Designing Great Products and Building High Performing Teams with DFMA

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Abstract. Hypertherm designs and manufactures plasma, laser, and water jet cutting equipment. Our products incorporate electro-mechanical assemblies, molded components, and machined parts – all of which present ample opportunities to apply both design for assembly and design for manufacture (DFMA) concepts. In this paper we'll discuss our experiences with forming cross-functional teams to apply DFMA as part of the new product development process as well as integrating it into our Lean manufacturing approach. We'll discuss a specific case study of how DFMA was applied to the recently launched Powermax45 XP plasma arc cutting system. Compared to a previous generation product, this design reduced parts count by 10%, fastener count by 20%, weight by 12%, assembly time by 15% and material cost by 6%. These material cost and operational improvements have a direct and lasting impact on the profitability of this business team.

Overview of Hypertherm and the Light Industrial Business. In Lean organizations, the objective is to reduce waste to maximize delivery of value to customers. At Hypertherm DFMA complements Lean in our quest to design great products that deliver maximum value to customers while taking advantage of the collaborative experience to build high-performing teams. The case study we'll share in this paper revolves around the development and introduction of Powermax45 XP Light Industrial plasma cutting system which launched in 2016. This new product shares a lineage of more than 20 years with similar, prior systems designed by Hypertherm, including the MAX43, Powermax600, and Powermax45. These systems are designed to cut metal up to 5/8" thickness while being very portable and affordable.

Figure 1. History of the 3/8-5/8" Light Industrial cutting systems

Hypertherm, Inc., located in Hanover, New Hampshire, is a company dedicated to providing the best industrial cutting solutions in our industry (www.hypertherm.com). The company was founded in 1968 by Chairman of the Board Dick Couch and Dartmouth College Engineering Professor Emeritus Bob Dean when the pair discovered the potential to cut metal with speed, accuracy, and precision using a narrowly-focused plasma arc (Figure 2).

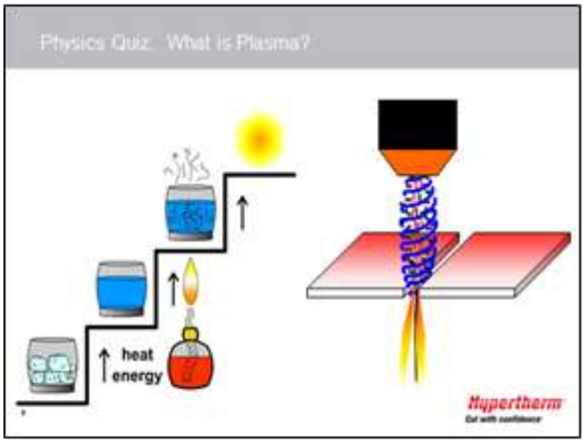

Figure 2. The conductive electric arc used for cutting is a result of adding energy to a gas to dissociate its molecules and ionize its atoms.

Our focus on technology remains strong with product offerings in several cutting-related markets: plasma arc, laser, and water jet cutting, as well as CNC motion control hardware/software and CAM software solutions (Figure 3). More than 10% of our 1430 Associates work in engineering roles and we have been awarded more than 100 patents. Of those 1430 Associates, approximately 1100 work in one of our eleven Upper Valley facilities located in and around the Hanover/Lebanon, NH area. Nearly all our manufacturing is done in the United States while the company has a global presence in 93 countries. In 2013 North American markets accounted for 45% of sales and exports to Europe, Asia, and South America accounted for the remaining 55%.

Figure 3. Hypertherm plasma, laser, and waterjet cutting.

Lean Enterprise Culture and Operational Excellence. A culture of continuous improvement has been central to Hypertherm's value system for more than 25 years. The pursuit of Operational Excellence (OpEx) through Lean principles (Duggan, 2011) aligns naturally with such a culture. Design for Manufacture and Assembly (DFMA) has become an essential element in our OpEx strategy, with an initial formal appearance in 2003 and subsequent re-emphasis in the last 3 years. It's well established that DFA - when deployed and executed - can address several of the seven Lean wastes (Shipulski, 2006) such as inventory, travel, motion, waiting, etc. by eliminating unnecessary parts and reducing parts count. Consequently, the space, time, and effort to maintain a steady stream of supply is reduced as well.

Lean improvements to the value stream alone will not lead to Operational Excellence. Design improvements reducing parts count, executed through DFMA methodology, must take place as well. Our experience at Hypertherm is revealing that DFMA, when integrated into each product development cycle, can produce step change improvements in material and labor costs. In between product development cycles operations teams employ Lean principles to drive labor costs lower and reduce material costs as well through strong supply chain partnerships.

