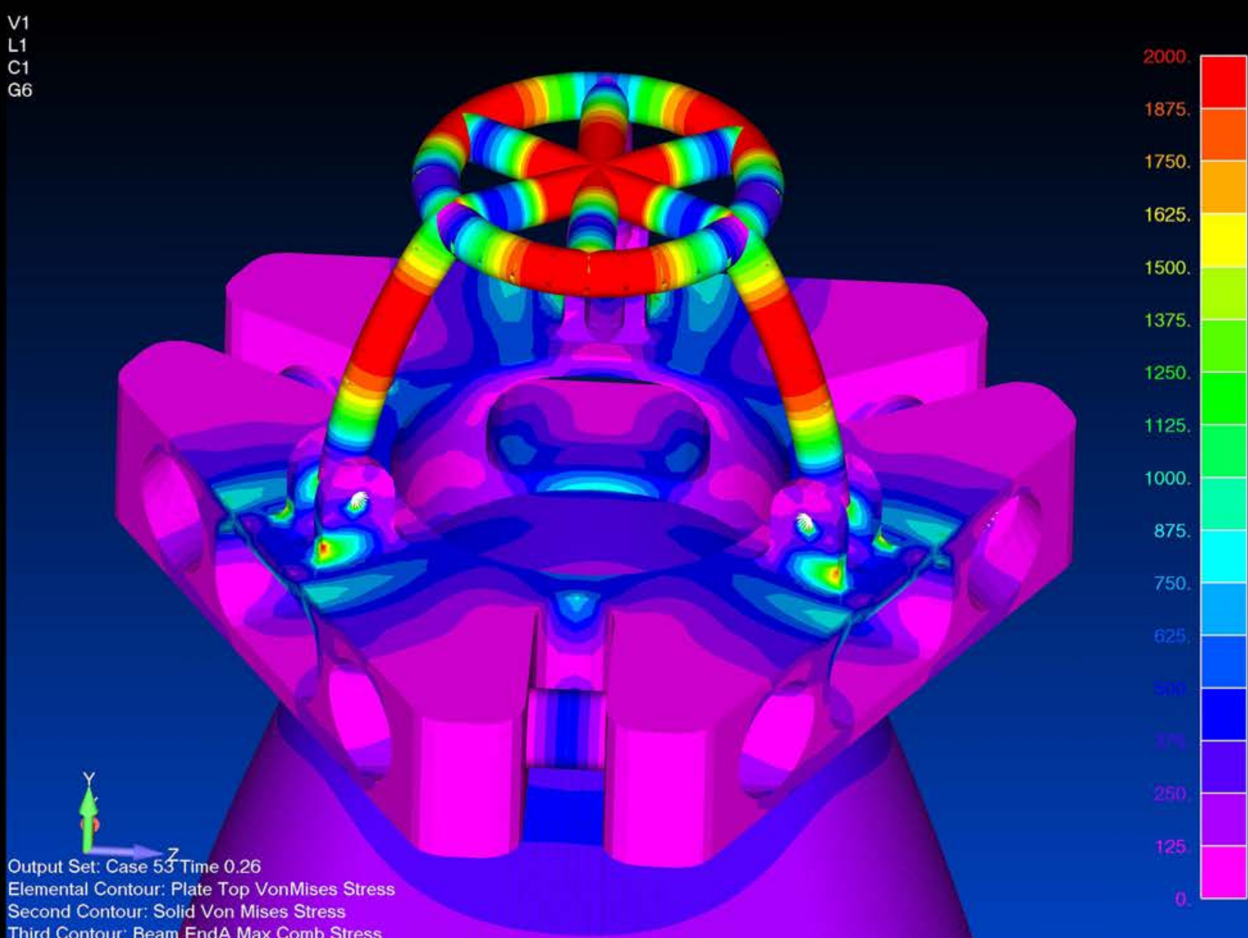
Rapid Response Report

MANUFACTURING 101
An Education and Training Curriculum for Hardware Entrepreneurs



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Manufacturing 101

An Education and Training Curriculum for Hardware Entrepreneurs

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A "Manufacturing 101" Curriculum for Entrepreneurs

1.0 Executive Summary

Manufacturing 101 is an education and training curriculum designed to provide Cleantech[1] entrepreneurs with the requisite manufacturing knowledge to effectively transition their functional prototypes into commercial products manufactured at scale. Participants in a June 2016 workshop laid the foundation for the development of a new education and training program built around four phases: *Engage, Educate, Enhance,* and *Execute*.

The curriculum consists of eight modules that describe the topics in manufacturing most relevant to entrepreneurs during product scale-up. The modules described in this report are envisioned to be technology agnostic and applicable to a great majority of early-stage companies building physical products. The recommended curriculum is broad enough to apply to a range of different technologies, but is also sufficiently specific so that entrepreneurs can apply the lessons to their own Cleantech innovations.

Upon successful completion of the *Manufacturing 101* program, entrepreneurs will gain a basic level of understanding about manufacturing processes, and each student will also understand the current Manufacturing Readiness Level (MRL) of their product. Topics taught in *Manufacturing 101* will help entrepreneurs more effectively achieve critical product development and commercialization milestones, and will also give entrepreneurs the knowledge and vocabulary to engage with design engineers, consultants, and manufacturing companies during the product scale-up process.

Recommended education and training modules for the *Manufacturing 101* curriculum include:

- "Manufacturing for Entrepreneurs": Introduction and self-assessment
- "Material Selection": Material properties and design considerations
- "Manufacturing Processes": Basics and key terms
- "Design for Manufacturing": Design for X (DFX) topics
- "Supply Chain": Basics and cost estimation
- "Bill of Materials and Bill of Process": Basics and cost estimation
- "Standards and Regulations": Regulations, standards, and best practices
- "Securing Mutually Beneficial Manufacturing Partnerships": Basics, best practices, and intellectual property

To deliver technical content to entrepreneurs, an "*M-Corps*" program is recommended. The *M-Corps* process requires entrepreneurs to learn first-hand about manufacturing using a combination of lectures, case studies, hands-on workshops and personal collaboration with manufacturing experts.

Manufacturing 101 is designed for delivery using a combination of online resources and personal engagement with manufacturing experts and mentors-in-residence whenever possible. Recommendations seek to bridge the gap between existing entrepreneurial ecosystems and manufacturing expertise networks, and to connect incubators and accelerators with Manufacturing Extension Partnerships (MEPs) and Design for Manufacturing (DFM) consultants.

[1] *Cleantech* in the context of this report refers to a diverse range of products, services, and processes that make use of renewable materials and energy sources.

2.0 Introduction

Start-ups are engines of innovation. From Square to SpaceX, inventive young organizations have revolutionized diverse sectors of the American economy. Today, new start-ups in the emerging Cleantech sector are developing novel innovations in wind, solar, fuel cells, bioenergy, geothermal, and vehicle technology that promise to reduce carbon emissions, increase energy independence, and create more affordable and reliable energy.

But, for most start-ups, innovation isn't enough.

Not only is it necessary to conceive of a great idea or even develop a technically-viable product— it is also necessary to bring production to scale. It is one thing to build a functioning prototype and it is quite another to bring a safe, attractive, cost-effective, durable product to market. Making this leap requires expertise in a subject matter that is not always addressed in entrepreneurial circles, engineering design classes, or MBA programs: Manufacturing.

It is essential to help start-ups bridge the gap between innovation and manufacturing, and this can be done through a training program for entrepreneurs. This report outlines the most relevant topics to include in a *Manufacturing 101* course as well as effective methods of delivery. The intended audience for this course includes entrepreneurs developing Cleantech innovations, but the course content is equally valuable to any other hardware or software start-up interested in manufacturing. The course is designed to teach entrepreneurs the basics of manufacturing so that start-ups can transition their functional prototypes into viable commercial products. One of the main barriers to quick and cost-effective product scale-up for start-ups is a lack of manufacturing know-how among entrepreneurs. The *Manufacturing 101* curriculum provides a basic understanding of materials and manufacturing techniques, as well as awareness of Design for Manufacturing issues to be addressed during the product development stage.

The Department of Energy's (DOE) office of Energy Efficiency and Renewable Energy (EERE) invests approximately $1.7 billion per year in research and development (R&D) to support technology development in fuel cells, bioenergy, wind, geothermal, water, vehicle, and building technologies[2] including approximately $33 million per year through its Small Business Innovation Research (SBIR) program.[3] In addition, EERE's Technology-to-Market program[4] supports the launch of many new Cleantech start-ups each year. Desiring to better leverage federal investment in research and development in Cleantech and support the global transition to a clean energy future, EERE brought the issue of entrepreneurs' lack of manufacturing know-how to MForesight's attention. Although EERE's focus is on Cleantech entrepreneurs, the goal of providing a basic education and training in manufacturing and scale-up challenges is a cross-cutting issue, and the information in this report can be used to build an educational program that is useful for any hardware inventor who hopes to successfully bring a product to market.

2.1 Problem Statement

Start-ups usually require longer lead-times and heavier capital lifts to bring their innovations to market. Such firms frequently work with small teams with limited or no manufacturing personnel

[2] EERE Budget Request. http://www5.eere.energy.gov/office_eere/current_budget.php
[3] "SBIR/STTR Budgets by Agency, FY2015." DOE's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. http://science.energy.gov/~/media/sbir/powerpoint/FY16_Phase_I_Release_2_FOA_Webinar_final.pptx
[4] http://energy.gov/eere/technology-to-market/technology-market-program

on staff during early stages of development. This limitation puts the company's innovation at risk in two important ways:

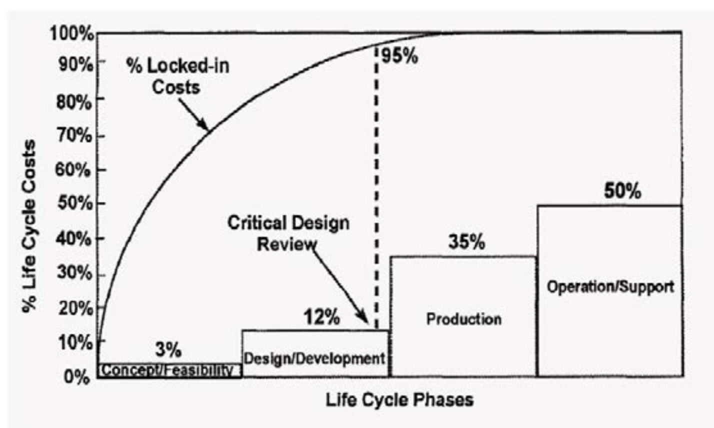
- **Expertise:** Without a basic understanding of manufacturing principles, entrepreneurs struggle to transition their prototype into a viable commercial product that can be affordably manufactured at-scale.
- **Manufacturing Plan:** Without a formal manufacturing plan, entrepreneurs cannot demonstrate the manufacturability of their innovations to potential strategic partners. This limits access to capital as well as follow-on investment. Scale-up plans and evidence of manufacturability are increasingly important to investors and partners.

Learning the essentials of product design for manufacturing will allow entrepreneurs to transform their prototypes into products that can be successfully manufactured as market-ready and optimized for volume and scale expectations.

2.2 Benefits of Manufacturing Education and Training

Many start-ups excel at creating technically viable prototypes, but ultimately fail because of the engineering challenges related to safety, cost-effectiveness, durability, and other factors. In some cases, the product was not sufficiently durable or was too complex to manufacture or assemble. In other cases, the product could not reach the appropriate price point because the cost of production was too high. A basic understanding of how products are engineered, manufactured and assembled can help entrepreneurs avoid critical mistakes early in the development process.

Start-ups often face a common problem: the need to redesign the product to address manufacturing challenges. As shown in Figure 1, a large fraction of a product's lifecycle costs is ideally determined during the concept and design phases of the product. If a prototype design cannot be produced cost-efficiently at quantity, a new design cycle is needed to adapt the product to large-scale manufacturing, thus increasing cost and timing. Product redesign is expensive, and is often a consequence of the entrepreneur's lack of manufacturing knowledge.



Architectural Design for Reliability, R. Cranwell and R. Hunter, Sandia Labs, 1997

Figure 1: A large fraction of a product's life cycle costs are typically incurred early in the project. The need to redesign a product substantially increases development costs.

However, the use of well-known, reliable *Design for Manufacturing* tools can eliminate the need for (and cost of) a product redesign. By including manufacturing best practices early in the design process, entrepreneurs will save time and money, speed the scale-up process, and accelerate the time-to-market.

Participation in manufacturing education and training gives the entrepreneur another critical advantage: the ability to create a manufacturing plan for potential industry partners or future investors. Most investors expect a hardware start-up to have a manufacturing strategy that accurately shows the product's Bill of Materials and Bill of Process. The strategy should detail a step-wise plan for moving from prototype to small volume to high volume. For each target volume, the plan should describe salient variables such as cost of materials, inventory requirements, assembly costs, and test and packaging costs (consisting of floor space, labor, capital equipment, and utilities). Ideally, the manufacturing plan will be presented as a manufacturing *pro forma*, detailing all costs over the short- and long-term.

2.3 Developing the Curriculum

The recommendations in this report were developed in collaboration with a panel of manufacturing experts with experience in both entrepreneurship and Design for Manufacturing (DFM) methods. MForesight hosted a workshop with the panel on June 17, 2016 in Ann Arbor, Michigan to seek their input on the *Manufacturing 101* curriculum and its delivery method. Please see Appendix D for biographies of all workshop participants.

3.0 Workshop Objectives & Agenda

The goal of the *Manufacturing 101* workshop was to outline an effective method for educating and training entrepreneurs (in the Cleantech community and elsewhere) in the fundamentals of product design and manufacturing so they can skillfully bring their products to market.

