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A Comparative Meta-Life Cycle Inventory Analysis:

Energy and Water Consumption of 3D Printing Methods vs. Conventional Manufacturing in Clothing Production

Jujube Li

A Thesis in the field of Sustainability and Environmental Management

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

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Abstract

In the past three decades, textile fiber production has grown more than twofold, reflecting an increasing demand for both fossil and natural resources resulting in the intensification of environmental impacts such as water scarcity, abiotic depletion, and toxic pollution. Although potentially disruptive technology such as three-dimensional printing (3DP) can eliminate entire supply chain components and potentially reduce energy and water in textile and apparel production, 3DP as an application for clothing production is still at its nascent stage of development—the world's first 3D-printed garment being created only in 2010. As prevention is preferable to mitigation, it is timely to examine key environmental impacts of potentially disruptive technology in advance of its proliferation. By using environmental management tools such as ISO14044:2006 and the life cycle inventory analysis (LCI) method to identify hotspots for two key impact areas—water and energy consumption—of prevalent 3D printing methods versus that of the conventional cut-and-sew method in clothing production, environmental sustainability parameters can then be established to target underperforming areas and improve the design, manufacture, use, and disposal of future garments. Using one standard T-shirt as a functional unit, this meta-life cycle inventory analysis will compare the energy and water demands of using three main AM techniques—selective laser sintering (SLS), fused deposition modeling (FDM), and field guided fabrication (FGF)—against that of using the conventional cut-and-sew method to create one standard T-shirt out of six most representative materials.

Dedication

I dedicate this thesis to Harvard University Extension School's founder Abbott Lawrence Lowell, and to all the faculty members of the Sustainability and Environmental Management program—in particular, Dr. Thomas Gloria, Dr. Mark Leighton, Dr. Robert Pojasek, Dr. John Spengler, Dr. Ramon Sanchez, and Mr. George Buckley—for choosing to dedicate your lives to environmental sustainability by empowering a global community of catalysts seeking to create a livable future for all.

Acknowledgments

"*One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike—and yet it is the most precious thing we have."* – Albert Einstein.

It was with what I believed to be a crystal clear objective in mind that I embarked upon the path towards obtaining a masters degree in Sustainability and Environmental Management. Since then, each assignment and classroom experience has opened up new dimensions of understanding for me in the field of environmental science and sustainability management, propelling my growth and development as an environmental sustainability professional towards entirely new trajectories at each phase.

Listening to the in-depth, real-world experiences brought to life under the intimacy of classroom settings by sustainability professionals, I was inspired by both the challenges they each faced and the solutions they sought. The three most important takeaways from the culmination of these two years of learning are: i) to maintain relative objectivity even until after the null hypothesis has been accepted or rejected, since correlation does not necessarily mean causation, ii) to appreciate the value of high-quality sampling, large sample sizes and quantifiable data, and iii) to be able to communicate the costs and benefits of sustainability management solutions to stakeholders using a common language.

In particular, I would like to take this opportunity to express my deep gratitude towards research advisor and ENVR-210 Critical Analysis of Environmental Systems professor Dr. Mark Leighton, for demonstrating step by step how scalable change is

possible through sound quantitative analysis, and in such a way, providing me with a new framework from which I can better approach sustainability.

By the same token, I would like to express my most heartfelt gratitude to my thesis director, ENVR-158 Industrial Ecology professor, and now Director of the Sustainability Program at Harvard Extension School, Dr. Thomas P. Gloria—without whom this thesis would not have been possible—for inspiring solutions-oriented strategic thinking with his penetrating knowledge in industrial ecosystems and life cycle assessment tools, and for providing me with sturdy guidance to keep my progress aligned with my thesis objectives along the rigorous and tedious research process.

Last but not least, I would like to thank my peers at Harvard for sharing new ideas and perspectives with their diversity, resourcefulness, and camaraderie.

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Definition of Terms

3D printing (3DP): An additive process for making physical objects from a three-dimensional digital model, typically by laying down many successive thin layers of a material. Also known as “additive manufacturing” (AM), “stereolithography” (SL or SLA), “rapid prototyping” (RM), or “freeform fabrication” (Oxford dictionaries).

Acetone: A volatile fragrant flammable liquid ketone C_3H_6O used chiefly as a solvent and in organic synthesis and found in abnormal quantities in diabetic urine (Merriam Webster).

Acrylonitrile butadiene styrene (ABS): A tough rigid plastic used especially for automobile parts and building materials (Merriam-Webster dictionary).

Additive manufacturing (AM): Also referred to as “rapid prototyping” (RM) or 3D printing, additive manufacturing processes include “stereolithography” and “Fused Deposition Modeling” (FDM). See “3D printing.”

Biodegradable fibers: Fibers that can be broken down into simpler substances by microorganisms, light, air, or water in a non-toxic process over a relatively short period of time (Fletcher & Grose, 2012, p. 17).

Biopolymers: Polyester fibers that biodegrade, including fibers made from polylactic acid (PLA) made from agricultural crops such as corn or sugar cane (Fletcher & Grose, 2012, p. 18).

Cellulose acetate (CA): An amorphous, transparent and colourless, glossy and reasonably hard thermoplastic with good clarity but only moderate UV stability and chemical resistance. Its high moisture absorption can lead to the normal difficulties of dimensional changes. Applications include spectacle frames, tool and brush handles and packaging including stiff thin-walled tubes for "display packaging". Films are widely used for graphics purposes (Goodfellow, 2015).

Deposition: In the 3DP industry, “deposition” refers to deposition processes whereby “a material stream is deposited without point source heating, such that selectivity is governed by motion of the material stream.” Two key types of deposition modeling are: i) filament-based, where a polymer-matrix filament is fed into a heated nozzle that melts the polymer and flows it into position on the build part; and ii) inkjet-based, whereby powder is deposited in layers by rolling, then sprayed with adhesives as in inkjet technology (Beaman et al., 2004, p.24). See also “FDM.”

End-of-life (EOL): the life cycle stage at the end of a product’s lifetime.

Field Guided Fabrication (FGF): an electrospinning process of converting polymer-based cellulose nano-fiber liquid solutions into solid fibers, which are then deposited onto a

three dimensional template that can be made of nearly any material, such as cardboard, vinyl, or metal (Electroloom, 2015; Hipolite, 2015).

Fused deposition modeling (FDM): a 3DP method that creates objects layer-by-layer by heating and extruding thermoplastic filament material on a base plate. Where support or buffering is required, the 3D printer deposits a removable material to hold up the desired build form that will be broken off and disposed of by the user after the print is done (Stratasys, 2015). See also "Deposition."

Greenhouse gas (GHG): a gas that contributes to the greenhouse effect by absorbing infrared radiation, e.g. carbon dioxide and chlorofluorocarbons (Oxford dictionaries).

Lamination, 3DP category: also known as laminated object manufacturing (LOM) in 3DP, lamination refers to a process whereby the desired object is derived from sequentially layering together sheets of its cross-section taken at different latitudes (Beaman et al., 2004, p.25).

Life cycle assessment (LCA): 1) a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle, serving as an adequate instrument for environmental decision-making (UNEP); 2) compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040:2006).

Life cycle inventory analysis (LCI): also "Life Cycle Inventory Analysis"— 1) a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (Environmental Protection Agency); 2) phase of life cycle assessment aimed at understanding evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 14040:2006).

Life cycle impact assessment (LCIA): 1) phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (ISO 14044:2006).

Manmade fibers: Fibers that have had their chemical compositions, structure, and properties significantly modified during the manufacturing process. Manmade fibers are spun and woven into a large number of consumer and industrial products, including garments, home furnishings, and industrial parts (Britannica).

Nylon-12 (N-12): See "PA-12."

Nylon: Also known as polyamide—a tough, lightweight, elastic synthetic polymer with a protein like chemical structure, able to be produced as filaments, sheets, or molded objects; fabric or yarn made from nylon fibers; a generic designation for a family of synthetic polymers known as aliphatic polyamides (Oxford dictionaries, Encyclopedia of Polymer Science).

PA-12: Polylaurolactum, also known as Nylon-12, is composed of "a straight-chain structure with acid amide groups and 12 carbon atoms in its monomer unit" (Griehl & Ruestem, 1970).

PA-2200: A Nylon 12-based fine-powder on the basis of polyamide 12 specifically formulated to meet FDA requirements that is "characterizd by higher crystallinity and higher melting point" (Lasersintering.com; EOS, 2015).

Polycaprolactone (PCL): A polymer-miscible and biodegradable polymer produced from two possible pathways: [1] polycondensation of a hydroxycarboxylic acid 6-hydroxyhexanoic acid, and [2] ring-opening polymerization (ROP) of a lactone – caprolactone (-CL) (Labet & Thielemans, 2009).

Polyethylene terephthalate (PET): polyethylene terephthalate—a synthetic resin made by copolymerizing ethylene glycol and terephthalic acid, widely used to make polyester fibers (Oxford dictionaries).

Photopolymers: also known generically as photoresists; in the 3DP industry, as photopolymer resins or UV resins. Photopolymers are imaging compositions based on polymers, oligomers, or monomers that can be selectively polymerized and/or cross-linked upon image wise exposure by light radiation such as ultraviolet light, such that they can be composed into desired solid or gel-like forms. In liquid form, they can also be used for non-imaging applications such as adhesives, coatings, and inks. (Photopolymer.com; Beaman et al., 2004, p.24).

Polylactic acid (PLA): polylactic acid fibers originated from agricultural crops such as corn and sugar cane, melt-spun in a process similar to that of polyester fibers (Fletcher & Grose, 2012, p. 18).

Polyamide: a synthetic polymer of a type made by the linkage of an amino group of one molecule and a carboxylic acid group of another, including many synthetic fibers such as nylon. See "Nylon." (Oxford dictionaries).

Polyester: a synthetic resin in which the polymer units are linked by ester groups, used chiefly to make synthetic textile fibers; also known as PET (Oxford dictionaries).

Polymers: chemical compounds from which manmade fibers are produced; a class of compounds characterized by long, chainlike molecules of great size and molecular weight, e.g. regenerated cellulose (rayon), polycaprolactam (nylon), and polyethylene terephthalate (Dacron), known for their strength, toughness, resistance to heat and mildew, and ability to hold a pressed form (Britannica).

Polypropylene (PP): a synthetic that is a polymer of propylene, used especially for ropes, fabrics, and molded objects (Oxford dictionaries).

Powder: in 3DP, there are two main types of powder application—i) selective laser sintering (See "SLS"); and ii) powder spray, whereby powder is deposited locally and

fused together simultaneously using a laser beam on a substrate (Beaman, J.J. et al., 2004, p.25-26).

Rapid prototyping (RP): refers to any manufacturing process that uses CAD data to produce a part (Lou & Grosvenor, 2013); also referred to as "additive manufacturing" (AM), "stereolithography," or 3D printing. See "3D printing."

SL or SLA: See "Stereolithography."

Selective laser sintering (SLS): an additive manufacturing technology that uses high power carbon dioxide (CO2) lasers to fuse plastic, metal, or ceramic powder particles together, layer by layer, to form a solid object (3D Systems, 2014).

Synthetic fibers: a group of manmade fibers made of polymers that do not occur naturally but are produced entirely in the chemical plant or laboratory instead, almost always from by-products of petroleum or natural gas. These polymers include nylon, polyethylene terephthalate, acrylics, polyurethanes, and polypropylene (Britannica).

Stereolithography (SLA): stereo lithography apparatus, also known as stereolithography (SL), optical fabrication, photosolidification, solid freeform fabrication, solid imaging, optical shaping, additive manufacturing, electron beam melting, etc.---a technique or process for creating three-dimensional objects, in which a computer-controlled moving laser beam is used to build up the required structure, layer by later, from a liquid polymer that hardens on contact with laser light (Oxford dictionaries).

Subtractive manufacturing: a manufacturing process that subtracts or removes any excess material from a block of material in order to derive at a desired shape or form. "CNC milling and turning" is a subtractive manufacturing process (American Precision Prototyping, 2014).

TPU-85A: a thermoplastic polyurethane elastomer (Lubrizol, 2015).

TPU-92A-1: a new class of thermoplastic polyurethanes (TPUs) more durable, more elastic, and stronger than polyamide known as Desmosint X 92A-1 that is used in powder form for selective laser sintering (Grimm, T., 2012).

Chapter I

Introduction

As the world population approaches 9.6 billion in 2050 as projected by the United Nations (UNDESA, 2013), the burgeoning middle class in developing countries like China have greatly increased their resource consumption in parallel with per capita income in the recent decade, driving up the global demand for energy, food, clothing, shelter, and transportation.

Dressing for 9.6 Billion in 2050

According to a 2010 industry report, "the global textiles, apparel & luxury goods industry is forecast to have a value of $3,179.7 billion" in 2015—a growth of 22.4% from 2010 (Datamonitor, 2011, p.2). The intensifying demand for clothing and apparel products as a result of income per capita growth translates into an accelerated rate of water scarcity, natural resource depletion, food shortage, and environmental pollution.

> In 2000 the world's consumers spent around US$1 trillion worldwide buying clothes. Around one third of the sales were in Western Europe, one third in North America, and one quarter in Asia. […] More than a quarter of the world's production of clothing and textiles is in China, which has a fast growing internal market and the largest share of world trade. […] Growth in volumes is almost entirely associated with polyester—volumes of natural fiber production and use having remained approximately constant for years. […] The sector's contribution to climate change is dominated by the requirement for burning fossil fuels to create electricity for heating water and sir in laundering. Other major energy uses arise in providing fuel for agricultural machinery and electricity for production. […] Water consumption—especially the extensive use of water in cotton

crop cultivation—can also be a major environmental issue as seen dramatically in the Aral Sea region. (Allwood, Laursen, Rodriguez, et Bocken, 2006)

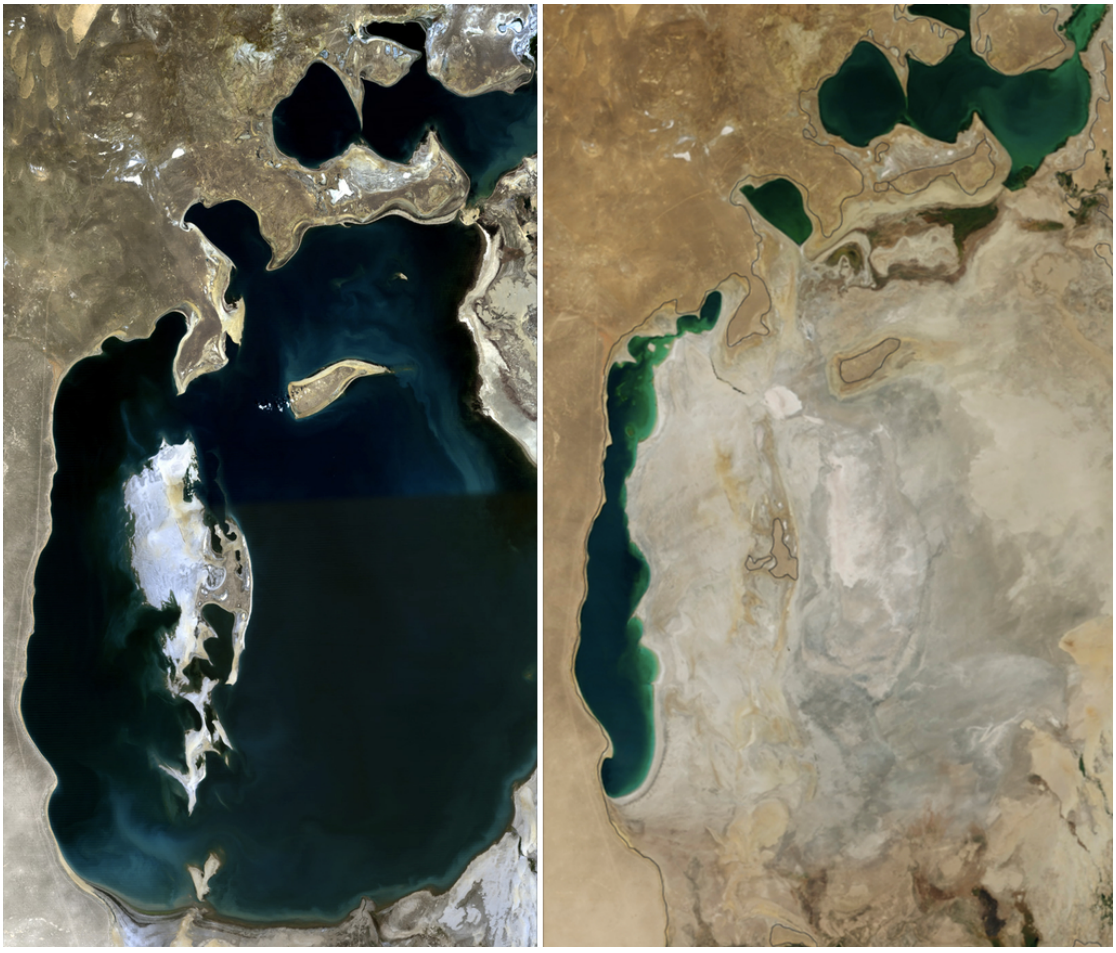


Figure 1. The Aral Sea photographed in 1989 (left) and 2014 (right) (Thompson, 2008).

One example of how the unsustainable use of water for industrial purposes can lead to severe social and environmental degradation over just a few decades is the Aral Sea region (Figure 1). The Aral Sea was once the world's fourth largest saline lake. Its desiccation led to a steep increase in water salinity that caused commercial fishing catches to fall from 43,430 tons in 1960 to zero in 1980. This also led to the

desertification (Figure 2) of once fertile lands from soil salinity, and soil erosion as a result of abusive fertilizing practices that further deteriorated soil quality (Thompson, 2008). Socioeconomic impacts of diverting freshwater streams to the Aral Sea region for cotton and rice cultivation include an increase in poverty, displacement of over 100,000 people, and a eightfold increase in anemia, brucellosis, bronchial asthma, typhoid, and tuberculosis that affected over 5 million people in the region (Thompson, 2008).

While all textile and garment production invariably affects the ecological system in some way, these impacts vary in terms of type and intensity from one fiber type to the next, resulting in multifarious trade-offs between environmental impacts that need to be averted. For instance, synthetic fibers may be energy intensive and contribute to abiotic depletion, but they are not water-intensive and land-consuming like natural fibers are, even though natural fibers have the advantage of biodegradability.



Figure 2. Farmer looking at a patch of land desecrated by soil salinity (Thompson, 2008).

Shift Towards Sustainability

Recent innovation of new materials for environmentally-friendly textile and garment production has been mainly concentrated around three interconnected areas: 1) renewable raw material sources, 2) reduced inputs of water, energy, land, and chemicals, and 3) reduced outputs of non-biodegradable waste through biodegradable fiber innovation and recycling (Fletcher & Grose, 2012, p.13).

Although each of these three approaches aims to reduce the environmental impact of textile production, each produces negative offsets in other areas. For example, cotton is a renewable and biodegradable raw material, but it tends to be water intensive in both the production and use phase (WFN, 2014). While it requires only 135 litres of water to produce a polyester fleece top compared to the 379 litres of water for a cotton-lyocell blended women's top (Fletcher & Grose, 2012, p.30), polyester is non-biodegradable and contributes to abiotic depletion, as it is derived from fossil-fuel sources.

There has been a burgeoning of attempted innovations in the past decade targeted at reducing the environmental impacts of textile and garment industry in key areas:

1. Fashion products
    a. Materials
    b. Processes
    c. Distribution
    d. Consumer care
    e. Disposal
2. Fashion systems
    a. Multi-functional or self-adjusting garments
    b. Clothing lifespan optimization
    c. Use-impact reduction
    d. Damaged apparel reparation
    e. Leasing instead of selling
    f. Design customization
    g. Localizing sourcing and production

    h. Biomimcry
    i. Slow production
    j. Designing for specific lifestyle and emotional needs
    k. Engagement through co-designing, crafting, or hacking
3. Fashion design practice
    a. Designer as communicator-educator
    b. Designer as facilitator
    c. Designer as activist
    d. Designer as entrepreneur

(Fletcher & Grose, 2012)

Some examples of the more disruptive transformations that have recently taken place in materiality, processes, and distribution of textile and garment production are**:** i) sustainable fiber innovation, ii) fiber hybridization, iii) distributed production, and iv) additive manufacturing techniques.

Sustainable fiber innovation in recent years has seen the invention of a wide variety of recycled synthetic and natural fibers (e.g. recycled polyester, recycled cotton), manmade cellulosic fibers made from both protein and plant based cellulose (e.g. milk, soy, flax, beech wood, banana leaves, cane, eucalyptus, coconut husk, coffee grind), and performance fibers (e.g. glass, carbon, aramids, acrylic, sulfar, polybenzimidazole, polyphenylenebenzobisozazole) designed for task-specific purposes, which increases clothing durability and lifespan while achieving functional objectives.

However, each has its own limitations. Not all used synthetic and natural fibers are recyclable as a result of fiber length being too short for reuse at the disposal stage; even if they were recyclable, fiber quality degrades with each cycle of reuse that results in the eventual landfilling and incineration of the apparel product. Manmade cellulosic fibers, especially plant-based cellulose, may not always be derived from renewable sources and some may even compete with food sources. Performance fibers are usually

synthetic, derived from petrochemical sources, and bioaccumulative; requiring the use of hazardous additives such as perfluorinated compounds (PFCs), antimicrobials, and halogenated flame retardants that pose significant risks to human health and the environment (Hoguet, 2014).

Perhaps, the greatest limitation for sustainable fiber innovation is the lack of a recognizable and verifiable standard for communicating the material composition and related environmental or health benefits of each fiber type to the end user down the garment supply chain. Without distinctive and reliable certification standards being established, if not on a global level then a national one, to distinguish between the attributes of different sustainable fiber products, end users are left confused and adverse to claims made by various brands purporting to be environmentally conscious.

In fiber hybridization, different fiber types are woven or knit into one continuous fabric to achieve different properties desired of fabric performance. As in the case of Levi's 29% recycled polyester-71% cotton "Waste<Less" jeans, the water-intensity of cotton-based denim apparel is reduced by blending recycled polyester fibers with cotton fibers to create a denim textile that consists of less cotton fibers (Chirico, 2013). By reducing water-intensive cotton fibers in the fiber content, these jeans require significantly less water in both the production and use phases. The approach not only reduces the garment's water intensity, but also provides a second life for the polyester content that would have otherwise been discarded. However, despite achieving reductions in both water-intensity and energy-intensity (from using recycled polyester as opposed to virgin polyester), fiber hybridization inhibits decomposition at the end-of-life phase due

to the difficulty of separating the fibers for recycling purposes (Fletcher & Grose, 2012, p.17) and compounds upon waste accumulation in the biosphere.

Instead of focusing on materiality, distributed production—synonymously known as distributed manufacturing, mass customization, personalization, peer production, "suggests an alternative to mass production that differs in scale, location and consumer-producer relationship" (Kohtala, 2014, p.1), whereby the focus is on creating alternative processes and business models that allow for greater "flexibility, agility and greater customer orientation in manufacturing and mass customization" (Kohtala, 2014, p. 2). Characteristics of distributed production include: i) agility, rather than centralization or decentralization; ii) distributed economies, where the focus is on creating social equity through the promotion of flexible micro local networks to meet local needs; iii) "prosumption," whereby "production becomes part of the consumption process" (Kohtala, 2014, p. 2), iv) "commons based peer production," or peer-to-peer networking, and v) "personal fabrication" or "fabbing," whereby consumers design and manufacture their own products either individually or through "commons-based peer production of physical goods" (Kohtala, 2014, p. 2).

In the overlap between mass customization and personal fabrication (Kohtala, 2014, p.4) is 3D-printing (3DP), otherwise known as additive manufacturing (AM), direct digital manufacturing (DDM) or rapid prototyping (RP). While subtractive manufacturing refers to the process of removing or subtracting material from a material block in order to derive at the desired product form, additive manufacturing is the opposite in that it refers to the process of adding layers of material to produce the desired form. Not to be confused with "direct-to-garment (DTG) digital printing" that prints artwork onto

clothing directly using two-dimensional (2D) inkjet printing technology (Kruse, 2011), 3D garment printing has the potential to become disruptive technology in the near future, given the strong public interest.

Technological Innovation

Even though 3D printers designed specifically for garment production are still in nascent stages of development, various styles, sizes and models of consumer-grade 3D printers designed to print small, hard parts have already been in retail for the past decade.

The most common type of consumer-grade 3D printer available today uses fused deposition modeling (FDM) technology that extrudes a wide range of filament materials––from fossil-based acrylonitrile butadiene styrene (ABS) plastic to biodegradable polylactic acid (PLA)—through a nozzle head, to print objects layer by layer on a base plate. Its simplicity allows for the mass customization or personal fabrication of small objects, or "build parts" in industry jargon.

Other than the wide range of FDM-based consumer-grade 3D printers available in the market today, there are also a variety of commercial-grade 3D printers purposed for rapid prototyping (RP) or direct digital manufacturing (DDM) of commercial products by industry-users.

While industry has mainly employed 3DP technology for concept modeling, there has been a shift towards using 3DP for manufacturing actual commercial products in recent years, often with the aim of increasing production efficiency and reducing costs by eliminating the need for extensive manpower. Some companies have even managed to successfully 3D-print entire buildings and automobiles, while others have found it

profitable to provide commercial-grade 3DP services, in combination with online retail and shipping capabilities, to individual creators and artists who only want to focus on product design and have limited capital to produce their designs in the high minimum quantities required by brick-and-mortar retailers.

There are four broad categories of commercial 3DP (Beaman et al., 2004, p.24):

1) photopolymers (stereolithography, photo-solidification, resin printing):

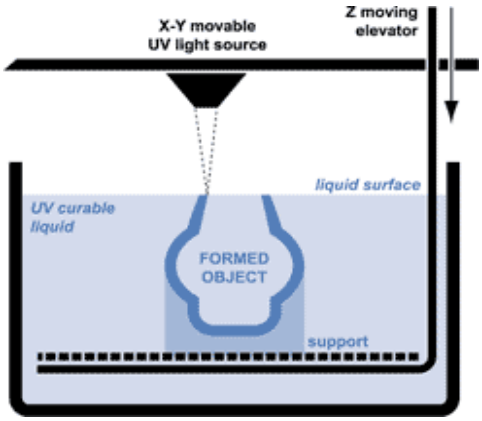


Figure 3. Stereolithography diagram (Burns, 2004).

2) deposition (filament and inkjet):

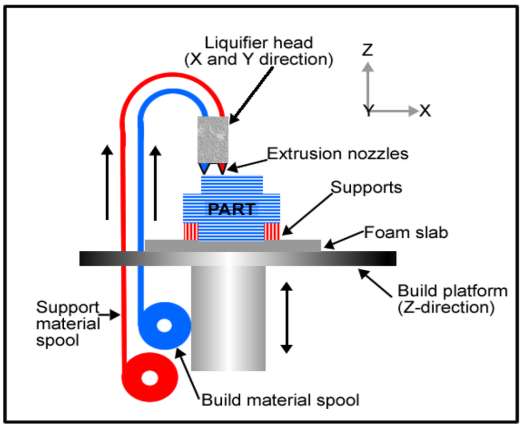


Figure 4. Fused deposition modeling diagram (Sidambe, 2014).

3) lamination (laminated object manufacturing):

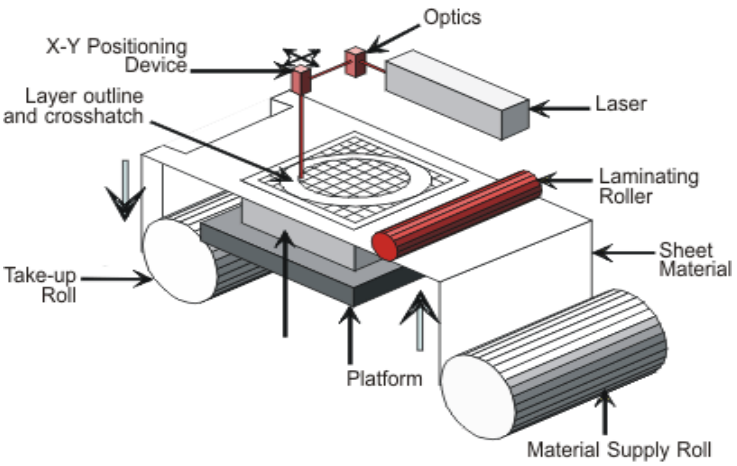


Figure 5. Laminated object manufacturing diagram (Azom.com, 2013b).

4) powders (layered and sprayed, as in selective laser sintering)

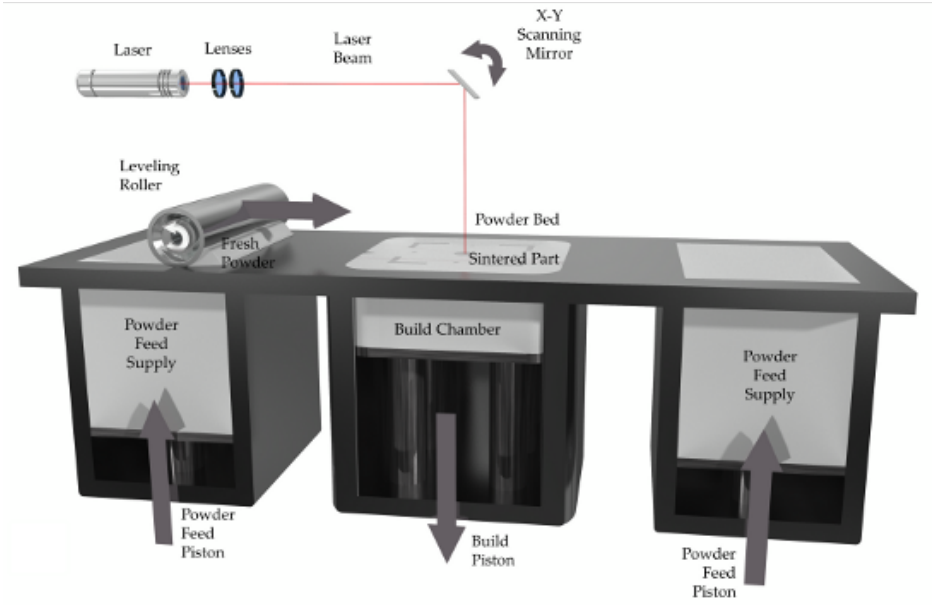


Figure 6. Selective laser sintering diagram (Bhaboeti, 2013).

Specific to clothing manufacture, recent applications of AM technology have mainly used deposition and powder techniques. Besides consumer- and commerical-grade 3D printers, there are also novelty 3D printers under way. A new technique known as "field guided fabrication (FGF)" is currently being developed by innovators Electroloom to 3D-print clothing (Kickstarter, 2015).

This comparative LCI analysis will include representative models from each of the three classes of 3D printers—1) consumer-grade (FDM technology), 2) commercial-grade (SLS technology), and 3) novel (FGF technology), and compare them against the conventional cut-and-sew manufacturing method to reflect recent trends and developments in 3D garment printing.

Case in Point: Nike Vapor Ultimate Cleat

In 2014, major sportswear brand and retailer Nike used 3D-printing technology to create the Nike Vapor Ultimate Cleat (Figure 7 and 8), a men's football cleat comprising of the 3D-printed zero-slip nylon sole called the "V-Plate" (Stinson, 2014), and the "Nike Flyknit" carbon fiber-and-polyester upper that uses flat-knitting to create the panel (Orr, 2014).

Launched in July 2014, the USD 250.00 Nike Vapor Ultimate Cleat (Orr, 2014) has revolutionized functional footwear by its carbon V-Plate design—a cleat plate comprising of an energy-enhancing carbon fiber layer that is fused with a second layer of 3D-printed nylon spikes that enable "zero-slip traction in accelerating and breaking" (The Engineer, 2014). At the same time, "Nike Flyknit" technology reduces stitching and scrap

waste while enhancing flexibility and support by substituting multiple linings, reinforcements, and additional panels with one continuous multifilament-yarn panel (Nicastro, 2012).



Figure 7. Nike Vapor Ultimate Cleat, 3D-printed "V-Plate" sole (Farmer, 2014).