Labor and material cost savings achieved over the life cycle of a product represent the collaborations of both the design and operations teams. As we'll discuss in this paper, the design community cannot be successful without the input of the operations team. Likewise, the operations community needs the design team to carefully consider design choices such that parts count, along with material and labor costs, are reduced without adverse impact on function.

One of the key measures tracked at the business team level is labor cost per system produced. At Hypertherm, Lean and continuous improvement efforts, combined with DFMA, have contributed to 37% decrease in labor/system for the Powermax product family over a 3-year period. These products are manufactured in two mixed-model value streams that have been designed with Lean principles then refined through multiple continuous improvement cycles. The Powermax45 XP is assembled in a 5-station flow cell that feeds a shared functional test/burn in area before being packaged for sale (Konstantakos, 2016). The Operations team responsible for this manufacturing value stream has invested in understanding the root causes of imbalance and variability in assembly operations leading to continuous improvement in product throughput.

Hypertherm received its formal introduction Design for Manufacture and Assembly in 2003 as part of a major redesign effort with a large, automated cutting system (Shipulski, 2006). Since that project launch DFMA has largely taken place through "organic" efforts within the company. Because of the cost-competitive landscape that the 45XP would launch into we decided that a more organized and structured approach would be beneficial. This should not imply that was not already happening within the design team - just that an infusion of innovative thinking would be needed to insure the success of the product.

Role of Learning DFMA in New Product Development of Powermax45 XP. To accomplish the business objectives of reducing cost and assembly complexity we explored enhancing our long-standing (but somewhat dormant) relationship with Boothroyd-Dewhurst. In addition, organizational learning objectives were also particularly important for many of our younger engineers who may not have had prior exposure to DFMA concepts. During early stages of the product development process we began arrangements for a Value Engineering and DFMA workshop that would combine both learning with execution. The learning element was an important consideration: at Hypertherm we have tried to align our strategic improvement programs with a learning program methodology known as the 6 Disciplines (Jefferson and Wick, 2015). While we are still in the process of implementing several of these elements effectively, these serve as valuable guidelines for our learning organization:

> *Define business outcomes (not just learning objectives)*. With DFMA the business outcomes are largely built-in: decrease parts count, reduce assembly complexity, cut assembly time, and drive down material costs. For our 45XP project we knew we had a 10% (material) cost reduction goal and that the strategy would necessarily rely heavily on DFMA. In addition, being relatively early in the product development timetable we felt that the team could incorporate a value engineering element into the workshop to promote a more functional approach to the design. Finally, less tangible but equally important goals included promoting collaboration,

communication, relationship building, and peer-peer networking in our engineering community. We believe that these are important elements is building a high performing team.

Define a complete learning experience (including transfer to work). A secondary, learning oriented goal was to have approximately 20 members of the engineering community trained or refreshed in DFMA concepts as well as software tools for application. With over 120 engineers on staff at Hypertherm we knew that this would be only one of several workshops that would eventually take place. We felt it was important to connect the workshop to a tangible product development project to avoid training for training's sake (i.e. just hoping that learning transfer would come at some later date). Everyone attending the workshop would contribute to the product design in some way.

Deliver learning for application and make learning easy. Chris Tsai, Director of DFMA for Boothroyd Dewhurst, became our contact for designing the workshop. Chris shares the philosophy of implementation-based learning so it was relatively easy to adapt the value engineering and DFMA implementation workshop approach for the project.

Drive learning transfer and avoid learning "scrap". On the Powermax45 XP project we were fortunate to have strong support for DFMA from the Engineering Team leader, Product Development Project leader, and design engineers themselves. After the workshop the application of DFMA principles was reinforced within the team on a regular basis.

Deploy performance support. Leadership attended the workshop as well so they were well-equipped to be the first level of performance support. Other key support attributes that we need to improve on are availability of resources (people and subject matter experts; reference documents, tools, and templates), that are practical, clear, and concise. We believe that this will come in the form of key, bite-sized e-learning reference/brush-up modules, as well as a library of tools, templates, and reference materials that are intranet accessible.

Document results/reflect. At the end of the workshop we created a tracking list that was reviewed at 30/60/90 day periods. In addition, documentation of DFMA was included in stage gate design and management reviews during product development.