The key objectives of the workshop were to:

1. Develop an outline of *Manufacturing 101* for start-ups including:
    - A list of recommended topics for education and training modules
    - An outline of recommended content for each module
    - A set of relevant case studies that demonstrate successful (or unsuccessful) scale-up of a product/business
2. Prioritize the education and training modules from most basic (content every hardware entrepreneur must know) to more specialized topics.
3. Recommend subject matter experts and organizations/groups that can help develop the modules.
4. Recommend delivery method(s) for the module contents.

Specific case studies of start-up companies that have successfully scaled-up were used to help define the target audience and frame the direction for training needs. Once the audience was defined and their unique needs were identified, workshop participants defined the most important foundational manufacturing topics during product scale-up. Different Design for X (DFX) principles were considered as they apply to early stage entrepreneurs, as well as a variety of methods for delivering the content of the *Manufacturing 101* education and training modules.

3.1 Defining the Audience

An important part of the workshop was to identify the audience to be served by the *Manufacturing 101* curriculum. The purpose was to have the curriculum tailored to meet the needs of different types of Cleantech entrepreneurs based on their specific technologies (e.g., products, materials, and manufacturing processes). This presents a substantial challenge due to the many different types of emerging developments in wind, water, solar, geothermal, bioenergy, fuel cells, vehicle and building technologies. Innovation comes in many forms, with start-ups developing different technologies that pose different set of challenges in DFM and scale-up. For example, in wind energy alone, innovation can be recognized at the system level (the development of an entirely new turbine system); at the component level (a new rotor blade design), at the material level (a new blade material) or at the production level (a new automated manufacturing approach to producing the blade).

Workshop participants understood that the target audience is Cleantech entrepreneurs, but the challenge is that Cleantech entrepreneurs are as diverse as the topics within Cleantech. For this reason, the modules are mostly technology agnostic and are sufficiently general so that *any* entrepreneur can benefit from the information. The course content will be particularly useful for start-ups transitioning from prototype to actual manufacturing. A follow-on curriculum (*Manufacturing 201*) could be designed to target the specific manufacturing challenges for a given type of Cleantech technology.

Groups that can benefit from this course include SBIR Phase II awardees, where *Manufacturing 101* can complement the commercialization training that most awardees are required to take. Other entrepreneurs who could benefit from this curriculum are technology developers with demonstrated prototypes. The highest impact for this curriculum will likely be start-ups entering the pre-production phase of product development.

3.2 Case Study

Case studies can provide insight into the typical problems encountered by entrepreneurs during the development process. Several case studies of Cleantech ventures were provided at the beginning of the workshop as a way for participants to understand the diverse audience for which the *Manufacturing 101* education and training curriculum is intended to serve.

The following case study highlights key issues that typically face an entrepreneur. Additional case studies can be found in Appendix E: Additional Manufacturing Case Studies.

3.2.1 Case Study: LED Luminaire by Company AA[5]

Company AA worked to develop a daylight emulator utilizing LED technology. By using color tunable LEDs, the company has targeted the indoor commercial lighting market with a unique product offering. However, as development progressed, the company faced a number of typical manufacturing challenges to commercialize their innovative technology.

Prototype development was successful with the company making good progress on their product's Technology Readiness Level (TRL). The TRL is a measure of a product's maturity from basic research (TRL1) to the system fully tested in an operational environment (TRL9). Company AA reached TRL7 by year three.

Figure 2: LED-based Daylight Emulator

Another metric for the progression of a product is the Manufacturing Readiness Level (MRL), which ranges from basic manufacturing implications identified (MRL1) to full rate lean production

[5] The company's name has been kept confidential and will be referred to as Company AA.

(MRL10).[6] MRL differs from the TRL in its focus on the scaled manufacturing of the product, rather than just the development and testing of the product and its functional features.

Both metrics are intertwined: challenges with progression of the MRL may set back the progress of the TRL as redesigns are needed. Company AA faced a number of issues with manufacturing. Even though the prototype had progressed to TRL7, they found themselves with an immature manufacturing process at MRL4.

3.2.2 Analysis

Company AA faced a problem that is typical for many small firms. After initial development, they needed to redesign their product to be more cost-effective to produce. This problem stems from the fact that many start-ups fail to recognize the MRL of their product, and how to optimize the product design to reduce cost, ensure performance, and meet the demands of their customers. In this case, the company needed to retreat in their TRL as they developed the second generation of their product to be easier and more cost effective to manufacture. See Figure 3.

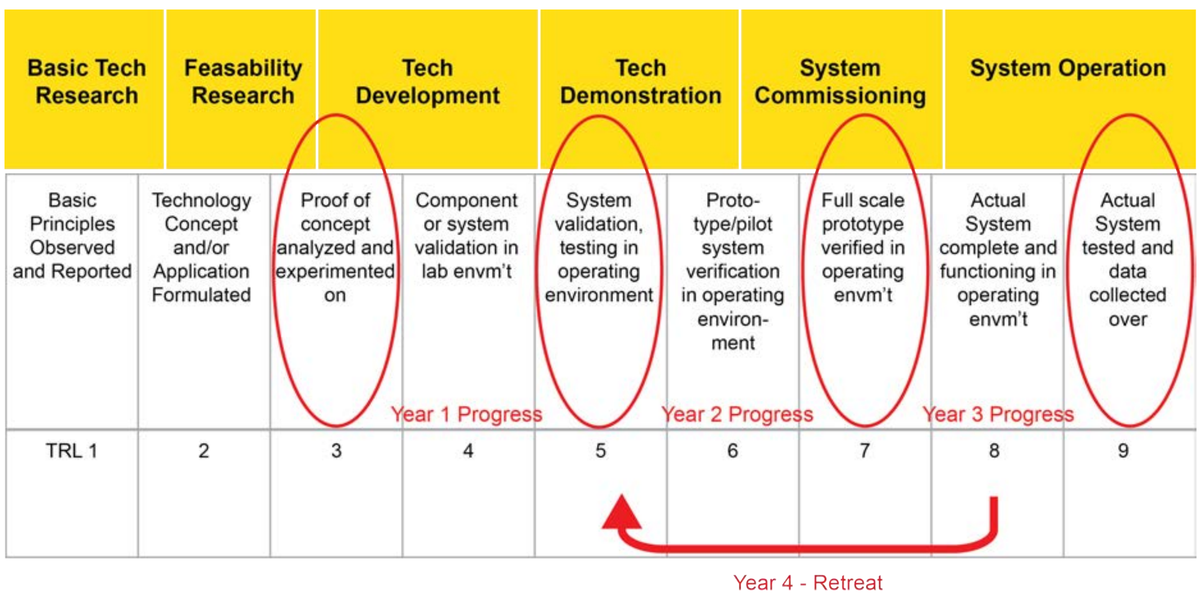


Figure 3: Challenges in Manufacturing Readiness Levels (MRL) required Company AA to retreat their product development and respective Technology Readiness Level (TRL).

Specific challenges for Company AA included:

- **A redesigned Bill of Materials (BOM):** Company AA did not perform a material trade-off analysis early in the process to optimize performance vs. cost.
- **A revised design to simplify installation:** Company AA did not consider that the total cost of a product often includes installation cost, and the product was not designed for ease of installation.
- **Securing a reliable supply chain:** Company AA did not include suppliers early in the design process and needed to rework the design when certain materials were not available.

[6] A chart of Manufacturing Readiness Levels is presented in Appendix C.

3.2.3 Solution and Lessons Learned

Company AA created a second version of their product, which improved the product's Manufacturing Readiness Level (MRL). Key solutions to their manufacturing challenges included:

- Working with a product engineering firm to redesign for lower manufacturing cost.
- Changing manufacturing processes, reducing tooling and BOM cost.
- Designing flexible tooling suitable for multiple product platforms.
- Redesigning with assembly in mind, reducing part count and labor.
- Redesigning for ease of installation.
- Securing multiple contract partners with adequate capacity and resources.

Company AA worked with their local incubator and Manufacturing Extension Partnership (MEP) consultants to find the people and expertise needed to implement these changes. ***Had the company personnel taken a Manufacturing 101-type course, they would have known to consider DFM in the initial design and to engage with DFM experts early on, saving multiple years of effort and a substantial amount of capital.***

4.0 Workshop Outcomes

The workshop resulted in an education and training curriculum for start-ups and entrepreneurs. Delivery of the course content was structured in a four-phase approach: *Engage, Educate, Enhance,* and *Execute*.

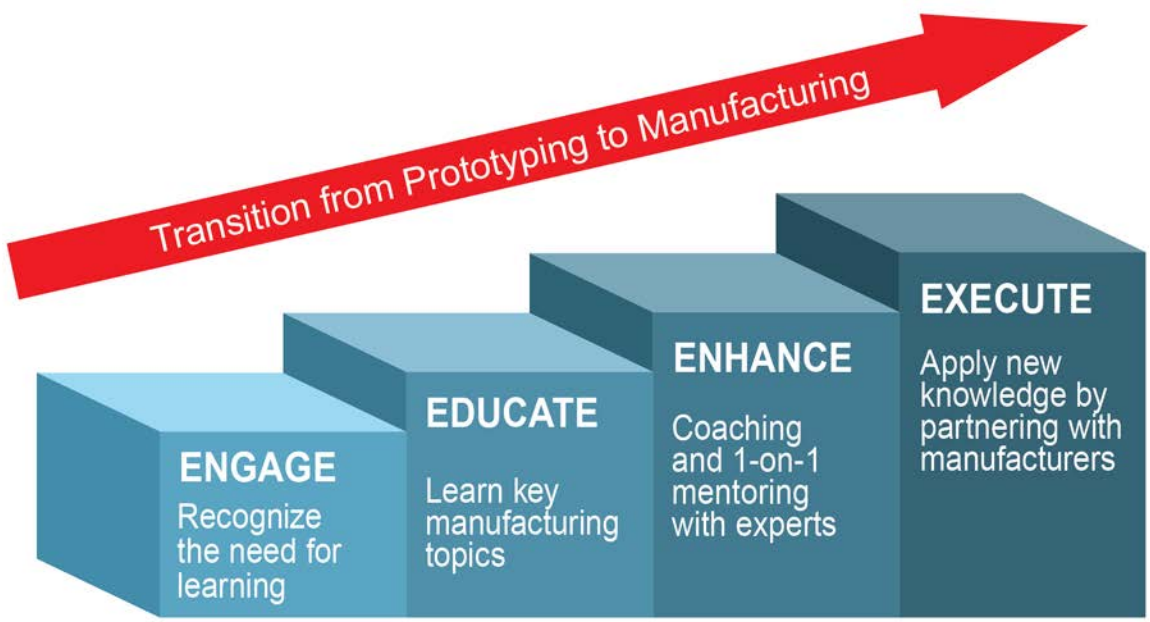


Figure 4: The four phases in Manufacturing 101

In the first phase, entrepreneurs discover the underlying need for training in the subject of manufacturing. This is the *Engage* phase, which motivates the entrepreneur to learn about the state of their own manufacturing readiness and to recognize the need for recognize typical manufacturing challenges.

In the second phase, start-ups *Educate* themselves on basics of manufacturing and associated design considerations. In gaining familiarity with manufacturing processes, materials, design considerations, and supply chain interactions, the entrepreneur becomes prepared to select the best processes and materials for his or her own product development. The first two phases of the curriculum, *Engage* and *Educate*, are intentionally technology-agnostic, providing basic information on manufacturing that can be readily applied to a wide range of products.

In the third phase, entrepreneurs *Enhance* the development of their product through specialized mentoring sessions with manufacturing experts. Coaching may include tailored hands-on workshops and individual meetings.

In the fourth and final phase, entrepreneurs work with product design firms, manufacturers, and suppliers to *Execute* the product's scale-up to production-scale manufacturing.

Eight individual modules were identified as the core curriculum. These modules cover the topics in manufacturing most relevant to entrepreneurs during product scale-up. Also included are recommended methods of delivery.

4.1 *Manufacturing 101* Curriculum Recommendations

Each of the eight key manufacturing topic areas are presented here as modules that can be translated into helpful education and training resources for hardware entrepreneurs.

Module 1: Manufacturing for Entrepreneurs

Manufacturing:
Why should I care?
Am I ready?

The key focus of the first module is to illustrate the importance of addressing manufacturing challenges early during product development. This is done in three primary ways:

1. Teach the differences between the Technology Readiness Level (TRL) and the Manufacturing Readiness Level (MRL), and then require the entrepreneur to take a self-assessment for each metric.
2. Illustrate various factors to be considered in order to manufacture at scale and why Design for Manufacturability matters as a critical discipline to commercialization success.
3. Explain the importance of manufacturing process innovation.

The first item is critical: companies need to be grounded on the current state of their product, and also need to know how to set realistic development milestones. The MRL framework provides a guide on how to develop a robust manufacturing strategy.

Completion of this module will help the entrepreneur gain a basic understanding of manufacturing in order to answer the following questions:

- What are typical manufacturing challenges?
- Why does design for manufacturability matter?
- What should I expect the product/process innovation to look like through my product's lifecycle (i.e. TRL and MRL)?
- What is the current manufacturing readiness level (MRL) of my product?
- What challenges to expect during product realization?

The module should also query entrepreneurs if they have thought about Design for X (e.g. Design for Assembly). This module need not go into details on any given DFX principle, but rather, the module should show entrepreneurs the types of questions they should be asking pertinent to various DFX principles.

Upon completion of Module 1, the entrepreneur should realize the benefit of early engagement with manufacturing issues.

Recommended Delivery Method – Module 1
Present the rationale for manufacturing education and training using case studies and other examples through online videos, interactive video-based education, and/or through interactive models/tools. In particular, demonstrate how attention to Design for Manufacturing will result in potential time and cost savings to the entrepreneur due to early planning and advance coordination with manufacturing professionals.
Ask the entrepreneur to perform a self-assessment of their product's TRL and MRL. Ideally, the self-assessment will be done collaboratively with an experienced manufacturing professional, but could be performed through an interactive online tool.