Figure 8. Nike Vapor Ultimate Cleat, "Nike Flyknit" technology (Farmer, 2014).

With innovators and mainstream apparel brands alike working progressively towards the same goal—a truly scalable and economically viable means of apparel manufacture that can eliminate successive steps along the supply chain—this is an opportune time to understand the key environmental impact metrics of potentially disruptive technology.

Potential Benefits of 3D-Printing

Given its potential for mass production or mass customization, AM and 3DP technology applied to garment production can become the convergence of all three areas of sustainability-led innovation—1) renewable raw material sources, 2) reduced inputs of water, energy, land, and chemicals, and 3) reduced outputs of non-biodegradable waste—due to the interconnectedness of their environmental impacts. Potential benefits of AM technology to clothing manufacture may include:

- Minimization of material waste by enabling the creation of perfect-fit, preferred, long term-wear garments generated in conjunction with design software to customize clothing product to the end user's exact body contours and personal taste
- Elimination of supply chain processes, such as the "brushing, singeing, desizing, washing, steaming, scouring, bleaching, dyeing, oxidation, soaping, rinsing, calendaring, sanforizing and finishing" steps required in just the finished fabric preparation process of conventional textile manufacturing alone (Muthu, 2014, p. 7)
- Reduction of energy consumption, as a result of eliminating multiple processing and finishing steps required in conventional clothing production

- Reduction of water consumption, as 3DP materials are mostly aliphatic and require little use of water in the garment production and use phase
- Lessened environmental toxicity, as a result of eliminating multiple processing and finishing steps required in conventional clothing production
- Lower human toxicity, as a result of less chemical use than in the multi-tiered finishing and processing steps of conventional clothing production
- Enhanced garment recyclability as a result of single-material use in 3D printing, removing the need for zippers, fasteners, and other trims made of different materials
- Reduction of landfill waste and bioaccumulation by maximizing garment biodegradability through 3D printer filament material development, for instance creating filament material from biodegradable inorganic polymers such as hydroxyapatite (HA), tricalcium phosphate (TCP), and polycaprolactone (PCL),or regenerated biomaterials such as chitosan and sodium alginate (Mogas-Soldevila et al., 2014)

Limitations of 3D Printing

As with any technology, additive manufacturing (AM) and 3D-printing (3DP) methods are not exempt from limitations that present opportunities for improvement:

- Time-consuming.
    - It took 48 hours to 3D-print one dress using SLS technology (London, 2014), 14 hours to 3D-print one tank top using FGF technology, and over 2000 hours or 83 days to 3D-print five complete outfits (approx. 400 hours or 17 days per outfit) using FDM technology (Peleg, 2015).

- 3D printers are costly.
    - The cost of commercial-grade printers such as stereolithography (SLA) and selective laser sintering (SLS) machines used for printing both prototypes and finished products can easily be in the six-figure range.
        - A SLA machine using the rapid prototyping (RP) system costs between US$100,000 and US$800,000 (Lou & Grosvenor, 2012).
        - A SLS machine costs US$270,000 to US$325,0000 (Lou & Grosvenor, 2012). The SLS machine used to create the Kinematics Dress cost "roughly US$1,000,000" (Certo-Ware, 2015).
    - Consumer-grade printers cost less, but are still priced at over US$1,000 in general.
        - A Makerbot 3D printer costs US$1,375 for the "Replicator Mini" compact model, US$2,899 for the "Replicator" desktop model, and US$6,499 for the "Replicator Z18" model (Makerbot, 2015).
        - The Witbox home printer included in this study costs about EUR1,700 or around US$1,900 (BQ, 2015).
        - Compared to consumer desktop printers that cost anywhere between 4 to 10 times less, 3D printers are still inaccessible to many households with limited income.
- 3D printing filament materials are costly.
    - PA-2200 costs about EUR40.00 or US$45.00 per kg (Arzauno.com). To print a T-shirt using PA-2200, it would cost US$0.045 x 1644g =

US$73.00 for the material alone (see Appendix 2 for weight of one PA-2200 T-shirt), but it cost Nervous System £1,900 or US$2,930 to print the Kinematics Dress with 3D printing company Shapeways (London, 2014).

  - TPU-92A-1 is only available through 3D printing company Materialise (Titsch, 2013), and costs about EUR 2.00 or US$2.30 per cm^3, plus a EUR5.00 or US$5.70 for the handling cost of one model, which totals to about US$8 per cubic centimeter (3due.com, 2015). To 3D-print a T-shirt using TPU-92A-1, it would cost about US$5.70 + US$2.30 x (1341g ÷ $1.2g/cm^3$) = US$2,576 (see Appendix 2 for density and weight of TPU-92A-1).
  - Each 500g-spool of TPU-85A filament costs around EUR20.00 or US$23.00 (Recreus, 2014). 3D-printing one highly porous jacket using the Witbox home printer and TPU-85A filament material costs around EUR70.00 or US$80.00 for 1 kg of TPU-85A (Marriott, 2015), not taking into account the cost of electricity consumption pre-processing and post-processing costs such as design, sampling, cutting, sewing, and assembly (Peleg, 2015). It would cost about US$0.08 x 1697 = US$136.00 to 3D-print a T-shirt using TPU-85A using the Witbox printer.

- Requires advanced computer aided design (CAD) skills.
  - CAD programs are not only used to design 3D-printable objects using the stereolithography (.STL) file type, but also for "generation, manipulation and repair "(Beaman, Atwood, Bergman, Bourell, Hollister, et Rosen, 2007, p. 20). In the past decade, CAD software research and development

in Europe have focused on specific features such as “repair of STL models, automatic/interactive operation, facet editing, 3D transformations, dimensioning, and separation/joining of connected components, bad components, faces, and parting lines” (Beaman et al., 2007, p. 20).

- In order to produce a complex 3D-printed object such as a fully-contoured, form-fitting clothing, digital software such as Solidworks, AutoCAD, PTC Creo, Rhinoceros (Rhino 3D), SketchUp, Inventor Fusion, or Blender (Jackson-Edwards, 2015) must often be used to create 3D-printable digital models. Knowing how to manipulate and edit these digital models for optimal 3D-printing is required to generate successful and accurate 3D prints efficiently.

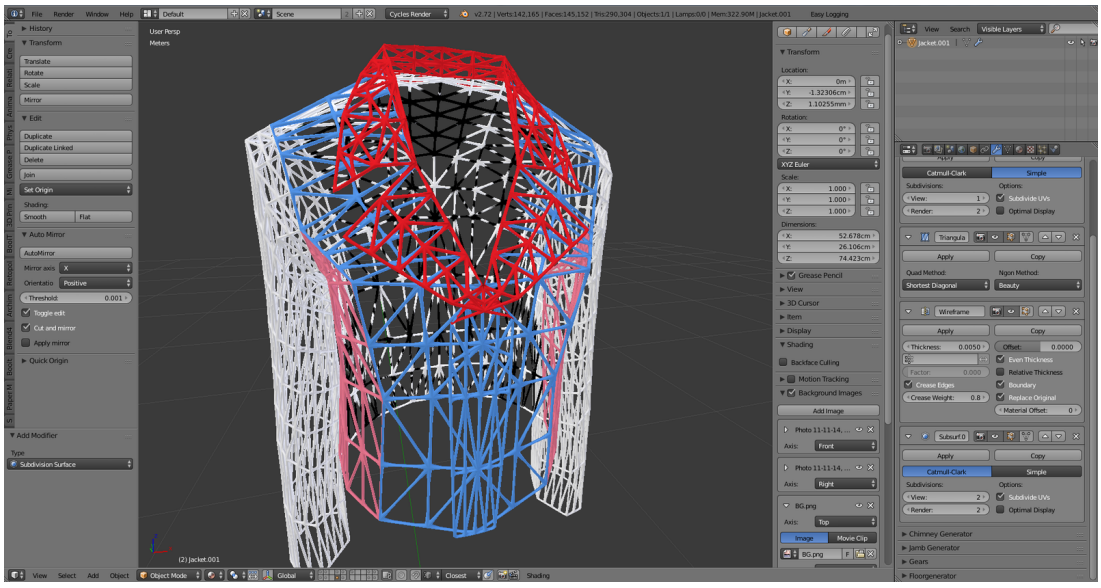


Figure 9. Graduate student modeled her apparel designs using CAD software Blender (Peleg, 2015a).

- Requires advanced apparel design knowledge.
    - In order to create form-fitting apparel even when using CAD software (Figure 10), specific apparel design skills are still required to design wearable and 3D-printable pieces that not only contour to the average human body, but can be 3D-printed using available technology. In the case of consumer-grade 3D printers like the Witbox, the small chamber size limits 3D clothing printing to the printing of partial flat textiles that require further cutting, sewing, gluing, and assembly.

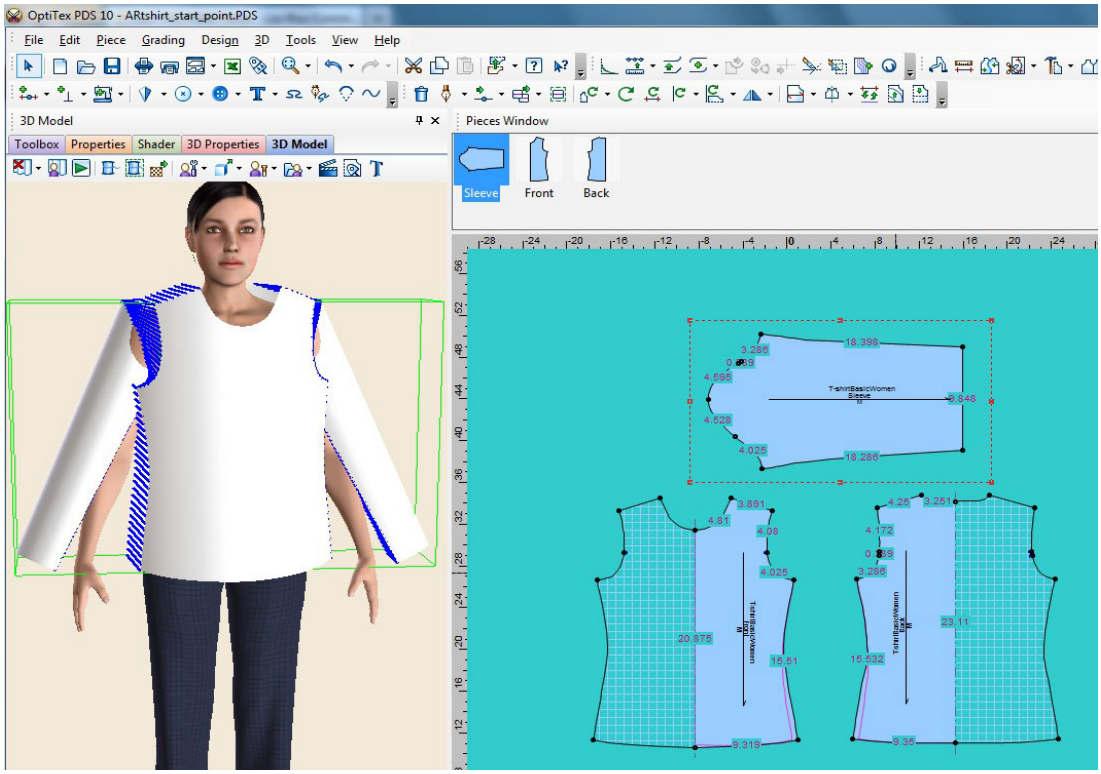


Figure 10. Patternmaking using CAD software Optitex (Derangeddesigns.com, 2015).

    - While Electroloom has presented the first 3D clothing printer prototype that can 3D-print garments seamlessly with no need for post-printing

assembly, apparel design knowledge is still required to create the basic 3D molds or templates upon which the fibers are deposited.

- Advanced apparel design skills and knowledge include patternmaking, draping, and sewing techniques. A garment is two-dimensional in textile form, but three-dimensional when fitted onto the human body.
  - Patternmaking (Figure 11) is the process of transforming three-dimensional human body contours into two-dimensional flat patterns that can be transferred onto flat textiles for cutting and sewing.

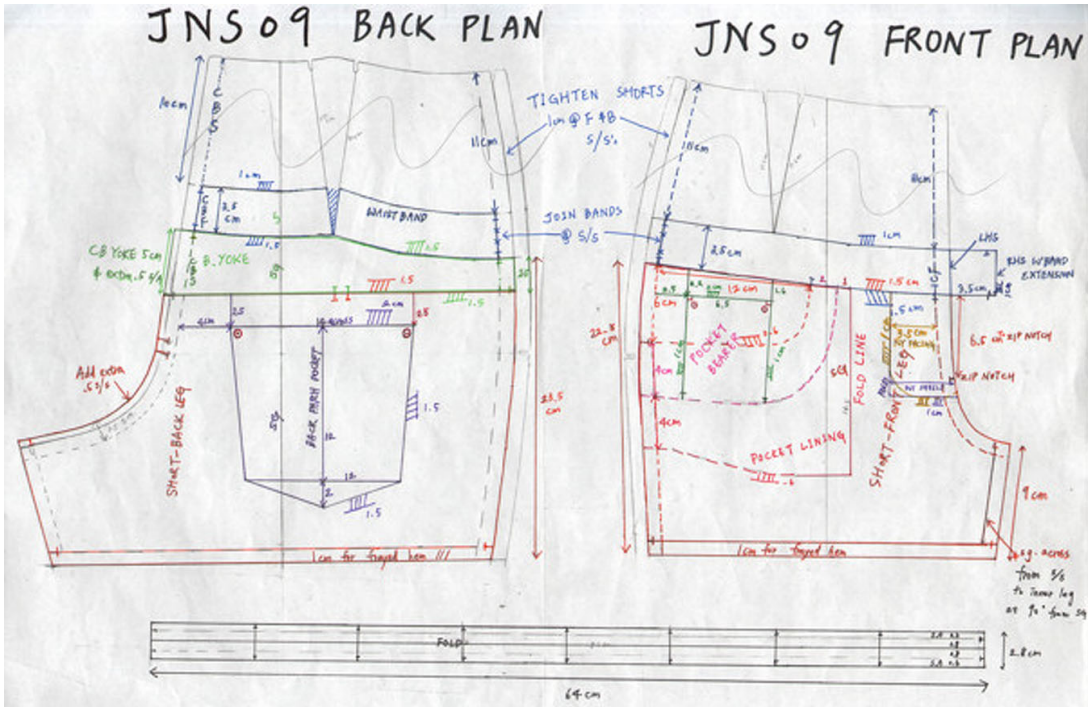


Figure 11. Hand drafted pattern for a pair of shorts (Lin, 2013).

- Draping (Figure 12) is the reverse of patternmaking, whereby muslin textile is draped over a mannequin to produce a three-

dimensional muslin model. After being roughly cut and sewn around the contours of the mannequin to achieve the desired form, the muslin model is then disassembled and flattened back into two-dimensional form that will become the formal clothing pattern used to produce the final garment, usually using more expensive textiles.



Figure 12. (Left to right) Draping a simple waist, draping a simple skirt, and dress form (van Rensselaer, 1919).

- Requires more ergonomic 3D-printer filament materials.
    - While many variants of 3D-printer filament materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) or flexible thermoplastic polyurethane (TPU) are commercially available and compatible with consumer 3D-printers, they lack the lightness and hence comfort of conventional knit and woven textiles. For example, the Kinematics dress

weighs 5,000g (Certo-Ware, 2015), whereas a conventionally manufactured viscose dress of similar length weighs only 245g.

- Resource intensive.
    - 3D-printer materials are generally aliphatic and energy-intensive to produce, as many are petrochemical based and 3D-printers generally consume a large amount of electricity in the 3D-printing process (Kellens et al., 2011), especially for older models of commercial-grade 3D-printers like the Sinterstation 2500Plus.
- Bioaccumulative.
    - Other than polyester-cellulose used in Electroloom's Alpha Unit, the filament materials used in 3D-printing are generally synthetic and non-biodegradable.
    - While biodegradable 3D-printer filament alternatives such as ethanol-based PLA (Makerbot, n.d.b), lignin-based BioFila Silk (3ders.org, 2014b) do exist, many are plant-cellulose based and can either compete with food sources if the demand exceeds supply for clothing production, or lead to deforestation if the supply chain is not properly managed, monitored and certified.

Nevertheless, some designers and innovators believe that 3DP technology is the way forward for garment production, and consumers are eager to be able to 3D-print clothing items from the safety and convenience of home, without having to worry about social equity and labor conditions associated with their clothing. Given the scalability of 3D garment printing being an imminent reality, it is imperative that not only the

limitations, but also the impacts, of 3D garment printing are addressed in prior. By understanding the resource intensities of 3D-printing methods—whether in terms of raw material, energy, or water consumption—and comparing these metrics to those for the existing conventional garment manufacturing method, it is then possible to identify hotspots that present opportunities for improvement not just in an environmental sense, but also in an economic sense.

Comparative Analysis: Additive vs. Subtractive Manufacturing

Abiotic depletion and water scarcity are two of the most pressing environmental burdens created by the garment production industry today, owing to the high demand of fossil-based polyester and water-consuming cotton garments as a result of their competitive price points. In response to these key issues, this comparative meta-life cycle inventory (LCI) analysis will investigate two key environmental impact hotspots—water and energy intensity—of three representative 3D garment printing methods versus conventional cut-and-sew or "making-up" clothing production.

While AM technologies have existed since the mid-1980s, available LCI data on AM technology specific to clothing production is still scarce, given that few 3D-printed garments have been created since the first 3D-printed garment was created five years ago in 2010 (Materialise, 2015). However, there has been ample documentation and media coverage of 3D garment printing owing to public interest in recent years. As more designers take on the challenge to produce wearable and potentially scalable 3D-printed clothing, more data regarding the use of 3DP and AM technologies as applied to apparel manufacture from non-academic sources can be collected for evaluation and analysis.

Combined with published life cycle inventory (LCI) data from academic and other professional sources on various 3DP technologies and conventional cut-and-sew manufacturing, the resource intensities of 3DP methods versus that of traditional clothing production can be identified or at least estimated.

By comparing three 3DP methods against conventional clothing manufacture, the objective of this study is to identify resource-intensive hotspots in the raw material extraction, production, distribution, use, and disposal phases. Six materials will be investigated in all—four 3DP materials (PA-2200, TPU-92A-1, "polyester-cellulose" solution, TPU-85A) and two conventional materials (cotton, PET). Using "one T-shirt, 100 wears, 50 washes," as the functional unit, a baseline scenario is constructed to reflect water and energy demands of all four methods and six materials. Five alternative scenarios then explore opportunities for improvement using altered parameters to derive at less resource-intensive outcomes.

Chapter II

Background

This chapter provides an introduction to the chronology of known 3D printed garments, an overview of 3D-printing nomenclature and processes, the four selected clothing production methodologies and materials, the four 3D garment printing materials, and the two conventional clothing production materials included in this comparative analysis.

3D Printed Garments

The first designer to apply additive manufacturing (AM) technology to clothing design is Dutch haute couture designer Iris van Herpen. With the help of architect Daniel Widrig, she designed the first 3D-printed garment as part of the "Crystallization" collection that was printed by .MGX by Materialise using selective laser sintering (SLS) and thermoplastic polyurethane (TPU-92A-1) powder (Materialise, 2015). Only known by its code name "CR0153," the pioneering 3D-printed garment (Figure 13) was debuted at Amsterdam Fashion Week in July 2010 (van Herpen, 2015). Since then, Iris van Herpen has continued to collaborate with architects and artists; combining her apparel design skills with their knowledge of unconventional materials and industrial fabrication to create aspirational runway pieces.

The strong media interest in 3D-printed apparel that ensued spurred other experiments in applying AM technology to apparel design and clothing production. In

2011, Mary Huang of Continuum Fashion presented the world's first 3D-printed "N-12 bikini" using PA-2200 fine-powder (a variant of nylon derived from nylon-12) and SLS technology (Shapeways, n.d.). By 2012, she had completed the "Strvct shoe" using the same materials and AM method (Continuum Fashion, 2015).



Figure 13. The world's first 3D-printed garment by Iris van Herpen and Daniel Widrig (van Herpen, 2015).

In 2013, Jessica Rosenkrantz and Jesse Louis-Rosenberg of Nervous System developed the "Kinematics" clothing design software that "creates complex, foldable forms composed of articulated modules" (Nervous System, n.d.), allowing "any three-dimensional shape [to turn] into a flexible structure using 3D printing" (Nervous System, n.d.). Combining "computational geometry techniques with rigid body physics and customization" (Nervous System, n.d.), the "4D printing" software makes it possible to compress large objects for 3D printing through computer simulation.

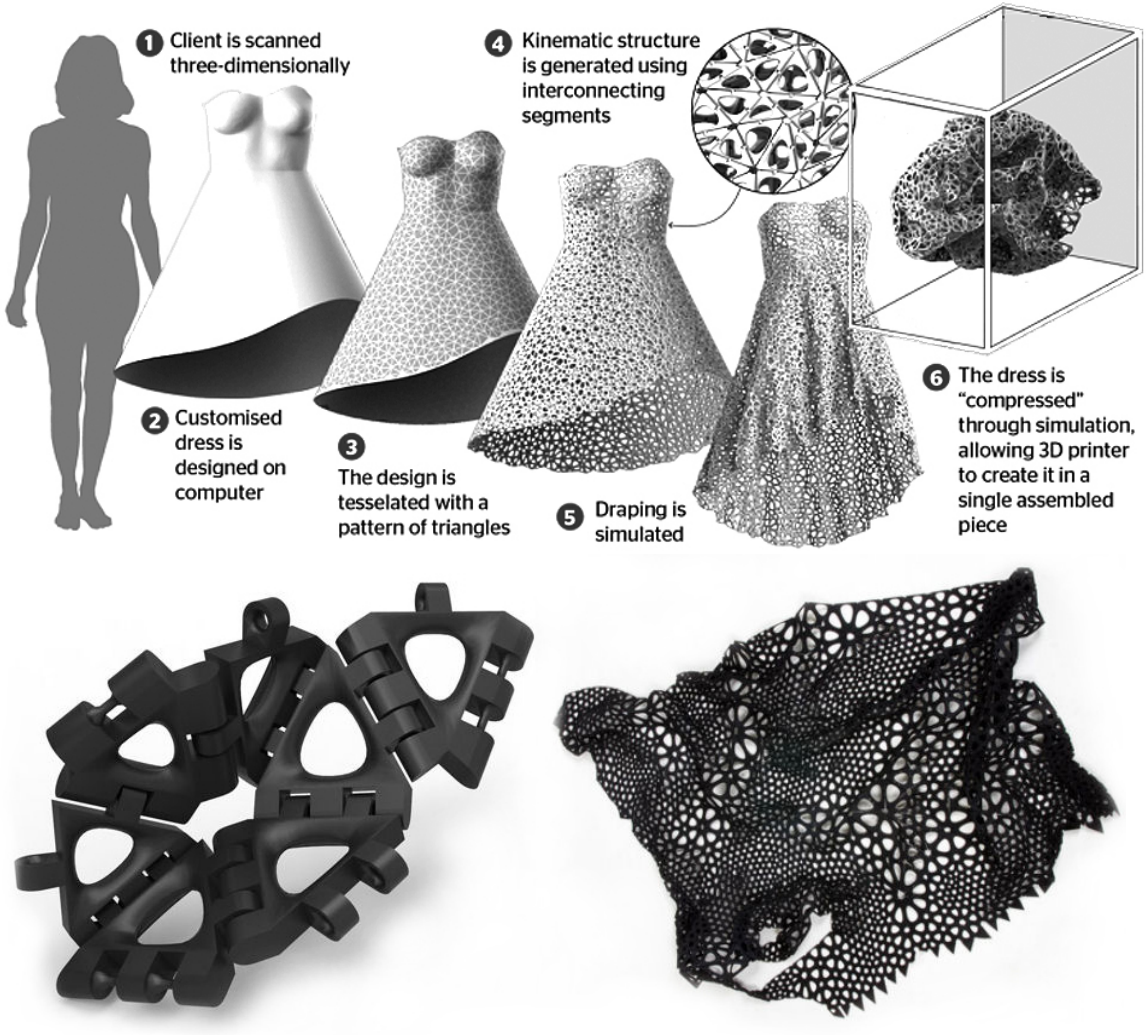


Figure 14. Kinematics "4D printing" by Nervous System (Garcia Sein Echaluce, 2014).

By 2014, Nervous System had successfully 3D-printed the “Kinematics dress” consisting of “2,279 unique triangular panels interconnected by 3,316 hinges” (Meinhold, 2014) using SLS technology and PA-2200 nylon powder.



Figure 15. Kinematics dress 3D-printed using the SLS method (Nervous System, 2014).

Inspired by techniques used in organic tissues engineering (Russell, 2015), engineers-turned-entrepreneurs Aaron Rowley, Joseph White, and Marcus Foley invented and launched the “Electroloom Alpha”—the world’s first 3D printer dedicated to printing clothing—on crowd-funding platform Kickstarter.com in May 2015.

Unlike other 3D printers that use selective laser sintering (SLS) or fused deposition modeling (FDM) technologies to 3D-print garments, the Electroloom Alpha unit (Figure 16) proposes an entirely different technique called Field Guided Fabrication (FGF) for 3D-printing apparel. Electroloom’s FGF technology is based on the electrospinning process, which is described in greater detail later in this chapter.

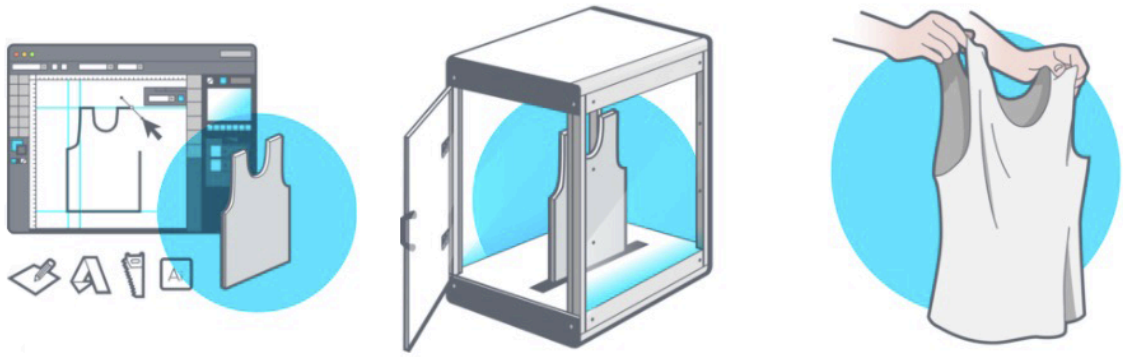


Figure 16. Electroloom's "3D fabric printer" (Electroloom, 2015).

A project still under research and development, the FGF method was used to successfully 3D-print a beanie, a skirt, and a tank top (Figure 17) using the Electroloom Alpha (Electroloom, 2015). Further research and development of CAD software usability, printer compatibility and printer filament materiality are in progress.



Figure 17. Electroloom 3D-printed skirt, tank top, and beanie (Electroloom, 2015).

To give a general overview of known recent developments in 3D garment printing technology, the table below provides a chronological list of 3D-printed apparel products, the associated 3DP technology, and filament materials used to create them:

Table 1. Chronology of 3D-printed garments, 2010-2015.

Chronology of 3D Printed Garments					
Year	**Creator**	**AM Type**	**AM Printer**	**AM Material**	**3D Printed Product**
2010	Iris van Herpen	SLS	Sinterstation 2500Plus	TPU-92A-1 (Powder)	Crystallization Collection: 1. Serpentine Skeleton Top (CR0153) w/ architect Daniel Widrig
2011	Iris van Herpen	SLS	Sinterstation 2500Plus	TPU-92A-1 (Powder)	Escapism Collection: 1. Wingless Bodice (ESC00121) 2. Black Full Bodice (ESC0031) 3. Wireframe Top (ESC011) 4. Wireframe Skirt (ESC0112)
2011	Continuum Fashion	SLS	EOSINT P760	PA-12 (Nylon Powder)	1. N-12 Bikini
2012	Iris van Herpen	SLS	Sinterstation 2500Plus	TPU-92A-1 (Nylon Powder)	Capriole Collection: 1. Skeleton Bodice Dress (CP0051)
2013	Iris van Herpen	SLA	–	Liquid Polymer	Hybrid Holism Collection: 1. Beeswax Lattice Dress (HH111) w/ architect Julia Koerner
2012	Continuum Fashion	SLS	EOSINT P760	PA-12 (Nylon Powder)	1. Strvct Shoe
2013	Iris van Herpen	SLS	Sinterstation 2500Plus	TPU-92A-1 (Nylon Powder)	Voltage Collection: 1. Voltage Dress (VT071) w/ architect Julia Koerner 2. B/W Coral Dress w/ Neri Oxman, MIT Professor (VT091)
2014	Iris van Herpen	–	–	Silicone	Wilderness Embodied Collection** : 1. Silicone Spine Dress 2. Gills Dress 3. Membrane Dress 4. Beaded Cape Dress 5. Tree Root Shoes w/ United Nude + Rem Koolhaas
2014	Iris van Herpen	–	–	Silicone	Biopiracy Collection** : 1. Kinetics Dress w/ architect Julia Koerner
2014	Nervous System	SLS	EOSINT P760	PA-12 (Nylon Powder)	1. Kinematics Tank Bodice 2. Kinematics Dress
2014	Continuum Fashion	SLS	EOSINT P760	PA-12 (Nylon Powder)	1. Laurel Tree Sandal 2. Myth Shoe Collection
2015	Iris van Herpen	–	–	Thermoformed Acrylic	Magnetic Motion Collection** : 1. Waffle-shell Dress w/ architect Philip Beesley
2015	Electroloom	FGF	Electroloom Alpha Unit	Polyester-Cellulose Solution	1. Beanie 2. Skirt 3. Tank Top
2015	Danit Peleg	FDM	Witbox 3D Printer	TPU-85-A ("FilaFlex")	Debut Collection (5 outfits, 10 pcs): 1. (a) Red Liberte Jacket, (b) Red Dress 2. (a) Mint-Green Crop Top, (b) B/W Gathered Skirt 3. (a) Mint-Green Sleeved A-line Dress, (b) White Lace Bodice 4. (a) White Bodice, (b) White Tank, (c) White Skirt 5. Black Knee-length Dress

*** Described as "3D printed," but may have used techniques other than AM or 3D printing, such as injection molding*

Since many abovementioned 3D-printed garments do not have designated nomenclature, descriptive names are provided to them in this literature for the purpose of differentiation and identification. As such, they are not to be taken as formally given names and any future references made using nomenclature from this table must clearly state this fact. From the table above, it is evident that the most dominant 3DP technology used in clothing manufacture is SLS. However, the SLS method is costly and not specifically tailored for clothing production. Soon after the cost and other shortcomings of 3D-printed clothing based on SLS technology were made known by the media, the search for other means to make 3D clothing printing a reality began.

While the first dedicated 3D garment printer was just launched by Electroloom in May 2015, graduate student Danit Peleg from the Shenkar College of Engineering and Design in Israel made a different proposition at around the same time.



Figure 18. Danit Peleg's 3D-printed collection using TPU-85A and FDM (Biella, 2015).

By 3D-printing an entire clothing collection (Figure 18) using the Witbox home 3D-printer based on fused deposition modeling (FDM) technology (Peleg, 2015b), Peleg has proven that even the most rudimentary 3D-printer—with the help of patternmaking knowledge, CAD software skills, and good 3D-modeling craftsmanship—can produce clothing of complex designs.

Since common 3DP filament materials such as ABS plastic are too rigid for the production of Peleg's feminine garments, 3DP industry professionals has to be consulted in determining a substitute material that would provide greater flexibility—a thermoplastic polyurethane filament material known as "FilaFlex," or TPU-85A (Recreus, personal communication, August 28, 2015).



Figure 19. Cutting, sewing, and gluing of 3D-printed textiles using FDM (Alec, 2015).

