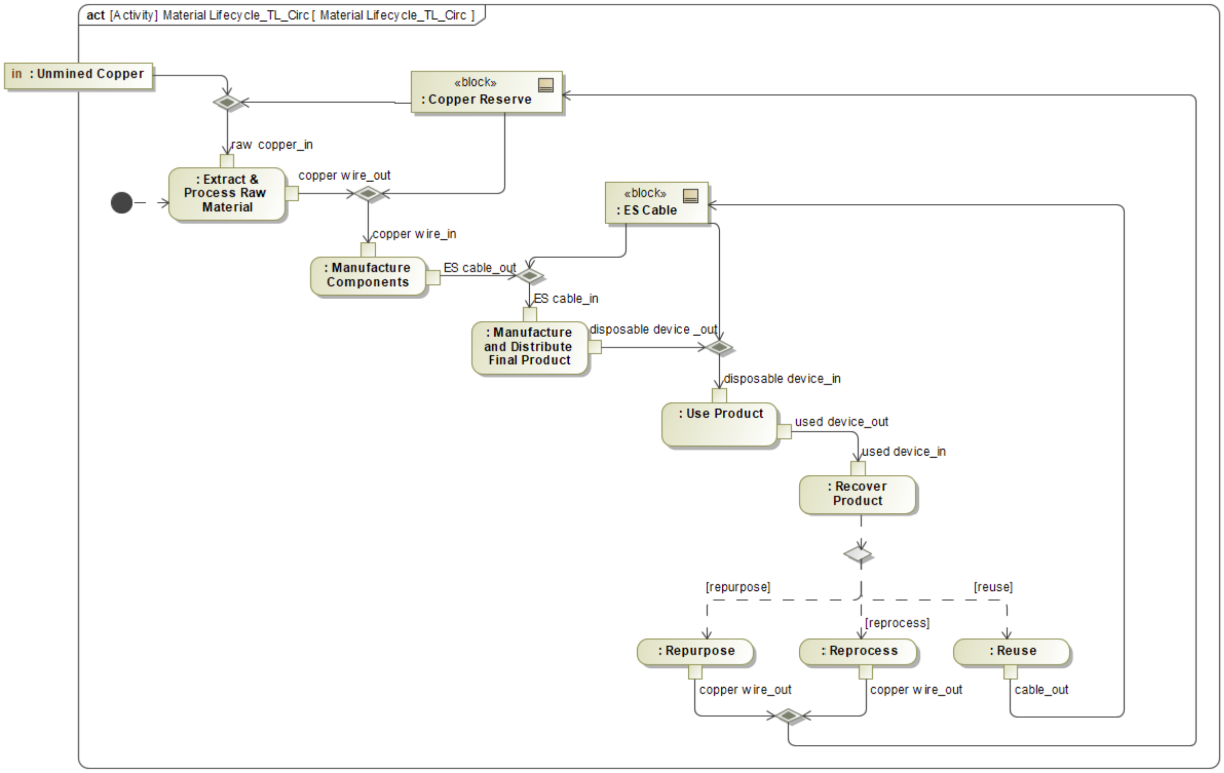

Figure 5. Illustration of the possible circular pathways in medical device manufacturing.

Three options are shown to demonstrate how the copper wiring of the ES cable can be maintained at varying levels of material value. Reuse refers to maintaining the ES cable in its whole form and being re-sterilized by either the original device manufacturer or the hospital central processing. Repurpose refers to harvesting the copper wires and reutilizing them in wire form. Reprocessing refers to complete recycling and use of raw copper in a new form. This is in contrast with the current linear system, in which the entire medical device is used once, and the copper is discarded as waste.

The analysis of the effects of copper reuse was prepared using SysML parametric analyses based on the definition of the Medical Device Domain in the context of electrosurgical systems shown in Figure 6.