Module 2: Material Selection

Material selection is a key challenge for many entrepreneurs. The material selected for initial prototype development may not be appropriate for higher volume production. An entrepreneur needs to consider multiple factors such as functional requirements (e.g. strength needed), constraints (e.g. total weight allowed), environmental considerations (e.g. corrosion), regulatory requirements, reliability, and end of life processing.

Materials:
How do I select the best materials given the performance requirements of the commercial product?

Education and training developed for this module should be able to provide information and insights to address the following questions:

1. What material properties are essential to product's performance?
2. How can materials be selected that have the desired properties and what are suitable material alternatives?
3. How do these choices interact with different manufacturing processes and the product's performance?

A conceptual description of various material properties (e.g. strength, toughness, hardness, creep, thermal conductivity, etc.) should be presented to provide an understanding of how different properties affect product performance. The next step is to separate primary or functional properties from secondary ones. That is, if the operating temperature is high, then materials with high thermal conductivity should be considered. Initial screening and final ranking of alternate materials should take into consideration performance metrics and constraints (e.g. the strength per weight of a material). Finally, the material of choice must be compatible with the manufacturing process in terms of shape, rate and volume of production, desired tolerances, etc.

Software tools such as Granta CES[7] and MatWeb[8] are highly valuable for material and process selection education and practice. Such programs contain thousands of materials and associated

[7] Granta CES, https://www.grantadesign.com/products/ces/ (Granta CES is a commercial software package with a fee to licence.)
[8] MatWeb, http://www.matweb.com/

properties in a database (including metals, plastics, ceramics, and composites). The software offers straightforward tools that guide the user through a rational material selection process. The software begins with a user-defined list of desired material properties, including cost and weight constraints, and quickly generates candidate materials. Equivalent or substitute materials can be evaluated with side-by-side comparisons.

Figure 5 shows an example how various materials rank based on a combination of strength and density, as two example parameters.[9] Users can choose any combination of desired properties to screen and rank alternate materials. Users can also explore details of any specific material including applicable manufacturing methods, sourcing, etc.

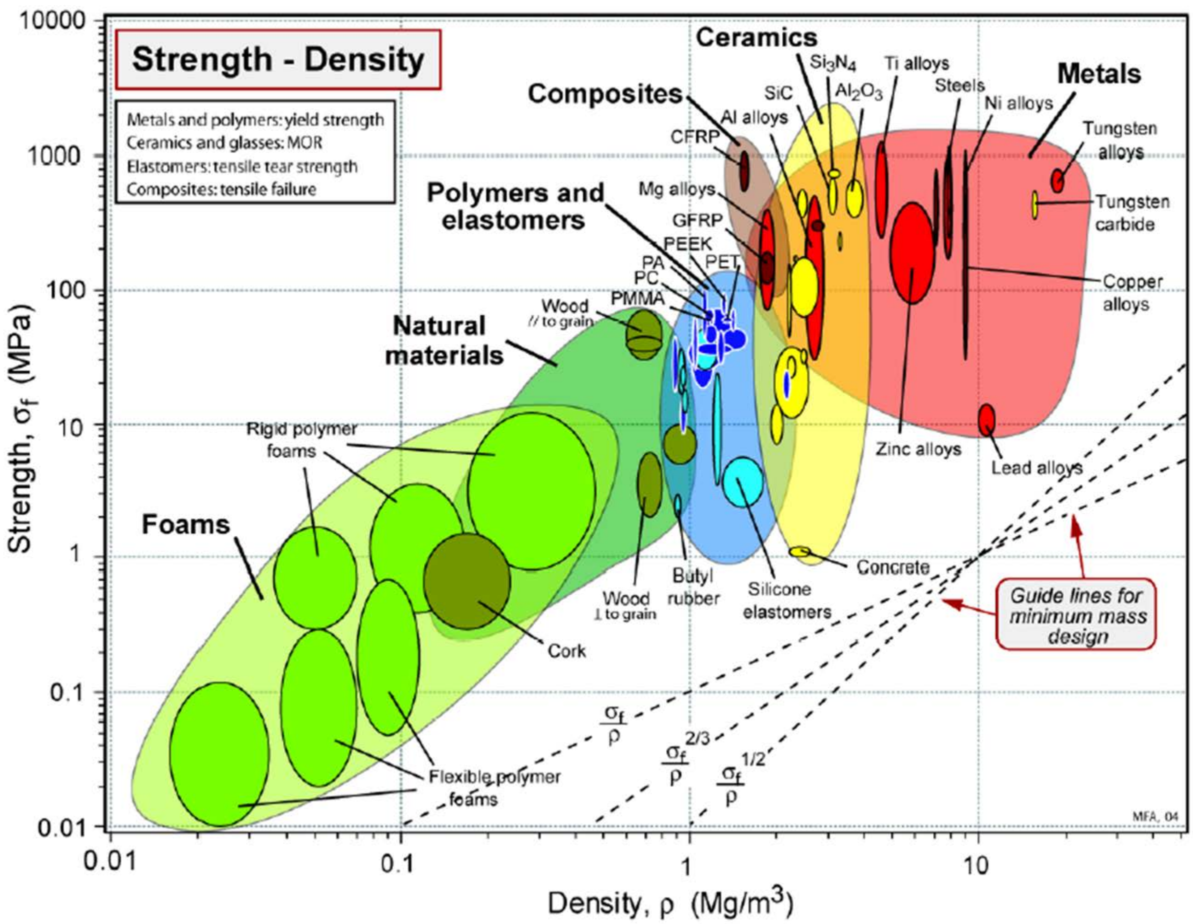


Figure 5: Software tools allow for the rapid selection of candidate materials based on combination of multiple performance parameters. This figure illustrates how various materials rank based on strength and density.

Recommended Delivery Method – Module 2
Deliver information on material selection through online videos, interactive video-based education, and/or through interactive models/tools.
Participate with local MEPs or other experts to assess material options. Direct engagement with an expert offers the opportunity to discuss the trade-offs between different materials, and the implications for manufacturing the product.

[9] Ashby's Material Selection Chart

	Provide an online, self-guided listing of available software tools for (a) Material selection based on functional requirements such as strength, stiffness, corrosion resistance, etc. and constraints such as lightweight, cost, etc., and (b) Process selection based on material, shape, required tolerance, surface finish, production rate, cost, etc.
	Develop collaborations with local universities or professional societies such as American Society of Metals (AMS) since the content proposed for this module is well-suited for a short-course format.

Module 3: Manufacturing Processes

Education and training developed for this module should be able to provide the background necessary to address the following questions:

1. What manufacturing processes are available?
2. What are key terms used (i.e. a glossary)?
3. What are the attributes of each process (e.g. tolerances, cost, material, shape, rate, etc.)?
4. What are the most appropriate and alternate manufacturing processes for each component of the product?

Process:
What manufacturing processes should I consider for my product?

Start-ups could benefit from a basic explanation of primary manufacturing processes such as molding, stamping, extrusion, casting, forging, etc. Depending on the entrepreneur's area of interest, a discussion of secondary processes such as machining, heat-treatment, surface treatment, joining methods, etc. should be considered. Module 3 should encapsulate, at minimum, the most common manufacturing process categories. Table 1 provides a sampling of the processes most likely to be important to an entrepreneur.

Extrusion	Injection molding	Stamping
Composite Processing	Forging	Compression molding
Pressure die casting	Joining/assembly methods	Thermoforming

Table 1: Manufacturing processes likely to be used by entrepreneurs.

A more detailed explanation of specific processes is appropriate if the product requires specific materials. For example, if an entrepreneur realizes that the product should be made out of a glass or carbon fiber composite, there are many production alternatives including injection molding, resin transfer molding (RTM), vacuum assisted resin transfer molding (VARTM), compression molding, pultrusion, and filament winding. Understanding these processes will help the entrepreneur make the best decision for their product.

Entrepreneurs also must understand and use the appropriate technical vocabulary when communicating with manufacturers. Table 2 shows a sample of the key vocabulary terms.

Springback	Thermal warping	Annealing
Work hardening	Boss, Cavity, Core	Sink marks
Cycle time	Flash	Gate
Residual stresses	Draft Angle	Grain/fiber orientation
Undercut	Billet	Cylindricity

Table 2: Vocabulary used in manufacturing.

Many of these terms cut across multiple manufacturing processes and inform various trade-offs (performance, cost, aesthetics) involved and help the entrepreneur avoid costly mistakes downstream. Thus, Module 3 should include definitions of key manufacturing terms.[10]

An essential part of this module is to help the entrepreneur select the most appropriate manufacturing processes based on the entrepreneur's current product design. The entrepreneur needs to understand the basic relationship between each manufacturing process and material choice, cost, quantity, size, shape, tooling needs, tolerance capabilities, and production rates. Figure 6 is a snap-shot of various steps involved in selecting an appropriate "shaping process" based on shape and material compatibility. Software tools such as Granta CES guide the user through various other considerations such as tolerances, production volume, rate of production, need for secondary finishing processes, etc. Another such resource is MatWeb[11] which is a free online material property data resource. MatWeb includes polymers (thermoplastic and thermoset), metals and alloys, ceramics, and a host of other engineering materials. Integrated search and comparison tools allow the user to explore alternate materials based on characteristics such as density, modulus, and material type.

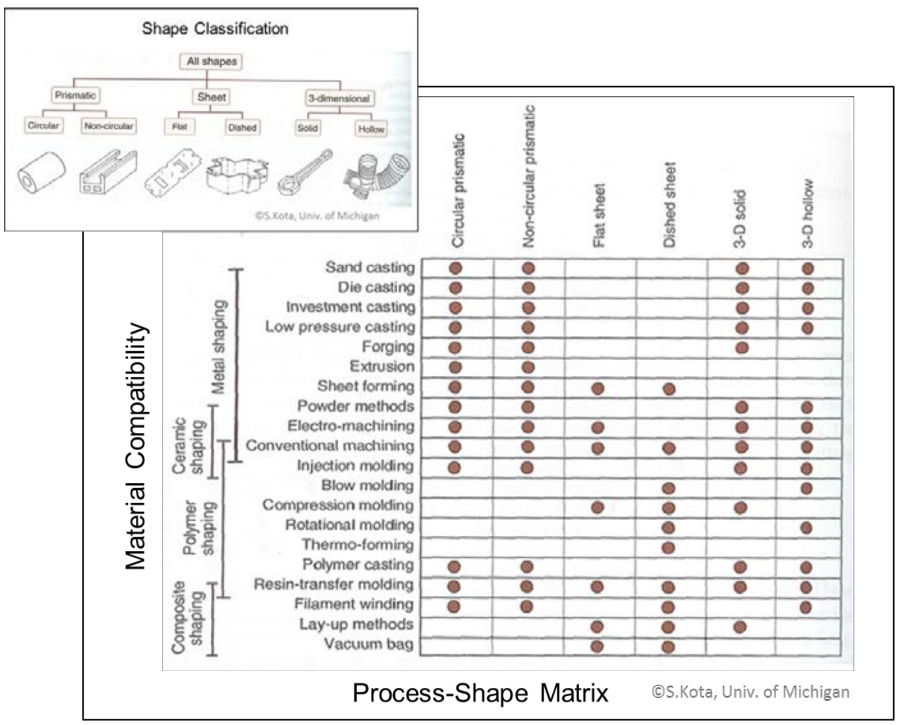


Figure 6: Process Shape Matrix for Process Selection

Once the entrepreneur understands the basic vocabulary and the range of process options, an ideal process can be selected based on:

- Cost,
- Performance requirements,
- Production volume and rate, and
- Competitive products.

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[10] Many resources already exist including https://www.manufacturing.gov/news-2/news/glossary-of-advanced-manufacturing-terms/; http://www.industryweek.com/manufacturing-glossary.
[11] http://www.matweb.com/search/AdvancedSearch.aspx

Module 3 can be presented as two sub-modules:

1. **Sub-module 3a** – *Manufacturing Process Overview*: In this sub-module, the entrepreneur is given an overview of the various manufacturing processes. The major manufacturing processes can be outlined, with a discussion on capabilities and limitations of each. Development of a high-level, easy-to-use flow-chart for process selection is recommended.
2. **Sub-module 3b** – *Detailed Manufacturing Processes*: The second sub-module provides details of selected processes of interest. This will be particularly useful if the geometric and performance features of the product are mapped against selected manufacturing processes. Sub-module 3b will help the entrepreneur begin the process of matching their product requirements to the appropriate manufacturing process.

Recommended Delivery Method – Module 3
Deliver information on the most relevant manufacturing processes and their primary attributes through online videos, interactive video-based education, and/or through interactive models/tools. Investigate manufacturing processes used to produce similar products on the market.
Create a glossary of key terms used in different manufacturing processes. (The glossary should link to other resources or videos to act as both an educational tool and a valuable reference sheet.)
Create an online tool that can help the entrepreneur benchmark their current Bill of Materials and Bill of Process.
Given the large number of trade-offs in material selection, the entrepreneur would benefit from direct engagement with a manufacturing expert. This is especially true when the entrepreneur's product design calls for unique performance or features.

Module 4: Design for Manufacturing and Design for X

Most hardware companies are familiar with the principle 'Design for Manufacturing' but are not sure how to include it into the development plan. Furthermore, many entrepreneurs do not realize that DFM represents a wide range of different design strategies, each targeted to achieving certain goals. For this reason, entrepreneurs need to be exposed to the range of Design for X (DFX) disciplines.

DFX:
What design disciplines are most relevant to my product?

Design for X refers to a range of design guidelines that seek to control and improve particular traits of a product. The "X" can refer to Assembly, Cost, Quality, etc. For each topic, a specific set of design rules and tools is applied to achieve the desired outcome.