TPU-85A would give her garments the texture and flexibility close to that of rubber or silicone, such that they can achieve the proper drape required of conventional clothing. Unlike SLS garments that are printed in true three-dimensional forms responding to the curvatures of the human body, Peleg's home-printed garments are created by 3D-printing

two-dimensional textile panels, which then have to be cut and glued together (Figure 19) (Alec, 2015), not unlike the process of conventional cut-and-sew manufacturing.

Given that each of the three AM techniques has the potential for scalability, this study will comprise the SLS, FGF, and FDM methods, as well as their associated 3D-printing materials. For the SLS method, both types of powders PA-2200 and TPU-92A-1 that are used in 3D garment printing will be included in this comparative analysis.

3D Printing Industry Nomenclature

Additive manufacturing (AM*)* refers to "any manufacturing process where parts are built up from raw material (generally powders, liquids, or molten solids) rather than cut out of a stock material such as a block of wood or metal" (Lou & Grosvenor, 2012). Although the term "additive manufacturing" is often used interchangeably with the term "3D-printing" today, 3D printing originally "referred to a specific technology [that is] the lower end of the industry (non-production parts, such as prototypes) " (Lou & Grosvenor, 2012).

3D printing (3DP) most originally referred to the specific "powder-and-binder based technology patented in 1993 by Ely Sachs and Mike Cima of the Massachusetts Institute of Technology (MIT)" (Lou & Grosvenor, 2012). Like SLS, this specific 3DP method uses a powder method, but "a binder (glue) is injected into the powder using an inkjet-like printing head" as opposed to sintering or melting the powder particles together using a laser beam as in the SLS process (Lou & Grosvenor, 2012). The term 3DP is now used synonymously with additive manufacturing.

Rapid prototyping (RP) refers to "any manufacturing process that uses CAD data to produce a part" (Lou & Grosvenor, 2012). Sometimes used interchangeably with the term "direct digital manufacturing (DDM)" (Lou & Grosvenor, 2012), RP and DDM differ in that DDM refers to "production-level manufacturing rather than just prototyping" (Lou & Grosvenor, 2012). In the late 1980s and early 1990s, RP was the general term used to describe AM as the technology was mostly used by the automotive industry that "strictly used it for prototyping" (Lou & Grosvenor, 2012), since the build parts were generally not cost-effective to be mass-produced and did not have the durability of production parts. Once the technology proved to be able to build production parts instead of prototypes, however, the industry moved towards using the term DDM for processes that can produce end-use built parts (Lou & Grosvenor, 2012).

In this study, the terms 3DP and AM are used interchangeably as general terms, rather than terms that refer to a specific method or technology, to reflect the most common language used to describe non-subtractive prototyping and/or manufacturing technologies collectively.

3D Garment Printing Process

While 3D garment printing is a broad term that refers to the creation of 3D-printed clothing using AM or 3DP technology, the specific AM or 3DP technology being used will involve different sub-processing steps. The generalized 3D garment printing process steps required are:

Step 1: Raw material preparation
Step 2: Digital design and modeling
Step 3: 3D-printing of prototype
Step 4: Post-print handling (extraction, assembly, finishing, shipping)

Step 5: Editing and modifying digital model
Step 6: 3D-printing of finalized or commercial product
Step 7: Post-print handling (extraction, assembly, finishing, shipping)
Step 8: Repeat Steps 5-7 until satisfactory results have been achieved
(Weijmarshausen, 2014a)

Even though AM technology can eliminate many processing steps (e.g. spinning, knitting, cutting, sewing) from the conventional garment-manufacturing model, it does not eliminate the possibility of errors and the need for prototyping. Unless the creator (who can be a designer or a consumer) is relatively experienced and skilled in both apparel design and 3D-printing, it may require repeating the 3DP process, especially steps 5 to 7, a few times to achieve all the desired characteristics for the finished product. However, since 3DP companies with the professional knowledge and skill sets to avoid error are usually the ones responsible for actual printing and finishing of 3DP garments, it is assumed that steps 5 to 7 are unnecessary and only steps 1 to 4 are included in creating the LCI model.

Prototyping and its associated resource demands have been excluded from this study for all 3DP methods, as is the case for sampling (referring to the process of making clothing samples for a few rounds before the design is confirmed for mass production) in relation to conventional clothing production. Another reason that prototyping and sampling have been excluded from this study is that the number of attempts may vary greatly from one product to another, especially between conventional and 3D-printed products. The randomness of prototyping and sampling has been excluded from this study to achieve better comparability.

Selected Clothing Production Methodologies & Materials

By comparing collected data on three 3DP methods (i.e. SLS, FGF, FDM) against that of the conventional cut-and-sew manufacturing method (Table 2) to perform a comparative meta-LCI, the objective of this study is to detect resource-intensive hotspots:

Table 2. Selected clothing production methods & materials.

Selected Clothing Production Methodologies & Materials								
Conventional				3DP				
	Method		Material		Method		Printer	Material
1)	Cut-Sew ("Making-Up")	a.	Cotton	1)	SLS	a.	Sinterstation 2500Plus	TPU-92A-1
		b.	PET			b.	EOSINT P760	PA-2200
				2)	FGF	c.	Electroloom Alpha	Polyester-Cellulose Fiber Solution
				3)	FDM	d.	Witbox Home Printer	TPU-85A

Using one standard T-shirt as the functional unit, or basis of comparison, a baseline scenario will be constructed to reflect current water and energy demands of all four methods and six materials. By adjusting parameters (e.g. clothing lifespan, number of washes, garment care method) that affect water and energy consumption levels of baseline scenario hotspots, five alternative scenarios will explore the outcomes such that more sustainable options can be identified.

Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is an AM technology that “uses high power carbon dioxide (CO2) lasers to fuse plastic, metal, or ceramic powder particles together, layer by layer, to form a solid object” (3D Systems, 2014). SLS parts usually have a “grainy surface but all kinds of (very) fine finishing are possible. They can be sandblasted,

colored (dyed), painted, covered, coated, polished, chemically smoothed" (Materialise, 2013). SLS machines are commercial-grade and mainly operated by 3D-printing companies such as Materialise or Shapeways. The SLS process steps include (Weijmarshausen, 2014b):

- Checking the design
- Planning the printing trays
- 3D-printing
- Extracting the parts
- Cleaning the parts
- Sorting the parts
- Post processing (tumbling, dyeing, sorting)
- Shipping

In order to achieve the elasticity required of wearable clothing, two powder-form materials have generally been used to create 3D-printed garments in recent years: 1) PA-2200 on the basis of nylon-12 (EOS GmbH, 2001), and 2) TPU-92A-1, an aliphatic thermoplastic polyurethane powder (Palsenbarg, 2015).

Even though the used powder can be recycled, a high portion of virgin powder material is required to maintain the quality of the build part (Figure 20). "The industry standard is to run each build with 50% new and 50% old powder. Each tray has roughly 5% of volume in parts so after each build you are left with 95% old powder. Of this old powder you can reuse 50% in the next build" (Weijmarshausen, 2014b). Hence, the total waste material is around 95% ÷ 2 = 47.5% accordingly.

Another study by Kellens et al. reports the EOSINT P760 machine producing 44.9% and 43.9% of waste material for PA-2200 powders printed at 0.12mm and 0.15mm layer thickness respectively (Kellens et al., 2011, p.7), and that "waste material

rates around 45% fit well within the manufacturer's recommendations about the refresh rates, which is the ratio between virgin and used powder" (Kellens et al., 2011, p.7).



Figure 20. SLS process using Sinterstation 2500Plus to 3D-print Iris van Herpen's "Voltage Dress" (Palsenbarg, 2013).

While 3D-printed clothing made from these materials are flexible, they are heavy (Certo-Ware, 2015) and lack the comfort of conventional cut-and-sew knit clothing made from cotton or polyester. To reduce print time and minimize material cost, apparel products 3D-printed using SLS technology are often designed with large holes (≥5mm

dia.) in the textile membrane, making it challenging to provide sufficient coverage and prevent indecent exposure.

Iris van Herpen collaborated with 3D-printing company Materialise to use the Sinterstation 2500Plu*s* that fuses TPU-92A-1 powder particles together for the printing of the first few prototypes of 3D-printed garments (Figure 20) (Palsenbarg, 2015). For Continuum Fashion and Nervous System, the N-12 bikini and Kinematics Dress were both printed in collaboration with 3D-printing company Shapeways using the nylon powder PA-2200 and the plastic laser sintering system EOSINT P 760.

Field Guided Fabrication (FGF)

Field Guided Fabrication is "an electrospinning process [that] converts liquid [polyester-cellulose fiber] solutions into solid fibers [that] are then deposited onto a 3D mold" (Electroloom, 2015), whereby an internal electric field within the build chamber guides fibers onto the surface of a user-defined "3D template" of a simple garment (such as a tank top, or skirt) where the fibers bond together.

Also known as electrostatic fiber spinning, electrospinning (Figure 21) is "a versatile method to prepare fibers with diameters ranging from several microns down to 100nm through the action of electrostatic forces" (Dufresne, 2012, p.51):

> In this process a polymer solution is positively charged to high voltage to produce the submicron scale fibers from an orifice to a collector (Huang et al., 2003). At a voltage sufficient to overcome surface tension forces, fine jets of polymer solution or polymer melt shoot out toward a grounded collector. The jet is stretched and elongated before it reaches the target, dries and is collected as an interconnected web of fibers with typical diameter of several hundred nanometers. Electrospinning shares characteristics of both electrospraying and conventional solution dry spinning of fibers. This process is non-invasive and does not require the use of coagulation chemistry or high temperatures to produce solid threads from solution. This makes the process particularly suited to the production of

> fibers using large and complex molecules. Electrospun fibers have a much thinner diameter (from nanometer to micrometer) than those obtained from conventional spinning processes (melt spinning, solution spinning and so on). The principle of this technique therefore differs notably from others since it does not consist in a top-down deconstruction of natural fibers. / Difficulties to find solvents to dissolve cellulose and to process it in the melt state make cellulose nanofibers difficult to be directly prepared by electrospinning. It therefore requires either chemical derivatization or physical dissolution in a suitable solvent. (Dufresne, 2012, p.51-52)

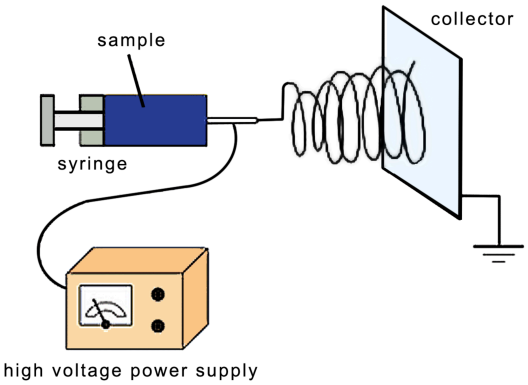


Figure 21. Electrospinning set up (Dufresne, 2012).

The plant-cellulose derived 3DP material used in FGF is loosely referred to as "polyester-cellulose fiber solution" at this stage of development (A. Rowley, personal communication, August 25, 2015).

A tank top requires 1.5L ÷ 4 tank tops = 0.375L of polyester-cellulose solution (Electroloom, 2015) and 14 hours to 3D-print using FGF technology, and was printed using an Alpha model that has ten nozzles in all (Figure 22), with five nozzles on each side of the build chamber (A. Rowley, personal communication, August 25, 2015). Increasing the number of nozzles to the printer reduces the printing time (Russell, 2015).

From available photo- and video-documentary evidence, one key point to take note of for the Alpha model is the template (Electroloom, 2015).

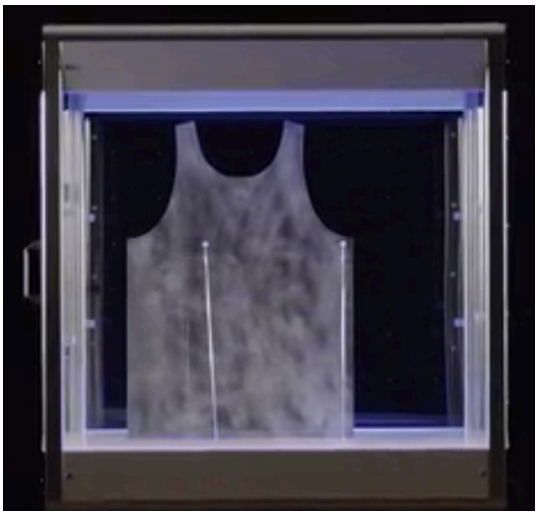


Figure 22. Electroloom's 3D fabric printer—"Alpha Unit" (Electroloom, 2015).

The template is a two-dimensional interpretation of a three-dimensional apparel product that assumes the front and back of the piece to be identical to each other (Figure 22). Usually, the front pattern and the back pattern are not identical to each other, as the front of the human body is usually smaller and has different contours than the back. According to Electroloom, this mold or template can be made of almost any material such as cardboard or vinyl (A. Rowley, personal communication, August 25, 2015).

Upon completion, the finished 3D-printed garment is then by removed from the template by gently peeling and pulling it off the template (Electroloom, 2015), as demonstrated below (Figure 23):

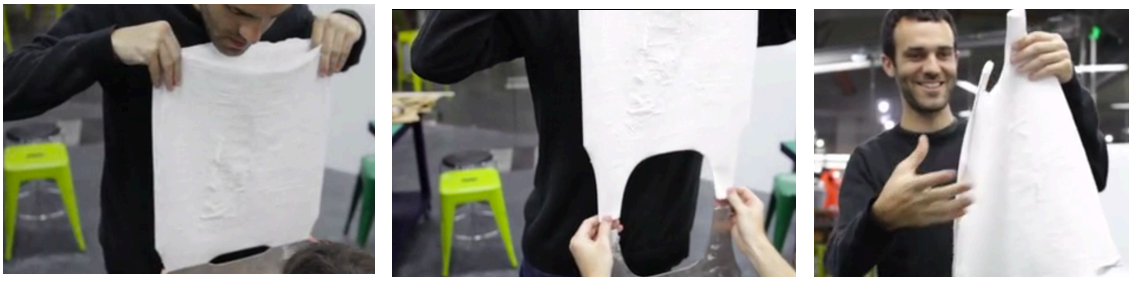


Figure 23. Process of removing the tank top from the 3D mold (Electroloom, 2015).

According to co-founder Rowley, the 3D-printed garment created using FGF technology resembles the texture of conventional cotton textiles and garments. Electroloom's video documentary of the 3D-printed tank top and 3D-printed skirt further demonstrates the opacity, lightness and drape of the material.

From the information gathered, the implied processing steps required for FGF are:

- Manufacturing the 3D template
- Electrospinning
- Removing the part from the mold
- Cleaning the mold
- Post processing (trimming, dyeing)

Electroloom's Alpha Unit uses a material only known as "polyester-cellulose fiber solution" to 3D-print clothing articles. While the specific raw material contents cannot be publicly disclosed at this phase of Electroloom's development (A. Rowley, personal communication, August 25, 2015), they have been privately disclosed and carefully accounted for in the LCI calculations found in this study.

The finished 3D-printed garment will disintegrate if it is machine-washed or being exposed to a significant quantity of water (A. Rowley, personal communication, August 25, 2015). However, its contents can be fully dissolved by solvent process for reprint. Electroloom has attempted the dissolving and reprinting process once (A. Rowley, personal communication, August 25, 2015), but no further testing has been attempted to determine how many times the process can be repeated before the quality of the original materials are degraded to a point where they can no longer be reused.

Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is an "extrusion-based technology developed by Scott Crump of Stratasys in 1988" (Lou & Grosvenor, 2012) that creates objects layer-by-layer by heating and extruding thermoplastic filament material on a base plate. Where support or buffering is required, the 3D-printer deposits a removable material to hold up the desired build form that will be broken off and disposed of by the user after the print is done (Figure 24) (Stratasys, 2015).

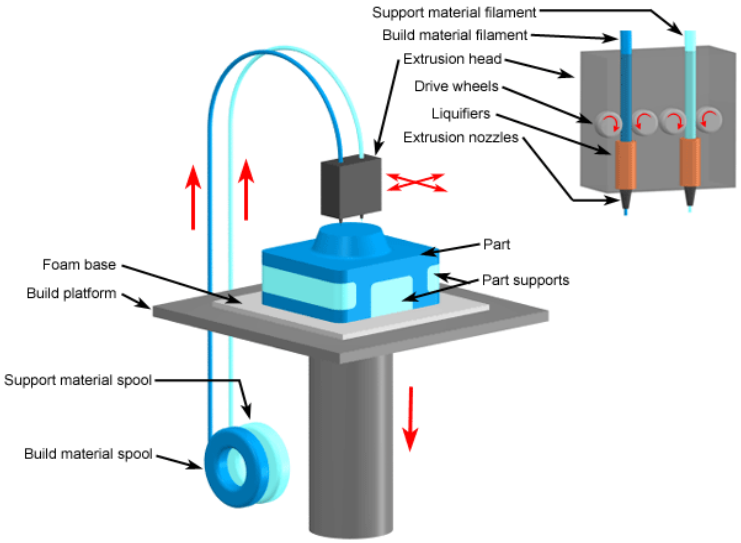


Figure 24. Fused deposition modeling (FDM) technology (CustomPartNet, n.d.).

Most consumer-grade 3D-printers are based on FDM technology. The most commonly used 3D printer filament material is petrochemical-based acrylonitrile butadiene styrene (ABS) plastic. However, in the only known attempt to 3D-print clothing using the FDM-based home 3D printer, TPU-85A filament material (Recreus, personal communication, August 28, 2015) was used instead of the more generic ABS,

together with the Witbox home printer (Figure 25) to 3D-print five outfits comprising of ten separate pieces in Danit Peleg's debut collection.

Figure 25 below shows several Witbox 3D printers lined up on a work desk in what appears to be Danit Peleg's residence. Despite renting multiple of these FDM-based 3D printers to simultaneously complete the printing of her ten-piece collection, Peleg reported spending approximately 2000 hours 3D-printing over the course of 9 months (Peleg, 2015).

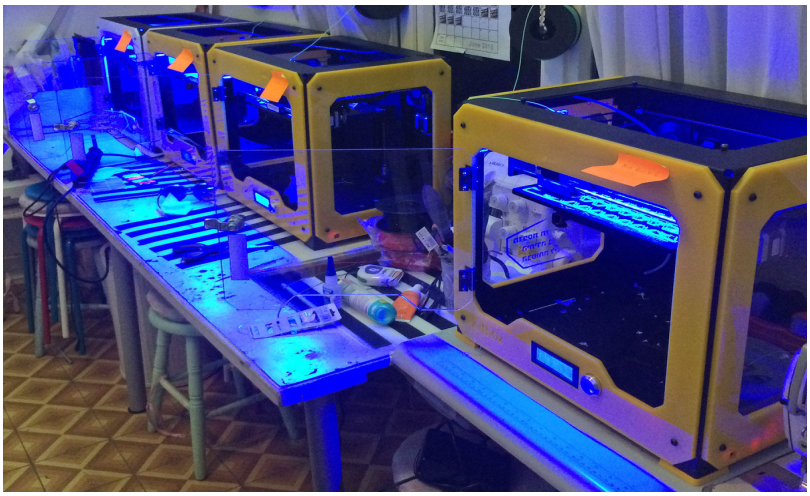


Figure 25. Witbox home 3D-printers that use FDM technology (Andretta, 2015).

Conventional Cut-and-Sew Garment Manufacture

The clothing production supply chain is a complex one that is "highly global and decentralized" (Muthu, 2014, p.2), with each different clothing product requiring different materials, finishing, assembly, and distribution technique. Global outsourcing of clothing production has resulted in increased tiered complexity of supply chain components, making it nearly impossible to identify every single component of the supply chain in some cases, much less be able to fully map them in detail.

However, clothing production generally involves the following processing steps (Muthu, 2014, p. 4):

- Stage 1: Raw material preparation
- Stage 2: Raw material to fiber conversion
- Stage 3: Yarn preparation
- Stage 4: Grey fabric preparation
- Stage 5: Finished fabric preparation
- Stage 6: Apparel manufacturing
- Stage 7: Use phase
- Stage 8: End-of-life phase (recycling, reuse, landfill/incineration)

For this LCI study, stages 1 to 5 are grouped together under the heading "material preparation phase," whereby all the steps leading up to the finished textile in conventional manufacturing is considered to be part of the material preparation phase and not the production phase, as the purpose of this study is to compare clothing production methods, not textile production methods.

In stages 1 & 2, the raw material preparation phase for synthetic fibers production includes the following sub-processes (Muthu, 2014, p. 4): 1) Oil acquisition and refining, 2) cracking, 3) preparation of chips/pellets, 4) fiber conversion process. The synthetic fiber selected for this study is polyester (PET) as it is the most dominant fiber in the clothing market as well as in the synthetics fiber category (see Chapter 2). It is included in this study as a basis of comparison for 3DP materials that are mostly synthetic in nature. For cotton fiber production, the following sub-steps are required before yarn spinning takes place (Muthu, 2014, p. 4): 1) raw fiber (cotton), 2) ginning, 3) fiber ready to be spun. Cotton is the world's most dominant natural fiber in terms of market demand (see Chapter 2). It is included in this study as a benchmark for 3DP materials that use plant cellulose as a printing material.

LCI data on energy and water consumption regarding steps described in Stages 3 to 5 are generally derived from the van der Velden et al. "LCA benchmarking study," whereby an extensive literature review has been performed to include both primary and secondary sources of LCI and LCA data. In stage 3, yarn manufacturing involves (Muthu, 2014, p. 5): 1) opening and cleaning, 2) carding, 3) combing, 4) drawing, 5) roving, 6) spinning (ring frame). The van der Velden study provides LCI data on all the stage 3 steps other than opening and cleaning, drawing, and roving.

In stage 4, the sub-processing for grey fabric preparation are simplified below (Muthu, 2014, p. 6): 1) winding, 2) warping, 3) sizing, 4) weaving. For this study, the functional unit is one knitted T-shirt. In general, T-shirts are made from knit materials, not woven ones. The van der Velden study provides data on both, but data sets on weaving are excluded.

In stage 5, finished fabric preparation involves (Muthu, 2014, p. 7): 1) brushing/cropping, 2) singeing, 3) desizing, 4) washing, 5) steaming, 6) washing, 7) scouring, 8) washing, 9) bleaching, 10) washing, 11) mercerizing, 12) dyeing, 13) washing, 14) oxidation, 15) soaping, 16) washing and rinsing, 17) calendaring, 18) sanforizing and finishing, 19) making-up, 20) inspection. For this study, the conventionally manufactured T-shirt textiles are taken to be bleached, but not dyed to maintain consistency both in terms of representativeness (i.e. T-shirt color most manufactured) (The Adair Group, 2015) as well as comparability (i.e. with 3D printed garments that may use different chemicals and methods of dyeing).

In stage 6, apparel manufacturing steps include (Muthu, 2014, p. 8): 1) design preparation, 2) patternmaking, 3) cutting, 4) tailoring, 5) ironing, 6) packaging, 7)

storage. For this study, design preparation for both conventional manufacturing and 3D printing methods are excluded as they can vary greatly from pencil sketching to digital modeling, frequently without significant LCI data recorded on these processes.

In stage 7, a typical model for the use phase is as follows (Muthu, 2014, p. 8): 1) end user first wear, 2) dry cleaning, or 3) washing, 4) drying, 5) ironing, 6) consecutive cycles. Since the functional unit for this study is "one standard T-shirt," dry cleaning and ironing are excluded from the study as T-shirts are generally machine-washed and tumble dried. The conventional cotton and polyester T-shirts are machine-washed at 60ºC using the standard washing machine for the baseline scenario of this study. The Steinberger et al. "spatially-explicit" LCI study includes data points and scenario analyses regarding the changes in environmental impacts when machine wash temperatures are lowered to 40ºC (Steinberger et al., 2009).

Finally, in stage 8, the following options are available for the disposal phase (Muthu, 2014, p. 9): 1) recycle, 2) reuse, 3) landfill, 4) incineration. The conventionally manufactured cotton and polyester T-shirts included in this study are disposed via a standard landfill and incineration combination. The Steinberger et al. "spatially-explicit" LCI study includes energy consumption data on the standard landfill/incineration of one 250g cotton T-shirt and one 500g polyester jacket (Steinberger et al., 2009).

Conventional clothing manufacture is a multi-tiered process that is specific to each different garment's material and finishing requirements. For the conventional production of one standard T-shirt, only the most basic steps are included for this study.

3D Garment Printing Materials

This section will introduce the four 3DP materials included in this meta-LCI.

PA-2200

PA-2200 is a nylon powder belonging to the semi-crystalline thermoplastics class of plastics (Klein, 2011, p.8) used in selective laser sintering (SLS) that has been used to create 3D-printed apparel products N-12 bikini (Figure 26) and Strvct shoes (Figure 27) by Continuum Fashion (Continuum Fashion, 2015) and Kinematics Dress by 3D-printing software developer Nervous System (Garcia, 2014). After the powder particles are sintered together during the SLS process, the solid object is a flexible and durable one that is suitable for creating wearable garments (Shapeways, n.d.).

Polyamide is a "tough, lightweight, elastic synthetic polymer with a protein like chemical structure, able to be produced as filaments, sheets, or molded objects" (Oxford dictionaries). The term "nylon" is "a generic designation for a family of synthetic polymers known as aliphatic polyamides" (Encyclopedia of Polymer Science). Fabric or yarns made from nylon fibers have similar properties as that of polyester or PET. They are non-biodegradable, derived from petrochemical sources, energy-intensive, but require little water to produce and maintain in the use phase (Fletcher, 2014, p.17). There are many different forms of nylon, such as nylon 6.6, nylon 6.9, nylon 6.10, nylon 6.12, nylon 11, nylon 12, and nylon 4.6 (Palmer, 2001). Where LCI data is insufficient for PA-2200 in this study, available LCI data on nylon-66 or nylon 6.6 have been used as the nearest substitute values.

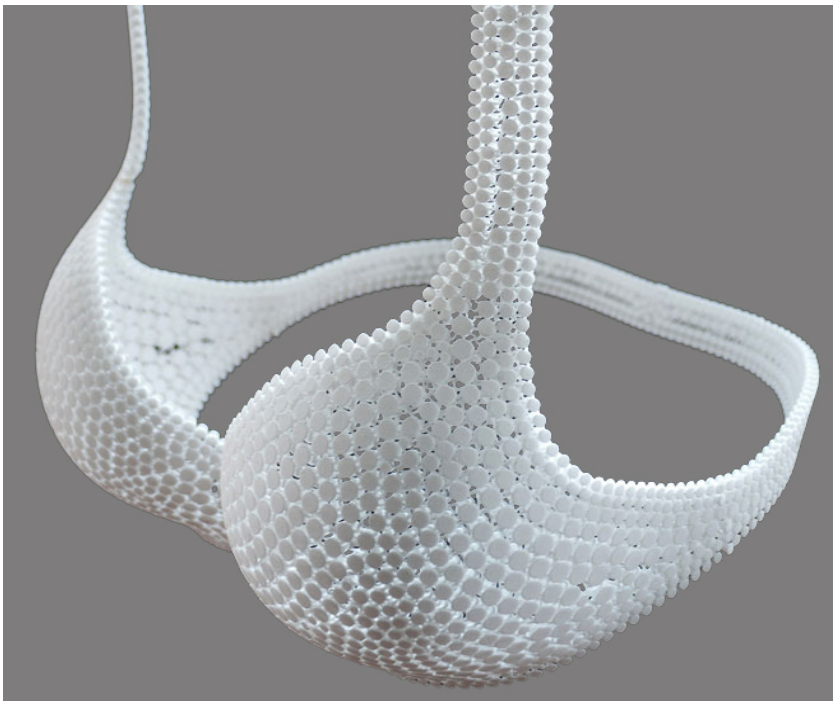


Figure 26. N-12 bikini top using PA-2200 nylon powder (Continuum Fashion, 2015).

As with polyamide used in conventional garment manufacture, sintered PA-2200 is non-biodegradable. It is also considered non-recyclable as its molecule structure degrades under exposure to high heat (Klein, 2011, p.13) from the SLS process and "a very high portion of new powder material" has to be used together with old powder even when attempting to reuse the old powder (Kellens, Yasa, Renaldi, Dewulf, Kruth, et Duflou, 2011, p. 7).

3D-printing company Shapeways estimates that "the industry standard is to run each build with 50% new and 50% old powder" (Shapeways, n.d.), and that "each tray has roughly 5% of volume in build parts […] After each build you are left with 95% old powder. Of this old powder you can reuse 50% in the next build" (Shapeways, n.d.). However, "the general amount of waste is process dependent" (Kellens et al., 2011, p.7).

For this study, the percentage of waste powder is estimated by observing the video documentaries of the SLS process used to create the Kinematics Dress by Nervous System (Shapeways, n.d.). Since the products created by SLS technologies in this study are production-grade and not prototype-grade, no recycled powder has been included in the LCI parameter "Est. Material Waste (%)."



Figure 27. Strvct shoes 3D-printed using PA-2200 (Continuum Fashion, 2015).

At the end of life (EOL) phase, recycling nylon presents significant challenges when compared with conventional polyester or other thermoplastic filaments (Fletcher, 2014, p.17). While conventional nylon fibers have been recycled using either the mechanical method or the chemical method.

Using the mechanical method, "the raw material is cleaned, cut and re-melted" (Textile Exchange, n.d.) before being spun into yarn. Using the chemical method, whereby "the raw material is cleaned, cut, de-polymerized to the base molecule and then re-polymerized with the help of chemical additives" (Textile Exchange, n.d.), recycling nylon is still more challenging than recycling other types of plastic such as polyester

(Patagonia, n.d.), owing to the numerous variations of nylon materials existent in the market that require additional sorting and identification (Eco U.S.A., n.d.).

Hence, PA-2200 is assumed to be landfilled and incinerated at the EOL stage in this LCI study.

TPU-92A-1

TPU-92A-1 is a thermoplastic elastomer compound (TPE-U) that belongs to the linear thermoplastic polyurethane (TPU)-class. It is more durable, more elastic, and stronger than polyamide known as Desmosint X 92A-1 (Figure 28) that is used in powder form for selective laser sintering (Grimm, T., 2012).

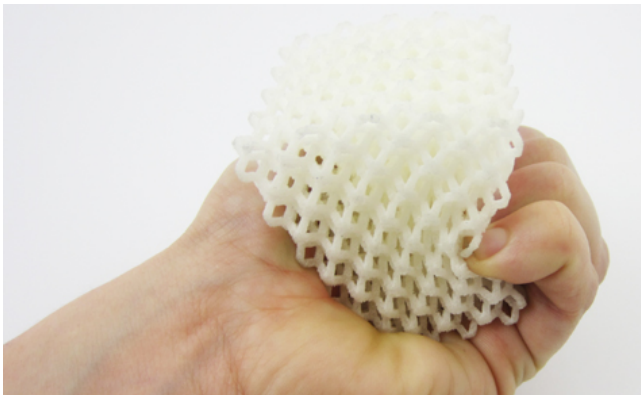


Figure 28. 3D-printed cube using TPU-92A-1 (3Dprinteresting, n.d.).

Also known as TPE-U or thermoplastic polyurethane elastomer, they were “first commercialized in the 1950s and are one of the oldest TPE types in existence” (Klein, 2011). TPU-92A-1 was the 3DP material used by the Sinterstation Plus 2500 in the selective laser sintering (SLS) process to create the “Voltage dress” (Figure 29) designed by Iris van Herpen.



Figure 29. "Voltage dress" by Iris van Herpen (van Herpen, 2015).

TPU-85A

TPU-85A is a thermoplastic elastomer compound (TPE-U) that belongs to the linear thermoplastic polyurethane (TPU)-class. TPUs are “used in applications where a product requires excellent tear strength, abrasion resistance, and flex fatigue resistance” (British Plastics Foundation), such as in creating industrial belting, wire, cable, or shoe soles. The hardness of TPUs are “restricted to the high end of the Shore A scale, typically >80 Shore A” (British Plastics Foundation).

It has been used together with the Witbox home 3D-printer to create Danit Peleg’s graduate collection. More commonly, TPU-85A has been used to create the trendy sneakers as shown in Figure 30 below:



Figure 30. Shoes made from TPU-85A (Recreus, 2014).