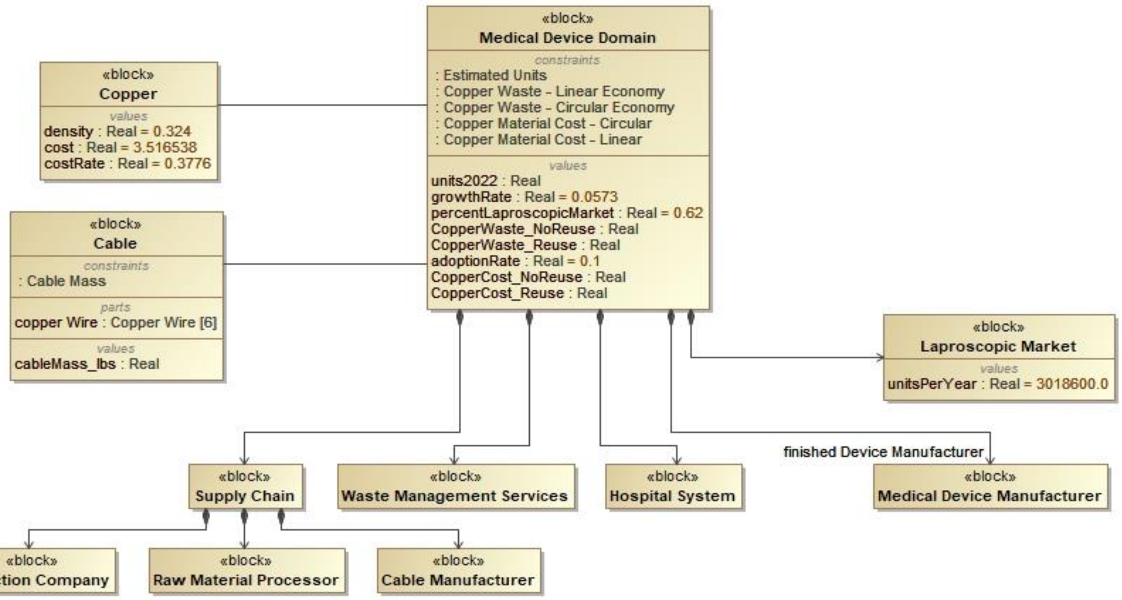

Figure 6. Definition of domain of electro-surgical systems.

The analysis was completed using the parametric diagram shown in Figure 7. This parametric analysis considers both the case where copper is reused and the case where it is discarded.

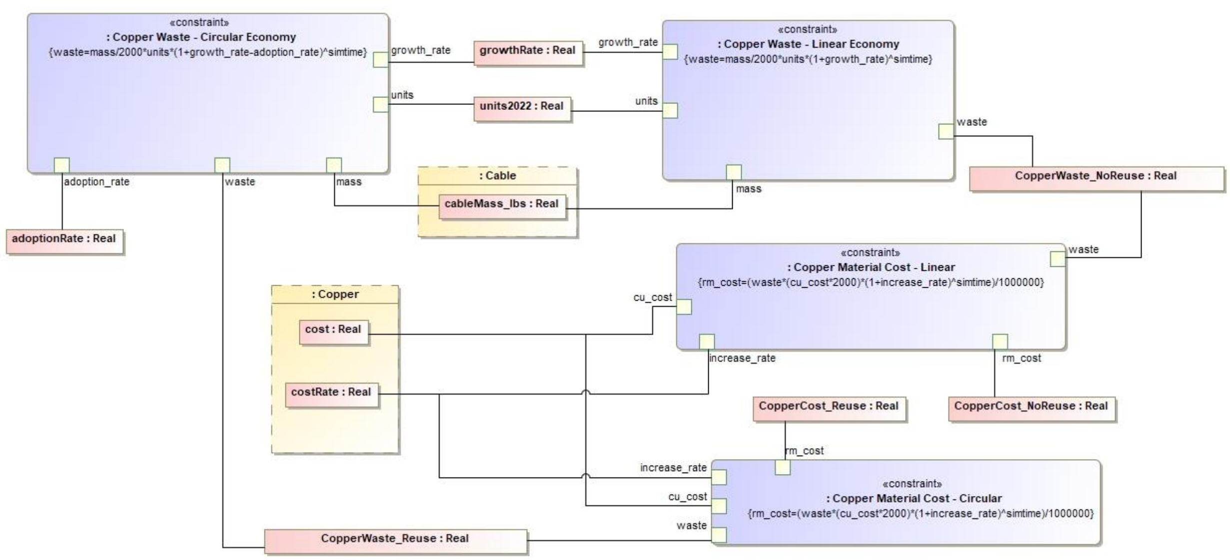

Figure 7. Top-level parametric analysis comparing circular to linear economies for copper use in electro-surgical devices.