Some further comments on the workshop timing are noteworthy. It probably is possible to hold a workshop too early in the NPD cycle (for instance, the market needs are not well defined) but our experience is that "…earlier is better." It is well documented (e.g. Smith and Reinertsen, 1996) that design changes are relatively easy to exercise early in the NPD process while the cost associated with engineering change increases dramatically in latter stages. Along those lines, there's a popular quote at Hypertherm attributed to a former design engineer now turned engineering manager along the lines of "… I can incur more cost to a product with one poor design choice at an early product development phase than an expert Lean manufacturing engineer can remove in a year."

Another important aspect of pre-work for the workshop was to define the composition of the team. Of course, the core engineering group participating in the new product project would take part. In addition, we gave careful thought to representation from other groups within Hypertherm as well as potential suppliers. Our desired participants included:

- Mechanical, electrical, and software design engineers from the project team
- Engineering technicians from the project team
- Engineering team and project leaders
- Manufacturing process engineers supporting the product
- Assemblers from the value stream assembling the product

- Procurement and supply chain associates
- Quality, reliability, and regulatory engineers
- Design engineers from outside of the business team (i.e. design different products)
- Supplier engineers

Overall we had 25 participants in the workshop. This was quite large and certainly could be smaller. We erred on the side of being inclusive and it worked out fine. During the sessions where the DFMA principles were applied to the product the large group was split into 4 smaller teams. Several of the roles listed above deserve additional discussion. For instance, the presence of manufacturing process engineers and assemblers was vital. These associates provided real world insight related to DFA related questions as well as what was possible within the existing value stream. Our design engineers needed to understand what was challenging about assembling the existing product. In addition, we wanted to create a collaborative team that would not only work well within the workshop but also continue to exist well beyond the workshop itself as the design matured.

We invited several design engineers from outside of the business team (but within Hypertherm) to participate. Their outside perspective on design decisions was similarly very valuable.

Supply chain and procurement representation was essential as a large fraction of the components in the assembly were sourced, which included sheet metal, molded parts, electrical components, pneumatic controls and gas handling, and printed circuit boards. We included supply chain and commodity managers from within the company as well as representation from several key suppliers. These suppliers were invited once we had formulated targets of key subassemblies where we felt there were opportunities to reduce parts count, reduce complexity, and reduce costs. This led to representation from our printed circuit board supplier and electro-magnetic (transformer/inductor) supplier.

Workshop Plan. The DFMA workshop took place over five days and had four main elements: Function analysis and value measurement, DFMA analysis of baseline design, creative design activity, and concept development/documentation of opportunities. Learning modules were interspersed throughout the workshop on each topic.

Function analysis and value measurement (M.L. Shillito and D.J. De Marle, 1992) confirmed which subassemblies would be the targets for DFMA (Figure 4). In future Value Engineering/DFMA efforts we believe the function analysis and value measurement exercise could be done separately in advance of DFMA efforts, and with a smaller team.

The DFMA baseline analysis revealed 79 hardware items (fasteners) as well as many assembly improvement opportunities. The teams transitioned into the creative design phase where the objective was to identify as many design improvements as possible without any restriction as to how easily these could be implemented. The workshop participants, especially the engineers, found value in the creative phase, especially in small group format, and spent considerable time sketching concepts on white boards while discussing concepts and options which were each captured on self-stick sheets of paper (Figure 5). There were 97 distinct design improvements that were identified. At the end of the creative phase all the improvements were grouped into three categories that reflected ease of implementation.