Overviews of the DFX disciplines will provide an entrepreneur a basic background on proven methods to design and manufacture a product that meets cost and performance goals. DFX disciplines include (*See also Appendix B).*

- *Design for Quality (Robustness):* Render a design insensitive to variations in manufacturing (part-to-part variation or tolerances) or operating conditions (loading conditions, chemicals, component degradation, etc.) or noise factors such as temperature, pressure, humidity, vibration, etc.
- *Design for Assembly:* Part count reduction, process step reductions, simplifying assembly steps, preventing assembly error

- *Design for Process:* Reducing capital equipment and tooling cost, with specialized modules for the most common manufacturing processes such as:
    - Design for Extrusion
    - Design for Injection Molding
    - Design for Stamping
    - Design for Composite Processing
- *Design for System Integration*: System operating dynamics, transient impacts on connecting components
- *Design for Installation, Maintenance, and Serviceability*: Ease of installation and service, part replacement
- *Design for Packaging and Logistics:* Product protection, logistics, transportation costs
- *Design for Sustainability*: Ease of recyclability including ease of disassembly and use of biodegradable products and packaging. Reduced energy consumption during manufacture and operation
- *Design for Compliance:* Design to meet government regulations and certification requirements as well as awareness of International Traffic in Arms Regulations (ITAR)

Figure 7 is an example of how the complexity of a given assembly (and assembly cost) can be decreased substantially using Design for Assembly (DFA) principles.

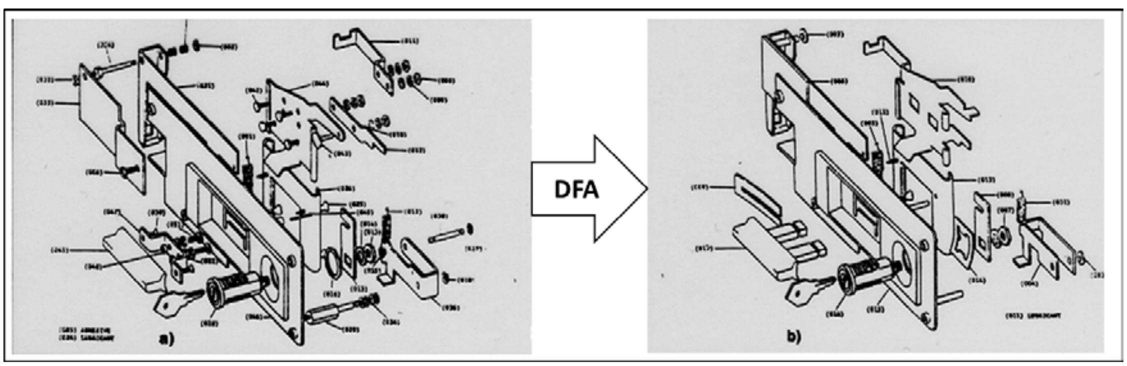


Figure 7: Decrease in part count and complexity using the Design for Assembly principles

Figure 8 shows an example of how the overall part-count can be reduced from 13 parts to two parts by simply switching from stamping to pressure die-casting.

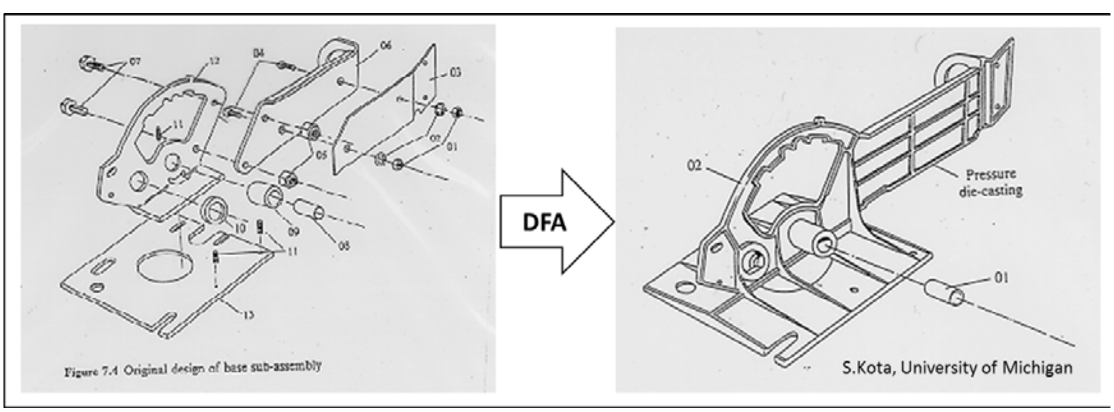


Figure 8: Overall part count can be drastically decreased using Design for Assembly techniques. In this example, the overall part-count was reduced from 13 parts to 2 parts.

Recommended Delivery Method – Module 4
Online videos, or interactive video-based education.
A series of presentations at local incubators, MEPs, and/or universities.
Direct interaction with manufacturing experts through Expert-in-Residence (EiR) programs, or an *M-Corps*[12] style program focused on manufacturing.
Note: Each DFX topic can be presented as a separate lesson using videos and/or presentations followed by a hands-on exercise in application of DFX principles to the entrepreneur's unique product design.

Important Note: The majority of Design for Manufacturing topics are sufficiently general for most electromechnical products, but the emphasis may shift depending on the specific product or technology. For example, Design for Assembly discusses general concepts that can be broadly applied, and all entrepreneurs should learn Design for Quality (Robustness). Similarly, Design for Sustainability covers issues such as energy consumption and carbon footprint for various materials and manufacturing processes. Some DFX topics, however, are more specific such as Design for Printed Circuit Board (PCB) which applies only to a product containing PCBs. Ideally, the *Manufacturing 101* curriculum should have the ability to be tailored to allow the entrepreneur to learn about the specific processes and DFX disciplines that are applicable to their product.

Module 5: Supply Chain

Supply Chain:
How do I ensure reliable delivery of materials, and long-term quality of the product?

The supply chain is essential to any manufacturing endeavor, and it includes many trade-offs and potential pitfalls for a new company. Education and training developed for this module should be able to provide direction on answering the following questions:

1. How is a “buy vs. make” decision made? That is, what process is used to decide which components to buy and which ones to manufacture in-house?
2. How can sub-contractors be identified for assembly (or sub-assemblies) of the product?
3. How are costs estimated for the supply chain and manufacturing options?
4. What logistics are involved with the supply chain?
5. What are non-recurring expenses (NREs) and Bills of Materials (BOMs)?
6. How are suppliers identified and vetted?
7. What internal processes are needed to successfully interact with the supply chain?
8. How does the supply chain change with volume?
9. What are best practices (“Dos and Don’ts”) to follow in selecting a supplier, manufacturer, or a contract service?
10. What is the impact of outsourcing manufacturing or design service on the core intellectual property?

Many of these issues overlap with each other, but each is important to include in the module. The “buy vs. make” decision involves addressing quality control, a tally of direct costs and an accounting of the true cost of inventory, supply chain disruption, in-house expertise, iterative improvements, and value added by the company. Assembly involves many of the same questions, but focused more on labor and automation than machinery and capital, with an interest in capital equipment investments (e.g., automation) vs. manual labor investment trade-offs. Cost

[12] See Section 4.2 for a description of the recommended *M-Corps* training program

estimation, NREs, and BOMs are an extensive topic, and should be introduced (BOMs are covered more extensively in Module 6). Finding and vetting suppliers includes certifications, capacity, expertise, payment methods, and communication in a manufacturing setting. Internal processes include standard operating procedures (SOP), revision control, traceability, part numbers, and processes for supplier interaction. Best practices are particularly important here, augmented by a list of "Dos and Don'ts."

Recommended Delivery Method – Module 5
Deliver information on supply chains through online videos, interactive video-based education, and/or through interactive models/tools.
Collaborate with manufacturing experts to assess supply chain options. Experts can be paired with entrepreneurs through Expert-in-Residence (EiR) programs, or the entrepreneur can blend coursework and mentorship in an *M-Corps* style program.

Module 6: Bill of Materials (BOM) and Bill of Process (BOP)

BOM/BOP:
How do processes and materials affect overall product cost?

Cleantech entrepreneurs need a clear understanding of their BOM and BOP. By using well-known cost estimation techniques, an early stage company can accurately assess its cost of goods sold (COGS) in order to evaluate market acceptance and margin setting. Existing BOM and BOP evaluation methods or tools such as consultation on Lean Design or Lean Manufacturing methods (through MEP centers or other practitioners) and Value Stream Mapping,[13] can help an entrepreneur to separate product cost (e.g. materials and components) from production costs (e.g., facility, capital equipment, tooling, labor, utilities), as well as fixed vs. variable costs.

Detailed knowledge of BOM and BOP also allows a start-up to develop a realistic manufacturing *pro forma* to show potential investors/partners. The BOP and BOM contain critical data during scale-up planning, giving the entrepreneur and potential investors a reliable view of cost-of-production.

It is highly recommended that this module also include a section that outlines what investors expect in a manufacturing *pro forma*.

Education and training developed for this module should be able to provide guidance for addressing the following questions:

- What is the current BOM and BOP for the product?
- How does the BOM and BOP impact the COGS?
- What are fixed and variable costs?
- How can a realistic *pro forma* be developed based on the BOM and BOP?

Recommended Delivery Method – Module 6
Deliver information on BOM/BOP through online videos, interactive video-based education, and/or through interactive models/tools.
Formal training programs that allow entrepreneurs to partner with manufacturing experts to create a detailed BOM and BOP and assess the impact of BOM/BOP to their COGS.

[13] Value stream mapping is a Lean Manufacturing or Lean Enterprise technique used to document, analyze and improve the flow of information or materials required to produce a product or service for a customer.

	Provide a template for a manufacturing *pro forma* that describes income and expenses in the near- and long-term. Present several examples using the *pro forma* template. Include a description of what investors are looking for in a manufacturing *pro forma*.
	Explore adapting/licensing commercial BOM/BOP tools to *Manufacturing 101.*

Module 7: Standards and Regulations

Standards & Regulations:
Are there standards and regulations that will impact my manufacturing decisions?

To sell into certain markets, products need to meet government regulations (environment, safety, etc.), industry test standards, or specific certifications. These topics are important for start-ups to understand.

This module will give entrepreneurs the tools and framework to consider the following questions:

- What industry regulations and test standards will drive the product design or manufacturing?
- Is pre- or post-manufacturing product testing needed to meet certain standards or receive specific industry certification?
- What product performance or manufacturing quality measures are required?
- What is the appropriate level of quality for the product (throughout its lifecycle)?
- Should part traceability be built into the product manufacturing process?
- What are the requirements on product packaging, shipping, and transportation?

A key goal for Module 7 is to enable entrepreneurs to know *what* questions to ask, *when* to ask them, and *who* to turn to for needed assistance for successful product realization. For instance, once the applicable standards and regulations have been identified, an appropriate mentor/expert can assist the entrepreneur in ensuring that all standards and regulations are met.

Recommended Delivery Method – Module 7	
	Create a guide that outlines major regulations for different products.
	Develop tools on how to identify industry-specific regulations and standards through online videos, interactive video-based education, and/or through interactive models/tools. (Provide case studies of select energy and transportation products to learn about relevant standards and regulations.)
	Collaborate with subject matter experts to determine which regulations apply to the entrepreneur's product. Because standards and regulations are very specific to certain industries, entrepreneurs will benefit most from direct interaction with an expert in their particular industry. Experts can be found via local MEPs or through EiR programs.

Module 8: Securing Mutually-Beneficial Manufacturer Partnerships

Partners:
How do I find the right manufacturing partners?

At an early stage, it is usually cost-prohibitive for entrepreneurs to capitalize manufacturing operations for their products. This requires start-ups to reach out to contract manufacturing partners who have resources to support their early production needs. Additionally, entrepreneurs must understand the needs of higher tier supply chain partners, but typically do not have experience with the entire supply chain.

As such, many start-ups struggle to find appropriate and willing partners. There are many reasons for these difficulties, including the following:

- Entrepreneurs are unfamiliar with the manufacturing industry.
- Many manufacturers decline orders from start-ups because of unrealistic expectations for volumes, limited capital, and a lack of knowledge about manufacturing processes.
- A manufacturer often needs to educate an entrepreneur on basic production methods.
- Start-ups are unfamiliar with the business structure of the supply chain.
- Start-ups have limited resources, and are inexperienced with standard practices when engaging with suppliers.

The issue of intellectual property (IP) can be especially challenging for a new entrepreneur when discussing potential manufacturing plans with a contract vendor. A balance must be struck between sharing all relevant technical information and protecting the company's IP position. Entrepreneurs need to understand the boundaries of their IP before engaging with a manufacturer, and should be willing to consider sharing (or offering compensation for) additional process innovations that may be developed during the manufacturing process, especially if such IP is likely to be generated by their supply partners.

For the above reasons, start-ups need basic information on how to identify, communicate, and collaborate with manufacturing partners. Education and training developed for this module should provide guidance to answer the following questions:

- What are the key incentives for a manufacturer to engage with an early-stage entrepreneur?
- What investments do manufacturers build into their pricing (tooling, machine equipment time, labor)?
- At what stage should an entrepreneur approach a contract manufacturer?
- How do supply chain dynamics limit or strengthen a manufacturer's capabilities?
- What are the "Dos and Don'ts" when engaging with a manufacturer?
- What additional services (e.g. shipping, packing, storage, etc.) can a manufacturer offer?
- How can a strategy for securing different manufacturing partners be developed as the company grows in volume, market penetration, and geographic distribution of the product?
- What engagement options can be offered to manufacturing partners if the start-up is cash limited?
- How do entrepreneurs avoid pitfalls with IP? Is there a way to recognize potential innovations in tooling or manufacturing methods specific to the product?
- How can IP concerns be presented to supply partners or manufacturing partners in a constructive manner?
- How can IP be shared, or how can the manufacturing partner be compensated for developing design modifications or any new manufacturing methods associated with the product?

Recommended Delivery Method – Module 8
Module 8 can best be delivered using a structured course that combines coursework and "supplier discovery" with manufacturers, i.e. identifying and meeting potential manufacturing partners (See section 4.2).