“Polyester-Cellulose” Solution

The “polyester-cellulose fiber solution” used in the Field Guided Fabrication (FGF) process can only be described here as a solution blended with plant-based

cellulose nanofibers. The solution evaporates during the 3DP process to give an end product with a texture similar to that of cotton.

From initial experiments, the fiber solution can be dyed to give very light pigmentation of basic colors (Figure 31), but research is still in progress for the material to adopt more complex hues and patterns. Experimentation with silk and acrylic blends (Figure 31) to create apparel products of varying texture using FGF's electrospinning-based technology is also still in progress. Confidential information regarding the exact raw material composition required to create this fiber solution has been revealed in a personal interview with Electroloom, solely for the purpose of performing energy and water consumption calculations in this meta-LCI study.

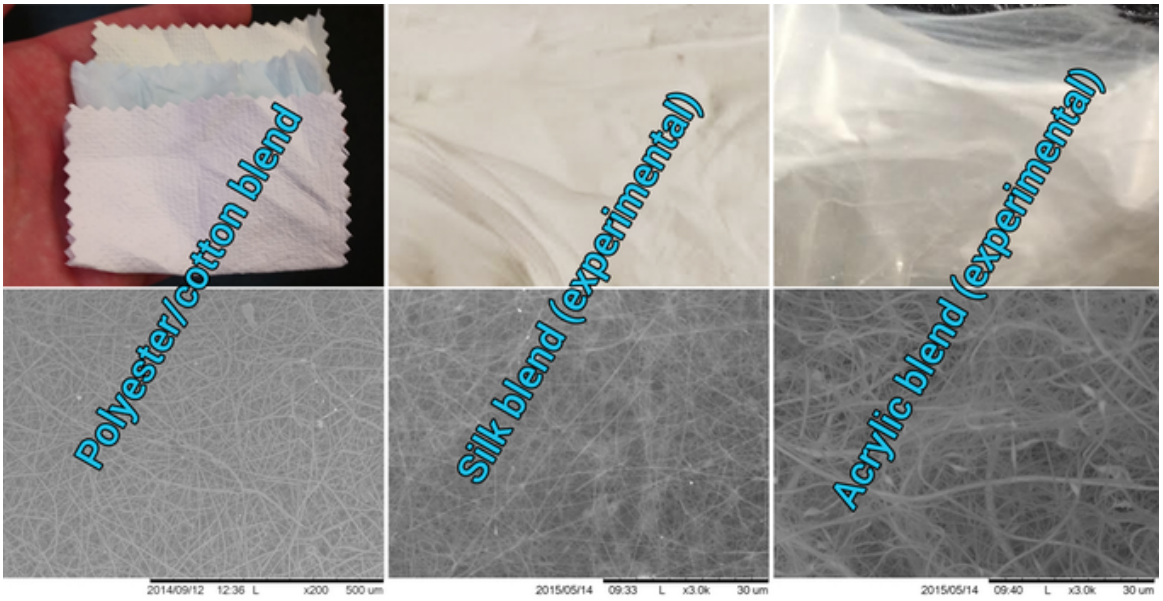


Figure 31. Materials and blends for Electroloom's fiber solution (Electroloom, 2015).

Conventional Clothing Production Materials

Cotton and polyester fibers "dominate global clothing fiber inputs (by weight of fiber), together supplying over 85% of all fiber used in clothing" (The Carbon Trust, 2011, p.9), with cotton representing 28% of the global fiber consumption and 77% of natural fiber use; and polyester 77% of synthetic fiber production (Figure 32).

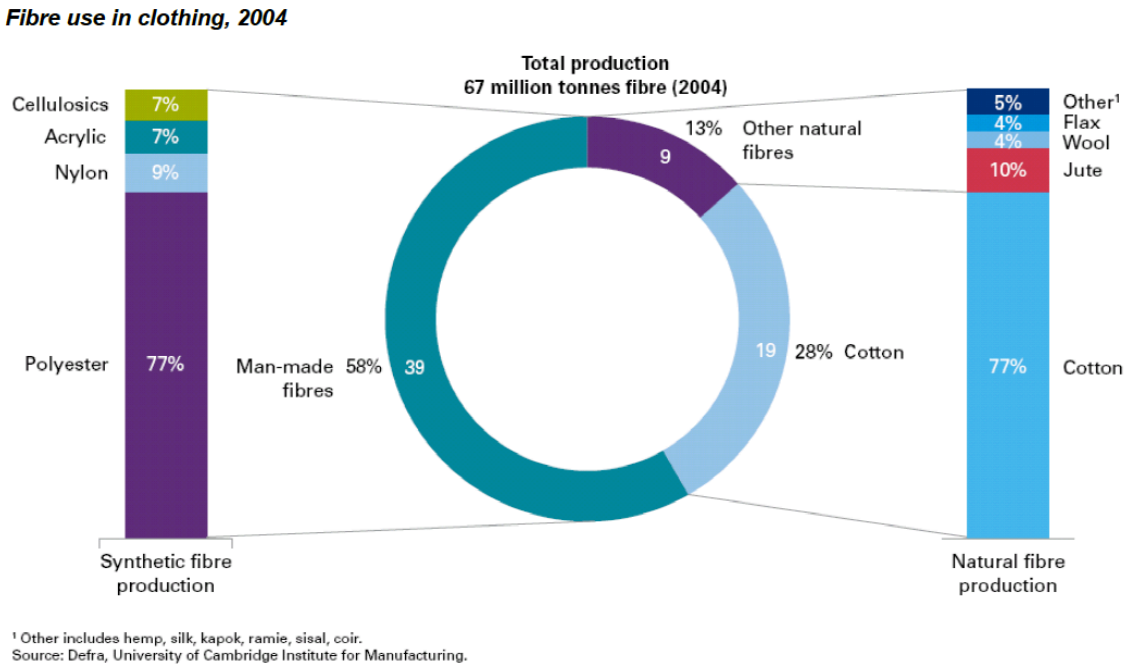


Figure 32. Fiber use in clothing, 2004 (The Carbon Trust, 2011).

Cotton

Cotton is defined as: "1a) Any of various shrubby plants of the genus Gossypium, having showy flowers and grown for the soft white downy fibers surrounding oil-rich seeds; 1b) The fiber of any of these plants, used in making textiles and other products; 1c) Thread or cloth manufactured from the fiber of these plants; 2) any of various soft

downy substances produced by other plants, as on the seeds of a cotton wood" (Freedictionary.com).

Cotton represents 82.6% of all natural fibers used for garment and textile production. Responsible for 40% of the world's textile production (WFN, 2014), cotton is the most widely produced natural fiber (Figure 33) and most water intensive crop (Mother Jones, 2012) in the world—cotton cultivation requires 256 Gm^3 of water annually, whereby "42% is blue water, 39% green water" (WFN, 2014).

Cotton fiber production involves the following steps (Muthu, 2014, p.9):

- Sowing cotton seeds
- Growth state
- Harvesting
- Ginning
- Baling



Figure 33. Cotton fiber production in Xinjiang, China (China Development Bank, 2005).

Growing cotton crop and producing fiber from the plant source "requires various inputs such as water, energy from both renewable and non-renewable sources, land, pesticides (Figure 34), and fertilizers" (Muthu, 2014, p.10). These resource intensive processes contribute to major environmental issues—"Many studies have pointed out that the production of conventional cotton is perceived as environmentally and socially hazardous as it requires a higher usage of pesticides and fertilizers" (Muthu, 2014, p.10).



Figure 34. Pesticide used in cotton cultivation (Team Nukleus, 2012).

In terms of energy consumption, it is reported that 55MJ/kg of fiber is required to produce conventional cotton, whereas US organic cotton requires 14MJ/kg of fiber (Muthu, 2014, p.11). A comprehensive LCI study by van der Velden et al. provided detailed LCI data on the water and energy consumption levels of each production phase––from cotton fiber production to fabric finishing—of cotton textile production from both primary and secondary sources (van der Velden, Patel, Vogtlander, 2013, p. 335-343).

Cotton production has significant impacts on the environment, including:

1) Surface water and groundwater pollution from pesticide use,
2) Marine life biodiversity endangerment,
3) Pest proliferation,
4) Soil salinization,
5) Soil fertility degradation,
6) GHG emissions (i.e. nitrous oxide) from nitrate application,
7) Water resource depletion, and
8) High energy consumption required of fertilizers used for cotton farming (ICCO et al., n.d. a).

Furthermore, cotton processing poses environmental and human health impacts from its dyeing, bleaching, and finishing steps, which require the use of chemicals of varying toxicity---heavy metals, formaldehyde, azo dyes, benzidine, and chlorine bleach (ICCO et al., n.d. b). These chemicals can seep into the ground and pollute potable water as well as groundwater, endanger aquatic and terrestrial ecosystems with their toxicity, and cause allergies, eczema, anaemia, and cancer in humans through skin contact, inhalation, and ingestion.

The environmental impacts of cotton production can be alleviated by:

1) Reducing agrochemical usage levels,

2) Developing alternative biodegradable materials for garment production,

3) Decreasing or eliminating the use of sizing chemicals,

4) Substituting chemicals with enzymes,

5) Using alternative garment production techniques,

6) Using alternative vegetable dyes, dye controllers and low liquor ratio dyeing machines,

7) Using minimal or no dyes that will enter back into the water ways,

8) Recycling water where possible,

9) Capturing and/or neutralizing toxic chemicals,

10) Capturing and/or neutralizing harmful gas emissions

Polyester (PET)

Polyester, also known as polyethylene terephthalate (PET), is an aliphatic synthetic fiber made from "purified terephthalic acid (PTA) or dimethyl terephthalate (DMT) and mono ethylene glycol (MEG)" (Muthu, 2014, p.14). Polyester is petroleum-based, and non-biodegradable. The majority of fiber used in clothing production is synthetic (The Carbon Trust, 2011, p.9), of which polyester is the most dominant. Polyester fiber production usually consists of the following steps (Muthu, 2014, p. 4), illustrated in Figure 35 below:

- Oil acquisition and refining
- Cracking
- Preparation of chips
- Fiber conversion process

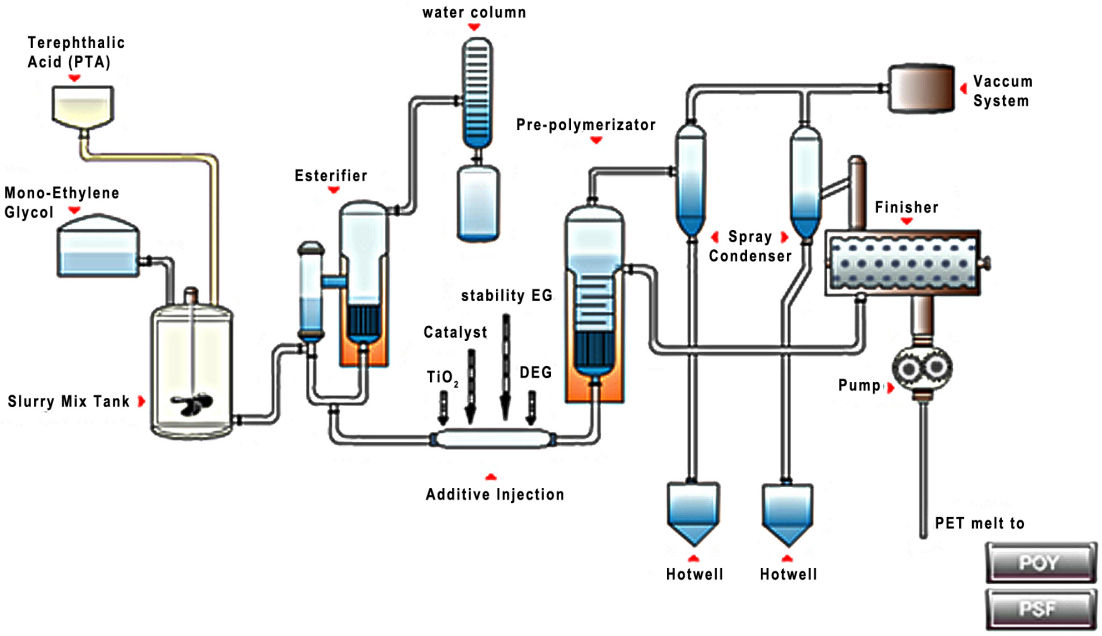


Figure 35. Polyester staple fiber production process (CPMA, 2012).

The manufacture of synthetic clothing fibers such as polyester is generally energy intensive, consuming as much as "125 MJ/kg of fiber" (Muthu, 2014, p.14), and produces high levels of greenhouse gas emissions. "A study by Cherret et al. (2005) indicated that production in America has a higher energy consumption, i.e. 127MJ/kg, than that in Europe (104MJ/kg)" (Muthu, 2014, p.14). Steinberger et al. reported that a 500g-polyester jacket requires 26.82MJ of energy in a "spatially explicit life cycle inventory (LCI)" (Steinberger, Friot, Jolliet, et Erkman, 2009, p.450). An exhaustive LCI study by van der Velden et al. provided detailed LCI data on the water and energy demands of each production phase—from pellet production to fabric finishing—of polyester textile production from both primary and secondary sources (van der Velden et al., 2013, p. 344-347).

While fossil-based and energy-intensive, polyester production has lower water-intensity than natural fiber production, and used polyester garments can be recycled (Figure 36).

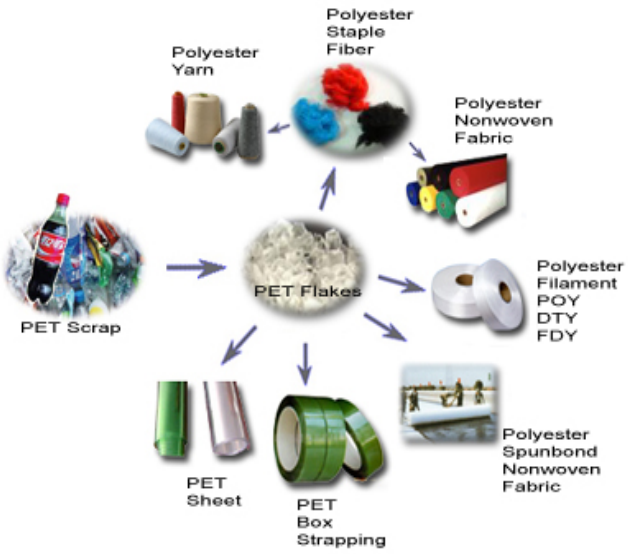


Figure 36. Products made from recycled polyester (Zhongda International, n.d.).

Polyester fiber “can be recovered form a mixture of post-industrial fiber waste and post-consumer plastic (the most ubiquitous being the PET drinks bottle)” (Fletcher & Grose, 2012, p. 70), after which they are then “chopped, ground and melted to reform polyester chip, which is them extruded, processed, and textured just like virgin polyester” (Fletcher & Grose, 2012, p. 70).

Recent developments in recycling technology chemically disintegrates the polyester polymer into monomers, the basic building blocks of polyester, followed by repolymerization “to produce a recycled material that is purer and of a more consistent quality than that produced by the mechanical method” (Fletcher & Grose, 2012, p. 70). Over 50% of polyester fiber in Europe is currently made from recycled material, as improvements to synthetic fiber recycling technology have alleviated the degradation of fiber quality.

Chapter III

Research Methodology

This chapter introduces comparative meta-life cycle inventory (LCI) analysis, a combination of the meta-analysis method and LCI method, as the research methodology used for this study. As LCI is part of the life cycle assessment (LCA) process as issued by the International Organization for Standardization (ISO), an overview of ISO 14040:2006 and ISO 14044 provides a definition for the LCI method. As part of the LCI process, the goal and scope, the system boundary, the functional unit, and the advantages and limitations are defined in this chapter as a basis for carrying out the comparative analysis of the four clothing production methodologies and six materials in question.

Comparative Meta-Life Cycle Inventory Analysis

> Meta-analysis: A melding of data from multiple studies, usually involving additional mathematical analyses, with the goal of utilizing this synergy of information and data size to answer questions that cannot be answered by existing individual studies or to improve the certainty or impact of known findings by increasing the sample size. (Zumsteg, Cooper, & Noon, 2012)

Meta-analysis is defined as "a statistical technique for combining the findings from independent studies" (Crombie & Davies, 2009, p.1). The International Organization for Standardization defines LCI as the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO14040:2006). When applied to life cycle inventory analysis (LCI), meta-analysis is "an analysis of a set of published [LCI] results to estimate a single

or multiple impacts for a single technology or a technology category, either in a statistical sense […] or by quantitative adjustment of the underlying studies to make them more methodologically consistent" (Brandao, Heath, & Cooper, 2012, p.S3).

This comparative meta-life cycle inventory analysis or comparative meta-LCI will focus on two impact categories of clothing production—water and energy consumption. Existing LCI data on a total of four clothing production methodologies and six most prevalent materials they use for garment manufacture is collected through a systematic literature review. The objective of this LCI study is to compare the resource intensity of three additive manufacturing (AM) or three-dimensional printing (3DP) methods against the conventional method.

The clothing production methods and materials included in this LCI are:

1. Selective laser sintering (SLS)
    a. PA-2200
    b. TPU-92A-1

2. Field Guided Fabrication (FGF)
    a. "Polyester-cellulose" fiber solution

3. Fused Deposition Modeling (FDM)
    a. TPU-85A

4. Conventional Cut-and-Sew or "Making-Up"
    a. Cotton
    b. Polyester

The LCI data regarding water and energy consumption from the three 3DP methods will be compared against that of the conventional cut-and-sew manufacturing method with the purpose of understanding their relative resource-intensity.

Unlike a full life cycle assessment (LCA), however, this meta-LCI study does not "reflect a comprehensive set of environmental issues related to the product system being

studied" (ISO14040:2006), such as those included in most life cycle impact assessment (LCIA) methods. The Recipe method, for instance, includes 18 midpoint indicators (i.e. climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion, and fossil fuel depletion) and 13 endpoint indicators (e.g. damage to human health, damage to ecosystem diversity, damage to resource availability) (Muthu, 2014, p.121-123).

This meta-LCI study is not comprehensive in that it only focuses on water depletion and energy consumption, two midpoint indicators that may lead to endpoint indicators such as damage to ecosystem diversity and damage to resource availability.

ISO 14040:2006

The first standard for life cycle assessment (LCA) methodology was issued by the International Organization for Standardization (ISO) in 1997 (Baumann & Tillman, 2004, p. 43). ISO 14044 was established for the purpose of establishing LCA norms in relation to environmental management. Last reviewed in 2010, the latest version available is the ISO14040:2006, which is to be used together with the first edition of ISO 14044 in order to cancel and replace all previous updates indicated below, from 1997 to 2000 (ISO.org):

> ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. […] ISO 14044 was prepared by Technical Committee ISO/TC 207, Environmental management, Subcommittee SC 5, *Life cycle assessment*. This first edition of ISO 14044, together

> with ISO 14040:2006, cancels and replaces ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000, which have been technically revised. (ISO, 2006)

While performing a life cycle inventory analysis (LCI) is not the same as carrying out the more comprehensive LCA, in which LCI represents only part of the LCA process, it can provide valuable insight to key life cycle impacts by the identification of hotspot areas. As such, the investigation requirements for LCI stated in ISO14040:2006 will be used as the framework for this meta-LCI even though it is more often used as guidelines for carrying out a full LCA.

According to the ISO 14040:2006, "when executing the plan for the life cycle inventory analysis, the operational steps outlined [below] should be performed" to derive at a complete life cycle inventory (Figure 37). As part of the LCI requirements, ISO14040:2006 stipulates specific guidelines for calculating data and allocation that are fully listed in Appendix 3.

In addition to fulfilling the LCI requirements and carrying out due process as prescribed by ISO 14040:2006 in the diagram below, this study also includes the construction of a baseline scenario for two impact categories—water consumption and energy use—against which five alternative scenarios will be compared. The baseline scenario is created based on assumptions that represent actual conditions under which T-shirts made from six most representative materials are more likely produced using four most representative production methods, in order to compare the water and energy demands of the four selected clothing manufacture methodologies and six materials against one another. The five alternative scenarios then compare these water and energy

demands under five different sets of parameter changes with the purpose of assessing how they impact hotspot areas identified in the baseline scenario.

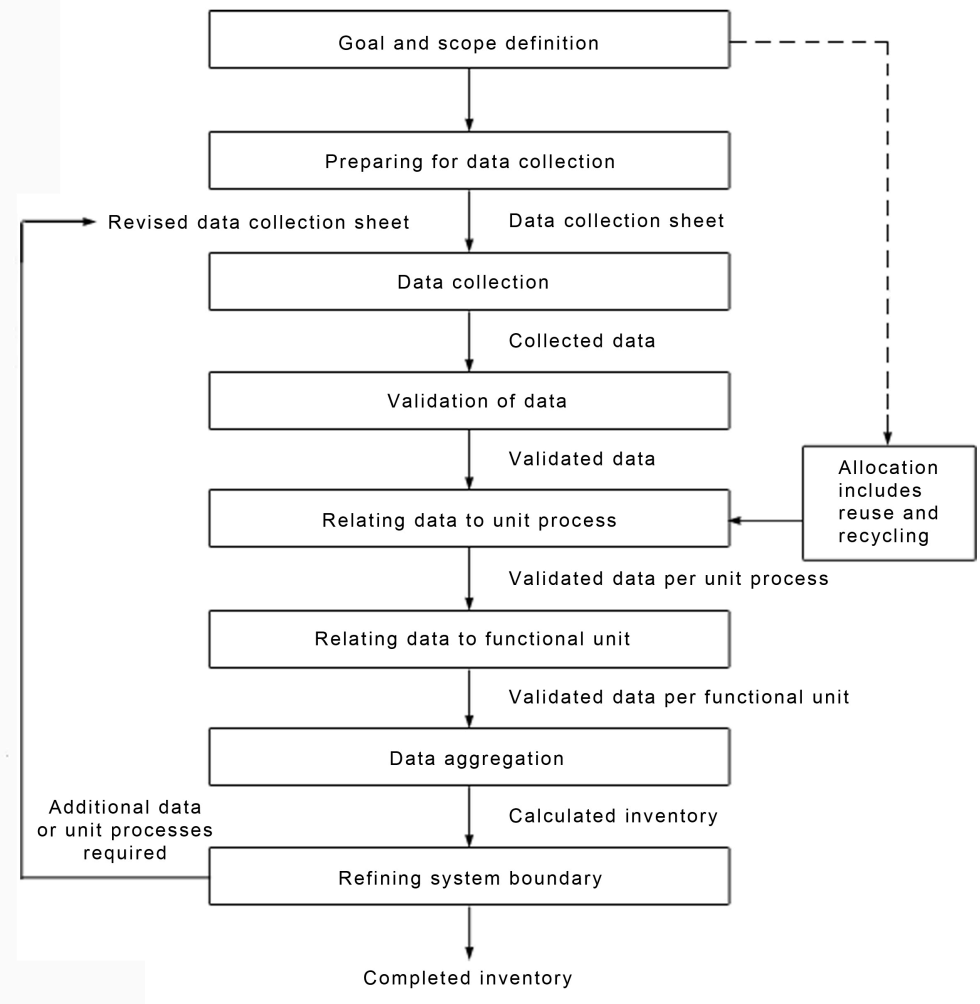


Figure 37. Simplified procedures for inventory analysis (Muthu, 2014).

Goal and Scope Definition

ISO14040:2006 requires the following items to be unambiguously stated in performing a life cycle assessment (LCA):

1) the intended application

2) the reasons for carrying out the study

3) the intended audience, i.e. to whom the results of the study are intended to be communicated

4) whether the results are intended to be used in comparative assertions intended to be disclosed to the public

According to the World Economic Forum's 2014 report, water scarcity has been rated as the top environmentally related global risk of highest concern, and third overall top global risk (WEF, 2014, p.9). As water scarcity is a systemic risk, it can have severe implications on geopolitical, societal, and economic stability worldwide. The Environmental Protection Agency (EPA) reports that fossil fuel consumption is the main source of greenhouse gas (GHG) emissions, with energy supply (26% of global emissions) and industry (19% of global emissions) being the two largest sources of global GHG emissions (EPA, 2015).

In response to these two pressing environmental issues—water scarcity and fossil fuel consumption—the goal of this meta-LCI is to compare the water and energy intensities of three 3DP methods against that of the cut-and-sew method. This study is intended for industry professionals in the textile and apparel-manufacturing sector, including fashion designers, textile and clothing suppliers, and apparel brands. The results will be used for academic research purposes and intended to be publicly disclosed in select academic and professional journals.

System Boundary

Since this meta-LCI investigation includes four different clothing production methods that vary greatly from one another—with each method involving complex

systems that can be expanded to include multiple sub-processes, which may not be directly comparable to those in other clothing production methods (e.g. handling of excess powder for sintering in the SLS method, manufacturing the 3D template in the FGF method, or singeing and mercerizing in the conventional method)—a simplified system boundary diagram (Figure 38) adapted from Muthu's life cycle assessment of textiles and the clothing supply chain is used to illustrate the scope of this study.

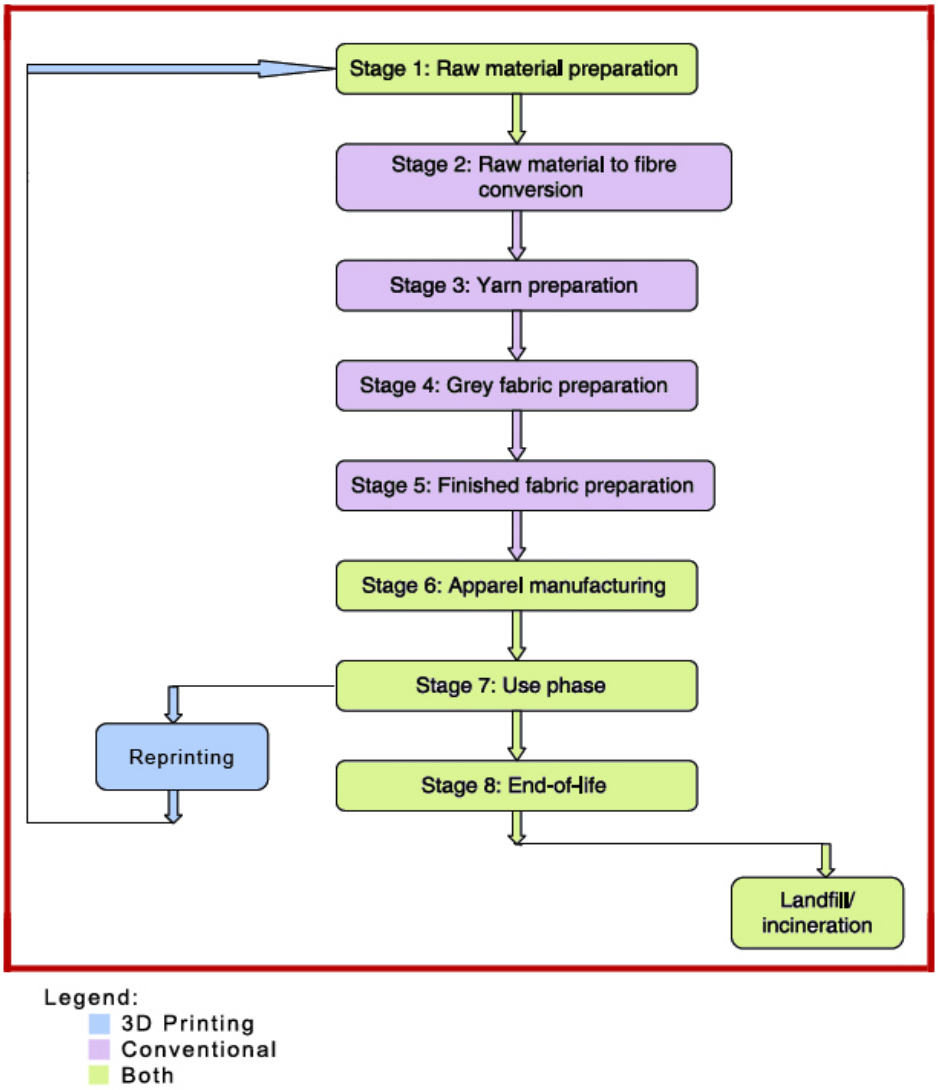


Figure 38. System boundary (Muthu, 2014).

In this simplified system boundary diagram (Figure 38), the cumulative system boundaries of the four clothing methods are captured using only generalized process descriptions, such that stages 2 to 5 apply only to conventional cut-and-sew and "reprinting" applies only to the FGF method. The system boundary for this comparative meta-LCI of 3DP versus conventional manufacturing garment production methods includes the cradle-to-grave life cycle stages of clothing production as illustrated in the boundary diagram (Figure 38) above.

Functional Unit

The ISO14044-based Sustainable Apparel Coalition (SAC) Product Category Rule (PCR) provides a guideline (Earthsure, 2013) for determining the functional unit in this comparative meta-LCI. As a finished apparel product, the functional unit "one standard T-shirt, 100 wears, 50 washes" encompasses all the cradle-to-grave life cycle phases of an apparel product. 100 wears is equivalent to once a week for two years, or every two days for two seasons. 50 washes for 100 wears means that the T-shirt is washed once every two wears before final disposal.

Since the goal of this comparative meta-LCI is to evaluate the water and energy intensity of clothing production methods, the apparel product selected should be a representative one for the specific method used to create it. Generally, it is assumed that the conventionally cut and sewn cotton and polyester T-shirts are made from knits. For 3D-printed T-shirts other than the one made from polyester-cellulose, it is assumed that they are made using the Kinematics design, consisting of small distinctive triangular panels interconnected by hinges.

Due to being costly and time-consuming, 3DP technology has generally been used to create clothing of more complex designs instead of generic T-shirts. Due to lack of data for 3DP T-shirts, this study uses extrapolations from existing LCI data on other 3D-printed apparel to calculate the estimated material, energy and water consumption required to produce each of four 3DP T-shirts included in this meta-LCI.

Advantages and Limitations of Meta-LCI

Meta-LCI provides data on the selective environmental impact categories (such as water depletion and fossil fuel depletion) created by a product from its cradle-to-grave. It is important to emphasize here that a LCI differs from a LCA in that it does not "reflect a comprehensive set of environmental issues related to the product system being studied" (ISO14044:2006), for example those concerning human health or ecosystem quality included in many life cycle impact assessment (LCIA) methods.

Some advantages of the meta-LCI methodology are as follows:

- Methodically analyze and address environmental profile of a product from raw material extraction to disposal holistically
- Compares different products or product systems and alternative processes to identify opportunities for environmental sustainability improvement
- Aids in quantifying resource intensities of products or product systems
- Helps detect hotspots nested production processes
- Practicable recommendations for improvements can be suggested based on LCI hotspot analysis to reduce the environmental impacts
- Viable tool for opting the best management practices

- Introduces economic benefits by:
  - Reducing costs and increasing profits
  - Increasing brand equity
  - Improving corporate image
  - Providing better market access
  - Providing a quantitative basis for corporate sustainability
  - Enhancing customer relationships
- Helpful as a corporate evaluation tool to define sustainability objectives
- Raises environmental awareness
- Useful for public engagement (e.g. eco-labeling)
- Can be used to establish performance criteria for supply chain risk management
- Applicable to environmental reporting, green procurement and regulatory compliance
- Can be used for industrial benchmarking

Some limitations of meta-LCI studies include the following:

- Complex and highly data intensive
- Performed using different assumptions and subjective valuation procedures
- Addresses potential impacts rather than actual impacts
- Requires high degree of expertise
- Quality data availability is limited
- Focuses primarily on industrial processes instead of market mechanisms
- Location-specific and are not directly applicable to other locales
- Limited availability of relevant and updated databases
- Transparency may be lacking or perceived to be lacking
- Uncertainties in data and modeling

Chapter IV

Data and Results

The goal of this meta-life cycle inventory analysis (LCI) is to compare the water and energy intensities of potentially disruptive 3D garment printing methods against that of the conventional cut-and-sew method (Table 3):

Table 3. Methods & materials: comparison matrix.

