DESIGN FOR SCARCITY

By

Hannah D. Budinoff

Graduate student, University of California, Berkeley

1 Introduction

To assess how to best position a company to become a leading major high-tech global design and manufacturing enterprise in the year 2035, it is necessary to evaluate the social and economic backdrop. The economic outlook for 2035 is bright: billions of new customers will have emerged on the global market in recent years, predominately in developing economies like China and India. Current predictions estimate that by the year 2030, Asia will account for two thirds of the global middle class population [1]. Worldwide, the middle class population is expected to expand from approximately 3 billion to 6 billion by 2030, with consumption growing from \$35 trillion to \$60 trillion [1, 2].

Figure 1: The middle class is expected to grow rapidly in China and other parts of the world, fueling increased consumption of manufactured goods and the resources used to make them [1]

To build middle class lifestyles, new homes need to be constructed (Fig. 1), new products must be manufactured, and more resources must be consumed. Already, the past century has seen large growth in the amount of resources such as biomass, metallic ores, and fossil fuels (Fig. 2). With more and more consumers, the rate of resource consumption will continue to grow.

Today, the middle class consumes and subsequently discards a huge volume of products. Between 1960 to 2010 in the United States, a period of intense wealth accumulation, Americans tripled their volume of waste produced, from 88.1 to 249.9 million tons [4]. It is likely that the new rising middle class will follow a similar pattern. In a world of finite resources, this presents a problem. When will demand outstrip supply?

To meet the growing demand, increasing material costs will drive increases in efficiency of material extraction, but it is unlikely that increased efficiency alone can quench the thirst of the growing middle class for new products. Further, using “virgin” resources is not in line

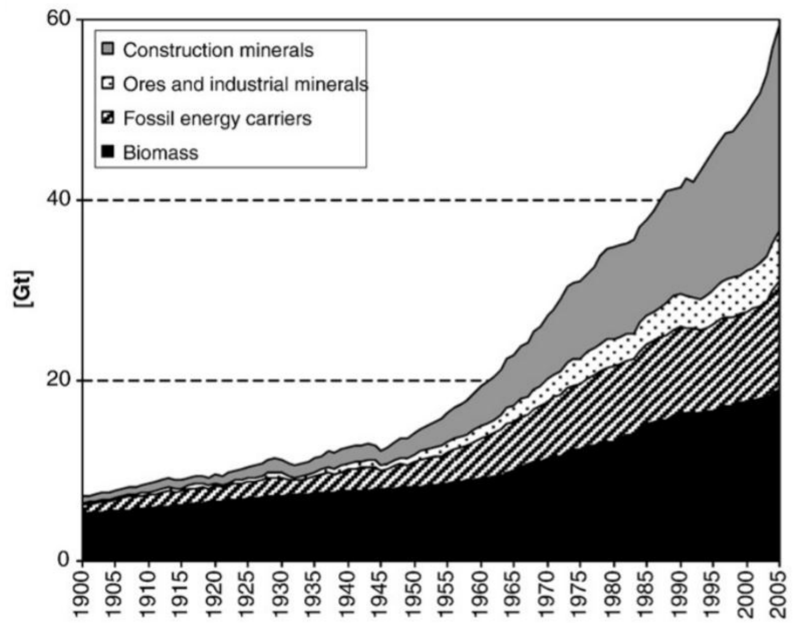

Figure 2: Resource use has grown substantially over the past century [3]

with sustainable development, often defined as meeting "the needs of the present, without compromising the ability of future generations to meet their own needs" [5].

Public perception will further increase the need to design and produce products sustainably. A 2010 survey of 5700 adults in developed countries found that more than 60% of those surveyed were shopping more mindfully than previously and that they felt good when making environmentally friendly choices [5]. Customers increasingly demand fair trade and ethically sourced products. [6]. Legislation, too, will make it necessary to reduce energy and material usage.