	Provide a list of “Dos and Don’ts” when dealing with suppliers and partners which gives an entrepreneur a set of basic guidelines for initial discussions.
	Provide a set of boilerplate intellectual property documents, including Non-Disclosure Agreements tailored to manufacturing partnerships or Joint Development Agreements for the manufacturing stage. These documents provide a good starting point for any small business when discussing potential teaming for production.
	Provide a checklist of critical items to consider as the manufacturing partnership matures.

4.2 Content Delivery – Recommendations

The content in *the Manufacturing 101* course can be delivered according to the four program phases listed in section 4.0.

Engage the Entrepreneur

The first step is to *Engage* entrepreneurs to bring awareness to the various challenges that must be overcome to transition a functional prototype into a design that can be physically realized at scale with consistency (manufactured). This can be done using existing resources and platforms, including incubators, universities, MEPs, DOE-supported programs, and publicly available videos and tools. This material should be readily available both online (videos or online mini-courses) and in-person (presentations, seminars, workshops, or add-ons to existing programs). Most materials for this phase should be easily scalable and be readily accessible.

Educate the Entrepreneur

Once the entrepreneur comes to an understanding of the importance of learning basic manufacturing concepts and challenges, the *Education* process begins.

Online content could be delivered using a variety of formats:

1. Develop a “MFG-Channel” that consolidates *Manufacturing 101* video resources into one central location. The advantage of *MFG-Channel* is that it provides a framework for a range of educational and training tools, including:
    a. Videos that illustrate various manufacturing processes directly, including demonstrations from the shop floor with accompanying interviews/explanations from operators. Videos can also include teaching tools with diagrams and other multimedia content. Commercial firms specializing in manufacturing could be tapped to develop videos on specific subjects.
    b. TED-style videos of talks presented at a conference or workshop, then saved online and categorized for broad access.
    c. Video presentations from organizations such as the Society of Manufacturing Engineers (SME) can be very useful and may be incorporated (with appropriate authorization).
2. Use an interactive wiki or other main landing page to provide videos on areas of interest (or by topic), rather than in a sequential manner. The advantage of the wiki is the ability to link to different types of resources including DOE web portals, videos, graphs, PDFs, outside websites, tutorials, and more. An interactive site would allow users to provide feedback or ratings on the most useful tools and suggest additional useful content.
3. Some topics are best delivered using interactive tools. For example, an interactive BOM development tool or a cost estimation tool would allow the entrepreneur to explore different

options for materials and processes. Full-scale commercial tools for this exist on the market already, but these tools could potentially be adapted into a "lite" version for learning entrepreneurs.

4. The *Manufacturing 101* education and training modules can be offered through EERE and Advanced Manufacturing Office websites. Occasional webinars may be offered to highlight current topics.
5. *Manufacturing 101* education and training modules can be integrated into existing entrepreneurial training programs delivered by SBIR commercialization assistance providers, or by incubators/accelerators.

A key advantage of the *Educate* portion of the program is that it is highly scalable and accessible at a low cost, and would provide a foundational knowledge for entrepreneurs.

Enhance the Entrepreneur's Knowledge

As described earlier, it can be a challenge to translate vast amounts of general manufacturing knowledge to an entrepreneur's unique product and manufacturing challenges. To address this, one-on-one coaching is recommended in order to *Enhance* an entrepreneur's manufacturing knowledge through a combination of coursework and personal interaction with an expert.

One potential method for delivering content is to develop an "*M-Corps*" program modeled after the NSF I-Corps program.[14] One of the most powerful aspects of I-Corps is the requirement for participants to personally engage with a large number of potential customers or partners. Using a philosophy of "get out of the building and talk to your customer," the I-Corps program requires entrepreneurs to meet in-person with the people most important to their company's success: their customers. In the same way, the *M-Corps* process requires entrepreneurs to learn first-hand about manufacturing via personal interaction with their manufacturing partners.

The proposed *M-Corps* approach consists of a combination of lectures, case studies, hands-on workshops, discovery, and direct support from manufacturing experts. Benefits of this approach include:

- Entrepreneurs working as a team to learn about basic manufacturing topics in a classroom setting.
- An experienced mentor assists and supports a specific entrepreneur or team to help them learn about manufacturing options for their specific product. Mentors are embedded with each team for the duration of the course. Mentors could be general manufacturing experts or specific technology experts who offer advice tailored to each entrepreneur's specific product.
- Entrepreneurs meet with potential manufacturing partners *at the manufacturing facility* in order to fully grasp specific manufacturing processes and issues. Content delivery starts with in-class presentations, but critically, entrepreneurs must then follow up each classroom module with site visits to manufacturing facilities.

Existing educational *Manufacturing 101* resources (videos, interactive tools, webinars, etc.) should be used whenever possible, especially for the lectures, case studies, and workshops.

An *M-Corps* program could be hosted in a variety of locations. Existing incubators may offer a good starting point since many possess the needed resources. If the training framework were to

[14] NSF Innovation Corps, https://www.nsf.gov/news/special_reports/i-corps/

be developed, incubators could license the curriculum in order to launch their own regional programs and scale training delivery. It is recommended to explore best practices for executing these types of programs, beginning with existing approved I-Corps instructor nodes.[15]

Mentors are a critical part of the proposed *M-Corps* approach, offering coaching and one-on-one support to start-ups.

- Mentors can come from a range of organizations, including existing MEPs or from well-respected product engineering DFX consulting firms, or they could be retired engineers with product-specific or manufacturing expertise.
- Mentors do not teach basics; instead, they guide the companies on specific product/process decisions.
- Mentors play an important role of "course-correction."
- Mentors should be compensated for participating in the program.
- Mentors should be certified to ensure qualifications and so they are trusted by entrepreneurs, partners, investors, and the DOE.

The *Enhance* phase of the *Manufacturing 101* program offers the benefit of a scalable, moderate-cost process that will add greater depth to the entrepreneur's manufacturing knowledge, and connects entrepreneurs with the regional manufacturing ecosystem and local experts. This phase is designed to reduce a start-up's potential missteps and could significantly accelerate the product realization process.

Execute the Product Development Process

The final phase is *Execute*, where entrepreneurs apply the new knowledge to their product design and manufacturing process. After the basic coursework is completed and time is spent learning about manufacturing from on-site visits, the *Execute* phase can follow several paths. Examples include:

1. Entrepreneurs proactively engage manufacturing experts and resources to prepare their product for manufacturing. This can include contract manufacturers or product design firms.
2. Entrepreneurs assess their MRL status, launch a product/process design revision cycle, and develop a manufacturing plan. In addition, a manufacturing *pro forma* is developed, making the start-up more attractive to potential strategic and investment partners.

The process of matching experts to entrepreneurs can be assisted by the DOE, local MEPs, and local incubators. Suggestions for this part of the program include:

1. Online match-making to identify and connect retired and semi-retired manufacturing experts who are often eager to share their experience and knowledge with start-up companies. This could be a very effective method to accelerate product development and is also likely to be very cost-effective.
2. Use a cost sharing method to compensate the experts, where the cost could be shared between the company, the state, and the DOE.

The process of matching experts to entrepreneurs can be accelerated by leveraging existing networks of manufacturing experts and resources. The key is to match the right type of mentor to the entrepreneur's unique needs.

[15] I-Corps Nodes, http://www.nsf.gov/news/special_reports/i-corps/nodes.jsp

Additional actions that could be taken to support the *Execute* goal include:

1. Extend the concept of the Small Business Voucher (SBV) pilot program[16] to offer expert manufacturing and scale-up assistance to selected start-ups. Such vouchers for services may be offered through regional MEPs who have had a successful track record and other similar entities in addition to the DOE national labs.
2. For the companies furthest along, provide vouchers to enable the companies to collaborate with professional design firms specializing in manufacturing.
3. Support regional programs that help connect start-ups with local manufacturers to realize new products locally, and gain insight into the challenges that exist in creating such partnerships. Examples include the MassDevelopment-funded pilot program between Greentown Labs Manufacturing Initiative and the Massachusetts Manufacturing Extension Partnership (MassMEP);[17] and Michigan InnoState[18] and Pure Michigan Business Connect.[19] These programs connect start-ups with local manufacturing suppliers for consulting, prototyping, and scale-up services.

5. Conclusion

This report presents an outline for a *Manufacturing 101* education and training curriculum targeted to hardware entrepreneurs. Upon successful completion of the *Manufacturing 101* program, entrepreneurs will have a basic understanding of manufacturing disciplines, challenges, and best practices. As a result, entrepreneurs will be able to knowledgably engage with design engineers, consultants, and manufacturing companies during the product scale-up process.

Additional work is needed to augment the content, develop educational materials, and effectively deliver the program to the entrepreneurs and start-up firms that are in the process of scaling up to quantity manufacturing. Appendix A lists resources and experts that can assist with developing this training program.

The *Manufacturing 101* education and training program will have a significant positive impact on America's innovation culture, benefiting entrepreneurs and manufacturers alike. When entrepreneurs are empowered with manufacturing expertise, innovative ideas will reach the market more often and more efficiently.

[16] Small Business Vouchers Pilot, https://www.sbv.org/

[17] Morrill, M. (2014). "Greentown Announces Manufacturing Initiative to Support Startups Path to Commercialization." http://greentownlabs.com/greentown-announces-manufacturing-initiative-support-startups-path-commercialization/

[18] InnoState, http://innostatemi.com/about-us/

[19] Pure Michigan Business Connect, http://www.michiganbusiness.org/grow/pure-michigan-business-connect/

Appendix A: Cleantech Entrepreneur Network Resources

Networks, Programs, and Competitions

- DOE's Incubate Energy Network https://incubatenergy.org/
- DOE EERE http://energy.gov/eere/office-energy-efficiency-renewable-energy
- ACTION (New England) www.actionnewengland.org
- Clean Energy Action http://cleanenergyaction.org/
- New England Clean Energy Council http://www.necec.org/
- California Clean Energy Fund https://calcef.org/
- University entrepreneurial training programs
  - Michigan Center for Entrepreneurship http://cfe.umich.edu/
- National Laboratory entrepreneurial training programs
  - Lab-Corps http://energy.gov/articles/energy-department-announces-new-lab-program-accelerate-commercialization-clean-energy
- Entrepreneurial boot camp and training programs
  - I-Corps Energy and Transportation Program https://www.nextenergy.org/icorps/
- Cleantech business plan competitions and accelerator programs
  - Cleantech Open http://www2.Cleantechopen.org/
  - Clean Energy Trust Challenge http://cleanenergytrust.org/challenge/
  - Tumml's Urban Clean Energy Prize http://www.tumml.org/about/#apply
- DOE's Cleantech University Prize
- Technology validation and demonstration programs
  - National Renewable Energy Laboratory's Energy Systems Integration Facility http://www.nrel.gov/esif/
  - Fraunhofer TechBridge http://www.cse.fraunhofer.org/techbridge
  - Center for Evaluation of Clean Energy Technology http://cecet.com/
- Zahn Innovation Center Kylie Hardware Awards (New York) http://www.zahncetnernyc.com
- TechCrunch Hardware Battlefield (Las Vegas, NV) http://techcrunch.com/events/hardware-battlefield-2015/event-home/
- Entrepreneurial contract manufacturing match making programs
  - Greentown Labs Manufacturing Initiative http://www.greentownlabs.com/wp-content/uploads/2015/02/020515-Manufacturing-Initiative-PDF1.pdf
  - InnoState http://innostatemi.com/

Manufacturing Training Network Resources

- DOE EERE http://energy.gov/eere/office-energy-efficiency-renewable-energy
- Advanced Manufacturing Office (AMO) http://energy.gov/eere/amo/advanced-manufacturing-office
- National Network of Manufacturing Institutes (NNMI's) http://manufacturing.gov/nnmi/institutes.html
- Existing Design for Manufacturability training resources (e.g. Society of Manufacturing Engineers)
- Manufacturing Extension Partnerships (MEP's) programs http://www.nist.gov/mep/

DFX Training Resources

- Society of Manufacturing Engineers (SME) Tooling U – extensive online manufacturing training http://www.toolingu.com/
- SME Manufacturing Insights® videos http://www.sme.org/mi/
- SME Fundamental Manufacturing Processes (FMP) – A 44 video program on major manufacturing processes http://www.sme.org/fmp/
- SME DFMA training http://www.toolingu.com/ilt/915101/Design-for-Manufacturability-and-Assembly-DFMDFA
- Advice Manufacturing Processes – comprehensive list of short videos showing the range of processes common in manufacturing industry http://www.advice-manufacturing.com/Manufacturing-Processes.html
- The Manufacturing Institute – manufacturing skills certification programs http://www.themanufacturinginstitute.org/Skills-Certification/Certifications/NAM-Endorsed-Certifications.aspx
- AME Alliance – 8-week manufacturing certification courses http://amealliance.org/8-week-certificates
- Alison Institute – online manufacturing training classes, https://alison.com/learn/manufacturing
- DfR Solutions – Design for Manufacturing training programs, www.dfrsolutions.com
- Society of Automotive Engineers (SAE) Intl – DFM, DFA training, http://training.sae.org/seminars/92047/
- Tec-Ease, Inc. – Design for Assembly and GD&T training, http://www.tec-ease.com/design-assembly.php
- Engineers Edge – DFMA training, http://engineersedge.com/training_engineering/design-for-manufacturing-training.htm
- OMNEX – DFMA training, http://www.omnex.com/training/rd_Series/design_manufacturing_assembly.aspx
- SSA – DFMA training, http://www.ssa-solutions.com/training-program/design-for-manufacturing-assembly.php
- Manufacturing Skills training programs http://scientific-management.com/skills-training-programs
- Manufacturing Quality Training ASQ, www.asq.org
- Automotive Industry Action Group (AIAG) – developed the Advanced Product Quality Planning (APQP) manual with training available via courses or on-line http://www.aiag.org/store/training/details?CourseCode=ELCTO
- Electronics Manufacturing Training http://www.ipc.org
- Surface Mount Technology Association (SMTA) – online manufacturing training courses, SMTA, www.smta.org
- How It’s Made - as seen on The Science Channel http://www.sciencechannel.com/tv-shows/how-its-made/ https://www.youtube.com/channel/UCjHsPBHX1NNbIqTy4eXVTig
- Munro & Associates – *Lean Design* manufacturing optimization training http://leandesign.com/lean-design/
- Munro & Associates – *Design Profit* manufacturing costing software http://www.designprofit.com/
- Ricardo – Product development, engineering and manufacturing training and consulting http://www.ricardo.com/en-GB/What-we-do/knowledge/Training/