Selected Clothing Production Methodologies & Materials								
Conventional				3DP				
Method			Material	Method			Printer	Material
1)	Cut-Sew ("Making-Up")	a.	Cotton	1)	SLS	a.	Sinterstation 2500Plus	TPU-92A-1
		b.	PET			b.	EOSINT P760	PA-2200
				2)	FGF	c.	Electroloom Alpha	Polyester-Cellulose Fiber Solution
				3)	FDM	d.	Witbox Home Printer	TPU-85A

For this study, data published before the year 2000 are considered irrelevant and have been excluded other than when it is part of an ongoing record leading to the year 2000 and after.

General information regarding material specification, 3D printer specifications, the density of the material, and the raw material weight required to produce one T-shirt are provided in Table 4 below:

Table 4. Methods & materials: general information.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Weight of One Finished T-Shirt (g)	175	159	1134	1341	134	1357
Est. Material Waste (%)	25%	25%	45%	45%	5%	25%
Density (g/cm^3)	1.54	1.40	1.02	1.20	1.18	1.22
Raw Material, One T-Shirt (g)	219	199	1644	1944	431	1697

A systematic literature review of published LCA studies on clothing weight and textile densities showed that data found often vary from one source to another, requiring careful evaluation, weighting, and harmonization to maintain consistency throughout.

One study assumes the weight of one cotton T-shirt to be 250g, and that of one polyester jacket to be 500g, (Steinberger et al., 2009). The weight of the cotton T-shirt was most originally derived from the EDIPTEX (2007) study by Laursen, et al., whereby the "three different qualities of T-shirt have been weighed: 178g ('thin' quality), 223g and 292g (heavy quality)" (Laursen et al., 2007, p. 41) and the assumption for the weight of the T-shirt is determined as 250g.

From directly weighing three standard men's size-L 100% cotton T-shirts of three different qualities, however, the following T-shirt weights have been recorded: i) 184g, ii) 181g, and iii) 161g. Since primary data outweighs secondary data, the average of the three primary values–175g–is used as the weight of standard 100% cotton T-shirt in this meta-LCI.

The data on energy and water consumption per gram of cotton fiber collected from various sources are then multiplied by the weight of the standard cotton T-shirt to

provide inputs for corresponding parameters in each life cycle stage. The weight of the polyester T-shirt is calculated using the volume of the cotton T-shirt as a basis:

$$\text{Vol. of T-shirt}_{\text{Cotton}} = \text{Wt. of T-shirt}_{\text{Cotton}} \div \text{Density of T-shirt}_{\text{Cotton}}$$

$$\text{Wt. of T-shirt}_{\text{Polyester}} = \text{Vol. of T-shirt}_{\text{Cotton}} \times \text{Density of T-shirt}_{\text{Polyester}}$$

The weight of one PA-2200 nylon dress is "about 5lbs" or 2268g (Molitch-Hou, 2014) (Certo-Ware, 2015). A PA-2200 T-shirt is assumed to be half the weight of the PA-2200 dress. The weight of filament material it takes to 3D print a TPU-85A women's jacket is about 1kg (Banks-Walker, 2015). An estimated ten A4-sized sheets of 3D printed textiles are required to make one T-shirt, whereas an estimated fourteen A4-sheets of 3D printed textiles are required to make one jacket for this study.

LCI data on raw material weight required to produce one T-shirt or garment are scarce. Other than the polyester-cellulose T-shirt, the densities of the materials selected in this study are used to perform the calculations for the weight of raw material (in g) required to produce one T-shirt using the material specified is performed using the following formula:

$$\text{Wt. of one T-shirt} \times (1 + \% \text{ Est. Material Waste})$$

The raw material required for the polyester-cellulose T-shirt cannot be calculated using the same formula as the raw material changes from liquid state to solid state in the process of electrospinning, whereby almost all of the solvent evaporates in due process, leaving behind only the solid content.

In order to calculate the amount of fiber solution required for this process, primary information from personal communication with Electroloom, developers of the

FGF technology is used in this study, whereby it is given that 1.5L of the fiber solution can print 4 tank tops. A T-shirt is estimated to have 1.2 times the surface area of a tank top from rough measurements of the sleeves' surface areas and against that of the bodice's surface area of one standard size-L men's 100% cotton T-shirt. To obtain the weight (in grams) of 1.5L of fiber solution, the weight of each material within it is either identified by Electroloom or calculated using volume-to-weight conversion by density, then added together to give 1435g in total. The calculations for the aqueous raw material required to produce one polyester-cellulose T-shirt is as follows:

$$\text{Wt. of Fiber Solution} \div 4 \times 1.2 \approx 431\text{g}$$

The weight of one polyester-cellulose T-shirt, however, has been calculated independent of the weight of the fiber solution, as it is unclear how much of the liquid content evaporates, and how much residue it leaves behind. A more reasonable estimation is made by taking the volume of one cotton T-shirt used as the basis for study, and factoring it by the weighted densities of the remaining solid contents (i.e. excluding the solvent density) of the polyester-cellulose T-shirt to estimate the weight of the polyester-cellulose T-shirt, as indicated below:

$$\text{Vol. of T-shirt}_{\text{Cotton}} = \text{Wt. of T-shirt}_{\text{Cotton}} \div \text{Density of T-shirt}_{\text{Cotton}}$$

$$\text{Wt. of T-shirt}_{\text{Poly-Cellulose}} = \text{Vol. of T-shirt}_{\text{Cotton}} \times \text{Density of T-shirt}_{\text{Poly-Cellulose}}$$

The main LCI data sources for these calculations are indicated in Table 5 below:

Table 5. LCI data sources: material densities.

LCI Parameter	Source
Cotton & polyester densities	International Fiber Centre (n.d.). Fibre Densities.
PA-2200 density	EOS GmbH. (2001). Product Information EOSINT P/PA2200-Pulver.
TPU-92A-1 density	Materialise. (2015). Laser Sintering Materials Properties.
Polyester-cellulose fiber solution density	A. Rowley, personal communication, August 25, 2015
TPU-85A (FilaFlex) density	Recreus. (2014). About FilaFlex.
Wt. of cotton T-shirt & polyester jacket	Steinberger, J. K., Friot, D., Jolliet, O., & Erkman, S. (2009). A spatially explicit life cycle inventory of the global textile chain.
Wt. of PA-2200 dress	Steinberger, J. K., Friot, D., Jolliet, O., & Erkman, S. (2009). A spatially explicit life cycle inventory of the global textile chain.

Material Preparation Phase

In the material preparation phase, LCI data (Table 6) for the water and energy demands of cotton and polyester textile production have been extracted from four main sources:

i) van der Velden et al.'s LCI study (2014),

ii) S.S. Muthu's environmental impact assessment of the textiles and clothing supply chain (2014),

iii) the unit processes (UPR) datasets from Ecoinvent v3.1 database (2014),

iv) J.K. Steinberger et al.'s spatially explicit LCI (2009).

While most of these selected LCI sources attempt to provide specific data on the water and energy consumed for each stage of fiber-to-textile production including crop cultivation, yarn spinning, grey fabric preparation, and finished fabric preparation processes, the Ecoinvent v3.1 (2014) unit process datasets are less explicit in terms of allocation and do not indicate the specific processes to which the data refer.

Table 6. LCI data & calculations: material preparation phase.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
1. Material Preparation Phase						
Density (g/cm^3)	1.54	1.40	1.02	1.20	1.18	1.22
Raw Material, One T-Shirt (g)	219	199	1644	1944	431	1697
Raw Material						
Energy Consumption (MJ)	15.8	17.4	195	230	30.7	201
Water Consumption (L)	1172	12	36	43	6	38
Transportation, by Tractor (km)	1.9	1.9	89	89	89	89
(kg-km)	0.4	0.4	146	173	38	151
Yarn Spinning						
Energy Consumption (MJ)	6.2	5.4	–	–	–	–
Water Consumption (L)	438	437.5	–	–	–	–
Transportation, by Truck (km)	1207	1207	–	–	–	–
(kg-km)	264	264	–	–	–	–
Knitting / Grey Fabric Preparation						
Energy Consumption (MJ)	2.5	9.7	–	–	–	–
Water Consumption (L)	–	–	–	–	–	–
Transportation, by Truck (km)	86.9	86.9	–	–	–	–
(kg-km)	19.0	19.0	–	–	–	–
Finished Fabric Preparation						
Energy Consumption (MJ)	12.1	6.2	–	–	–	–
Water Consumption (m3)	18.7	–	–	–	–	–
Transportation, by Truck (km)	86.9	86.9	–	–	–	–
(kg-km)	19.0	19.0	–	–	–	–
Subtotal						
Energy Consumption, Processes (MJ)	36.6	38.6	194.7	230.2	30.7	200.9
Water, Material Prep (L)	**1629**	**449**	**36**	**43**	**6**	**38**
Transportation, by Truck (km)	1383	1383	89	89	89	89
(kg-km)	302	302	146	173	38	151
Energy Consumption, Transportation (MJ)	0.28	0.28	0.14	0.16	0.04	0.14
Energy, Material Prep (MJ)	**36.9**	**38.9**	**194.8**	**230.3**	**30.8**	**201.0**

For cotton, the following from van der Velden's LCI data collection (van der Velden, 2013, p. 335-343) have been included in this study based on nearest proximity to the requirements for one standard T-shirt:

1) Fiber manufacturing

- IFTH2 (n.a.), Biological production (6 countries)
- Laursen et al. (2007) EDIPTEX, Cotton cultivation and harvesting
- Laursen et al. (2007) EDIPTEX, Fiber production of cotton yarn

2) Yarn manufacturing

- Kaplan and Koc (2010), [Thermal energy for fixation] – Average of two values
- Kaplan and Koc (2010), Cotton combed knitting yarn – Average of two values
- Confidential source no. 7, [Rotor spinning of cotton]
- Dahllof (2004) Laursen, [Total energy demand for cotton spinning factory] – Average of two values

- SimaPro 7.2 educational, Idemat (2012), v0.0, [Yarn production, cotton fibers/kg/GLO+electricity, low voltage, at grid/CN U]
- Laursen et al. (2007) EDIPTEX, [Spinning of CO yarn]

3) Fabric manufacturing–Knitting

- Laursen et al. (2007) EDIPTEX, [2.3MJ per 1 shirt of 250g, >275g CO fabric needed]

4) Fabric manufacturing–Pretreatment & Wet processing

- Processor (2011) phase 4, [Bleaching average]
- Confidential source no. 7, [Wet treatment]
- Confidential source no. 7, [One time washing]
- Laursen et al. (2007) EDIPTEX, [3.1 MJ per 1 shirt of 250g (270g CO fabric)], Drying final fixing + set m^2 weight + softening 100% CO

Only energy consumption data on conventional cotton production has been included from Muthu's study (organic cotton production data has been excluded) for comparability with the two other data sources used in this study. The Muthu study does not provide water consumption data for cotton production and most other processes in textile and apparel production.

Ecoinvent v3.1 (2014) provides two types of aggregated datasets for the energy and water consumption of the production of cotton apparel—fiber production and textile production. As "one standard T-shirt" is the functional unit for this study, whereby the cotton and polyester T-shirts are assumed to be manufactured in China and consumed in the U.S.A., the "cotton production, China (CN)" dataset representing extrapolated primary data from global (GLO) production recorded from 2000 to 2014 and "knit cotton, batch-dyed, global (GLO)" dataset representing "global average based inputs from China, India, Latin America, and Turkey" recorded from 2005 to 2014 have been selected.

Steinberger's comparative study delineates the primary energy consumption of producing one 250g T-shirt by fiber, yarn, fabric, colored fabric, garment, and transport stages, but provides no data on water consumption.

For polyester, the following from van der Velden's LCI data collection (van der Velden, 2013, p. 344-347) have been included in this study based on nearest proximity to the requirements for one standard T-shirt:

1) Fiber + yarn manufacturing–Pellets/flakes production

- Confidential source no. 4, [PET flakes to staple fiber]
- IFTH1 (n.a.), PTA (purified terephthalic acid) and MEG (ethylene glycol) to staple fibers
- Laursen et al. (2007) EDIPTEX, Ring yarn according to formula

2) Fiber + yarn manufacturing–Spinning filament

- Barmag (2011) PET extruder spinning, [PET pellets to filament, FDY (fully drawn yarn)]
- Confidential source no. 5, [PET pellets to filament, FDY]

3) Fiber + yarn manufacturing–Texturing

- Barmag (2011), [Filament to textured filament, DTY (drawn textured yarn)] – Average of two values
- Confidential source no. 3, POY (partially oriented yarn) to DTY

4) Fabric manufacturing–Knitting

- Laursen et al. (2007) EDIPTEX, Circular knitting of 70% VI, 25% PA, 5% EL (0.222kg)

5) Fabric manufacturing–Pretreatment, Dyeing, Finishing

- Laursen et al. (2007) EDIPTEX, Pretreatment of synth. Knitted 70% VI, 25% PA, 5% EL (0.222kg)
- Laursen et al. (2007) EDIPTEX, Dyeing of 70% VI, 25% PA, 5% EL (0.222kg)

- Laursen et al. (2007) EDIPTEX, Finishing, drying, final fixing + set m^2 weight of 70% VI, 25% PA, 5% EL (0.222kg)

In the Muthu textile supply chain environmental impact study, energy values for polyester production are mainly based on values provided by European and American manufacturers. As the baseline scenario for this study assumes the polyester T-shirt production to take place in China, where energy demands are generally higher due to less energy-efficient infrastructure, the higher U.S.-based energy value for PET production of 127 MJ/kg has been selected. LCI data on water consumption is given as 60kg of water for the production of 1kg of bottle grade PET pellets in the Muthu study, and as 2200L (where 1kg = 1Lwater) for yarn production in the van der Velden study. These two values are weighted for one T-shirt and added together to give the subtotal of the amount of water required for PET textile production in the material preparation phase.

Ecoinvent v3.1 (2014) only provides aggregated energy and water consumption data on PET pellet production, but not individual data for fiber, yarn, grey fabric preparation, or finishing. Steinberger's comparative study delineates the primary energy consumption of producing one 500g polyester jacket by fiber, yarn, fabric, colored fabric, garment, and transport stages, but provides no data on water consumption.

The above LCI data findings on the water and energy demands of the material preparation life cycle phase for cotton and polyester fiber-to-textile production are detailed and summarized Table 7 below:

Table 7. Key LCI references: cotton & polyester textile production.

** Excluded from study due to incompleteness*

Key LCI References for Cotton & Polyester				
1) van der Velden LCA Study	**Cotton**		**Polyester**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw Material	82.7	18.1	82.1	16.3
Yarn Spinning	28.2	6.2	11.3	2.3
Grey Fabric, Knitting	8.5	1.9	18.2	3.6
Finished Fabric	121.9	26.7	45.1	9.0
	241.4	**52.8**	**156.7**	**31.2**
Water (L)				
Raw Material	9103	1991	0	0
Yarn Spinning	2002	438	2200	438
Grey Fabric, Knitting	0	0	0	0
Finished Fabric	0	0	0	0
	11105	**2429**	**2200**	**438**
2) Muthu LCA Study	**Cotton**		**Polyester**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw Material	55.0	12.0	127.0	25.3
Yarn Spinning	5.0	1.1	5.0	1.1
Grey Fabric, Knitting	10.2	2.2	10.2	2.2
Finished Fabric	41	9	41	9
	110.9	**24.3**	**182.9**	**37.5**
Water (L)				
Raw Material	–	–	60	12
Yarn Spinning	–	–	–	–
Grey Fabric, Knitting	–	–	–	–
Finished Fabric	–	–	–	–
	0	**0**	**60**	**12**
3) Ecoinvent v3.1	**Cotton**		**Polyester**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Fiber	37.7	8.2	1.6	0.3
Knitting to Finished	66	14.5	–	–
	104.0	**22.7**	**1.6**	**0.3**
Water (L)				
Fiber	1617	354	5	1
Knitting to Finished	85	19	–	–
	1702	**372**	**5**	**1**
4) Steinberger LCA Study	**Cotton**		**Polyester**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw Material	113.2	24.8	53.6	10.7
Yarn Spinning	52.3	11.4	58.5	12.8
Grey Fabric, Knitting	10.2	2.2	105.8	23.2
Finished Fabric	9	2	3	1
	184.6	**40.4**	**220.9**	**47.2**

LCI data on water and energy required to produce mostly petrochemical-based 3D printer filament materials PA-2200, TPU-92A-1, TPU-85A and the "polyester-cellulose" fiber solution are scarce. While a systematic literature survey has yielded LCI data from three sources on both nylon-6 and nylon-66 instead, only data from Muthu's study and Ecoinvent v3.1 (2014) are used in this study as substitutes for 3D-printer filament materials other than the polyester-cellulose fiber solution. As the data provided in the LCA of chemical processes and products by Yong Li (2007) seemed to have an unreasonably large discrepancy with the data provided from the other two sources, Li's findings have been excluded from the LCI calculations.

Nylon, or polyamide, is a "tough, lightweight, elastic synthetic polymer with a protein-like chemical structure, able to be produced as filaments, sheets, or molded objects" (Oxford dictionaries). The term nylon is "a generic designation for a family of synthetic polymers known as aliphatic polyamides" (Encyclopedia of Polymer Science). Fabric or yarns made from nylon fibers have similar properties as that of polyester. While nylon is energy-intensive, non-biodegradable, and derived from petrochemical sources, it requires little water to produce (Fletcher, 2014, p.17). There are many different forms of nylon, such as nylon 6.6, nylon 6.9, nylon 6.12, nylon 11, and nylon 12 (Palmer, 2001).

Nylon-6 is derived from caprolactum, while nylon-66 is produced from hexamethylene diamine and adipic acid (Muthu, 2014). The key difference in physical properties between the nylon-6 and nylon-66 is in the melting point. Nylon-6 has a lower melting point (210ºC - 225ºC) than nylon-66 (250ºC - 265ºC), which is slightly closer to the melting points of PA-2200 (181ºC - 184ºC), TPU-92A-1 (90ºC - 140ºC) and TPU-

85A (110ºC - 140ºC) than nylon-66 is. Furthermore, nylon-6 is more color fast than nylon-66 and thus possibly more suitable for use in clothing textiles.

Since PA-2200 is a type of nylon, the average water and energy demands of producing nylon-6 provided in the Muthu study and the Ecoinvent v3.1 (2014) database are used as substitutes for PA-2200 in performing the LCI calculations in Table 8 below. Likewise for thermoplastic elastomers TPU-92A-1 and TPU-85A that exhibit comparable physical properties to that of PA-2200, mean values from the same substitution datasets on nylon-6 are used to compute LCI results in this comparative study in Table 8 below:

Table 8. LCI references: nylon-6 production.

** Excluded from study due to incompleteness*

Key LCI References for Nylon (Substitute for PA2200, TPUs)				
Muthu LCA Study (2014)	**Nylon 6**		**Nylon 66**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw Material	120.5	26.4	138.6	27.6
	120.5	**26.4**	**138.6**	**27.6**
Water (L)				
Raw Material	22.2	4.9	191	38.1
	22.2	**4.9**	**191.5**	**38.1**
Ecoinvent v3.1 (2014)	**Nylon 6**		**Nylon 66**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw material	116.3	25.4	126.8	25.2
	116.3	**25.4**	**126.8**	**25.2**
Water (L)				
Cooling water	8.5	1.9	24.8	4.9
Process water	13.6	3.0	166.5	33.1
	22.2	**4.9**	**191.3**	**38.0**
Li, Y. (2007)	**Nylon 6**		**Nylon 66**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Raw material w/o recovery	8.31	1.82	9.48	1.88
	8.31	**1.82**	**9.48**	**1.88**
Water (L)				
Process water	809.0	177.0	98.0	19.5
	809.0	**177.0**	**98.0**	**19.5**
AVERAGE	**Nylon 6**		**Nylon 66**	
	(per kg fiber)	*(per T-shirt)*	*(per kg fiber)*	*(per T-shirt)*
Energy (MJ)				
Ave. of Selected	**118.4**	**194.7**	**132.7**	**218.2**
Water (L)				
Ave. of Selected	**22.2**	**36.5**	**191.4**	**314.7**

In the case of the confidential material used in the "polyester-cellulose" fiber solution (A. Rowley, personal communication, August 25, 2015), water and energy consumption values of producing virgin polyester pellets (or bottle-grade PET) are used as substitutes in the calculations since the material belongs to the aliphatic polyester class of polymers.

For the confidential materials used in the "polyester-cellulose" solution (A. Rowley, personal communication, August 25, 2015), LCI data was initially selected based on general information of the raw material's traditional production methods described in A. Chauvel's book *Petrochemical Processes* (1989), then further filtered and refined based on more recent information provided in Wittcoff et al.'s (2012) overview of advancements in the material's production since the 1980s. While A. Chauvel's book is dated, it contains important descriptions and important illustrations of industrial processes that are now no longer as easy to obtain from publicly available sources on the petrochemical industry. A. Chauvel's detailed accounts provided an overview of the production methods, chemical processes, and energy and water consumption data relating to a key material used to manufacture the polyester-cellulose fiber solution, but Witcoff et al. closed the information gap between the 1980s and present day technology by pointing out certain production techniques that have no longer been in use since the 1980s. This discovery in the data collection process led to the decision of eliminating A. Chauvel's findings from this study.

Instead, the water and energy consumption LCI data used for "polyester-cellulose" fiber solution calculations in this study are extracted from the frequently updated LCI database Ecoinvent v3.1 (2014), as shown in Table 9 below:

Table 9. LCI reference data: polyester-cellulose.

** Excluded from study due to irrelevance (outdated)*

Sensitiviy Analyses for "Polyester-Cellulose" Fiber Solution Components					
Description		Raw Material Production Method			
Liquid X		**Method A**			
	Data Source	Ecoinvent v3.1 (2014)		Chauvel et Lefebvre (1989)	
		(per kg)	*(per T-shirt)*	*(per ton)*	*(per T-shirt)*
Energy (MJ)					
	Raw Material	64.6	23.0	1510	0.54
		64.6	**23.0**	**1509.7**	**0.5**
Water (L)					
	Cooling water	3.93	1.40	28226	10.03
	Process water	3.20	1.14	0	0
	Treated water	0	0	0	0
		7.14	**2.54**	**28226**	**10.0**
Cellulose Y		**Method A**			
		(per ton)	*(per T-shirt)*	*(per ton)*	*(per T-shirt)*
Water (L)					
	Cooling water	3933	0.07	28226	0.53
	Process water	3205	0.06	0	0
	Treated water	0	0	0	0
		7138	**0.13**	**28226**	**0.53**

It is important to note that any values for cooling water presented in this study have been weighted based on Jefferies et al.'s (2012) "Water Footprint and LCA as approaches to assess potential impacts of products on water consumption," whereby it is assumed that "all freshwater abstractions are consumptive, with the exception of water used for cooling" (Jefferies et al., 2012, p. 160), and "only 5% of the abstracted [cooling] water is consumed (evaporated), whereas the remaining 95% is discharged again to the environment" (Jefferies et al., 2012, p. 156). Hence, the cooling water values presented in the table above have already been multiplied by a factor of 0.05 to reflect the true consumption of cooling water in industrial processes.

LCI data on energy expended from the transportation of materials from one facility to the next that are embedded in the raw material preparation sub-processes have been stochastically estimated and included in the calculations. Since it is assumed that the cotton and polyester fibers and textiles are manufactured in China for this meta-LCI study, the transportation distances relating to cotton and polyester fiber production in the material preparation life cycle phase have been modeled after cotton transportation distances reported in Qiao & Paggi's report on cotton transportation costs in China. The table below (Table 10) shows Qiao & Paggi's indication of distances measured from cotton crop cultivation to textile mill export:

Table 10. Cotton transportation distance in China (Qiao & Paggi, 2009).

	Distance (miles)	Transportation tool
Domestic cotton		
From Farmers' door to ginning factory	1.2	Tractor
From processing plant to textile mill		
Short distance	54	Truck
Middle distance	156	Truck
Long distance	2040	Truck
Export cotton		
From port to textile mill	480	Truck with special equipment

Note: 1 USD = 6.8 Yuan RMB; 1km = 0.6 mile.
Source: author survey, 2008.

A study by M.F. Ashby (2012) on the approximate energy and carbon footprint of transportation states the energy use of a 32-metric ton diesel truck to be 0.94 MJ/metric ton-km (Ashby, 2012, p.142) or 0.00094 MJ/kg-km (conversion formula: 1 metric ton = 1000 kg), and that of a light goods vehicle to be 2.5 MJ/metric ton-km or 0.0025 MJ/kg-

km. In the material preparation phase, the 32-metric ton diesel truck is assumed to be the mode of transport for pellets, fibers, and textiles between facilities, prior being sent to apparel manufacturing factories that cut and sew the T-shirt together. The calculations for the energy use of transportation by truck accounted for in the sub-processes of the material preparation phase are based on the following formula:

0.00094 MJ/kg-km x Wt. of Fabric/Filament (in kg) x Transportation Dist. (in km)

The findings on the water and energy intensities of the material preparation phase of are summated in the cluster bar graph (Figure 39) below:

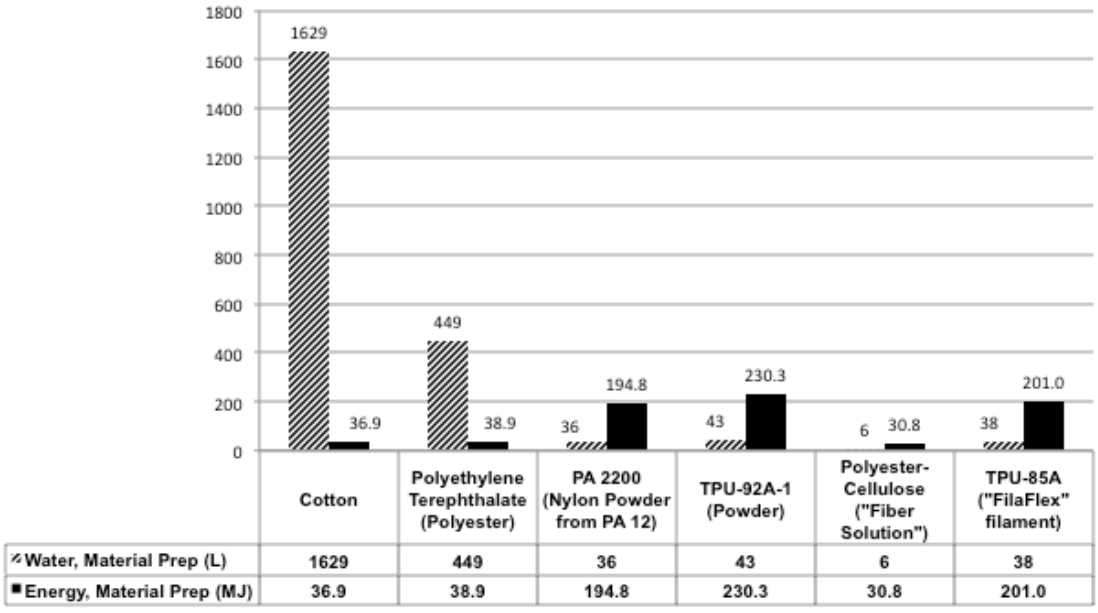


Figure 39. Water & energy consumption: material preparation phase.

Of importance in the material preparation phase of the garments' life cycle is the water consumption of cotton fiber and textile production. At 1629 litres, the amount of water required to produce the textile required for one cotton T-shirt is more than 270

times the water required to produce the fiber solution required to 3D-print one polyester-cellulose T-shirt using the field guided fabrication (FGF) method, and more than 37 times the water required to produce the TPU-92A-1 powder needed for 3D-printing one T-shirt.

Of the six, however, the most energy-intensive raw material to produce is the TPU-92A-1 powder used in 3D-printing technique selective laser sintering (SLS), which requires about 6 times the energy needed for manufacturing conventional cotton or polyester textile, and more than 7 times the energy required to produce than the fiber solution required for 3D-printing one polyester-cellulose T-shirt. TPU-85A and PA 2200 are not far behind, requiring 5 to 6 times more energy than that to produce than cotton, polyester, or the polyester-cellulose fiber solution.

This significant difference can be mostly attributed to the amount of material required to 3D-print one T-shirt for each of these three 3DP technologies. Other than the Kinematics design (Figure 14) being a factor in determining the volume of material required to 3D-print these 3D-printed T-shirt, the amount of material waste assumed is also another important factor. It takes 1944g or 1.9kg of TPU-92A-1 powder to 3D-print one T-shirt using the Sinterstation 2500Plus—out of which 45% goes to waste for each print—while it only takes 431g of fiber solution to 3D-print one polyester-cellulose T-shirt using the Electroloom Alpha Unit.

Although Danit Peleg's designs require less material use, they are highly porous and require layering to prevent indecent exposure (Figure 18). Hence, the Kinematics design that offers slightly more coverage has been selected as a more realistic option for 3D-printing T-shirts in this study, with the exception of the electrospun polyester-cellulose T-shirt.

Due to FGF technology being based upon electrospinning, it does not 3D-print in the way that other 3DP technologies do and cannot 3D-print items using the Kinematics app that requires a higher print head accuracy that only the SLS technique can achieve out of all the 3DP techniques included in this study.

Furthermore, the 3DP material that FGF uses has a very different chemical structure and material property than that of the other three 3DP materials. TPU-92A-1, TPU-85A, and PA 2200 not only have greater material densities than that of polyester-cellulose, but also have chemical bonds that are much more persistent and less biodegradable than the water-soluble polyester-cellulose fiber solution.

The difference in densities between the three 3DP materials and polyester-cellulose fiber solution is even greater when taking into consideration that much of the polyester-cellulose fiber solution evaporates during the 3DP process, leaving behind only solid fiber and polymer components that can be accountable for weight and density calculations. However, in the material preparation phase, the density and required volume of the polyester-cellulose fiber solution has been fully accounted for in its liquid state in this investigation.

While FDM cannot achieve the 3DP precision that SLS can (in order to achieve rotational functionality for each of the thousands of hinges in the Kinematics design), it is possible to 3DP a T-shirt with the likeness of the Kinematics design without the embodied rotational hinges and overall flexibility. Since this is a comparative study, it is assumed that the T-shirt printed using FDM technology is one based on Kinematics design, for comparability with other 3DP techniques.

The LCI data sources used in the calculations for this life cycle phase are indicated in Table 11 below:

Table 11. LCI data sources for material preparation phase.

LCI Parameter	Source
Cotton and polyester fiber-to-fabric production, energy & water consumption	Muthu, S.S. (2014). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain. van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane.
Nylon-6 & Nylon-66 (as substitutes for PA-2200, TPU-92A-1, & TPU-85A), energy & water consumption	Muthu, S.S. (2014). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain.
Polyester-cellulose fiber solution density	A. Rowley, personal communication, August 25, 2015
Fiber-to-textile transportation distances	Qiao, F. & Paggi, M.S. (2009). Cotton Transportation Cost in China.
Energy consumption of heavy diesel truck	Ashby, M. F. (2012). Materials and the Environment: Eco-informed Material Choice.

Garment Production Phase

In the garment production phase, there is no documented use of water as most of the processes involve only the use of either cutting and sewing machinery or 3D printers. The LCI data and calculations for the garment production phase are summarized in Table 12 below:

Table 12. LCI data & calculations: production phase.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
2. Garment Production Phase						
Weight of One Finished T-Shirt (g)	175	159	1134	1341	134	1357
Est. Material Waste (%)	25%	25%	45%	45%	5%	25%
Power Rating (kW)	–	–	6.1	14.8	0.68	0.35
Manufacturing Time (h)	–	–	24	30	17	240
Electricity Use (kWh)	–	–	146	447	12	84
Energy Consumption, Processes (MJ)	2.5	2.3	526	1611	41	301
Transportation, by Lt. Goods Vehicle (km)	773	773	–	–	–	–
(kg-km)	135	123	–	–	–	–
Energy Consumption, Transportation (MJ)	0.34	0.31	–	–	–	–
Energy, Production (MJ)	**2.9**	**2.6**	**525.7**	**1611**	**41.4**	**300.7**

For the four 3D printing processes, the total electricity use (in kWh) is derived multiplying the power rating of the 3D printer by the total time of the print job:

Power Rating (in kW) x Manufacturing Time (h)

The electricity use in kWh is then converted into energy consumption in MJ by using the following unit conversion formula:

1 kWh = 3.6 MJ

The power ratings for the EOSINT P760 and Sinterstation 2500Plus SLS machines (material: PA-2200) are both obtained from a study by Kellens et al. (2011) that uses multiple linear regression analysis to derive power levels of various SLS machines when in actual operation.