One solution to the growing problem of resource scarcity is adapting to a circular economy model. Rather than our current economy, in which materials are used to produce goods that are consumed by users and then disposed of, "a circular economy would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimizing waste...It would change economic logic because it replaces production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired" [7] (Fig. 3). A shift towards a circular economy could have far-reaching benefits. One study based on data from several European countries estimated that shifting to a circular economy would decrease each country's greenhouse-gas emissions by up to 70%, while increasing its workforce by roughly 4% [8] due to the additional need for labor to help reuse and recycle.

A design and manufacturing company operating in the year 2035 will have to compete in this resource-restricted environment. In order to succeed, the constraint of material scarcity must be considered early during the design of new products. Rather than creating products

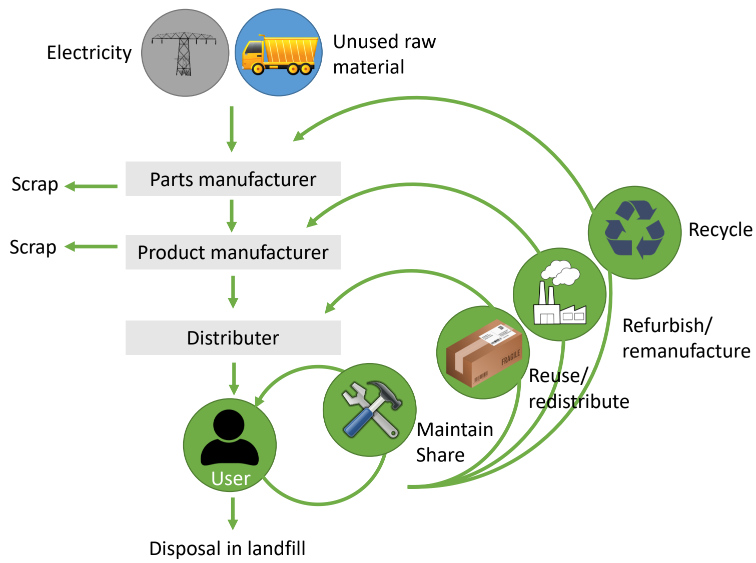

Figure 3: Diagram of the circular economy system, adapted from the Ellen MacArthur Foundation [9]

with the assumption that they will be used and disposed of, companies must consider how to build products for a new, circular economy. Companies that design and manufacture durable goods must strive to build durability and sustainability into every facet of their products.

2 Key company characteristics

A successful company operating in 2035 must update their design and manufacturing procedures to be successful in a resource-limited climate. The primary focus of such companies must be on design for sustainability and design for manufacturing. Although these goals are considered by companies today, they are typically pursued because they can also help their bottom line. In the future, the goals of sustainability and efficient manufacturing will not be an afterthought, considered secondarily to other product requirements, but rather primary requirements, considered as design constraints that dictate decisions throughout the new product development process. A successful company will need to be characterized by efficient manufacturing processes and robust product design. These two goals are also echoed in the first two principles of the circular economy: designing out waste and pollution; and keeping products and materials in use [10].

2.1 Efficient manufacturing

In order to design waste and pollution out of a product, the manufacturing process used to create that product must be efficient, with minimal scrap or energy use. The discrete manufacturing industry has relatively low energy efficiency, and could benefit from strategies such as more energy efficient production processes, energy utilization in collaborative frameworks, and management and control of energy consumption [5].

Today, almost any manufacturing process has a less-than-perfect yield rate, with a certain number of out-of-specification parts needing to be scrapped or reworked. Many manufacturing processes produce some waste, such as chips in machining. Manufacturing companies in the future should focus on efficient use of raw materials by moving towards zero-defect and zero-waste technologies [5]. By adopting more efficient processes, companies can reduce resource leaks in the circular economy and keep more resources in use. Additionally, they will reduce the effects of volatile energy and material prices on their business.