Figure 8. displays the anticipated copper consumption for electrosurgical devices over the next 50 years and the total price medical devices manufacturers should expect to spend on copper each year to support the manufacturing of surgical cable connectors given no reuse of cable

connectors. Figure 8. also displays the anticipated copper consumption and expenditure if manufacturers increased the reuse of cable connectors 1%, 5%, and 10% annually. This analysis assumes that the typical electrosurgical cable is ten feet long and comprises six strands of 30-gauge copper wire.

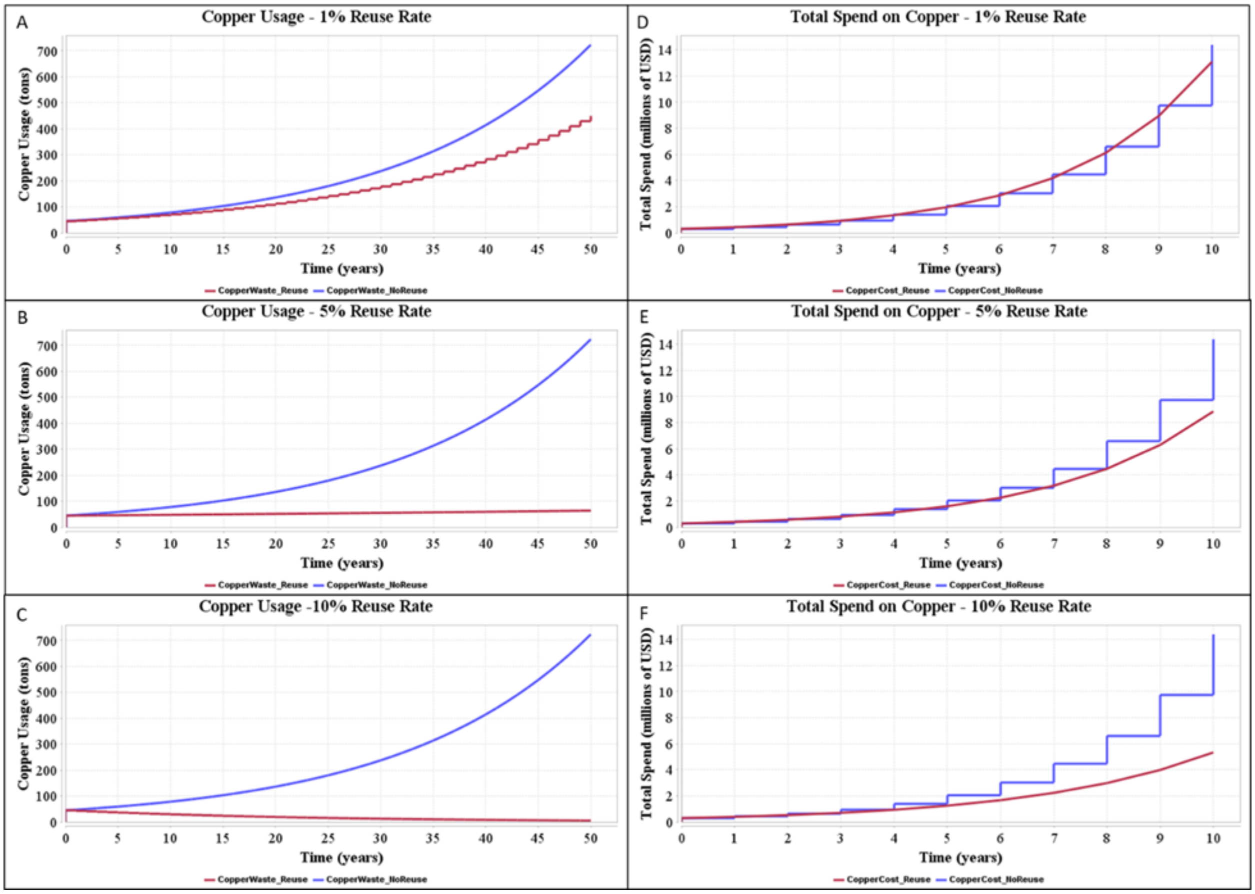

Figure 8. Anticipated copper usage from global copper reserve for electrosurgical devices over the next 50 years and the total price medical devices manufacturers should expect to spend on copper each year. A, B, C – Copper usage from reserve with 1%, 5%, and 10% annually increasing reuse rates. D, E, F – Total spend on raw material copper supply with 1%, 5%, and 10% annual increasing reuse rates.

Figure 8A, 8B, and 8C portray the anticipated use of copper from the global copper reserve given annual reuse rates of 1%, 5%, and 10%. In 50 years, medical device manufacturers could decrease the anticipated copper consumption by a third by increasing the reuse of cable connectors by 1% each year. Manufacturers could maintain the current consumption of copper by increasing their reuse rate by 5%. If device manufacturers increased their reuse rate by 10%, they could presumably decrease their consumption of copper. This effort would reduce the strain on the global copper reserve in addition to decreasing the environmental byproducts of medical waste incineration.

To support the electrosurgical market demand in 2030, medical device manufacturers will need to produce a total of 8.5 million surgical cable connectors consuming 70 tons of copper. Without introducing recycling, repurposing, or reuse of cable connectors, 70 tons of copper will be discarded at the point of use and $6.6 million USD will be incinerated alongside other biohazardous waste. Figure 8A, Figure 8B, and Figure 8C show that if medical device manufacturers increased their annual reuse rate by 1%, 5%, and 10%, respectively, the raw copper supply from the copper reserve would drop to 65, 47, and 31 tons. Figure 8D, Figure 8E, and Figure 8F show that the price device manufacturers should expect to spend on copper would drop from $6.5 million USD to $6.1 million USD, $4.5 million USD, or $3 million USD, respectively.