For the EOSINT P760, it is unclear whether the layer thickness was determined to be 0.12mm or 0.15mm for the 3DP of the PA-2200 Kinematics dress (Figure 15, p.37) that is used as a basis for the hypothetical PA-2200 T-shirt in this study, the average value is used to estimate energy consumption for this process.

$$6.2\ \text{kW} + 5.97\ \text{kW} = 6.1\ \text{kW}$$

The power rating for the Sinterstation 2500Plus that uses the TPU-92A-1 powder for SLS is derived from taking the average of manufacturer-provided specifications and Kellens et al.'s study on the Vanguard HiQ (later model of Sinterstation 2500Plus):

$$(10\ \text{kW} + 19.6\ \text{kW}) \div 2 = 14.8\ \text{kW}$$

The power rating for the Electroloom Alpha Unit's FGF process is provided directly by founder A. Rowley to be approximately 0.68 kW, which is inclusive of the hotplate, electronics, and computer equipment used in the 3D printing of the "polyester-cellulose" T-shirt.

The power rating of the Witbox home 3D printer comes from a manufacturer-provided technical specification sheet, stated as 0.348 kW.

LCI data on raw material quantities required to produce one T-shirt using most of the materials included in this study are scarce and are calculated using estimations of percentage raw material waste in this meta-LCI. The amount of raw material *(in g)* required to produce one T-shirt is derived using the following formula:

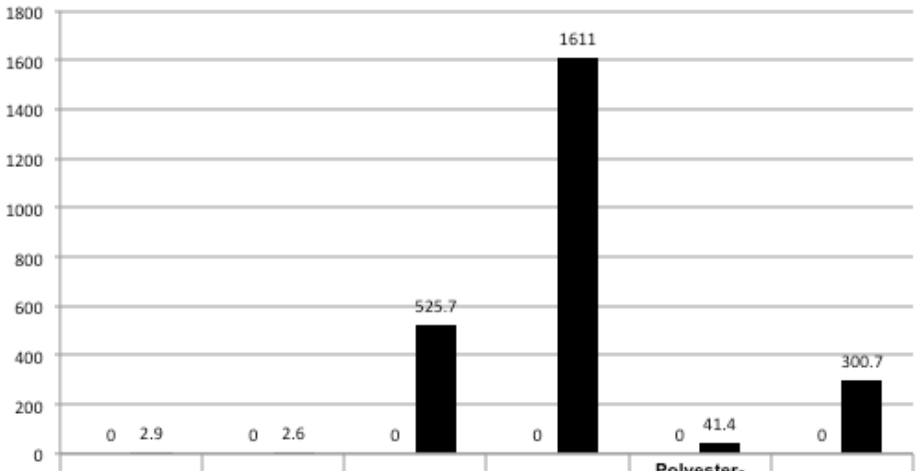
$$\text{Wt. of one T-shirt} \times (1 + \%\ \text{Est. Material Waste})$$

The energy required to transport the finished T-shirt is estimated using transportation data from M.F. Ashby (2012)'s study on materials and the environment, which determines the energy use of a light goods vehicle to be 2.5 MJ/metric ton-km (Ashby, 2012, p.142) or 0.0025 MJ/kg-km (conversion formula: 1 metric ton = 1,000kg).

The energy consumption of transportation finished T-shirts from factory to port in the garment production phase is thus calculated using:

0.0025 MJ/kg-km x Wt. of T-Shirt (in kg) x Transportation Dist. (in km)

The findings on the water and energy intensities of the garment production phase of this comparative study are summarized in the cluster bar graph (Figure 40) below:



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, Production (L)	0	0	0	0	0	0
Energy, Production (MJ)	2.9	2.6	525.7	1611	41.4	300.7

Figure 40. Water & energy consumption: production phase.

The 3DP of one TPU-92A-1 T-shirt using the SLS method and Sinterstation 2500Plus machine is the most energy-intensive, at about 3 times that of using the more efficient EOSINT P760 machine and 12 times that of the FGF method used to 3D-print the polyester-cellulose T-shirt. The least energy-intensive 3DP method in the production life cycle phase of this meta-LCI study is FGF using the Electroloom Alpha Unit, but it still requires some 16 times more energy than cutting and sewing one polyester T-shirt,

and 14 times more energy than conventionally manufacturing one cotton T-shirt. However, it is important to note that these results are for the production phase only, and not for the entire life cycle of the T-shirts in question. The aggregated energy consumption levels accounting for the entire life cycle of the T-shirts are provided later in this chapter. The LCI data sources used in the calculations for this life cycle phase are indicated in Table 13 below:

Table 13. LCI data sources: production phase.

LCI Parameter	Source
Power rating of EOSINT P760 SLS machine	EOS. (2014). Systems and Equipment for Plastic Manufacturing.
Power rating of Sinterstation 2500Plus SLS machine	Kellens, K., Yasa, E., Renaldi, R., Dewulf, W., Kruth, J. P., & Duflou, J. (2011). Energy and Resource Efficiency of SLS/SLM Processes (Keynote Paper). Laboratory for Concurrent Engineering & Logistics (LCEL). (2000). SLS: Sinterstation 2500Plus System Specifications. 3D Systems. (2009). Sinterstation HiQ SLS Systems.
Power rating of Electroloom Alpha Unit	A. Rowley, personal communication, August 25, 2015
Power rating of Witbox home printer	BQ. (2015). bq Witbox: Technical Specifications.
Wt. of cotton & polyester T-shirts	Muthu, S.S. (2014). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain. van der Velden, N. M., Patel, M. K., & Vogtländer, J. G. (2014). LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane.
Wt. of PA-2200 dress	Certo-Ware, R. (2015). Nervous System Just Upped the 3D Fashion Ante with This 4D Dress.
Energy consumption of heavy diesel truck	Ashby, M. F. (2012). Materials and the Environment: Eco-informed Material Choice.

Distribution Phase

In the distribution phase, a number of assumptions had to be made regarding how conventionally manufactured and 3D-printed garments are distributed in the baseline scenario, created with the purpose of representativeness. The LCI data and calculations for the distribution phase are stated in Table 14 below:

Table 14. LCI data & calculations: distribution phase.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
3. Distribution Phase						
Transportation, Sea Freight (km)	10592	10592	–	–	–	–
(kg-km)	1854	1685	–	–	–	–
Energy Consumption, Sea Freight (MJ)	0.30	0.27	–	–	–	–
Transportation, by Lt. Goods Vehicle (km)	2485	2485	2485	2485	–	2485
(kg-km)	6.21	6.21	2.04	2.04	–	2.04
Energy Consumption, Transportation (MJ)	0.016	0.016	0.0051	0.0051	–	0.0051
Energy, Distribution (MJ)	**0.312**	**0.285**	**0.005**	**0.005**	**0**	**0.005**

For the distribution phase, the following assumptions have been made to project a representative baseline scenario for the production of one standard T-shirt:

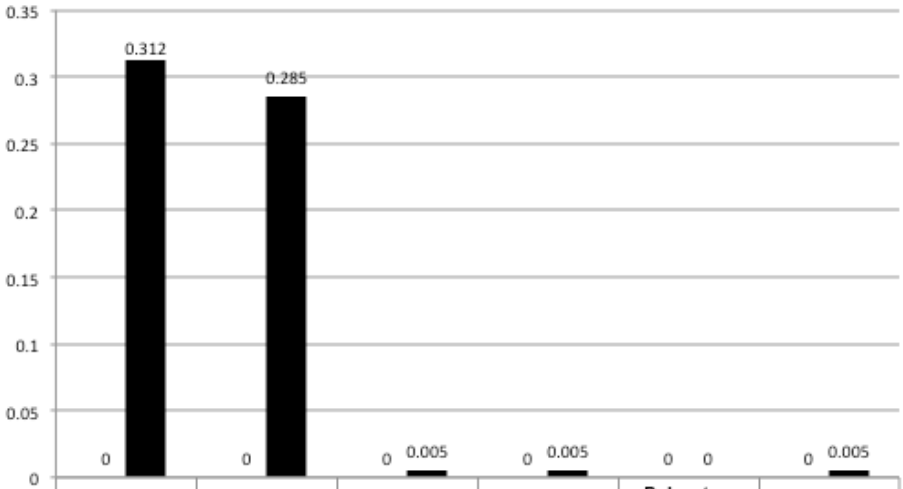
- The cotton and polyester T-shirts are cut and sewn in Shanghai, China, then shipped to the Los Angeles Port in the U.S. via ocean freight over a distance of 10,592.24 km (calculated using www.searates.com/reference/portdistance).
- The average land transportation distance from the distribution warehouse to the continental U.S.A.-based consumer is calculated by taking the average of the longest estimated land route (Los Angeles, CA to Portland, ME ≈ 4963km, using the travel-by-car setting in the route planning tool Google maps) and shortest estimated land

route (from a warehouse to the nearest residence ≈ 7km, using the travel-by-car setting in the route planning tool Google maps) from factory to user to give 2485km.

- The finished T-shirts are only shipped to end users in the continental U.S.A.
- It is assumed that all the T-shirts have a lifespan of 100 wears and require 50 washes throughout their lifetime.
- From personal communication with Electroloom founder A. Rowley, it is established that the polyester-cellulose T-shirt is not machine washable and will disintegrate if machine-washed.
- Due to its apparent fragility, it is assumed that the polyester-cellulose T-shirt must be reprinted instead of washed and dried in the use phase by the end user, which in turn implies that end users must each own an "Electroloom Alpha Unit" in order to be able to reprint clothing from home.
- Since end users reprint instead of wash and dry the polyester-cellulose T-shirt from home, this T-shirt will not require distribution.
- With the exception of the polyester-cellulose T-shirt created using FGF technology, the 3D printed T-shirts are all printed in and shipped from the same warehouse location in Los Angeles, U.S.A., where the cotton and polyester T-shirts are stocked after being exported from Shanghai, China.

The findings on the water and energy intensities of the distribution phase of this comparative meta-LCI study are summarized in the cluster bar graph below (Figure 41). The data in the graph indicate that the energy consumed for the distribution of cotton and polyester T-shirts are the most significant in this life cycle phase, as a result of the greater cumulative transportation distance (i.e. land and ocean freight from China to the U.S.)

required to import the finished cotton and polyester T-shirts from China based on the above assumptions for the distribution phase of this meta-LCI. Although less impactful than transportation distance, the material density and weight of the T-shirts to be transported also affects the energy demand in the distribution phase. It requires slightly less energy to transport the polyester T-shirt than the cotton T-shirt as the polyester T-shirt has a lower density and weight than the cotton T-shirt.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, Distribution (L)	0	0	0	0	0	0
Energy, Distribution (MJ)	0.312	0.285	0.005	0.005	0	0.005

Figure 41. Water & energy consumption: distribution phase.

Overall, it requires about 60 times less energy to distribute the 3D-printed T-shirts than to do so for the conventionally manufacture cotton and polyester T-shirts, based on the assumption that the conventionally manufactured T-shirts are to be manufactured in China before being shipped to the Los Angeles port and that 3D printed T-shirts are to be

produced at the Los Angeles warehouse, hence excluding the need for energy-intensive transpacific ocean freight.

Use Phase

In the use phase, a number of assumptions had to be made regarding how conventionally manufactured and 3D-printed garments are being cared for by end users in the baseline scenario, created with the purpose of representativeness. The LCI data and calculations for the use phase are stated in Table 15 below:

Table 15. LCI data & calculations: use phase.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
4. Use Phase						
Garment Care Requirements:						
No. of Wears	100	100	100	100	100	100
No. of Washes / Reprints	50	50	50	50	50	50
Energy Consumption, Machine Wash (MJ)	62.2	124.3	–	–	–	–
Vol. of T-shirt (cm^3)	113.6	113.6	1117.2	1117.2	113.6	1117.2
Water Consumption, Towel Wipe (L)	–	–	0.24	0.24	–	0.24
Water Consumption, One Reprint (L)	–	–	36	43	3	38
Water Consumption, H.E. Machine Wash (L)	6.1	6.1	–	–	–	–
Water Consumption, Std. Machine Wash (L)	7.6	7.6	–	–	–	–
Water, Use Phase (L)	**380**	**380**	**12**	**12**	**136**	**12**
Energy Consumption, Machine Dry (MJ)	238.0	295.1	–	–	–	–
Energy Consumption, One Reprint (MJ)	–	–	195	230	23.4	201
Energy, Use Phase (MJ)	**300.2**	**419.4**	**0**	**0**	**1168.4**	**0**

For the use phase, the following assumptions are made for the baseline scenario:

- The T-shirts are worn 100 times before disposal, or once a week for two years, or everyday for two seasons
- The T-shirts are washed once every two wears, or 50 times in their lifetimes before disposal

- The cotton and polyester T-shirts are washed in a full laundry load each time using a standard washing machine at 60ºC and tumble dried
- In order for the 3D-printed polyester-cellulose T-shirt to meet the 100-day criteria, it is dissolved and reprinted instead of machine-washed and tumble-dried once every two wears due to material physical limitations (A. Rowley, personal communication, August 25, 2015)
- There is assumed to be a 5% fiber loss, 5% polymer degradation, and 100% solvent loss every two wears of the 3D-printed polyester-cellulose T-shirt that need to be replaced for each reprint
- The other three 3D-printed T-shirts cannot be machine-washed or tumble dried as well, but are durable enough to be worn 100 times before disposal unlike the polyester-cellulose T-shirt. Instead of machine-wash and tumble-dry, their care requires wet towel wiping that uses about 0.24L of water each time.

The energy consumption figures for machine-washing the cotton and polyester T-shirts are extracted from the Alliance for Water Efficiency project on clothes washers. A standard washing machine uses approximately 40 to 45 gallons (151.4L to 170.3L) of water per cycle and has a water factor (W.F.) of $\geq$10 (AWE, 2011), whereby W.F. is defined as gallons of water per ft^3 laundry. High efficiency (H.E.) washing machines use 14 to 25 gallons (53L to 94L) of water per load (AWE, 2011) and have a water factor of 8. For this meta-LCI study, the water (in L) required to wash one cotton or polyester T-shirt is calculated as follows:

$$\text{Vol. of T-shirt (in } ft^3\text{)} \times \text{W.F. (in L/ } ft^3\text{)} \times \text{No. of Washes}$$

Unit conversion:	1 cm^3 = 0.000035315 ft^3 1 gallon = 3.785412L
Water Factor:	H.E. washing machine = 8 gal/ft^3 = 30.283 L/ft^3 Std. washing machine = 10 gal/ft^3 = 37.854 L/ft^3

The energy consumption figures for the tumble-drying the cotton and polyester T-shirts are the averages of two LCI data points taken from the Steinberger et al. spatially explicit LCI study (2009) of the global textile chain and the IMPRO Textiles report by Cordella et al. (2014). While the IMPRO Textiles report proposes figures based on half load per cycle scenarios, use phase choices vary regionally. For the baseline scenario of this meta-LCI, the end user is based in the continental U.S..

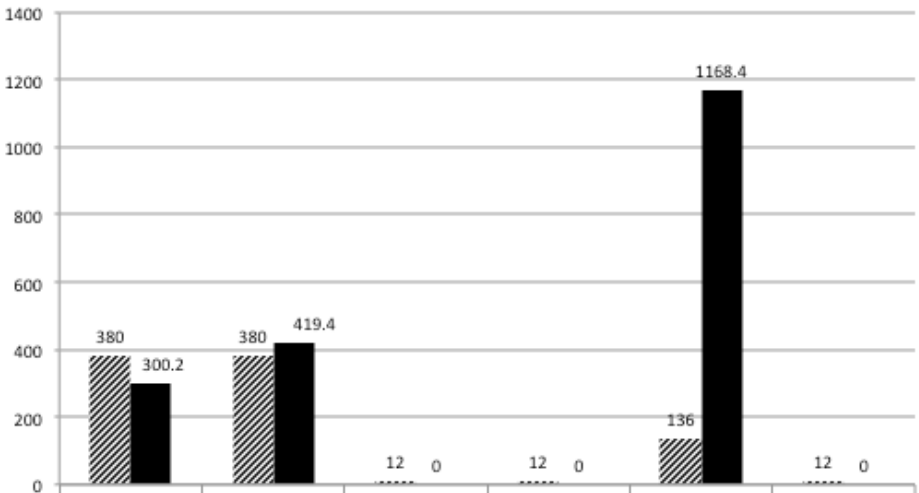
Hence, the selected tumble-dry energy use figure from the IMPRO report is 2.01 kWh/cycle, which was most originally provided by Pricewaterhouse Coopers (2009). Steinberger et al. states that it takes 114.23 MJ of energy to tumble dry the cotton T-shirt 50 times and 27.41 MJ of energy to tumble-dry a polyester jacket 6 times. Consequently, the calculation for the energy consumption of tumble-drying the cotton T-shirt is:

$$[(114.23\text{MJ} \div 50 \text{ times}) + (2.01\text{kWh} \times 3.6)] \div 2 \times 50 \text{ tumble-dries}$$

and the calculation for the energy consumption of tumble-drying the polyester T-shirt is:

$$[(27.41\text{MJ} \div 6 \text{ times}) + (2.01\text{kWh} \times 3.6)] \div 2 \times 50 \text{ tumble-dries}$$

The findings on the water and energy intensities of the use phase of this comparative meta-LCI study are summarized in the cluster bar graph (Figure 42) below:



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, Use Phase (L)	380	380	12	12	136	12
Energy, Use Phase (MJ)	300.2	419.4	0	0	1168.4	0

Figure 42. Water & energy consumption: use phase

From the graph above (Figure 42), it can be deduced that the polyester-cellulose T-shirt requires the most energy in the use phase of the baseline scenario out of all six use phase care methods, at about 3.9 times more energy required for washing and drying the cotton T-shirt and about 2.8 times more energy than washing and drying the PET T-shirt. This energy intensity can be attributed to the fact that the polyester-cellulose T-shirt needs to be reprinted after every 2 wears, or 50 times total throughout its entire lifespan, requiring a significant amount of raw material that need to be replenished each time. The energy consumption of the polyester-cellulose T-shirt presented in the table above includes the energy required to produce the fiber solution as well as reprint the T-shirt 50 times for 100 wears.

The cotton and polyester T-shirts consume the largest amounts of water in the use phase owing to the 50 machine-washes and tumble-dry required for 100 wears, at about

2.8 to 31.7 times more than that required for 3D printed T-shirts that cannot be machine-washed or tumble-dried. Based on the assumptions made for this life cycle phase, the PA 2200, TPU-92A-1, and TPU-85A T-shirts are all maintained by damp towel wiping that require only about 1 cup of water per cleaning. However, whether these 3D-printed T-shirts can truly last 100 wears with such minimal cleaning is uncertain, as there is no data available regarding the durability of the material relating to number of wears.

The LCI data sources used in the calculations for this life cycle phase are indicated in the table below:

Table 16. LCI data sources: use phase.

LCI Parameter	Source
Days of wear, frequency and number of washes	Steinberger, J. K., Friot, D., Jolliet, O., & Erkman, S. (2009). A spatially explicit life cycle inventory of the global textile chain.
Energy use for standard and high efficiency washing machines	Alliance for Water Efficiency (AWE). (2011). Clothes Washer.
Energy use for drying machine	Cordella, M., Dodd, N., Wolf, O., & Kougoulis, J. (Eds.). (2014). Environmental Improvement Potential of textiles (IMPRO Textiles). Steinberger, J. K., Friot, D., Jolliet, O., & Erkman, S. (2009). A spatially explicit life cycle inventory of the global textile chain.

End of Life (EOL) Phase

In the EOL phase, a number of assumptions had to be made regarding how conventionally manufactured and 3D-printed garments are disposed of in the baseline scenario, created with the purpose of representativeness. The LCI data and calculations for the EOL phase are stated in Table 17 below:

Table 17. LCI data & calculations: EOL phase.

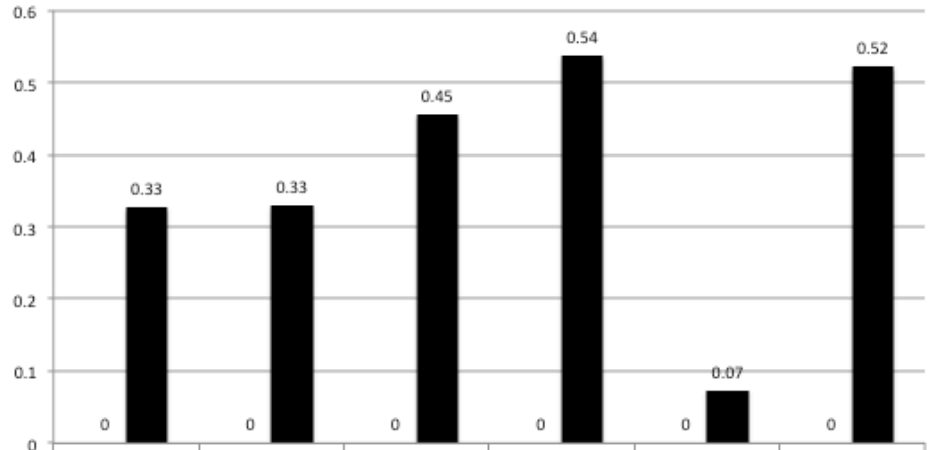
	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
5. End of Life						
Est. Transportation, by Truck (km)	600	600	600	600	600	600
(kg-km)	105	95	680	804	81	814
Energy Consumption, Transportation (MJ)	0.28	0.28	0.14	0.16	0.04	0.14
Landfill + Incineration (MJ)	0.04	0.04	0.32	0.38	0.04	0.38
Energy, EOL (MJ)	**0.33**	**0.33**	**0.45**	**0.54**	**0.07**	**0.52**

In the end-of-life (EOL) phase, the following assumptions have been made to create the baseline scenario:

- The T-shirts are all disposed of at the EOL by standard landfill and incineration.
- The T-shirts are not recycled at the EOL.
- It is important to note that the polyester-cellulose T-shirt is considered to be no longer able to be dissolved for reprint at the EOL stage, but discarded instead.
- The reprinting process required in the “care” of the polyester-cellulose T-shirt is considered to substitute machine-washing and tumble-drying “care” that is required for a conventional T-shirt, and does not represent recycling at the EOL phase since the T-shirt is not disposed for good until after 50 reprints.
- It takes an estimated 600km to transport the discarded T-shirts from the end user’s location to the final landfill and incineration site based on estimations provided in Cordella et al.’s 2014 IMPRO textiles report.
- A 32-metric ton truck is used to transport the discarded T-shirts from the end user’s location to the final landfill and incineration site (Ashby, 2012).
- It requires 0.06 MJ of energy to discaard a 250g cotton T-shirt (Steinberger et al., 2009), or 0.06 MJ ÷ 250g x 175g = 0.04 MJ for a 175g cotton T-shirt.

- It requires 0.14 MJ of energy to landfill and incinerate a 500g polyester jacket (Steinberger et al., 2009), or 0.14 MJ ÷ 500 x Wt. of T-shirt to landfill the other five T-shirts (i.e. polyester, PA-2200, TPU-92A-1, polyester-cellulose, TPU-85A).

The findings on the water and energy intensities of the EOL phase of this comparative meta-LCI study are summarized in the cluster bar chart below (Figure 43):



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, EOL (L)	0	0	0	0	0	0
Energy, EOL (MJ)	0.33	0.33	0.45	0.54	0.07	0.52

Figure 43. Water & energy consumption: EOL phase.

The 3D printed TPU-92A-1 T-shirt created by the Sinterstation 2500Plus requires the most energy to landfill and incinerate in the EOL phase, followed closely by the TPU-85A T-shirt created by the Witbox home printer using FDM technology. Both materials belong the to thermoplastic elastomer class and weigh most in this study, thus requiring the most energy to transport, landfill, and incinerate.

Conversely, the lightweight and low-density polyester-cellulose T-shirt 3D-printed using the Electroloom Alpha via FGF technology requires the least amount of

energy to transport, landfill and incinerate upon disposal of all six T-shirts in question, requiring about 7.7 times less energy than disposing the TPU-based T-shirts.

Like the distribution phase, the energy demands of the disposal or EOL phase plays a much less significant role than the material preparation phase, production phase, and use phase of the four methods and six materials under study. The energy demands of the distribution phase are tens to thousands of times less than that of other life cycle phases, rendering it one of the life cycle phases of least concern.

The cumulative resource demands accounting for the full life cycle of all methods and materials being compared in this study can be found later in this chapter for a fuller perspective and greater understanding of where the resource intensive hotspots are.

Results from Findings

The totals for water and energy consumption of the 4 clothing production methods and 6 materials are summarized in Table 18 below:

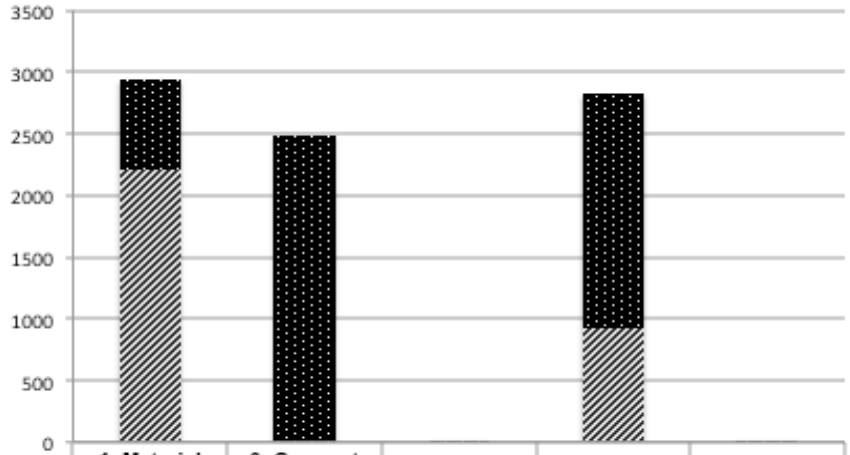
Table 18. Total water & energy consumption: 4 methods, 6 materials.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
TOTAL						
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**

Across all categories, the most resource intensive (i.e. water and energy) life cycle phase is the material preparation phase, characterized by water use for the cotton T-shirt.

Of nearly equal intensity is the use phase, characterized by the energy consumption of required by machine-washing and tumble-drying of conventionally-manufactured T-shirts, as well as the 50 reprints required for the 3D-printed polyester-cellulose T-shirt to sustain 100 wears. Following closely is the garment production phase, characterized by the energy-intensive 3DP processes.

The overall resource intensity of each life cycle phase is analyzed in the graph (Figure 44) below:



	1. Material Preparation Phase	2. Garment Production Phase	3. Distribution Phase	4. Use Phase	5. End of Life
Energy Consumption (MJ)	733	2484	1	1888	2
Water Consumption (L)	2202	0	0	931	0

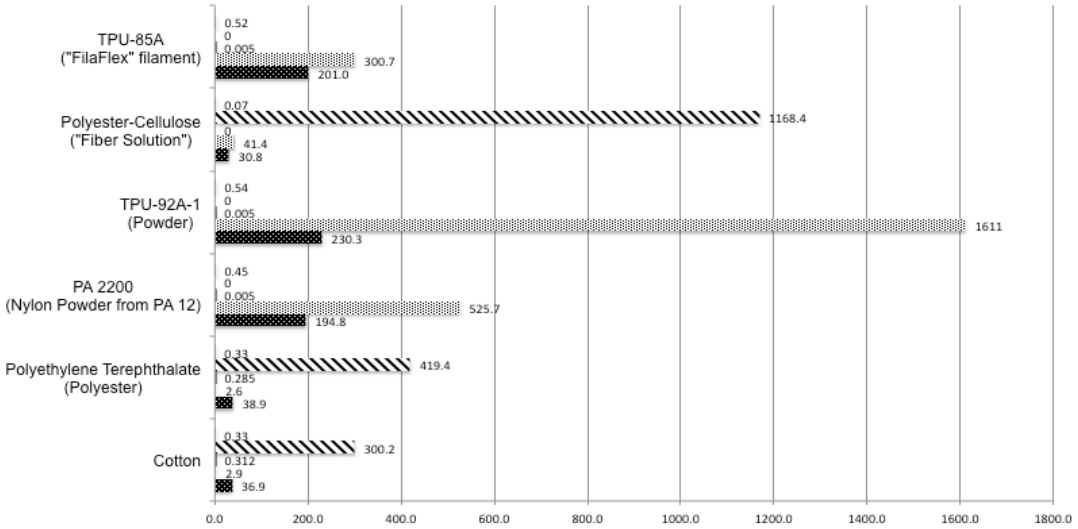
Figure 44. Total resource intensity by life cycle phase: baseline.

While this meta-LCI does not take into account other natural resources (e.g. metals and minerals) used as a LCA would, water and energy consumption are key areas of concern in garment production.

The graph below indicates that the most energy-intensive single category is the production phase of the TPU-92A-1 T-shirt created using SLS technology, owing to the

large amount of energy consumed by the Sinterstation 2500Plus during 3DP process, as well as the volume of the T-shirt required to be printed, based on the hinged-fabric design created using the Kinematics applet. Should it be possible to 3D-print a durable T-shirt that can sustain 100 wears and 50 cleanings using other design specifications that do not require cut-and-glue assembly post-print, the energy demand for this hotspot should decrease correspondingly. To illustrate the energy intensity of the commercial-grade 3D-printer Sinterstation 2500Plus, the energy used in the production phase of one TPU-92A-1 T-shirt alone exceeds that required for 50 reprints of the polyester-cellulose T-shirt in the use phase by about 1.4 times.

The findings on the energy demands of all six materials throughout all life cycles phases are illustrated in the following bar graph (Figure 45):

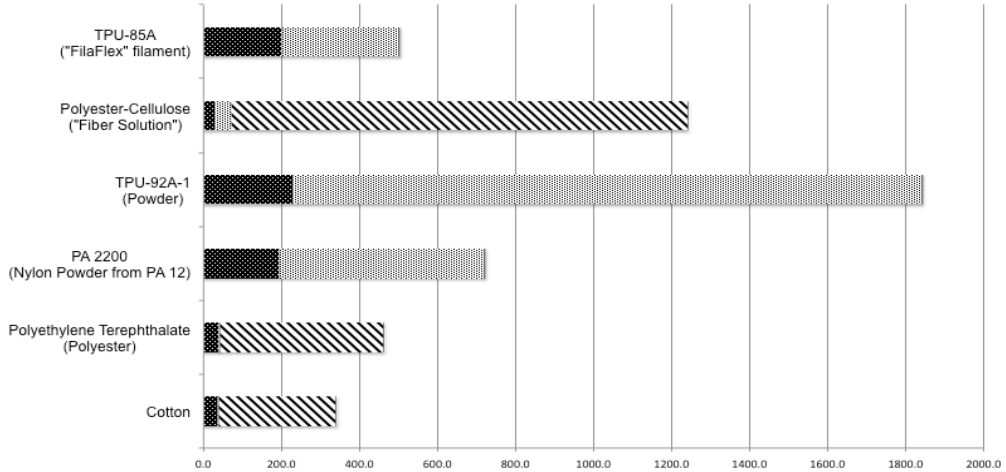


	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy, EOL (MJ)	0.33	0.33	0.45	0.54	0.07	0.52
Energy, Use Phase (MJ)	300.2	419.4	0	0	1168.4	0
Energy, Distribution (MJ)	0.312	0.285	0.005	0.005	0	0.005
Energy, Production (MJ)	2.9	2.6	525.7	1611	41.4	300.7
Energy, Material Prep (MJ)	36.9	38.9	194.8	230.3	30.8	201.0

Figure 45. Total energy consumption by life cycle phase: baseline.

The next single-category energy hotspot is the use phase of the polyester-cellulose T-shirt that is 3D-printed using the FGF technology. While the Electroloom Alpha Unit is the 3D-printer that requires the least amount of electricity in both the material preparation and production phases, the 50 reprints required to meet the 100 wears criteria for the basis of this comparative study renders it the most energy-consumptive method in the use phase.