Although some parts of the manufacturing process can be optimized without changing the product design or part specifications, the design itself can determine a significant portion of the manufacturing process. Parts designed to be made of particular materials with particular features can only be made using a small set of manufacturing processes. Design for manufacturing helps designers consider manufacturing constraints and costs early in the development for a new product, ensuring that product can be manufactured easily and inexpensively. In 2035, design for manufacturing will focus heavily on creating parts that can be manufactured efficiently, with minimal material and energy usage. Design for manufacturing methodologies, as summarized in [11], can improve the quality of designs; allow designers to understand trade-offs between product performance and manufacturing yield; reduce product development cycle time; reduce manufacturing cost and manufacturing cycle time; realize higher and more predictable manufacturing yields; and reduce maintainability/serviceability efforts and warranty costs.

2.2 Robust products

To keep products in use for longer, the products need to be reliable and robust, and have the potential to be reused, repaired, or remanufactured. These attributes are determined by the design of the product assembly and each of its individual parts. There are a variety of strategies and tools intended to help designers create parts that are robust to failure, including failure mode and effects analysis or finite element stress analysis, but they are not used by all companies or for all products. Because many early-stage firms have restricted access to staff and funding, their new product development process is skeletal and does not conform to commonly recommended practices [12]. In the future, more design support software will become open access and computing costs will decrease, making it easier for early-stage firms to adopt better design for reliability practices. The constraints of resource scarcity and the public's demand for more sustainable products will cause all companies to use more failure analysis to make reliable products.

One potential solution for designing robust products that can be repaired is modularity, where a product is made with sub-assemblies that can easily be swapped out should one component fail. Sub-assemblies or modules can be made interchangeable and independent from each other, so that a product can be updated by upgrading a single module, rather than buying a whole new product. Additional benefits are that modular products tend to have fewer parts and are therefore cheaper to assemble, and can be cheaper to repair because less reliable components can be grouped together and easily accessed [13]. Parts can also be grouped into modules that are recycled in the same manner, reducing tear down and recycling costs [13].

3 Research challenges

There are numerous research challenges that must be addressed in the intervening years to support successful business in the future. Some important challenges include: improving the efficiency of recycling; and better understanding of the engineering design process.

3.1 Recycling

Currently, the amount of recycling of certain goods is limited because it is not cost effective to spend resources (e.g. labor, electricity) required to process a discarded product into its constitutive materials. But as demand for materials grow, there will be an increasing financial impetus to encourage more processing of scraped goods.

One major research hurdle is in extracting individual pure materials from a product that uses blends of materials. We need to better understand how to efficiently process metal alloys to extract the different constitutive elements [7]. Similarly, for polymers, plastic films are extremely common but very difficult to recycle, and more chemical recycling research is needed to return it to its monomer form [14].

There is also a need to understand how to design better products that utilize recycled materials. For example, the quality of recycled plastic may not be as high as virgin material because of the difficulty in sorting out different types of plastics [4]. How can designers plan for material inconsistencies and impurities? Especially when coupled with the demand for more durable and reliable products, optimizing product designs to use recycled materials will be a difficult problem to solve. However, a company that successfully addresses this challenge will be well-positioned to create more sustainable products at a reduced cost.

3.2 Engineering design process

Although the design of products to meet the needs of society is central to all of engineering, research on the design process itself still needs further improvement [15]. More research is needed to understand how to support designers who must make a myriad of interconnected, complex decisions during the design of a new product, especially as we add additional design requirements like sustainability and ease of manufacture.

One area of interest is how computers, models, and big data will affect the engineering design process. While humans are creative and flexible, computers can compute quickly and without fatigue [16]. In the future, most design activities, including life-cycle and manufacturability analysis, will likely be computer-supported activities. More research is needed to better understand how to leverage the benefits of humans and computers in the design process.

Design for X, or DFX, refers to a set of methodologies and concepts to help optimize some variable (X) during the design process. Design for manufacturing and design for sustainability are two examples of DFX. Many DFX tools are targeted to processes later in the design cycle, once detailed design is mostly complete [17]. Researchers must better understand how to support DFX during concept generation. However, DFM feedback has been found to possibly constrain creativity [18], so we must find a balance.