- Six Sigma U – design for six sigma training http://www.6sigma.us/design-for-six-sigma-dfss.php
- NPD Solutions – design for maintenance and serviceability workshops http://www.npd-solutions.com/featuredworkshops/dfsws
- TU Delft/UNEP – design for sustainability http://www.d4s-sbs.org/
- Dragon Innovations - BOM development tools https://www.dragoninnovation.com/dragon-standard-bom
- Greentown Labs and MassMEP – Best Practices for Training Start-ups to work with Manufacturers http://greentownlabs.com
- Invent@NMU – hardware entrepreneur accelerator program focused on acceleration to market through DFX principals http://www.nmu.edu/invent/home
- Connecting Green Technology Entrepreneurs - Building connections for green technology entrepreneurs https://www.infodev.org/infodev-files/connecting-green-technology-entrepreneurs-full.pdf
- E2 by Shoptech – All-In-One Manufacturing Software (quoting, accounting, production, inventory etc.)
  www.shoptech.com
- Basic CAD tools – Autodesk Fusion 360 http://www.autodesk.com/products/fusion-360; or SolidWorks www.solidworks.com
- Geometric Global – Design for Manufacturing Software http://info.geometricglobal.com/design-for-manufacturing-software
- Design-IV – DFM/DFA Software http://www.design-iv.com/

Design for Manufacturing Training, Instructional Content, and Curriculum Experts

- Dale Lee, Plexus – Design for Excellence (Manufacturing, Assembly, Reliability) training, dale.lee@plexus.com
- Greg Caswell, DfR Solutions – Design for Manufacturing for Electronics training, gcaswell@dfrsolutions.com
- Fred Schenkelberg, FMS Services, Design for Manufacturing, fms@fmsreliability.com, http://reliabilitycalendar.org, http://accendoreliability.com
- Sandy Munro, Munro & Associates – Design for Manufacturing/Profit training programs, smunro@leandesign.com, http://leandesign.com
- DfR Solutions (Craig Hillman, Greg Caswell, Randy Schueller, Cheryl Tulkoff) – comprehensive and timely catalogue of online and onsite training courses designed including Electronics Design Manufacturing Reliability Training programs, Cheryl Tulkoff, ctulkoff@gmail.com, www.dfrsolutions.com
- VentureWell – entrepreneur training development and delivery including I-Corps and Lean Launchpad, https://venturewell.org/
- Sharon Ballard, EnableVentures Inc. – entrepreneur training on business plans, SBIR and STTR, sharon.ballard@enableventures.com, http://enableventures.com/home.php

Manufacturing Shared Asset Facilities and Prototyping Services:

- TechShop – shared manufacturing space http://www.techshop.ws/
- Makerspace – shared manufacturing space http://makerspace.sp.edu.sg/
- Quick Parts – 3D printing service http://www.3dsystems.com/quickparts
- R&D Technologies – 3D printing service rnd-tech.com

- Protolabs – 3D printing, CNC machining, injection molding service www.protolabs.com
- Maketime – CNC machining service www.maketime.io
- Rapid Manufacturing/Vaupell – prototype sheet metal/machined parts/cabling service https://uploads.rapidmanufacturing.com/?gclid=CJCAkfPIvs0CFUpahgodAzoFgg
- Circuit Hub – on demand PCB manufacturing service https://circuithub.com/

Entrepreneur-Manufacturer - Supplier Consulting and Match Making

- Vendop – Manufacturing vendor matching portal https://www.vendop.com/
- Greentown Labs Manufacturing Initiative – Cleantech hardware incubator partnership with Massachusetts Manufacturing Extension Partnership (MassMEP) http://www.greentownlabs.com/wp-content/uploads/2015/02/020515-Manufacturing-Initiative-PDF1.pdf
- InnoState – Michigan entrepreneur-manufacturer match making program organized by MEP Michigan Manufacturing Technology Center (MMTC) http://innostatemi.com/
- Pure Michigan Business Connect – buyer seller match making events and portal http://www.michiganbusiness.org/grow/pure-michigan-business-connect/

U.S. Cleantech Incubators

Note: this list is a sample, and not inclusive of all incubators in the U.S.

- ACRE/ Urban Future Lab/ Powerbridge (New York) http://ufl.nyc/
- Austin Technology Incubator (TX) http://ati.utexas.edu/
- Clean Energy Trust (Chicago, IL) http://cleanenergytrust.org/
- Cleantech San Diego (CA) http://Cleantechsandiego.org/
- CLT Joules (Charlotte, SC) http://cltjoules.com/
- Colorado Renewable Energy Collaboratory http://www.coloradocollaboratory.org/
- Cyclotron Road (Berkeley, CA) http://www.cyclotronroad.org/
- Greentown Labs (Boston, MA) http://greentownlabs.com
- GreenTech Endeavors (Miami, FL), www.greentechendeavors.com
- Hawaii Energy Exelerator http://energyexcelerator.com/
- Los Angeles Cleantech Incubator http://laincubator.org/
- Michigan Alternative and Renewable Energy Center http://www.gvsu.edu/mihub/
- Midwest Energy Research Consortium (Wisconsin) http://m-werc.org/
- NextEnergy (Michigan) www.nextenergy.org
- Northeast Ohio Economic Development Council (Cleveland) http://www.teamneo.org/
- Oregon BEST http://oregonbest.org/
- Prospect Silicon Valley (San Jose, CA) http://prospectsv.org/

Hardware Based Accelerators

North America

- Alphalab Gear (Pittsburgh, PA) http://www.alphalabgear.org/
- Bolt (Boston, MA) https://www.bolt.io/
- First Batch http://www.firstbatch.org
- Greentown Labs http://greentownlabs.com

- Hax https://hax.co/about/
- Highway1 powered by PCH (San Francisco, CA) http://highway1.io/
- Invent@NMU http://www.nmu.edu/invent/home
- LabiX powered by Flextronics (San Jose, CA) http://www.labix.io/
- Lemnos Labs (San Francisco, CA) http://LemnosLabs.com
- Make in LA (Los Angeles, CA) http://makeinla.com/
- NextEnergy www.nextenergy.org
- RGA powered by Techstars (New York, NY) http://rgaaccelerator.com/connecteddevices/
- Tandem Capital (Burlingame, CA) http://tandemcap.com/

Asia

- Brinc IoT (Hong Kong, China) http://brinc.io
- HAX formerly HAXLR8R (Shenzhen, China) http://HAXLR8R.com/ http://Hax.co
- Makers Boot Camp (Kyoto, Japan) http://www.makersboot.camp
- NEST VC / Infiniti (Hong Kong, China) https://www.infiniti.com.hk/infiniti-lab.html
- Enchant VC (Singapore) http://www.enchant.vc/

Europe

- builtit (Estonia) http://buildit.ee/
- Hardware.co (Berlin, Germany) http://hardware.co
- Industrio (Rovereto, Italy) http://www.industrio.co/
- Startupbootcamp HightechXL (Eindhoven, Netherlands) http://www.startupbootcamp.org/accelerator/hightechxl/
- Techfounders (Munich, Germany) http://www.techfounders.com/

Appendix B: Design for Manufacturing – Key Topics

Design for Assembly
Types of assembly operations (e.g. grasp, move, orient, insert)
Human vs. Machine (tradeoffs, advantages of each)
Part reduction
- Can parts be combined?
- Can a single part serve multiple roles?
Modular designs
Symmetry
Avoiding parts that tangle or nest
Eliminating fasteners
Nesting features
Open assembly (i.e. easy access to parts being assembled)
Error proofing assembly
Boothroyd Dewhurst model
Ease of handling parts (size, flexibility, fragility, adhesion, etc.)
Reduce required precision
Alignment features
Geometric dimensioning and tolerancing

Design for Durability/Robustness
Statistical noise parameters
- Environmental
• *Noise (acoustic)*
• *Vibration*
• *Harshness*
• *Impact & Loading Conditions*
• *Temperature*
• *Chemicals*
• *Manufacturing*
Dimensions
Materials
Assembly
Component degradation
Removing noise, compensation for noise, design insensitivity to noise
Quality characteristics
- Types (target, larger, smaller)
Control parameters (transfer function on noise to quality)

Design for Electronics
Standardize
- Use COTS parts
- Use common components
- Standardize design, procurement, process, assembly, and equipment
Part and process reduction
- Reduce parts
Modular design
Multi-use or multi-functional parts
- Reduce labor steps
- Reduce process equipment
- Reduce workstations
Lean design
- Holes (placement and design)
- Soldering
- Handling
- Assembly
• *Error proofing*
• *Tool clearance*
• *Self-alignment*
Waste
- Avoid overproduction and scrap
Part Handling
- Symmetry
- Orientation in sourced parts
- Avoid fragile parts
- Ease of manipulation
Joining
- Avoid fasteners
- Standardize fasteners
Error proofing
- Clear, easy assembly process
- Verifiability
- Keying
Tolerances
Test and Service
- Spacing
- Self-tests
Disassembly

Design for Manufacturing - Key Topics (continued)

Design for Packing and Logistics
Packaging for shipping
Ease of packing
Ease of tracking
Shape and size
Standardization
- Parts
- Process
- Product
- Procurement
Design for Sustainable Packaging

Design for Sheet Metal Forming
Die types
Hydroforming (tube and sheet)
Forming limits of the material
Deep drawing
Springback
Trimming, piercing, flanging, drawing, and punching operations
Wall angles
Panel Depth
Avoiding backdraft and die lock
Corner design
Hole design and placement

Design for Sustainability
Material recyclability and
Energy and carbon footprint
Regulations: waste, efficiency, and
Environmental impact

Design for Injection and Blow Molding
Polymer types, their advantages, and typical uses
Draft angles
Uniform wall thickness
Structural ribs (use and design)
Ejection Pins
Holes and Slots (placement and design)
Snapfits (use for assembly, design, and placement)
Screw bosses
Undercuts
Slides
Thermal warping
Ultrasonic, spin, and hotplate welding
Blow Molding
- Blow ratio/cavity depth
- Inner and outer radii
- Structural panels and ribs

Appendix C: Manufacturing Readiness Levels[20]

Phases	MRL	Definition
Operations and Support	10	Full Rate Production demonstrated and lean production practices in place.
Production and Deployment	9	Low Rate Production demonstrated; Capability in place to begin Full Rate Production.
Engineering and Manufacturing Development	8	Pilot line capability demonstrated; Ready to begin low rate initial production.
	7	Capability to produce systems, subsystems, or components in a production representative environment.
Technology Maturation & Risk Reduction	6	Capability to produce a prototype system or subsystem in a production relevant environment.
	5	Capability to produce prototype components in a production relevant environment.
Material Solutions Analysis	4	Capability to produce the technology in a laboratory environment.
	3	Manufacturing proof of concept developed.
	2	Manufacturing concepts identified.
	1	Basic manufacturing implications identified.

[20] More information about Manufacturing Readiness Levels can be found in the "Manufacturing Readiness Level (MRL) Deskbook, published by the Department of Defense. http://www.dodmrl.com/MRL_Deskbook_V2.4%20August_2015.pdf

Appendix D: Workshop Information and Biographies

Dan Radomski, former VP at NextEnergy Cleantech incubator, was hired as a consultant to assist with determining experts, facilitating the workshop, and preparing this report.

Experts in Cleantech entrepreneurship were:

- Micaelah Morrill
- Peter Russo
- Dan Radomski

Providing expertise primarily in educating entrepreneurs and assisting with manufacturing engagement were:

- Brian Anthony
- David Ollila
- John Taylor
- Patrick Dempsey

Design for Manufacturing expertise included:

- Mark Ellis
- Jason Schug
- Cheryl Tulkoff
- Sridhar Kota
- Josh Bishop-Moser
- Joe Tesar

Many of these experts have extensive knowledge in multiple of these categories, providing further value to their contributions. The range of experts was selected based on the experts' unique experiences in supporting Cleantech hardware companies and/or training of DFM disciplines to a broader audience. All participants were also asked to provide case studies of Design for Manufacturing and its use in Cleantech ventures, DFM resources, and contacts to content matter experts.

Also in attendance at the workshop were participants from the Department of Energy: Eli Levine, Johanna Wolfson, and Brenna Krieger.

MForesight Staff

Sridhar Kota is the Director of MForesight: Alliance for Manufacturing Foresight and Herrick Professor of Engineering; Professor of Mechanical Engineering at the University of Michigan, Ann Arbor. Professor Kota developed a senior/graduate level Design For Manufacturability course in Fall 1990 and taught for several hundreds of on-campus students as well as practicing engineers through University of Michigan distance-learning program until 2004. This course is currently taught by other faculty members at the University of Michigan. Professor Kota served for three years (2009-12) in the White House Office of Science and Technology (OSTP) as the Asst. Director for Advanced Manufacturing. His primary contributions were initiating and championing the National Manufacturing Innovation Institutes and the National Robotics Initiative. Dr. Kota has authored over 200 technical papers on engineering design and bio-inspired design and holds over 25 patents. He is the founder and President of FlexSys Inc., an engineering firm that developed the world's first modern commercial aircraft with shape-changing wings.