Not only is energy required for the 3DP process, but also for compensating raw material loss and degradation every two wears. The solvent in the "polyester-cellulose" fiber solution requires most compensation, followed by the polymer content (assumed a 5% loss every two wears, with a ±100% uncertainty), and the cellulose fiber (also assumed a 5% loss every two wears in this study, with a ±100% uncertainty).



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy, Material Prep (MJ)	36.9	38.9	194.8	230.3	30.8	201.0
Energy, Production (MJ)	2.9	2.6	525.7	1611	41.4	300.7
Energy, Distribution (MJ)	0.312	0.285	0.005	0.005	0	0.005
Energy, Use Phase (MJ)	300.2	419.4	0	0	1168.4	0
Energy, EOL (MJ)	0.33	0.33	0.45	0.54	0.07	0.52

Figure 46. Total energy consumption by life cycle phase: baseline.

The stacked bar graph above (Figure 46) provides further insight into the ratios of energy consumption for each of the six clothing production methods by life cycle phase.

By plotting the ratios of energy use in each life cycle phase, it is possible to identify that the most energy-consumptive life cycle phase across categories is the use phase, with ranked highest to lowest in energy consumption:

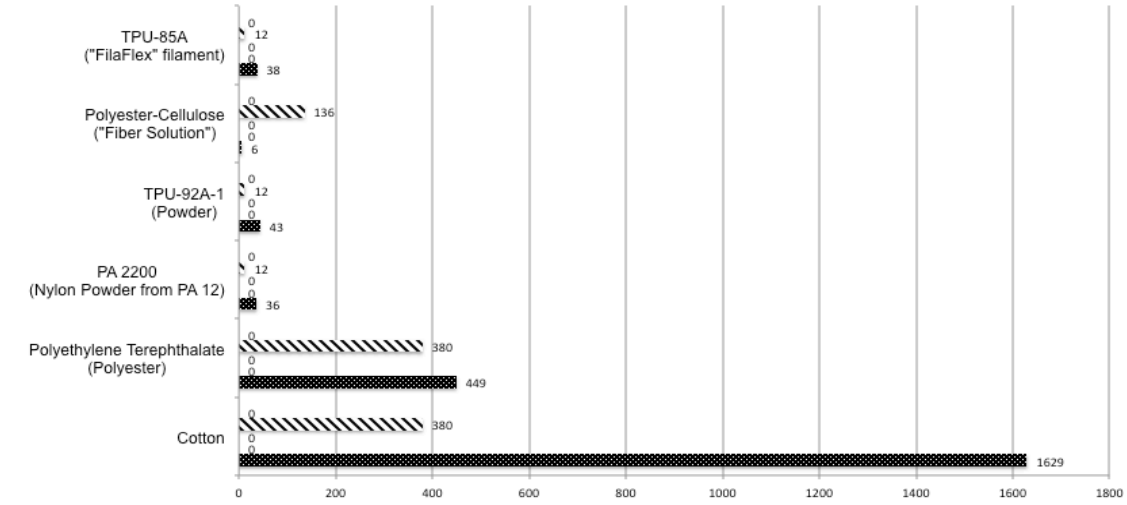
1) Electroloom Alpha Unit, FGF method (Polyester-cellulose)
2) Conventional cut-and-sew method (Polyester)
3) Conventional cut-and-sew method (Cotton)

Following closely is the production phase of the other three 3D-printed T-shirts, ranked in order of highest to lowest energy consumption levels below:

1) Sinterstation 2500Plus, SLS method (TPU-92A-1)
2) EOSINT P760, SLS method (PA-2200)
3) Witbox home printer, FDM method (TPU-85A)

The most water-intensive single-category is the material preparation phase of the cotton T-shirt. At about 3.6 times the water intensity of the polyester T-shirt and 271.5 times that of the 3D-printed polyester-cellulose T-shirt, the cotton T-shirt's water demand is clearly an outlier within the context of this LCI comparative study. Should the cotton be cultivated using rain fed water instead of irrigated water, however, it could significantly decrease the water-intensity of cotton apparel products to the polyester T-shirt's water consumption levels.

The findings on the water intensity levels of the all six materials and four clothing production methods for all life cycles phases combined in this comparative meta-LCI study are summarized in the cluster bar graph (Figures 47) below:



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, EOL (L)	0	0	0	0	0	0
Water, Use Phase (L)	380	380	12	12	136	12
Water, Distribution (L)	0	0	0	0	0	0
Water, Production (L)	0	0	0	0	0	0
Water, Material Prep (L)	1629	449	36	43	6	38

Figure 47. Total water consumption by life cycle phase: baseline.

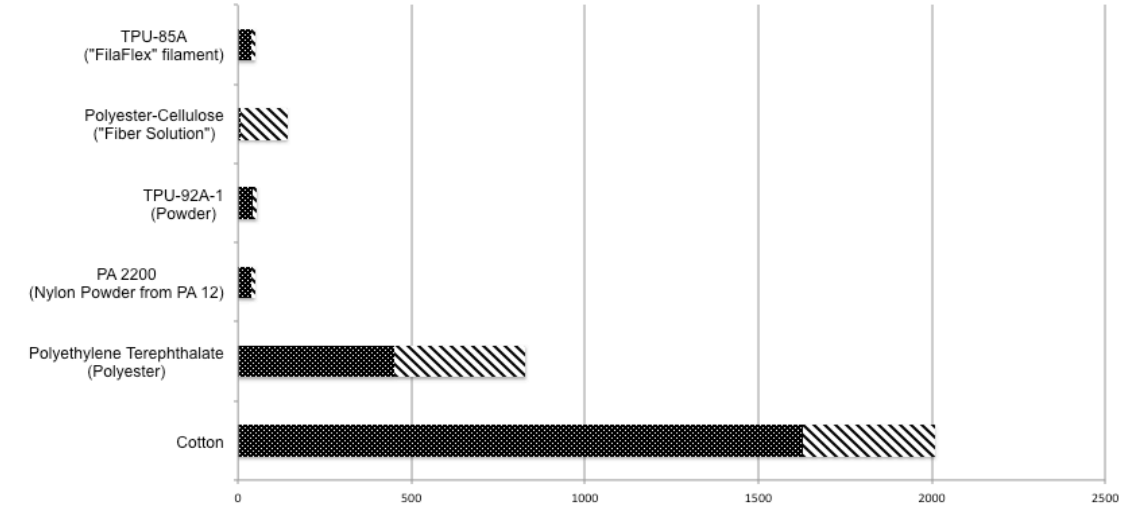
In general, the 3D-printed T-shirts require much less water throughout their lifetimes as compared with conventionally manufactured garments, requiring 6 to 42 times less water over all life cycle phases. Even though the polyester T-shirt requires less water use than the cotton T-shirt, it still consumes about 6 times more water than for 50 times of reprinting the polyester-cellulose T-shirt. The PA-2200 T-shirt requires the least water overall, at 42 times less than that required for the cotton T-shirt.

However, it is important to highlight that LCI data of nylon-6 was used as a substitute for the PA-2200 T-shirt's water and energy consumption in the material preparation phase, thus incurring a ±25% uncertainty. Even though PA-2200 belongs to the nylon family, there are numerous variations of nylon that have such significantly different material properties that they cannot be considered the same polymers. A

comparison of nylon-6 to nylon-66 (Lewin, 2006) provides an example of how much nylon's mechanical and physical properties can vary.

Should there be more LCI data concerning water and energy consumption available for PA-2200 and thermoplastic polyurethanes, a more accurate baseline model can then be constructed for the material preparation phase that accounts for the production of 3D-printer filament materials in this study, which would in turn provide better insight to key resource intensities and efficiencies of 3D garment printing methods as compared with conventional garment manufacturing methods.

The stacked bar graph below (Figure 48) provides further insight into the ratios of water consumption for each of the six clothing production methods by life cycle phase:



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Water, Material Prep (L)	1629	449	36	43	6	38
Water, Production (L)	0	0	0	0	0	0
Water, Distribution (L)	0	0	0	0	0	0
Water, Use Phase (L)	380	380	12	12	136	12
Water, EOL (L)	0	0	0	0	0	0

Figure 48. Total water consumption by life cycle phase: baseline.

By comparing the ratios of water consumption in each life cycle phase, it becomes apparent the material preparation phase is the most water-intensive life cycle phase across all categories, accounting for >50% of water use overall, with the only exception being the case of the polyester-cellulose T-shirt, whereby water consumption is highly concentrated in the use phase mainly as a result of having to replace 100% (±10% uncertainty) of the solvent in the polyester-cellulose fiber solution for each of the 50 reprints required to meet the criteria of 100 wears in this meta-LCI.

Overall, the material preparation phase and the use phase are the two most water-intensive life cycle stages, as little or no water is used in other life cycle stages.

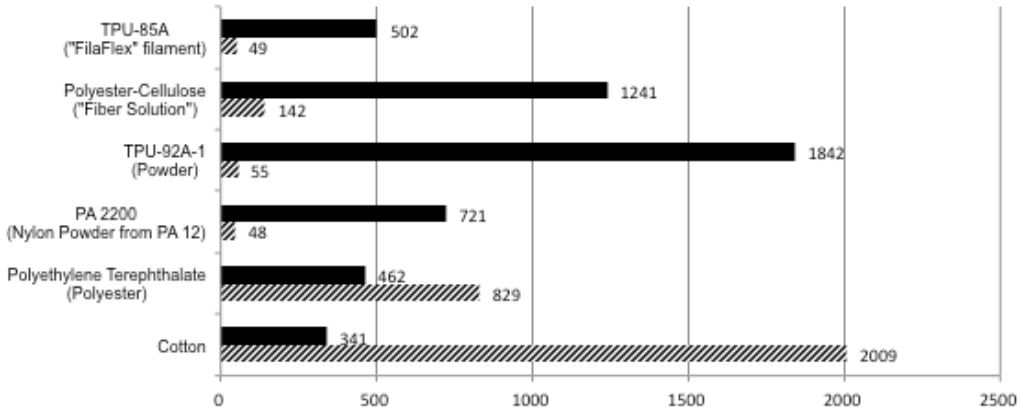
Baseline Scenario

Using the results and findings from this meta-LCI, a baseline scenario comprising of both water and energy consumption totals for all six apparel products is constructed based on the following parameters:

- 100 wears (once a week for 2 years, or everyday for 2 seasons)
- 50 washes (standard machine-wash, tumble-dry)

Based on the graph below (Figure 49) , and on prior total-LCI findings in Chapter 4.5, three key resource-intensity hotspots have been identified, listed below from high to low impact:

1. Conventional Cut-Sew, Cotton (Water consumption, Use phase)
2. SLS, TPU-92A-1 (Energy consumption, Production phase)
3. FGF, Polyester-Cellulose Solution (Energy consumption, Use phase)



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	341	462	721	1842	1241	502
Water Consumption, Total (L)	2009	829	48	55	142	49

Figure 49. Total LCI: baseline scenario.

Chapter V

Interpretation and Analysis

In this chapter, five alternative use phase scenarios will be compared against the baseline scenario, with the objective of addressing the following key areas of concern, listed below by order of significance:

- Conventional Cut-Sew, Cotton (Water consumption, Use phase)
- SLS, TPU-92A-1 (Energy consumption, Production phase)
- FGF, Polyester-Cellulose Solution (Energy consumption, Use phase)

Each of the five scenarios has each been constructed with different adjustments to key parameters in order to compare the change in resulting energy and water intensities for all six garment production methods against that of the baseline scenario. As described in the previous chapter, the baseline scenario is defined as 100 wears, 50 washes using the standard washing machine, tumble-dry. While the 3D-printed T-shirts cannot be machine-washed or tumble-dried, they require towel-wipes, or reprinting in the case of the polyester-cellulose T-shirt.

The first alternative scenario will focus on addressing the use phase of the conventionally manufactured cotton and polyester T-shirts, whereas the following four alternative scenarios will adjust the number of wears and number of washes. Decreasing the number of wears or lifespan of the T-shirts provides insight as to how much energy and water will be required to replace the discarded T-shirt to meet the same 100-wear

criteria of the baseline scenario. On the other hand, decreasing the number of washes tests for how much water and energy can be saved as compared the baseline scenario.

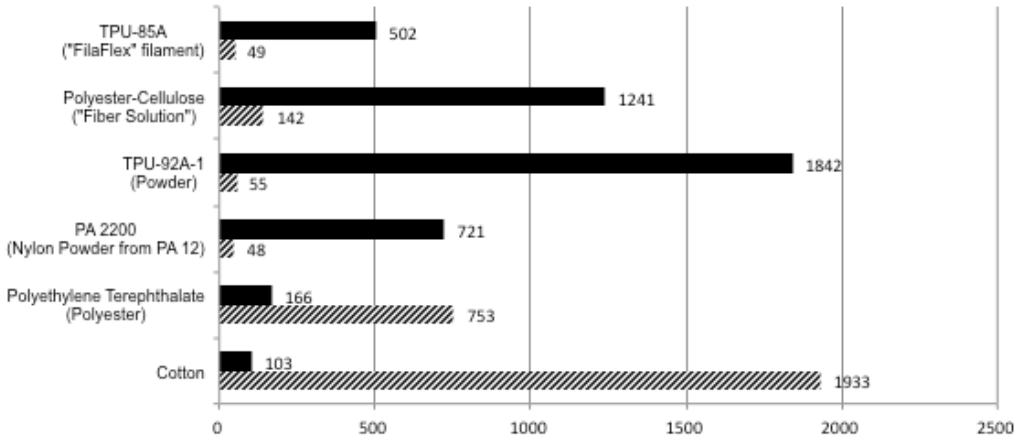
Alternative Scenario 1: High Efficiency Machine Wash, Line Dry

In the first alternative scenario, the standard washing machine has been replaced by a high efficiency (H.E.) model, and line drying is used instead of tumble-drying, with all other factors remaining unchanged from the baseline scenario. The resulting energy and water intensity by using these alternative washing and drying methods are indicated in Table 19 below:

Table 19. LCI data for alternative scenario 1: H.E. machine wash, line dry.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 1: H.E. Mach. Wash, Line Dry						
Water Consumption, Total (L)	**1933**	**753**	**48**	**55**	**142**	**49**
Water Efficiency (%)	4	9	0	0	0	0
Energy Consumption, Total (MJ)	**103**	**166**	**721**	**1842**	**1241**	**502**
Energy Efficiency (%)	70	64	0	0	0	0

From Figure 50 below, it is evident that using a H.E. washing machine and line drying instead of standard washing machine and tumble drying results in only +4% water efficiency for the cotton T-shirt, the energy efficiency is 17.5 times higher at +70%, revealing that the H.E. washing machine is better used for targeting energy savings rather than water savings.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	103	166	721	1842	1241	502
Water Consumption, Total (L)	1933	753	48	55	142	49

Figure 50. Alternative scenario 1: H.E. machine wash, line dry.

Similarly for the polyester T-shirt in this scenario, there is a +9% water efficiency and much higher +64% energy efficiency being observed. Since water consumption is high in both the use phase and the material preparation phase for the polyester T-shirt, water savings in both areas need to be addressed to improve overall performance. Less washes throughout the garment's life cycle is one way of reducing water consumption in its use phase, until more water-efficient washing machines are available. For the material preparation phase, industrial processes can be improved to include steam recovery and reduce or recycle cooling water, processing water, and treatment water throughout.

Despite switching to the more efficient washing machine, the cotton T-shirt still maintains high overall water intensity at 40 times that of the PA-2200 T-shirt created using the SLS method and EOSINT P760 commercial-grade 3D-printing machine. Since most of the water use occurs in the material preparation phase for the cotton T-shirt, targeting water efficiency will require examining water saving strategies for cotton crop

cultivation, such as relying on recycled water rainwater rather than freshwater and groundwater sources for irrigation, or considering the cultivating genetically-modified cotton seeds that require less water in its growth phase.

Alternative Scenario 2: 100 Wears, 25 Washes

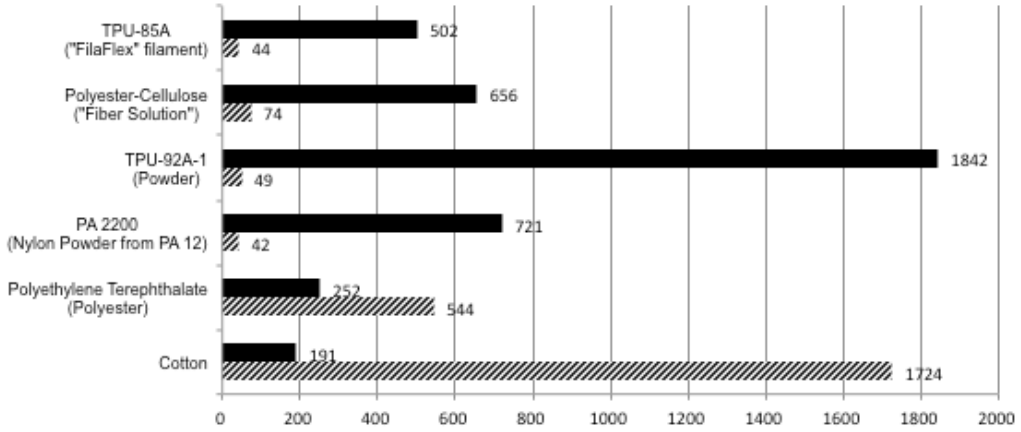
In this second alternative scenario, the parameters are adjusted to "100 wears, 25 washes" from "100 wears, 50 washes" in the baseline scenario, with all other factors remaining unchanged. The resulting energy and water demands from reducing the number of washes by half of that in the baseline scenario are stated in Table 20 below:

Table 20. LCI data for alternative scenario 2: 100 wears, 25 washes.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 2: 100 Wears, 25 Washes						
Water Consumption, Total (L)	**1724**	**544**	**42**	**49**	**74**	**44**
Water Efficiency (%)	14	34	12	11	48	12
Energy Consumption, Total (MJ)	**191**	**252**	**721**	**1842**	**656**	**502**
Energy Efficiency (%)	44	45	0	0	47	0

From Figure 51 below, it is apparent that for a one-time print, the Electroloom Alpha is the least energy-consumptive 3D printer out of all three included in this study. If the T-shirts were to be washed 50% less, it would result in +48% water and +47% energy efficiency for the 3D-printed polyester-cellulose T-shirt, as the number of reprints required have been halved for 100 wears. Not only does this save energy and water use in

the production phase, but also in the material preparation phase as less material in the fiber solution needs to be replenished.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	191	252	721	1842	656	502
Water Consumption, Total (L)	1724	544	42	49	74	44

Figure 51. Alternative scenario 2: 100 days of wear, 25 washes.

Improving the durability of the polyester-cellulose T-shirt such that it can be worn more times before a reprint is necessary will greatly reduce energy demands of the polyester-cellulose T-shirt overall, as the energy use is highly concentrated in the use phase. If the polyester-cellulose fiber T-shirt were made to last 10 days before a reprint is necessary, requiring a total of 10 reprints throughout its lifetime instead of 50, then the resulting energy demand of 306 MJ would be lower than even that of the cotton T-shirt at 341MJ in the baseline scenario. This is a significant benchmark to undercut and can be made a goal for the development of the Electroloom Alpha's FGF technology; it would mean that 3DP can become more energy efficient than conventional cut-and-sew manufacturing. This may also have implications on energy cost savings.

The polyester-cellulose T-shirt requires about 3 times more water than other 3DP methods. At 10 reprints for 100 wears, the polyester-cellulose T-shirt will not only be the least energy-intensive but also the least water-intensive. Reducing the number of reprints does not necessarily mean reducing the number of cleanings. The other three 3DP T-shirts require only a small amount of water for damp towel wiping every 2 wears. It may be possible for the polyester-cellulose T-shirt to be maintained with care methods that require little water and energy use.

Alternative Scenario 3: 50 Wears, 25 Washes

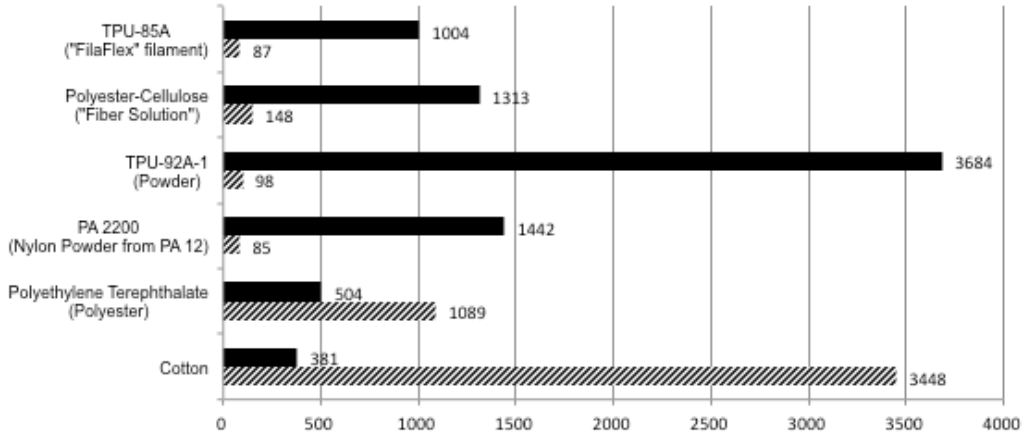
In this scenario, the parameters have been changed to "50 wears, 25 washes," with all other factors remaining unchanged from baseline. The lifespan and use phase requirements are halved, resulting in the following resource demands (Table 21):

Table 21. LCI data for alternative scenario 3: 50 days of wear, 25 washes.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 3: 50 Wears, 25 Washes						
Water Consumption, Total (L)	**3448**	**1089**	**85**	**98**	**148**	**87**
Water Efficiency (%)	-72	-31	-76	-78	-4	-76
Energy Consumption, Total (MJ)	**381**	**504**	**1442**	**3684**	**1313**	**1004**
Energy Efficiency (%)	-12	-9	-100	-100	-6	-100

From Figure 52 below, we may conclude that if the T-shirts were to have their lifespans and use phase requirements both reduced by half, it would result in -100% decrease in energy efficiency and -78% decrease in water efficiency for the 3D-printed

TPU-92A-1 T-shirt, causing it to become the most resource intensive single life cycle category overall in this alternative scenario.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	381	504	1442	3684	1313	1004
Water Consumption, Total (L)	3448	1089	85	98	148	87

Figure 52. Alternative scenario 3: 50 days of wear, 25 washes.

The reason that more water and energy demand is higher than the baseline for all methods and materials in this alternative scenario, despite number of wears and washes both halved, is because this scenario assumes that a new T-shirt identical to the one being disposed will be required to replace the original T-shirr in order to meet the 100-wears criteria for fair comparison. When the first T-shirt is discarded after 50 wears and 25 washes, replacing it with another T-shirt of the same lifespan and wash requirements would result in twice the energy and virgin filament material required, which will in turn result more resource used in all life cycle phases.

In this alternative scenario, 72% more water and 12% more energy than the baseline scenario is required for a cotton T-shirt that lasts only 50 wears, 25 washes, resulting in the need for one replacement to fulfill the criteria for 100 wears in this study.

For the PET T-shirt in this scenario, 31% more water and 9% more energy than the baseline scenario is required. On the other hand, the polyester-cellulose T-shirt experiences only a -6% decrease in energy efficiency and a -4% decrease in water efficiency in this alternative scenario, as the only extra water and energy incurred more than the baseline is that used in the end-of-life phase. Otherwise, the energy and water requirements remain the same as the polyester-cellulose T-shirt still requires 50 reprints for 100 wears overall.

One key observation here is that the TPU-92A-1 T-shirt is now almost 3 times more energy-intensive than the polyester-cellulose T-shirt, while the difference was only 1.5 times in the baseline scenario. This scenario reveals the severe implications of the Sinterstation 2500Plus' energy intensiveness when the SLS process needs to be repeated, especially when translated into energy costs in the case where it is scaled up for mass production. Much higher energy efficiency SLS 3D printers and 3DP materials will need to be developed should the Sinterstation 2500Plus and TPU-92A-1 want to become relevant for commercial-grade clothing manufacture. The EOSINT P760 that uses PA 2200 to create garments is one example of a more energy efficient SLS 3D-printer, requiring less than half the energy of the Sinterstation 2500Plus. However, it still requires more energy for just 2 prints than the Electroloom Alpha requires for 50 prints in this alternative scenario.

Even being the least energy-intensive 3D-printer in this study, the Electroloom Alpha can still greatly benefit from improving its energy demands should it aim to eventually replace conventional garment manufacturing. Requiring only 2.6 times more energy than the conventionally manufactured PET T-shirt, the Electroloom Alpha needs

only to make the polyester-cellulose T-shirt last 5 times longer before a reprint is necessary to replace conventional garment manufacturing within the foreseeable future.

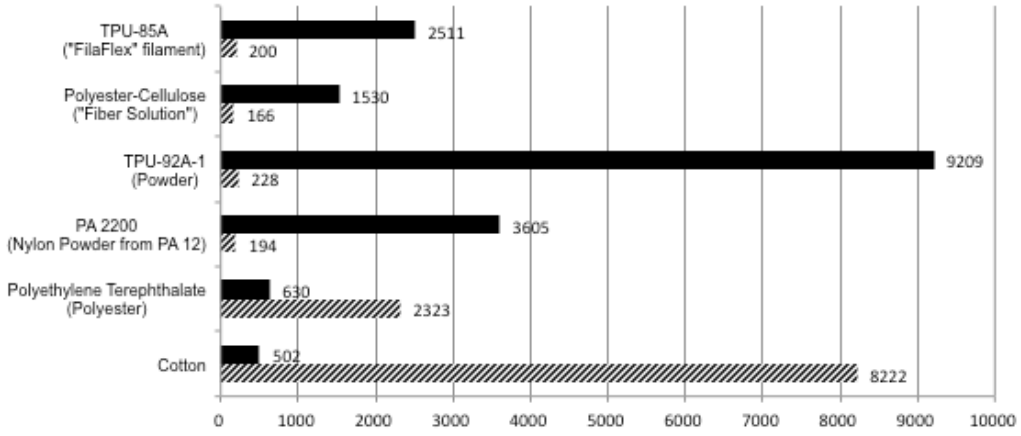
Alternative Scenario 4: 20 Wears, 10 Washes

In the fourth alternative scenario, the parameters have been further decreased to "20 wears, 10 washes," with all other factors remaining unchanged from the baseline scenario. The resulting energy and water demands are as presented in Table 22 below:

Table 22. LCI data for Alternative scenario 4: 20 days of wear, 10 washes.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 4: 20 Wears, 10 Washes						
Water Consumption, Total (L)	**8222**	**2323**	**194**	**228**	**166**	**200**
Water Efficiency (%)	-309	-180	-302	-314	-17	-304
Energy Consumption, Total (MJ)	**502**	**630**	**3605**	**9209**	**1530**	**2511**
Energy Efficiency (%)	-47	-37	-400	-400	-23	-400

From Figure 53 below, we derive at the fact that if the T-shirt were to be worn just 20 times, it would have to be replaced 5 times over. This is the main reason for the exponential water and energy consumption level decreases observed in this fourth alternative scenario for the use phase. This alternative scenario highlights the consequences of discarding garments frequently, whether out of need or habitual preference, as opposed to preserving and maintaining them for a greater lifetime of wears.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	502	630	3605	9209	1530	2511
Water Consumption, Total (L)	8222	2323	194	228	166	200

Figure 53. Alternative scenario 4: 20 days of wear, 10 washes.

A 400% increase in energy demand and ±300% increase in water demand is observed (Figure 53) for the PA 2200, TPU-92A-1, and TPU-85A 3D-printed T-shirts in this alternative scenario whereby a T-shirt is worn only 20 times and washed 10 times before it is being discarded, requiring 5 replacements in order to meet the 100 wears criteria for this meta-LCI. In comparison, the polyester-cellulose T-shirt requires only 23% more energy and 17% more water than in the baseline scenario, as the additional resources required comes mainly from the repeating the material preparation phase of the polyester-cellulose T-shirt 5 times over. Interestingly, the polyester-cellulose T-shirt is the least water and energy intensive 3DP method in this scenario, even when it is counted for 50 reprints and the other 3DP T-shirts are counted for only 5 reprints.

The key significance of this scenario is that it reveals the dramatic increase in resource intensity (at hundreds of times the baseline) of the shortened lifespan of an

apparel product. More importantly, it implies the reverse—that there exists great opportunities for resource efficiency improvement simply by increasing garment lifespan.

Alternative Scenario 5: 100 Wears, 0 Washes

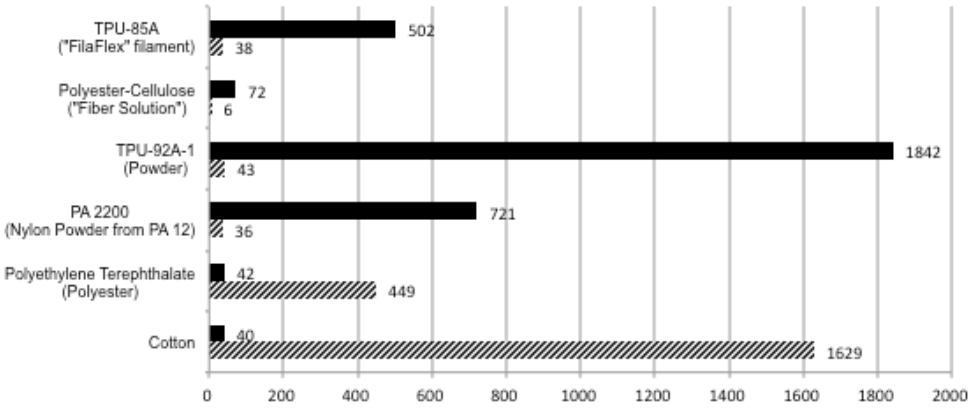
Defined by "100 wears, 0 washes," the purpose of this scenario is to consider the resource demand if the T-shirts are made to last 100 wears without aftercare. The data and results for this scenario are presented in Table 23 below:

Table 23. LCI data for Alternative scenario 5: 100 days of wear, 0 washes.

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 5: 100 Wears, 0 Washes						
Water Consumption, Total (L)	**1629**	**449**	**36**	**43**	**6**	**38**
Water Efficiency (%)	19	46	24	22	96	24
Energy Consumption, Total (MJ)	**40**	**42**	**721**	**1842**	**72**	**502**
Energy Efficiency (%)	88	91	0	0	94	0

From Figure 54 below, we can derive that the polyester-cellulose T-shirt has the highest energy efficiency and water efficiency values when benchmarked against the baseline scenario, as most of the resource intensity comes from the use phase of this product. If the need for reprinting is completely removed, 96% of water and 94% of energy can be saved from avoiding the 50 reprints required in the baseline scenario. If the polyester-cellulose T-shirt's durability can be increased without requiring more energy in the 3D-printing phase, even avoiding half the reprints required can translate into

significant improvement on resource intensity overall for the FGF garment manufacturing method using the Electroloom Alpha Unit.



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Energy Consumption, Total (MJ)	40	42	721	1842	72	502
Water Consumption, Total (L)	1629	449	36	43	6	38

Figure 54. Alternative scenario 5: 100 days of wear, 0 washes

Another way of interpreting the efficiency values presented in this alternative scenario is that the water and energy efficiency percentages are now equivalent to the percentage of water and energy required in the baseline scenario use phase of each garment manufacturing method. In other words, 19% of water and 88% of energy required to produce one conventionally manufactured cotton T-shirt in the baseline scenario can be attributed to its use phase. Likewise, 46% of water and 91% of energy required to produce one PET T-shirt is incurred by its use phase in the baseline scenario.