4 Mode of operation

Although the primary activity of a successful company must be focused on design, it is important that they also carefully consider manufacturing. Two possible modes of operation to ensure successful product production are in-house and contract manufacturing.

Manufacturing in-house affords better control of the final product. Large companies with vast amounts of capital will likely form some type of vertical integration, where they buy key suppliers and partners to streamline their production. This trend has recently been seen in other industries (e.g. Amazon and Whole Foods or Aetna and CVS [19]). While smaller companies will not be able to vertically integrate, they must form close relationships with suppliers and vendors. Quality control and frequent vendor inspections will become universal norms across all industries, not just certain industries like medical devices. There will be more visibility in where products comes from and how they are made. Additional details will be discussed in the subsequent section.

5 Partnerships

5.1 Suppliers and vendors

For companies that are not vertically integrated, it is important to identify like-minded vendors to supply resources such as raw materials or sub-components. If a vendor supplies a key sub-assembly but is extremely wasteful and produces a substantial scrap, resources leak from the circular economy system (Fig. 3). Therefore, for a design and manufacturing company to be successful in the resource-limited environment of 2035, they need to select suppliers that are willing to adopt good practices with regard to sustainability.

5.2 Refurbishing and remanufacturing

As seen in the diagram of the circular economy system (Fig. 3), there are several feedback loops for returning resources into use. For a company to support these feedback loops, it needs to identify partners who can interface with customers to help maintain products, or reuse or refurbish products if necessary. The exact form of these partners is difficult to determine, but it could be a system of locally-owned repair stores that are affiliated with particular companies, similar to bicycle sale and repair shops today. The partner that exists in the community with the customer can perform small repairs, resell repaired products, or send products back to be refurbished or redistributed to the manufacturer.

Efforts made by a successful design and recycling company to support recycling also help close the life-cycle loop of their own products. By supporting recycling business through the purchase of materials derived from scrap, more robust systems will be in place so that it will be more cost-efficient to recycle the companies products once they can no longer be refurbished or remanufactured.

5.3 Strategic partnerships

In order to gain an advantage in procuring recycled materials, companies should develop a strategic partnership with the Institute of Scrap Recycling Industries (ISRI), a Washington, DC-based trade association for the scrap industry. ISRI sets the specifications for varying grades of quality in scrap and is therefore a vital partner. Participating on advisory councils or staying in frequent communication with ISRI would enable a company to help set specifications that meet its needs, and understand scrap industry dynamics.

Given the research challenges outlined earlier, it would also be advantageous for companies to seek out academic and government research partnerships. Programs currently run by the National Science Foundation, such as the Industry-University Cooperative Research Centers (IUCRC) Program, can provide funds to jump-start these relationships. Long term, the influx of funding provided through these programs is likely to be small, but participation is key to developing the relationships needed facilitate technology transfer. By leveraging outside resources (e.g. NSF) to develop collaborations, the company has little to lose and much to gain by ensuring that they participate in the research that will contribute to advances in strategic areas, including recycling.

6 Necessary technology development

6.1 Engineering design support tools

Research on the engineering design process can be used to create effective design support tools. Design support tools are helpful for designers, serving as an extension of designers short term memory [20] and allowing them to focus on other more demanding tasks. Design support tools will serve an important role for companies in the year 2035 because they will help designers more efficiently perform design for manufacturing and design for sustainability analysis. Design support tools will allow designers to efficiently search design solution space, and to understand tradeoffs between manufacturing costs and quality.

While there are tools that currently help assess a product's manufacturability [21] and life-cycle impact [22], further development is needed to address several missing features, including estimating cost in real-time as a CAD model is updated, integration of vendor-specific manufacturing and assembly information, and better guidance for helping the designer determine what to do next [20]. Quantifying uncertainty and issues with handling multiple conflicting objectives are also problems [22]. Insights from the field human-computer interaction should also be used to improve existing systems and new systems developed by academic researchers.