Integrating Value Streams

While collaboration across sectors is possible, internal repurposing pathways from waste to new production material is the most efficient pathway in closing the waste to value stream gap (Boons 2002). In-order to build a sustainable model, three focus points must be addressed during the experimentation phase of the system as outlined by Bocken et al (2019):

1. Construct clarity: the issue is a lack of defined contextualization in the development and testing of sustainable models
2. Boundary setting: without a defined boundary, a system will not be easily evaluated, and its functionality cannot be accurately represented
3. Uncertainty in outcomes: it cannot be guaranteed that a change in the model will result in a more sustainable functioning

Systems Engineering provides several tools and techniques that, when properly applied and considered, are useful in both characterizing current state of process and identifying evolutions of current state to achieve the necessary future state of sustainable and circular development. The following four considerations identified by Boons (2013) are transferable to systems engineering practice.

1. Causal complexity. This is a familiar concept to Systems Engineers. The characterization of the impact of interactions among and between systems and their interfaces is a foundational concept in systems engineering.
2. Adaptability. Translated to systems engineering vernacular, adaptability refers to the resilience of engineered systems, production mechanisms, supply chains to consider future states and plan for the inclusion of circular design.
3. Inclusive system boundaries. By recognizing environments and environmental factors as stakeholders of our system, we expand our scope of practice to ensure our design decisions properly capitalize on opportunities to include elements of circularity.
4. Selection pressure. By actively considering environmental factors, systems engineers can apply pressure to vendors and suppliers to source materials and components from

increasingly circular sources. This work begins with appropriately inclusive requirements.

Final Thoughts

Romero-Hernandez and Romero propose eliminating waste streams through efficient production design (2018). The following points, if addressed by systems engineers, may contribute to a reduction in overall waste by aiding in the conversion from linear design to circular design, thereby converting existing and future waste streams into value streams.