Dan Radomski, Optimal Inc., is the Chief Strategy Officer of Optimal Inc., an innovative group of small businesses and startups focused on reverse engineering, competitive benchmarking, automotive vehicle engineering and lightweighting technologies. He leads strategy, business development and commercialization efforts for all three companies located in Plymouth and Ann Arbor, MI. Mr. Radomski was previously Vice President of Industry and Venture Development at NextEnergy, an energy and transportation technology incubator located in Detroit, MI, and was also an instructor for I-Corps Energy & Transportation Program sponsored by Department of Energy (DOE) and ARPA-E leading recruitment of participants, secured over 50 industry mentors, customization of program curriculum. Mr. Radomski was also responsible for industry outreach, market research, value chain analysis and technology road mapping of several energy market segments including power electronics, energy storage, energy efficiency, smart grid and renewables.

Joseph Tesar is the Technical Program Manager for MForesight: Alliance for Manufacturing Foresight and has over 20 years of experience with new product development. He is the founder of a sustainable-energy company, Quantalux. Mr. Tesar earned a bachelor's degree in mechanical engineering and a master's degree in electrical engineering from the University of Minnesota, and also has a master's degree in optics from the University of Rochester. Mr. Tesar is a LEED Accredited Professional and a Licensed Builder in Michigan.

Joshua Bishop-Moser is a post-doctoral fellow with MForesight and a post-doctoral research fellow in Mechanical Engineering at the University of Michigan. Dr. Bishop-Moser's research focus is on compliant systems and elasto-fluidics. He is also the founder of a solar energy startup, Solhedron. Dr. Bishop-Moser earned a B.S. in Mechanical Engineering from UC Berkeley and M.S.E and Ph.D. degrees in Mechanical Engineering from the University of Michigan. He has experience teaching manufacturing and design for manufacturability through multiple courses at Michigan.

Sara Samuel is a Research Analyst for MForesight. Prior to joining MForesight in 2016, she was an Engineering Librarian at the University of Michigan. As an experienced research librarian, Ms. Samuel has the ideal skillset for scanning and analyzing large technology databases. She has a M.S. in Information (MSI) from the University of Michigan, and a Bachelor of Arts in Communication and Computer Science from Hope College.

Justin Talbot-Zorn advises MForesight on policy and communications. He has served as Legislative Director to three Members of Congress, as founder of a humanitarian nonprofit, and as an op-ed contributor to publications including T*he Washington Post, Time, Harvard Business Review, The Guardian, The Atlantic, Foreign Policy*, and CNN.com. A former Fulbright Scholar and current Truman National Security Fellow, Mr. Talbot-Zorn holds graduates degrees in public policy and international relations from Oxford University and Harvard University's Kennedy School of Government.

Workshop Participants from Industry - Biographies
(Alphabetical by last name)

Brian W. Anthony is the Director of the Master of Engineering in Manufacturing (MEngM) Program and Co-Director of the Medical Electronics Device Realization Center (MEDRC) at MIT. Dr. Anthony previously served as the Director of the Singapore MIT Alliance Manufacturing Systems and Technology Program. For these programs, he developed education-with-industry partnerships with both small and multi-national corporations in the U.S. and Singapore. Dr.

Anthony defined and built the MEngM program’s structure for the development and execution of company-based projects.

Through the end of 2015, Dr. Anthony served as Faculty Lead for Education and Deputy Director of the MIT Skoltech Initiative. He has over 20 years of commercial, research, and teaching experience in product realization.

Mark L. Ellis is a Senior Associate at Munro & Associates, Inc. and has over 20 years of executive leadership experience. Mr. Ellis has expertise in international negotiation, supplier consolidation, automation and machine tool systems, and cost reduction practices.

Prior to joining Munro & Associates, Inc., Mr. Ellis held a position as an independent consultant providing services in the area of battery and battery pack production, equipment, process development, and manufacturing cost models. He attended Rockford College where he participated in the American Management Association’s leadership degree program, and the University of Wisconsin for Business Administration and Mechanical Engineering.

Daniel Luria is an economist and the principal of Occupy Dan, LLC. Occupy Dan performs contract work for public, non-profit, and progressive private sector organizations in the areas of industrial policy and its evaluation, fuel economy and emissions regulation, energy policy, and automotive sector trends and sourcing. Until June 2012, Mr. Luria was the VP for Strategy & Measurement and Research Director at the Michigan Manufacturing Technology Center (MMTC).

Mr. Luria has co-authored three books and has published articles in the *Harvard Business Review, Challenge*, *Research Policy,* and the *International Review of Applied Economics*. He holds a BA from the University of Rochester, an MA from the University of Michigan, and a Ph.D. from the University of Massachusetts.

Micaelah Morrill is the Director of the Manufacturing Initiative at Greentown Labs, the largest clean tech incubator in the United States. In her role, she has developed a unique program to connect startups and manufacturers to help promote local commercialization and relationship building. Ms. Morrill sits on the boards of the Political Science Advisory Board at UMass Amherst and the Center for EcoTechnology (CET), serves as co-chair of the UMass Women into Leadership (UWiL) board and has a BA from UMass Amherst and a Master's in Urban & Environmental Policy & Planning from Tufts University.

David Ollila is the Founding Director of Invent@NMU. A life-long inventor and entrepreneur with a portfolio of 12 patents, Mr. Ollila founded multiple startups across several categories of products and services. Most notably, he was the first mover in the now multi-billion-dollar consumer electronic helmet camera category. He is a TEDx speaker on boot-strapped business practice, and was twice recognized by President Obama; once for establishing a company in a rural area that optimizes modern information technology, and once for manufacturing physical products in the United States. Mr. Ollila received his Bachelor’s degree from Northern Michigan University.

Peter Russo is the growth and innovation program manager at Massachusetts Manufacturing Extension Partnership (MassMEP). Prior to joining the MassMEP, Mr. Russo founded four start-up ventures based on innovative consumer products: The Real Boss, LLC; American-Craft.com; New Approach Designs, LLC; and New Approach Development, LLC. He has created, licensed and sold hundreds of products and personally holds 16 patents. Mr. Russo has an MBA and BS from Babson College.

Jason Schug is Vice President of Ricardo Strategic Consulting. He has executive responsibility for Ricardo Strategic Consulting's HEV/PHEV/BEV benchmarking program and all cost analysis programs. Mr. Schug has 21 years of experience in clean transportation and automotive engineering, and has led 10 automotive cost analysis programs over the last 4 years. Previous to Ricardo, Mr. Schug worked on product development for Vision Climate Control, and was a manufacturing engineer for Ford Motor Company. He received his BS in Mechanical Engineering from Rensselaer Polytechnic Institute, and his MBA from the Ross School of Business at the University of Michigan.

Cheryl Tulkoff has over 20 years of experience in electronics manufacturing focusing on failure analysis and reliability. She has had extensive experience in training others, and is a published author and a senior member of both ASQ and IEEE. She is also a Certified Reliability Engineer (CRE). Ms. Tulkoff earned a Bachelor of Mechanical Engineering degree from Georgia Tech and a Master of Science in Technology Commercialization (MSTC) from the University of Texas at Austin.

Department of Energy Workshop Participants

Johanna Wolfson is the Director of Technology-to-Market in DOE's Office of Energy Efficiency and Renewable Energy (EERE). In this position, she leads efforts to reduce barriers and inefficiencies in the U.S. innovation system in service of getting promising clean energy technologies to market. The Technology-to-Market group helps to launch entrepreneurs and new businesses out of universities and National Labs, support early-stage clean energy businesses with funding and incubator services, provides small businesses with technical support at National Labs, and positions startup companies for scale-up. Dr. Wolfson has a Ph.D. in Physical Chemistry from MIT, where she conducted research on photo-induced solid-state dynamics.

Brenna Krieger is an American Association for the Advancement of Science (AAAS) Science and Technology Policy Fellow, and is designing and implementing public-private partnerships to increase U.S. competitiveness in manufacturing and bring innovative clean energy technologies to market. Prior to joining the Technology-to-Market team, Dr. Krieger was in the DOE Clean Energy Manufacturing Initiative. She completed a Ph.D in Biophysics from Harvard University, and received a B.S. in Physics from Rutgers, the State University of New Jersey.

Eli Levine leads the Clean Energy Manufacturing Initiative (CEMI) to develop and leverage strategic partnerships to advance U.S. manufacturing. In this role, he is spearheading the Office of Energy Efficiency and Renewable Energy's (EERE) effort to increase U.S. competitiveness in manufacturing clean energy technologies by boosting energy productivity and leveraging low-cost domestic energy resources and feedstocks. Mr. Levine is a graduate of Washington University School of Law and Cornell University.

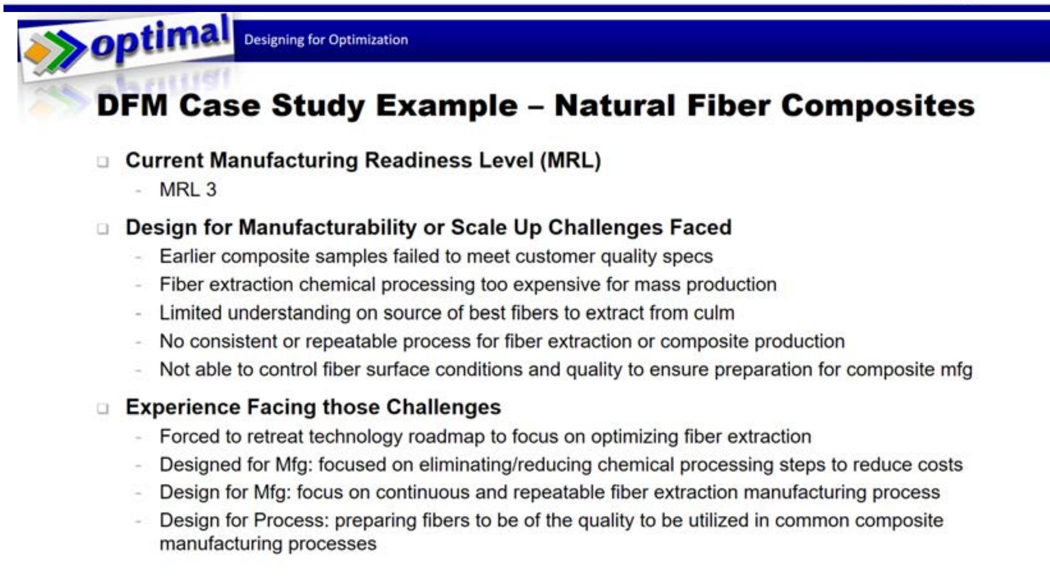
Patrick Dempsey is Director of Strategic Engagements at Lawrence Livermore National Laboratory (LLNL) in Livermore, California. He has over 25 years of experience delivering National Laboratory capabilities to the nation and industry. In his current role he develops partnerships that leverage the capabilities of industry and leading academic institutions to advance LLNL's science and technology efforts. Patrick is a registered professional mechanical engineer in the state of California, received a degree in Mechanical Engineering from California State University, and an MBA from UC Berkeley Haas School of Business and Columbia University.

John S. Taylor is the Group Leader of Precision Systems and Manufacturing at Lawrence Livermore National Laboratory. His past projects include satellite-based telescopes, optics for high energy lasers, targets and optical elements for the National Ignition Facility, and production cost analyses for precision components. He led a multi-national-lab team who designed and constructed the world's first full-field diffraction-limited imaging systems for EUV lithography in support of the chip industry's evolution to next generation technologies. Dr. Taylor is an adjunct professor and member of the graduate faculty at the Center for Precision Metrology at the University of North Carolina at Charlotte. He is a member of the ASTM F42 Committee on additive manufacturing, ASME, OSA, euspen, Past President of ASPE, and Fellow of SPIE. He received his Ph.D. in mechanical engineering from Purdue University.

Appendix E: Additional Manufacturing Case Studies

Case Study 1: Natural Fiber Composites for Vehicle Lightweighting

Case Study 1 describes the use of bamboo fibers for a recyclable composite material. In developing this material, the company was challenged with a limited understanding of how to extract the best bamboo fibers from culm, which led to substantial challenges in producing the base bamboo material. In addition, an incomplete understanding of the forming technology for composite materials led to inconsistent production. This company needed to retreat from technology development and apply Design for Manufacturing rules in order to improve the extraction of raw bamboo material. A Design for Process cycle improved the consistency of composite production. (*Case Study provided by Optimal Inc.*)



Case Study 2: Joining of Dissimilar Materials for Vehicle Lightweighting

Case Study 2 is an example of a manufacturing process that was viable in the laboratory, but faced a number of issues on the manufacturing floor. The company needed to develop a better understanding of the quality requirements, the customer and the existing production process in order to insert the new technology on the factory floor. (*Case study provided by Optimal Inc.*)

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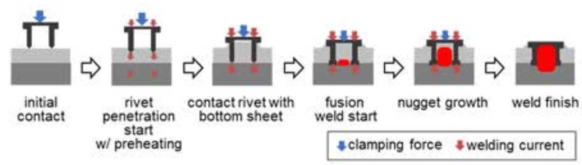
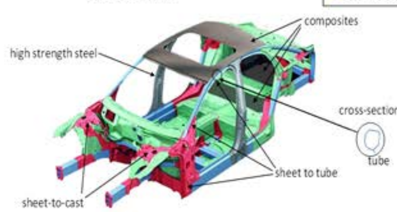
Design for Manufacturing Case Study Example
Vehicle Lightweighting - Rivet Weld Joining

- **Company Description:**
  - The hybrid rivet weld technology combines the advantages of self-pierce riveting with resistance spot welding in joining of dissimilar materials (aluminum to steel)
- **Company Type:**
  - ☐ Product
  - ☐ Material
  - √ Manufacturing Process
  - ☐ Manufacturing Service
  - ☐ Manufacturing Operations