6.2 Technology to support disassembly and recycling

In areas where most scrap material is processed, such as China and India, much of the processing is done manually with little regard for the human health and safety that regulate manual labor in the United States [4]. Burning of plastic installation is still relatively common. Human health and safety needs to be more carefully considered as recycling becomes more common. We need to develop methods to efficiently break down products into their component elements, without harming humans. If manual disassembly and processing is more efficient in terms of energy usage or yield, it must be done in a safe manner. We will need to develop ergonomic tools and guidelines to support manual processing (Fig. 4).

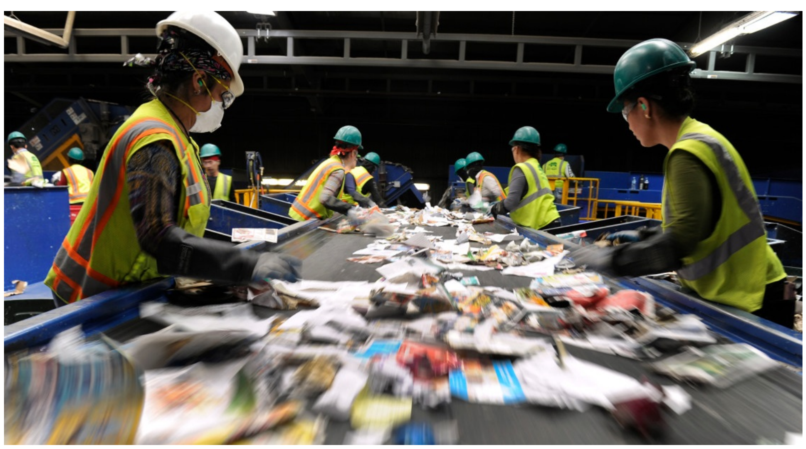

Figure 4: Manual processing of recycling material will need to be evaluated for efficiency and human health and safety. Photo by Kathryn Scott [14].

When manual disassembly or processing is not the most efficient use of resources, we will need to develop tools and processes to optimize material recovery. There are limits to today's recycling processing technology. For example, infrared light sensors used to sort different kinds of plastics, cannot sort out different colors of polyethylene bottles [4]. Disassembly and processing of electronic waste is a particularly important hurdle to overcome.

7 Conclusion

The future will bring companies major challenges, with scare resources, cost fluctuation, and supply instability. However, there is the potential for companies that are suitably prepared with good product design to thrive in such an environment. Hopefully, we can expect to see an increase in the availability of high quality products, designed with consideration of life-cycle impacts.

We are already observing some positive trends. Material is being used more efficiently, a hallmark of the past century of global industrialisation, with material intensity declining by 1% per year [3]. Increased efficiency in energy and material usage will make companies more stable among market volatility that will likely only worsen as the effects of climate change are felt more sharply. Also, some companies are already moving in towards more circular supply chains. In 2018, 11 companies, including The Coca-Cola Company, Unilever, and Walmart committed to working towards exclusively using packaging that is reusable, recyclable or compostable by 2025 [23]. As academic researchers, government entities, and like-minded companies invest in sustainable technology, engineering design best practices, and research on recycling, we will enable a brighter future, where a companies' core mission shifts from selling as much as possible to selling durable and sustainable goods. A successful company in 2035 will position themselves in advance to embrace this mission.

References

[1] Kharas, H., 2017. The unprecedented expansion of the global middle class. Brookings Institution. Accessed May 30, 3019. https://www.brookings.edu/research/the-unprecedented-expansion-of-the-global-middle-class-2/.

[2] Kharas, H., 2010. The emerging middle class in developing countries. OECD Development Centre Working Papers. No. 285.

[3] Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K. H., Haberl, H., and Fischer-Kowalski, M., 2009. "Growth in global materials use, GDP and population during the 20th century". *Ecol. Econ.,* ***68***(10), pp. 2696–2705.