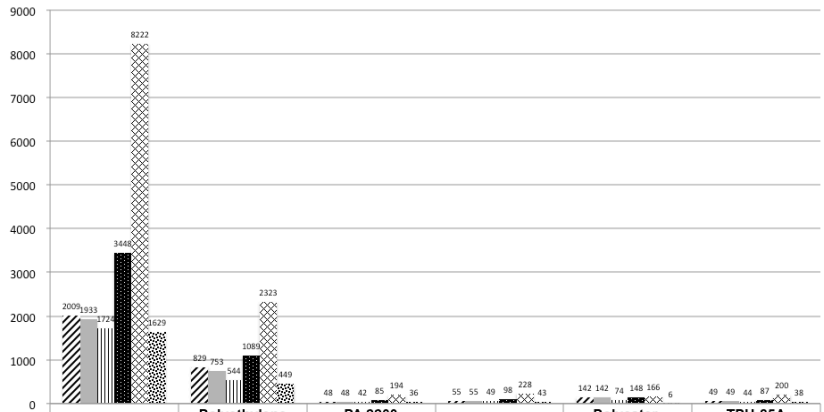
The clothing production methods with the highest resource consumption in their the use phase have the most to gain by focusing their efforts on reducing the resource

intensity of consumer care methods required for maintaining apparel created using their method.

Summary of Alternative Scenarios

The results on water consumption (Figure 55) and energy demand (Figure 56) from the five alternative scenarios are plotted against the baseline scenario below to give an overall summary of the findings in this chapter. Overall, alternative scenario 4 results in the highest resource intensity while alternative scenario 5 generates the lowest resource intensities.

The water intensity of conventionally manufactured T-shirts is generally many times greater than the water requirements for 3D-printed T-shirts (Figure 55):

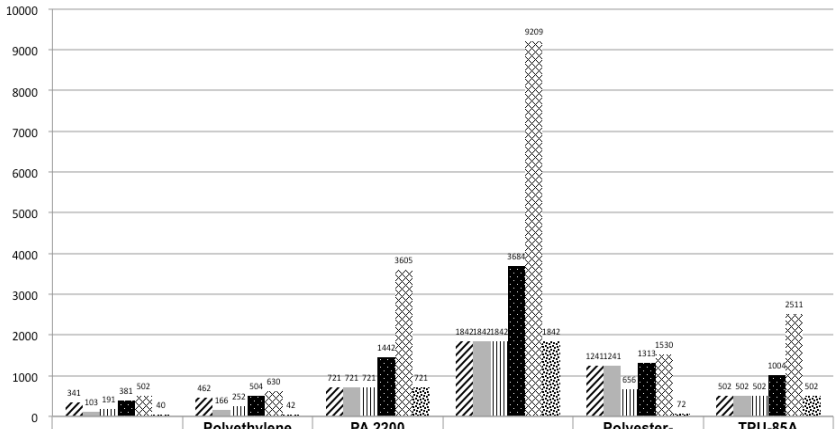


	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry	2009	829	48	55	142	49
Alt. Scenario 1: H.E. Mach. Wash, Line Dry	1933	753	48	55	142	49
Alt. Scenario 2: 100 Wears, 25 Washes	1724	544	42	49	74	44
Alt. Scenario 3: 50 Wears, 25 Washes	3448	1089	85	98	148	87
Alt. Scenario 4: 20 Wears, 10 Washes	8222	2323	194	228	166	200
Alt. Scenario 5: 100 Wears, 0 Washes	1629	449	36	43	6	38

Figure 55. Water consumption: baseline vs. alternative scenarios.

The conventionally manufactured cotton T-shirt remains the most water-intensive category throughout all scenarios, as its water intensity comes from mainly cotton crop cultivation in the material preparation phase. Targeting the use phase can only mildly improve water efficiency, but provides significant energy savings.

The energy intensity of 3D-printed T-shirts is generally many times greater than the energy required for conventionally-manufactured T-shirts, especially if the lifespan of the 3D-printed garments requires reprints to meet the same number of wears for the conventionally-manufactured T-shirts (Figure 56):



	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry	341	462	721	1842	1241	502
Alt. Scenario 1: H.E. Mach. Wash, Line Dry	103	166	721	1842	1241	502
Alt. Scenario 2: 100 Wears, 25 Washes	191	252	721	1842	656	502
Alt. Scenario 3: 50 Wears, 25 Washes	381	504	1442	3684	1313	1004
Alt. Scenario 4: 20 Wears, 10 Washes	502	630	3605	9209	1530	2511
Alt. Scenario 5: 100 Wears, 0 Washes	40	42	721	1842	72	502

Figure 56. Energy consumption: baseline vs. alternative scenarios.

While the SLS method is the 3DP method that consumes most energy per print, the FGF method is the 3DP method that consumes the least per print. However, due to the need for frequent reprints, the FGF method becomes the next most energy-intensive 3DP method (after SLS) to create a T-shirt that can sustain 100 wears.

Chapter VI

Discussion and Conclusions

The objective of this meta-life cycle inventory analysis (LCI) is to compare the water and energy intensities of prevalent 3D-printing methods against that of conventional manufacturing methods in order to understand the potential environmental impacts of 3D-printing methods when applied to clothing production. The functional unit is defined as "one standard T-shirt, 100 wears, 50 washes," as it encompasses processes in all the cradle-to-grave life cycle phases of an apparel product.

By performing a meta-LCI on six apparel products representing three 3D printing methods versus the conventional cut-and-sew method in garment manufacture, a baseline scenario modeled after business-as-usual conditions is constructed using available LCI data, based on the following criteria: i) 100 wears (once a week for 2 years, or everyday for 2 seasons), ii) 50 washes (standard machine-wash, tumble-dry). Based on findings from integrating LCI data derived from both primary and secondary sources, three key resource-intensive hotspots have been identified in order of their resource intensity:

1. Conventional Cut-Sew, Cotton (Water consumption, Use phase)
2. SLS, TPU-92A-1 (Energy consumption, Production phase)
3. FGF, Polyester-Cellulose Solution (Energy consumption, Use phase)

Across all categories, the most resource intensive (i.e. water and energy) life cycle phase is the material preparation phase, characterized by water use for the cotton T-shirt. Of nearly equal intensity is the use phase, characterized by the energy consumption of

required by machine-washing and tumble-drying of conventionally-manufactured T-shirts, as well as the 50 reprints required for the 3D-printed polyester-cellulose T-shirt to sustain 100 wears. Following closely is the garment production phase, characterized by the energy-intensive 3D-printing processes. While this meta-LCI does not take into account other natural resources (e.g. metals and minerals) used as a life cycle assessment (LCA) would, water and energy consumption are key areas of concern in garment production.

The water intensity of conventionally manufactured T-shirts is generally many times greater than the water requirements for 3D-printed T-shirts. The conventionally manufactured cotton T-shirt remains the most water-intensive category throughout all scenarios, as its water intensity is a result of irrigation required for cotton crop cultivation in the material preparation phase. Targeting the use phase can only mildly improve water efficiency, but provides significant energy savings. The energy intensity of 3D-printed T-shirts is generally many times greater than the energy required for conventionally-manufactured T-shirts, especially if the lifespan of the 3D-printed garments requires reprints to meet the same number of wears for the conventionally-manufactured T-shirts.

Although the SLS method is the 3D-printing method that consumes most energy per print, the FGF method is the 3D-printing method that consumes the least per print. However, due to the need for frequent reprints, the FGF method becomes the next most energy-intensive 3D-printing method (after SLS) to create a T-shirt that can sustain 100 wears. Of all four 3D-printers, the Sinterstation 2500Plus is the most energy-intensive per print, followed by the EOSINT P760, the Witbox, and finally the Electroloom Alpha

Unit. Their power ratings have a positive correlation to the ranking of their overall energy use, despite the different amounts of time required to 3D-print the same product by each.

By performing a scenario analysis consisting of five different alternative scenarios for the use phase, the following observations can be made based on the results and findings:

- Using high efficiency appliances in the use phase can greatly improve energy efficiency, but not so much for water efficiency
- Reducing the number of washes required for the same number of wears improves the resource efficiency greatly for garments that require high resource consumption in their use phase
- Increasing the lifespan of a garment significantly reduces resource intensity overall, since having to replace it with an identical piece would incur many times the resource demand depending on how many replacements are required
- The garment production methods that have the highest use-phase resource intensity have the most to gain by increasing the durability and prolonging the lifespan of the finished apparel product

LCI data collection proved to be the most challenging area in conducting this meta-LCI process, since relevant data of quality, if there exists any data at all, is scarce for certain LCI parameters such as those relating to 3D printers and 3D printer filament materials. Owing to the fact that 3D printing as a clothing production application is still very much a novelty, and also to the fact that 3D printing materials have more obscure chemical components than conventional textiles, 3D printing companies approached for interviews have generally been reluctant to divulge information deemed proprietary and therefore sensitive to their economic growth. Where primary data is unavailable,

information regarding 3D-printers, 3D-printing materials, 3D-printed clothing and their related sub-processes have been derived primarily from manufacturer websites, journal publications, academic sources, and numerous media sources that have conducted direct interviews with designers and 3D-printing companies.

While published LCI data on conventionally manufactured clothing are more abundant, functional units vary from study to study, and LCI data presented may have been aggregated over a number of undisclosed processes and confidential information sources due to the complexity of the textile and garment supply chain. In order to avoid double counting and miscalculations, selection and weighting of secondary data has been performed based on assessments of sub-processes involved, as in the case of cooling water used in producing 3D-printing materials. As secondary LCI data found are presented using varying unit systems, it was also necessary to perform unit conversions using a methodologically consistent approach to harmonize the collected data.

Despite additive manufacturing (AM) technology having the potential of replacing conventional textile and garment production in the future, there still exist limitations to its scalability currently that prevent 3D-printing technologies from becoming environmentally sustainable and commercially viable:

- Time-consuming. It takes 48 hours to 3D-print one dress using the selective laser sintering (SLS) method, 14 hours to 3D-print one tank top using the field guided fabrication (FGF) method, and >400 hours (17 days) to 3D-print one outfit using the fused deposition modeling (FDM) method.
- 3D printers are expensive. The cost of commercial-grade printers such as SLS machines can easily be in the six-figure range. A SLS machine costs US$270,000 to

US$325,0000 (Lou & Grosvenor, 2012). Consumer-grade printers are less expensive, but still cost over US$1,000 in general. The Witbox home printer included in this study costs US$1,900 (BQ, 2015).

- 3D printing filament materials are costly. PA-2200 costs ~US$45 per kg (Arzauno.com). It cost US$2,930 to 3D-print a PA-2200 dress (London, 2014). TPU-92A-1 costs ~US$2.30 per cm3. To 3D-print a TPU-92A-1 T-shirt, it would cost ~US$2,576. Each 500g-spool of TPU-85A filament costs ~US$23 (Recreus, 2014). 3D-printing one TPU-85A jacket costs ~US$80 (Marriott, 2015). It would cost ~US$136 to 3D-print one TPU-85A T-shirt.
- Requires advanced computer aided design (CAD) skills. In order to produce a complex 3D printed object, digital software such as Solidworks, AutoCAD, PTC Creo, Rhinoceros (Rhino 3D), SketchUp, Inventor Fusion, or Blender (Jackson-Edwards, 2015) must be used to create printable digital models. Knowing how to manipulate and edit these digital models for optimal 3D printing is required to generate successful and accurate 3D prints efficiently.
- Requires advanced apparel design knowledge. In order to create form-fitting apparel, specific apparel design skills (e.g. patternmaking/draping techniques) are required to design wearable and 3D-printable pieces that not contour to the average human body.
- Requires more ergonomic 3D printer filament materials. While many variants of 3D printer filament materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) or flexible thermoplastic polyurethane (TPU) are commercially available and compatible with consumer 3D printers, they still lack the lightness and comfort of conventional knit and woven textiles.

- Resource intensive. 3D printer materials are generally aliphatic and energy-intensive to produce, as many are petrochemical based and 3D printers generally consume a large amount of electricity in the 3D printing process (Kellens et al., 2011), which can translate to high overhead costs.

However, 3D garment printing holds potential to enhance clothing production as well, given its ability to create seamless apparel that does not require assembly or finishing in some cases, as with the Electroloom Alpha Unit. Should current technology be improved upon, some potential benefits of 3D garment printing may include:

- Minimization of material waste by enabling the creation of perfect-fit, preferred, long term-wear garments generated in conjunction with design software to customize clothing product to the end user's exact body contours and personal taste
- Elimination of supply chain processes, such as the "brushing, singeing, desizing, washing, steaming, scouring, bleaching, dyeing, oxidation, soaping, rinsing, calendaring, sanforizing and finishing" steps (Muthu, 2014, p. 7)
- Reduction of energy consumption, as a result of eliminating multiple processing and finishing steps required in conventional clothing production
- Less water consumption, as 3DP materials are mostly aliphatic and require little use of water in the garment production and use phase
- Lessened environmental toxicity, as a result of eliminating multiple processing and finishing steps required in conventional clothing production
- Lower overhead costs, as a result of lower resource demand
- Enhanced garment recyclability as a result of single-material use in 3D printing, removing the need for zippers, fasteners, and other trims made of different materials

- Reduction of landfill waste and bioaccumulation by maximizing garment biodegradability through advancements in 3D-printing material

This meta-LCI study presents only a starting point for analyzing the potential environmental impacts of applying 3D-printing techniques to clothing production. Some future research implications of this study include:

i) Comprehensive life cycle assessments (LCA) of 3D-printed garments that take into consideration a more comprehensive set of input and output flows, such that life cycle impact assessments (LCIA) methods can be applied to derive a more complete set of impact categories besides water and energy consumption

ii) More in-depth sensitivity analyses of 3D-printing processes and materials that further investigate a range of related issues, such as:

    a. Exploring the actual electricity use of 3D-printers in operation and how they compare with manufacturer-provided power ratings to give different resource consumption levels

    b. The minimum and maximum ranges of material densities and how they impact the weight of the garment and overall energy use

    c. The relationship between resource intensity and different CAD designs of 3D-printable textiles and garments

iii) Identification of less environmentally impactful raw material sources suitable for creating flexible and durable 3D garment printing filament materials

iv) Exploration of 3D-printing materials and methods to enhance the strength, durability and functionality of 3D-printed clothing such that they can be worn more times and washed fewer times, without incurring extra resource consumption costs

v) Further development of 3D-printing technology capabilities towards scalable garment production, such that resource consumption over the 3D-printed garment's lifetime can be less than that for conventionally-manufactured clothing

vi) Compiling a comprehensive database of 3D-printer specifications, 3D-printing materials, 3D-printed clothing parameters using primary data collected from designers, manufacturers, and suppliers

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Appendix 1 Meta-LCI Data Sheet

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
1. Material Preparation Phase						
Density (g/cm^3)	1.54	1.40	1.02	1.20	1.18	1.22
Raw Material, One T-Shirt (g)	219	199	1644	1944	431	1697
Raw Material						
Energy Consumption (MJ)	15.8	17.4	195	230	30.7	201
Water Consumption (L)	1172	12	36	43	6	38
Transportation, by Tractor (km)	1.9	1.9	89	89	89	89
(kg-km)	0.4	0.4	146	173	38	151
Yarn Spinning						
Energy Consumption (MJ)	6.2	5.4	–	–	–	–
Water Consumption (L)	438	437.5	–	–	–	–
Transportation, by Truck (km)	1207	1207	–	–	–	–
(kg-km)	264	264	–	–	–	–
Knitting / Grey Fabric Preparation						
Energy Consumption (MJ)	2.5	9.7	–	–	–	–
Water Consumption (L)	–	–	–	–	–	–
Transportation, by Truck (km)	86.9	86.9	–	–	–	–
(kg-km)	19.0	19.0	–	–	–	–
Finished Fabric Preparation						
Energy Consumption (MJ)	12.1	6.2	–	–	–	–
Water Consumption (m3)	18.7	–	–	–	–	–
Transportation, by Truck (km)	86.9	86.9	–	–	–	–
(kg-km)	19.0	19.0	–	–	–	–
Subtotal						
Energy Consumption, Processes (MJ)	36.6	38.6	194.7	230.2	30.7	200.9
Water, Material Prep (L)	**1629**	**449**	**36**	**43**	**6**	**38**
Transportation, by Truck (km)	1383	1383	89	89	89	89
(kg-km)	302	302	146	173	38	151
Energy Consumption, Transportation (MJ)	0.28	0.28	0.14	0.16	0.04	0.14
Energy, Material Prep (MJ)	**36.9**	**38.9**	**194.8**	**230.3**	**30.8**	**201.0**
2. Garment Production Phase						
Weight of One Finished T-Shirt (g)	175	159	1134	1341	134	1357
Est. Material Waste (%)	25%	25%	45%	45%	5%	25%
Power Rating (kW)	–	–	6.1	14.8	0.68	0.35
Manufacturing Time (h)	–	–	24	30	17	240
Electricity Use (kWh)	–	–	146	447	12	84
Energy Consumption, Processes (MJ)	2.5	2.3	526	1611	41	301
Transportation, by Lt. Goods Vehicle (km)	773	773	–	–	–	–
(kg-km)	135	123	–	–	–	–
Energy Consumption, Transportation (MJ)	0.34	0.31	–	–	–	–
Energy, Production (MJ)	**2.9**	**2.6**	**525.7**	**1611**	**41.4**	**300.7**
3. Distribution Phase						
Transportation, Sea Freight (km)	10592	10592	–	–	–	–
(kg-km)	1854	1685	–	–	–	–
Energy Consumption, Sea Freight (MJ)	0.30	0.27	–	–	–	–
Transportation, by Lt. Goods Vehicle (km)	2485	2485	2485	2485	–	2485
(kg-km)	6.21	6.21	2.04	2.04	–	2.04
Energy Consumption, Transportation (MJ)	0.016	0.016	0.0051	0.0051	–	0.0051
Energy, Distribution (MJ)	**0.312**	**0.285**	**0.005**	**0.005**	**0**	**0.005**
4. Use Phase						
Garment Care Requirements:						
No. of Wears	100	100	100	100	100	100
No. of Washes / Reprints	50	50	50	50	50	50
Energy Consumption, Machine Wash (MJ)	62.2	124.3	–	–	–	–
Vol. of T-shirt (cm^3)	113.6	113.6	1117.2	1117.2	113.6	1117.2
Water Consumption, Towel Wipe (L)	–	–	0.24	0.24	–	0.24
Water Consumption, One Reprint (L)	–	–	36	43	3	38
Water Consumption, H.E. Machine Wash (L)	6.1	6.1	–	–	–	–
Water Consumption, Std. Machine Wash (L)	7.6	7.6	–	–	–	–
Water, Use Phase (L)	**380**	**380**	**12**	**12**	**136**	**12**
Energy Consumption, Machine Dry (MJ)	238.0	295.1	–	–	–	–
Energy Consumption, One Reprint (MJ)	–	–	195	230	23.4	201
Energy, Use Phase (MJ)	**300.2**	**419.4**	**0**	**0**	**1168.4**	**0**
5. End of Life						
Est. Transportation, by Truck (km)	600	600	600	600	600	600
(kg-km)	105	95	680	804	81	814
Energy Consumption, Transportation (MJ)	0.28	0.28	0.14	0.16	0.04	0.14
Landfill + Incineration (MJ)	0.04	0.04	0.32	0.38	0.04	0.38
Energy, EOL (MJ)	**0.33**	**0.33**	**0.45**	**0.54**	**0.07**	**0.52**
TOTAL						
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**

Appendix 2 Meta-LCI Data Sheet (Alternative Scenarios)

	Subtractive Manufacturing		Additive Manufacturing			
	Cut-and-Sew Production		Selective Laser Sintering (SLS)		Field Guided Fabrication (FGF)	Fused Deposition Modeling (FDM)
General Information						
Material Specification:						
Material Name	Cotton	Polyethylene Terephthalate (Polyester)	PA 2200 (Nylon Powder from PA 12)	TPU-92A-1 (Powder)	Polyester-Cellulose ("Fiber Solution")	TPU-85A ("FilaFlex" filament)
Renewable Source (Y/N)	Y	N	N	N	N	N
3D Printer Specifications:						
3D Printer Model/Type	–	–	EOSINT P760 (used by Shapeways)	Sinterstation 2500 Plus (used by Materialise)	Electroloom Alpha Unit (Early prototype)	Witbox Home Printer (used by Danit Peleg)
Max. Build Volume (mm)	–	–	700w x 380d x 580h	330w x 280d x 419h	900w x 900d x 600h	210w x 297d x 200h
Layer Height (mm)	–	–	0.18	0.10	–	0.05
Print Speed (mm/h)	–	–	32	25.4	–	288,000
Baseline Scenario: 100 Wears, 50 Washes, Std. Mach. Wash, Tumble Dry						
Water Consumption, Total (L)	**2009**	**829**	**48**	**55**	**142**	**49**
Energy Consumption, Total (MJ)	**341**	**462**	**721**	**1842**	**1241**	**502**
Alt. Scenario 1: H.E. Mach. Wash, Line Dry						
Water Consumption, Total (L)	**1933**	**753**	**48**	**55**	**142**	**49**
Water Efficiency (%)	4	9	0	0	0	0
Energy Consumption, Total (MJ)	**103**	**166**	**721**	**1842**	**1241**	**502**
Energy Efficiency (%)	70	64	0	0	0	0
Alt. Scenario 2: 100 Wears, 25 Washes						
Water Consumption, Total (L)	**1724**	**544**	**42**	**49**	**74**	**44**
Water Efficiency (%)	14	34	12	11	48	12
Energy Consumption, Total (MJ)	**191**	**252**	**721**	**1842**	**656**	**502**
Energy Efficiency (%)	44	45	0	0	47	0
Alt. Scenario 3: 50 Wears, 25 Washes						
Water Consumption, Total (L)	**3448**	**1089**	**85**	**98**	**148**	**87**
Water Efficiency (%)	-72	-31	-76	-78	-4	-76
Energy Consumption, Total (MJ)	**381**	**504**	**1442**	**3684**	**1313**	**1004**
Energy Efficiency (%)	-12	-9	-100	-100	-6	-100
Alt. Scenario 4: 20 Wears, 10 Washes						
Water Consumption, Total (L)	**8222**	**2323**	**194**	**228**	**166**	**200**
Water Efficiency (%)	-309	-180	-302	-314	-17	-304
Energy Consumption, Total (MJ)	**502**	**630**	**3605**	**9209**	**1530**	**2511**
Energy Efficiency (%)	-47	-37	-400	-400	-23	-400
Alt. Scenario 5: 100 Wears, 0 Washes						
Water Consumption, Total (L)	**1629**	**449**	**36**	**43**	**6**	**38**
Water Efficiency (%)	19	46	24	22	96	24
Energy Consumption, Total (MJ)	**40**	**42**	**721**	**1842**	**72**	**502**
Energy Efficiency (%)	88	91	0	0	94	0

Appendix 3 LCI Guidelines (ISO14044:2006)

4.3 Life cycle inventory analysis (LCI)

4.3.1 General

The definition of the goal and scope of a study provides the initial plan for conducting the life cycle inventory phase of an LCA. When executing the plan for the life cycle inventory analysis, the operational steps outlined in Figure 1 should be performed. (It should be noted that some iterative steps are not shown in Figure 1.)

4.3.2 Collecting data

4.3.2.1 The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundary. The collected data, whether measured, calculated or estimated, are utilized to quantify the inputs and outputs of a unit process.

When data have been collected from public sources, the source shall be referenced. For those data that may be significant for the conclusions of the study, details about the relevant data collection process, the time when data have been collected, and further information about data quality indicators shall be referenced. If such data do not meet the data quality requirements, this shall be stated.

To decrease the risk of misunderstandings (e.g. resulting in double counting when validating or reusing the data collected), a description of each unit process shall be recorded.

Since data collection may span several reporting locations and published references, measures should be taken to reach uniform and consistent understanding of the product systems to be modeled.

4.3.2.2 These measures should include the following:

- Drawing unspecific process flow diagrams that outline all the unit processes to be modeled, including their interrelationships;
- Describing each unit process in detail with respect to factors influencing inputs and outputs;
- Listing of flows and relevant data for operating conditions associated with each unit process;
- Developing a list that specifies the units used;

– Describing the data collection and calculation techniques needed for all data;
– Providing instructions to document clearly any special cases, irregularities or other items associated with the data provided.

4.3.2.3 The major headings under which data may be classified include

– Energy inputs, raw material inputs, ancillary inputs, other physical inputs,
– Products, co-products and waste,
– Releases to air, water and soil, and
– Other environmental aspects.

Within these headings, individual data shall be further detailed to satisfy the goal of the study.

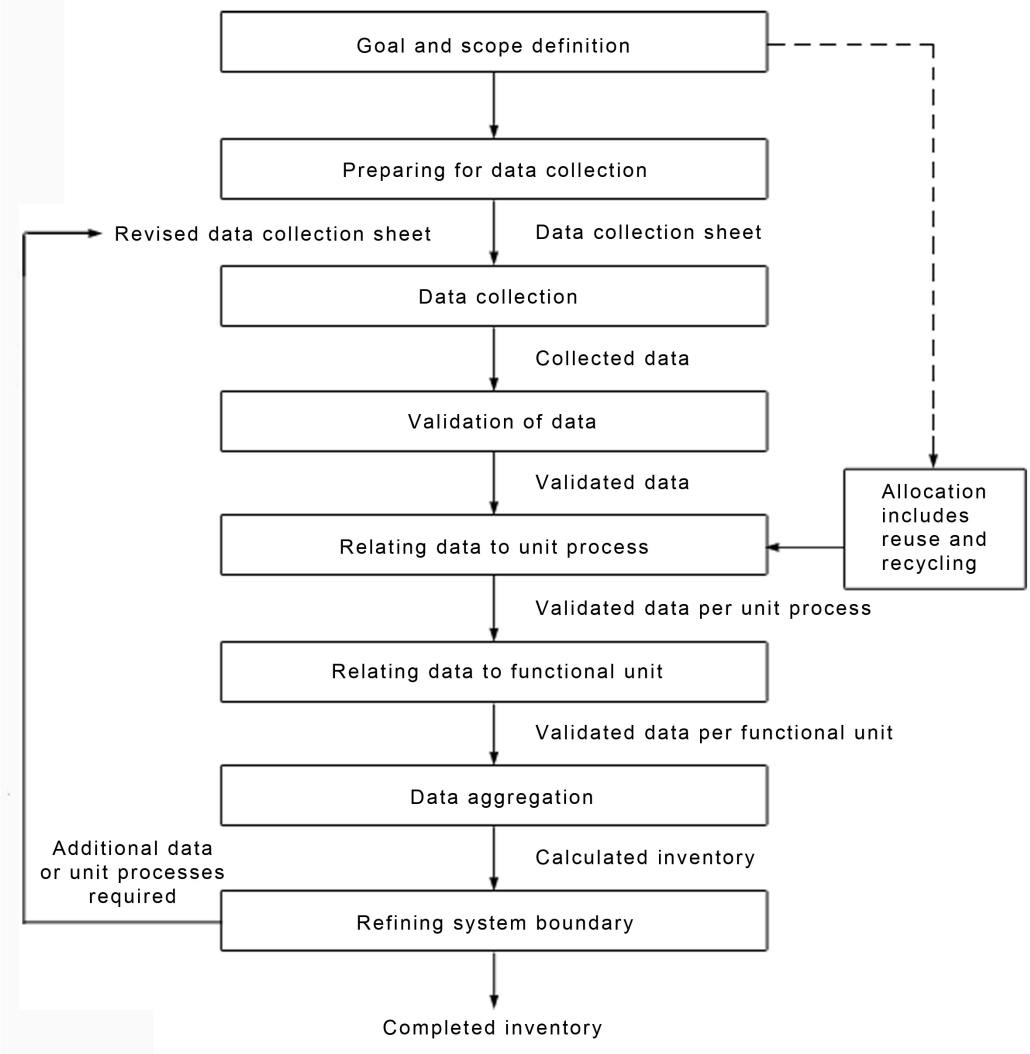


Figure 1 — Simplified procedures for inventory analysis

4.3.3 Calculating data

4.3.3.1 General

All calculation procedures shall be explicitly documented and the assumptions made shall be clearly stated and explained. The same calculation procedures should be consistently applied throughout the study.

When determining the elementary flows associated with production, the actual production mix should be used whenever possible, in order to reflect the various types of resources that are consumed. As an example, for the production and delivery of electricity, account shall be taken of the electricity mix, the efficiencies of fuel combustion, conversion, transmission and distribution losses.

Inputs and outputs related to a combustible material (e.g. oil, gas or coal) can be transformed into an energy input or output by mufti prying them by the relevant heat of combustion. In this case, it shall be reported whether the higher heating value or the lower heating value is used.

Several operational steps are needed for data calculation. These are described in 4.3.3.2 to 4.3.3.4 and 4.3.4.

4.3.3.2 Validation of data

A check on data validity shall be conducted during the process of data collection to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled.

Validation may involve establishing, for example, mass balances, energy balances and/or comparative analyses of release factors. As each unit process obeys the laws of conservation of mass and energy, mass and energy balances provide a useful check on the validity of a unit process description. Obvious anomalies in the data resulting from such validation procedures require alternative data that comply with the data selection as established according to 4.2.3.5.

4.3.3.3 Relating data to unit process and functional unit

An appropriate flow shall be determined for each unit process. The quantitative input and output data of the unit process shall be calculated in relation to this flow.
Based on the flow chart, and the flows between unit processes, the flows of all unit processes are related to the reference flow. The calculation should result in all system input and output data being referenced to the functional unit.

Care should be taken when aggregating the inputs and outputs in the product system. The level of aggregation shall be consistent with the goal of the study. Data should only be aggregated if they are related to equivalent substances and to similar environmental

impacts. If more detailed aggregation rules are required, they should be explained in the goal and scope definition phase of the study or should be left to a subsequent impact assessment phase.

4.3.3.4 Refining the system boundary

Reflecting the iterative nature of LCA, decisions regarding the data to be included shall be based on a sensitivity analysis to determine their significance, thereby verifying the initial analysis outlined in 4.2.3.3. The initial system boundary shall be revised, as appropriate, in accordance with the cut-off criteria established in the definition of the scope. The results of this refining process and the sensitivity analysis shall be documented.

The sensitivity analysis may result in

- exclusion of life cycle stages or unit processes when lack of significance can be shown by the sensitivity analysis,
- exclusion of inputs and outputs that lack significance to the results of the study, or
- inclusion of new unit processes, inputs and outputs that are shown to be significant in the sensitivity analysis.

This analysis serves to limit the subsequent data handling to those input and output data that are determined to be significant to the goal of the LCA.

4.3.4 Allocation

4.3.4.1 General

The inputs and outputs shall be allocated to the different products according to dearly stated procedures that shall be documented and explained together with the allocation procedure.

The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.

Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.

4.3.4.2 Allocation procedure

The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented below.

a) Step 1: Wherever possible, allocation should be avoided by

1) Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
2) Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.

b) Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

c) Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

Some outputs may be partly co-products and partly waste. In such cases, it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only.

Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration.

For example, if allocation is made to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system.

The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.

4.3.4.3 Allocation procedures for reuse and recycling

4.3.4.3.1 The allocation principles and procedures in 4.3.4.1 and 4.3.4.2 also apply to reuse and recycling situations.

3) Formally, Step 1 is not part of the allocation procedure.
4) In some countries and regions, recycling encompasses re-use, material recovery and energy recovery.

Changes in the inherent properties of materials shall be taken into account. In addition, particularly for the recovery processes between the original and subsequent product system, the system boundary shall be identified and explained, ensuring that the allocation principles are observed as described in 4.3.4.2.

4.3.4.3.2 However, in these situations, additional elaboration is needed for the following reasons:

- reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system;
- reuse and recycling may change the inherent properties of materials in subsequent use
- specific care should be taken when defining system boundary with regard to recovery processes.

4.3.4.3.3 Several allocation procedures are applicable for reuse and recycling. The application of some procedures is outlined conceptually in Figure 2 and is distinguished in the following to illustrate how the above constraints can be addressed.

a) A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material, in such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in applicable open-loop product systems may follow an open-loop allocation procedure outlined in b).

b) An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

4.3.4.3.4 The allocation procedures for the shared unit processes mentioned in 4.3.4.3 should use, as the basis for allocation, if feasible, the following order:

- physical properties (e.g. mass);
- economic value (e.g. market value of the scrap material or recycled material in relation to market value of primary material); or
- the number of subsequent uses of the recycled material (see ISO/TR 14049).