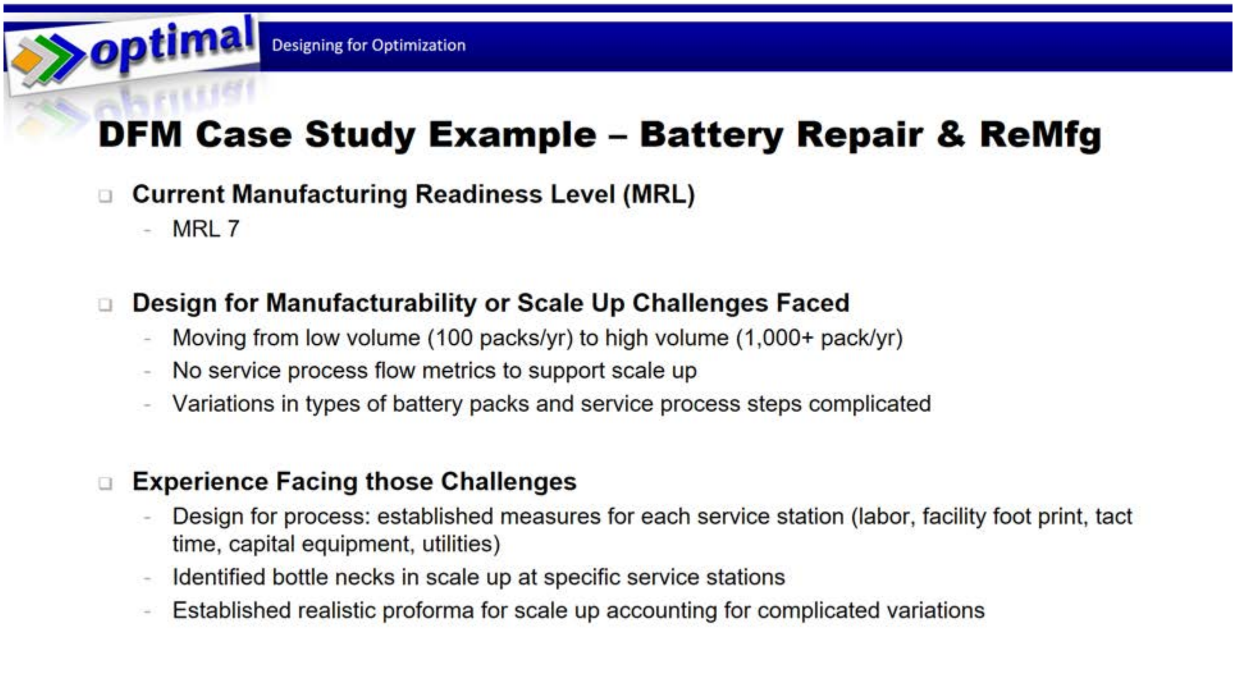
optimal — Designing for Optimization

DFM Case Study Example
Vehicle Lightweighting - Rivet Weld Joining Technology

- **Current Manufacturing Readiness Level (MRL)**
  - MRL 5
- **Design for Manufacturability or Scale Up Challenges Faced**
  - Some but not all joining samples met customer quality specifications
  - Process not repeatable and not proven on a variety of materials
  - Too much customized tooling
  - Poor understanding of cost trade offs of proposed process vs existing production processes
  - Equipment not optimized for mass production (automated material handling)
  - Equipment had no protection for operator, no quality control measurement
- **Experience Facing those Challenges**
  - Design for Quality: adopted in-situ weld assurance testing to ensure quality
  - Design for Customer: included demonstrations on a wide variety of mixed materials (Al, Mg, HSS)
  - Designed for Process: reduced customized tooling & aligned with existing production processes
  - Design for Process: included automated rivet feeder, user safety and user interface

Case Study 3: Lithium Ion Battery Repair and Remanufacturing

Case Study 3 describes a manufacturing service to recycle lithium ion batteries. The company faced substantial scale-up challenges, primarily due to the varying types of incoming batteries. A Design for Manufacturing cycle was able to adapt the processing line to different types of battery packages. A Design for Process cycle eliminated production bottlenecks, which led to improved remanufacturing processing rates. (*Case study provided by Optimal Inc.)*



Case Study 4: BioEnergy – Waste to Energy Plant

Case Study 4 describes a biomass gasification plant designed to process poultry litter. This operation needed to pursue a Design for Inventory cycle in order to assure a continuous supply of the poultry litter feedstock. A Design for Process cycle was also needed to assure that the feedstock met moisture limits before gasification, and that the plant could be efficiently run on variable amounts of poultry litter. (*Case study provided by Optimal Inc.)*

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Design for Manufacturing Case Study Example Waste to Energy Plant

- <u>Company Description:</u>
  - Waste to Energy biomass gasification systems with unique ceramic heat exchange technology, air turbine, allowing for conversion of organic waste (including high moisture content) to power and steam/heat for customer operations.
- <u>Company Type:</u>
  - ☐ Product
  - ☐ Material
  - ☐ Manufacturing Process
  - ☐ Manufacturing Service
  - ☑ Manufacturing Operations

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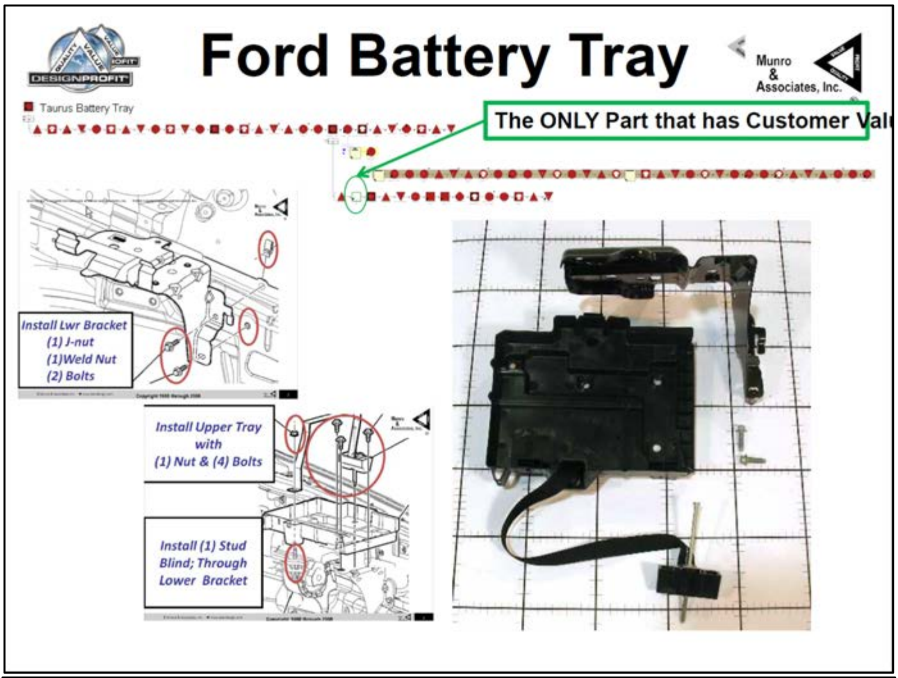
DFM Case Study Example – Waste to Energy Plant

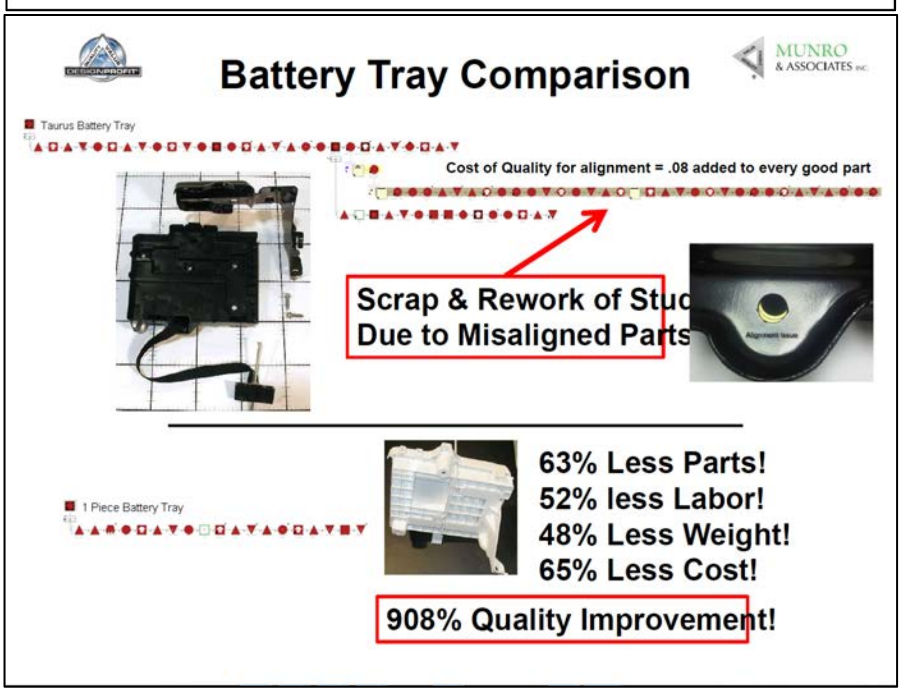
- **Current Manufacturing Readiness Level (MRL)**
  - MRL 6
- **Design for Manufacturability or Scale Up Challenges Faced**
  - Use of poultry liter feedstock proven in pilot production, must scale up to 50,000 lbs per hour!
  - Requirement to run at scale 24/7 while limiting operating down time
  - Not enough feedstock, no control/prep measures in place
  - Too much power for customer (need off-take partner)
  - No obvious use for residual material (50,000 lbs/yr of waste ash!)
- **Experience Facing those Challenges**
  - Design for Inventory: secured contracts for enough feedstock, material storage
  - Design for Process: added feedstock drying to control moisture, automated material feeding
  - Locked up PPA to sell excess power of turkey farming operations to utility
  - Design for Sustainability: found use for waste ash in fertilizer production

Case Study 5: Vehicle Battery Pack Tray

Case Study 5 is an example of how a Design for Assembly cycle led to substantial savings for the manufacturer. The initial vehicle battery tray consisted of three separate metal parts with a number of individual fasteners (J-nuts, weld nuts and bolts). By converting the battery pack tray to a single piece of molded plastic, part count went from 16 to 1, and the number of fasteners decreased from 11 to 4.

Of special interest is the resulting cost savings. Material costs dropped by over 70% and labor costs (installation) decreased by 40%. The manufacturer estimates a savings of over $2M annually due to this change. (*Case study provided by Munro & Associates*.)





Design Profit®

EXECUTIVE SUMMARY

Taurus Battery Tray

DESIGNPROFIT

	Taurus Battery Tray	1 Piece Battery Tray	% ↓
Parts	16	6	63%
Good Parts	1	1	0%
Steps	53	24	55%
Actual Time	210.00 sec	101.00 sec	52%
Fasteners	11	4	64%
Ergo Dangers	0	0	0%
Poka Yoke Issues	1	0	100%
Total Weight	1,736.54 gm	899.87 gm	48%
Piece Cost	$11.08	$3.22	71%
Total Labor Cost	$2.36	$1.40	40%
Q Burden	$0.59	$0.00	100%
Total Cost	$14.03	$4.62	67%
Investment Cost	$476,316	$85,000	82%
Annual Savings	N/A	$2,351,730	0%
Right First Time	9.83%	99.96%	-917%
Sigma	3.61	5.65	-56%

Other Cleantech Case Studies

http://www.theguardian.com/sustainable-business/Cleantech-case-studies
http://www.Cleantech.com/advisory/case-studies/
https://www.cleverism.com/Cleantech-complete-guide/
https://www.youtube.com/watch?v=d3DY6JbrdYg
http://www.azoCleantech.com/book.aspx?SaleID=29

Appendix F: Benefits of Manufacturing Training - Testimonials

MANUFACTURING INITIATIVE

Startup Testimonials

"MassMEP and Greentown Labs have been invaluable resources to Dynamo. We're preparing for scale up, with increased sales of 700% in the first 6 months of this year over last. **Without the help of MassMEP and Greentown we wouldn't have been able to supply those orders."**

- Dynamo Micropower

Proprietary low cost, ultra-portable microturbines with applications including oil and gas, portable power generation, and distributed residential and commercial cogeneration.

MANUFACTURING INITIATIVE

Startup Testimonials

"Startups are in over our heads when it comes to interfacing with traditional manufacturers. **Greentown Labs has figured out how to be a bridge connecting startups and manufacturing companies and giving us a common language with which to communicate.** *Greentown has figured out how to make this available to companies that would be at a loss without it. It's an incredible resource as we look to turn our prototypes into products."*

- Silverside Detectors

Helps governments reduce the threat of nuclear terrorism with an inexpensive radiation sensor that is low-cost and a "connected device" for networks of discreet detectors within and around cities, in transportation pathways, and nuclear material storage sites.

MANUFACTURING INITIATIVE

Startup Testimonials

"I was introduced to Mr. Russo by Micaelah shortly after she started working here at Greentown Labs. At the time we (Loci Controls) were a young company with a viable product but were struggling with sales and marketing. With little runway left we needed help fast. Fortunately Peter was able to immediately get us moving in the right direction. Not only did he provide valuable advice and guidance based on his many years in the manufacturing field, but also was able to share tools and exercises from MassMEP that helped us develop a comprehensive sales and marketing strategy. **Without Peter's help we would not be nearly as far along the path of commercialization as we are today."** - Shaun Bamforth, Loci Controls

MANUFACTURING INITIATIVE

Startup Testimonials

*"*Greentown Labs has been an immensely helpful resource in moving our company into the production phase. **With Micaelah's help, we've been introduced to all kinds of programs, suppliers, and vendors.** Micaelah helped us begin a working relationship with Algonquin, a Massachussetts based metal manufacturer, to get our parts ready to ship to our customers. **Through this relationship, we've begun to apply for manufacturing grants that will allow us to keep our manufacturing processes local."**

– Manufacturing Team, Voxel8

https://www.asme.org/career-education/articles/entrepreneurship/from-engineer-to-entrepreneur
http://www.missouribusinessalert.com/entrepreneurs/48545/2014/08/20/revamped-cortex-entrepreneur-training-includes-it-manufacturing/
http://www.theglobeandmail.com/report-on-business/small-business/going-global/hardware-accelerators-in-china-turn-engineers-into-entrepreneurs/article13545928/