[4] Minter, A., 2013. *Junkyard Planet: Travels in the Billion-Dollar Trash Trade*. Bloomsbury Press, New York, NY.

[5] Garetti, M., and Taisch, M., 2012. "Sustainable manufacturing: trends and research challenges". *Prod. Plan. Control,* ***23***(2-3), pp. 83–104.

[6] Kirkwood, D. A., Alinaghian, L. S., and Srai, J. S., 2008. "Maturity Model for the Strategic Design of Sustainable Supply Networks". *Management,* ***28***(5).

[7] Stahel, W. R., 2016. The circular economy. Tech. rep.

[8] Wijkman, A., Skånberg, K., and Berglund, M., 2016. The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency. Tech. rep.

[9] The Ellen MacArthur Foundation. Circular Economy System Diagram. Accessed May 30, 2019. https://www.ellenmacarthurfoundation.org/circular-economy/infographic.

[10] The Ellen MacArthur Foundation. What is the circular economy? Accessed May 30, 2019. https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy.

[11] Youssef, M. A., 1994. "Design for manufacturability and timetomarket: Part 1: Theoretical Foundations". *Int. J. Oper. Prod. Manag.,* ***14***(12), pp. 6–21.

[12] Marion, T. J., Friar, J. H., and Simpson, T. W., 2012. "New product development practices and early-stage firms: Two in-depth case studies". *J. Prod. Innov. Manag.,* ***29***(4), pp. 639–654.

[13] Gershenson, J. K., Prasad, G. J., and Allamneni, S., 1999. "Modular Product Design : A Life-cycle View". *J. Integr. Des. Process Sci.,* ***3***(4).

[14] Chuang T. The Colorado Sun. Colorado trash companies invest millions to speed up recycling. Now they just need more people to recycle. Accessed May 30, 2019. https://coloradosun.com/2019/05/08/colorado-trash-companies-investments/.

[15] Clive, D., Agogino, A., Eris, O., Frey, D. D., Leifer, L. J., Dym, C. L., Agogino, A., Eris, O., Frey, D. D., and Leifer, L. J., 2005. "Engineering Design Thinking, Teaching, and Learning". *J. Eng. Educ.,* ***94***(1), pp. 103–120.

[16] Egan, P., and Cagan, J., 2016. "Human and Computational Approaches for Design Problem-Solving". In *Exp. Des. Res.* pp. 187–205.

[17] Chiu, M.-c., and Okudan, G. E., 2010. "Evolution of Design for X Tools Applicable to Design Stages: A Literature Review". In Proc. ASME 2010 IDETC/CIE Conf.

[18] Abdelall, E., Frank, M. C., and Stone, R., 2018. "A study of design fixation related to Additive Manufacturing". *J. Mech. Des.,* ***140***(4).

[19] Garthwaite, C., Busse, M., Starc, A., and McCareins, M., 2018. What's Behind the Current Wave of Vertical Integration? Accessed May 30, 2019. https://insight.kellogg.northwestern.edu/article/whats-behind-the-current-wave-of-vertical-integration.

[20] Ullman, D. G., 2002. "Toward the ideal mechanical engineering design support system". *Res. Eng. Des.,* ***13***(2), pp. 55–64.

[21] Gupta, S. K., Regli, W. C., Das, D., and Nau, D. S., 1997. "Automated Manufacturability Analysis : A Survey". *Res. Eng. Des.,* ***9***(3), pp. 168–190.

[22] Reap, J., Roman, F., Duncan, S., and Bras, B., 2008. "A survey of unresolved problems in life cycle assessment: Part 2". *Int. J. Life Cycle Assess.,* ***13***, pp. 374–388.

[23] Climate Action, 2018. 11 leading companies pledge to recycle 100% packaging. Accessed May 30, 2019. http://www.climateaction.org/news/11-leading-companies-pledge-to-recycle-100-percent.