1. Identify environments as stakeholders in early stakeholder identification and research.
2. Expand system scope and boundary analyses to ensure interfaces with sources and sinks are considered.
3. Explicitly identify raw material suppliers and waste handlers as stakeholders.
4. Using the newly identified stakeholders listed above, ensure those stakeholders' needs are correctly and adequately transformed into system requirements.
5. Include environmental considerations in material and production process selection trade studies.
6. Include sources and sinks as references in manufacturing models such that interfaces can be described and the impacts of material selections and production methods on environmental interfaces can be assessed.

Global environmental conditions are shifting, and resilience in planetary systems is needed to meet the future. With a range of stakeholders from the environment to future generations, the flow between human-made systems and ecological ones becomes a point of transformation. By increasing system efficiency and valuing all by-products as resources the global economy can accelerate the evolution of human-designed systems (Boons et al 2013). Closing the gap between waste streams and value streams is vital in meeting economic material demands (Bocken et al 2019). In the pursuit of resilience, companies shifting to circular models for copper and other all resources have the opportunity to contribute to both internal and planetary prosperity.

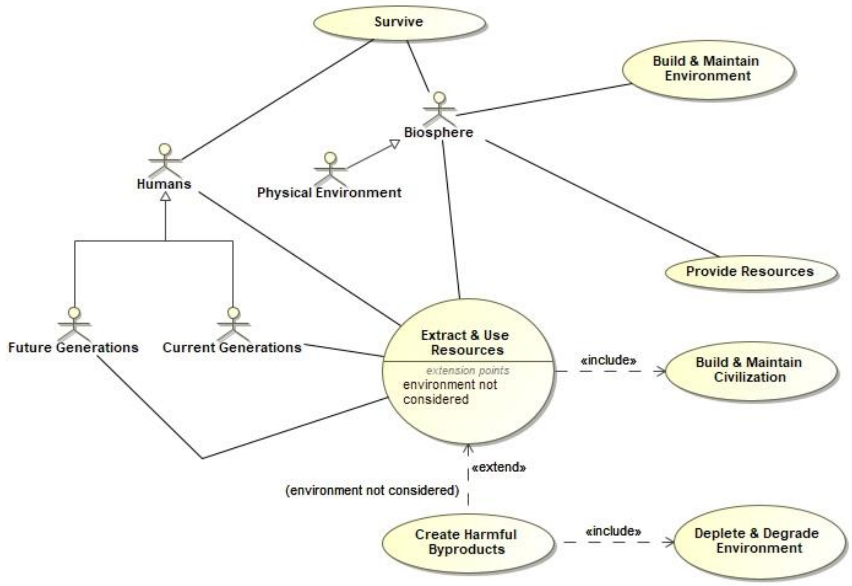

Figure 9. Use cases and stakeholders in association to resource extraction and use.

By taking the steps outlined above to begin moving toward a circular production design, we divert the waste stream pathway to create positive economic impact instead of environmental damage. As shown in Figure 9, resource use and disposal can be reimagined to reinforce ecological and economic prosperity; both now and for future generations. By limiting harmful byproducts and utilizing circular design, the environment is maintained alongside civilization.

The field of circular economic design needs continued innovation. Drawing inspiration from the wasteless design of ecosystems is an ideal place to start in the integration of economy and environment (Gamage & Hyde 2015). Shifting the definition of waste streams to value streams presents an opportunity to evolve the economy to meet the environmental, and therefore human, needs of the future.

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Diagrams created using Cameo Systems Modeler, version 19, service pack 4 by Dassault Systemes.

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Casey Medina leads Studio SE as the President and CEO. Under his leadership, Studio SE provides a range of exemplary professional development courses including Model-Based Systems Engineering. He has practiced systems and quality engineering across industries including medical device, aerospace, defense, and transportation industries. His expertise extends across disciplines including system development, requirements engineering, model-based systems engineering (MBSE), human factors, quality engineering, risk management, and medical device design control. Professionally, he is focused on developing the art of systems engineering in a manner that fosters adoption and acceptance by organizations resistant to change. He applies systems engineering practices and principles to enable rapid system development and is working to enhance the use of MBSE as an enabler for usability and human factors analyses. He has deployed MBSE to analyze social systems and homelessness. Casey and his team at Studio SE are pioneering the use of MBSE to evaluate natural systems and deploy MBSE to manage and solve sustainability issues.