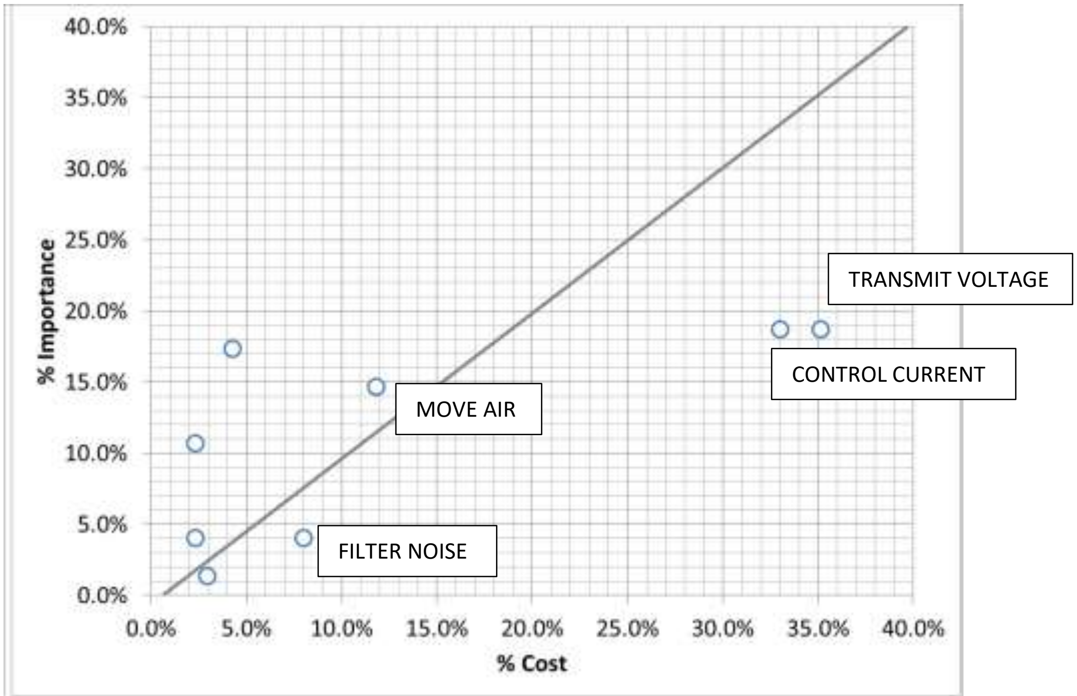

Figure 4. Value graph of major functional elements in power supply. Components and assemblies near or below the diagonal line are candidates for value engineering and DFMA. Three of the functions shown relate to the electrical system and printed circuit board. In addition, the gas flow control subassembly was another DFMA target. These were not the only areas of the product to be examined under the DFMA lens but they were the starting point.

The next step was to analyze and document each potential design improvement. This involved each sub-team doing enough detailed design work to establish an estimate of material and labor cost savings. Several of these designs were developed and documented in the workshop; however, the work to sift through each of the opportunities extended beyond the end of the workshop. Once the engineering prototype design was complete several months later, the tally stood at:

Design concepts identified: 97
Concepts analyzed and considered for implementation: 61
Concepts implemented: 21
Concepts moved to technology development hopper: 10
Remaining concepts were not considered further due to cost or feasibility

Figure 5. Photos of workshop participants during design conversations, analysis, and categorization.

Project Outcomes. Our DFMA efforts on the Powermax45 XP project produced many improvements. Fastener count was reduced by 23% and overall part count was reduced by 11% (added functionality in the design caused this number to be lower than the fastener reduction alone). Material cost avoidance of 6% compared to the prior product was achieved by designing parts that were easier to manufacture and by combining multiple parts into one. Ease of assembly was improved by integrating more wire routing features and labeling into injection molded parts. Numerous snap fits displaced screws for mounting the valve, fan, and three of the PCB Assemblies. More push-to-connect tube fittings were utilized to reduce assembly time and improve the mean time to repair. These improvements also resulted in approximately 5 minutes of assembly time avoided. At launch these cycle time benefits were not spread equally across each assembly station. Over the course of several months the Operations team organized a series of improvement projects that adjusted work content at the stations leading to better balance of cycle times and 10% throughput improvement. This represents essentially "free capacity" gained from the combined efforts of the cross-functional Operations/Engineering Design Team taking advantage of DFMA and Lean practices. Ultimately this drives down our labor cost per system manufactured.

A few specific examples of the Powermax45 XP DFMA efforts are elaborated below (Figure 6): The magnetics subassembly was completely redesigned to be smaller, lighter weight, and easier to assemble. The previous design was comprised of a metal plate that each of the magnetic components was strapped to. This assembly was fastened to the plastic power supply enclosure base with six screws on Hypertherm's assembly line. The original design provided a common ground connection as well as strength and rigidity to the enclosure which is important since the product is required to pass several drop tests. In the new design, the plate was replaced with a much smaller version used only for grounding. Since the plate no longer provides structural support, the molded plastic base had to be strengthened. This was done by increasing the cross-sectional area of the base and adding rib support structures. The magnetics are now strapped directly to the plastic enclosure base and all six fasteners were eliminated. Assembly time was reduced by nearly one minute since magnetics come pre-assembled to the plastic enclosure base.

The air valve incorporated many advancements that allowed for part reduction and easier assembly while adding functionality and reducing cost by 10%. The air valve on the 45XP is automatically controlled as compared to the manually controlled valve on the prior product. The valve body was injection molded which reduced cost and provided the freedom to design in additional assembly features such as integrated push-to-connect air fittings and snap hooks for mounting. This eliminated the need to install additional air fittings. On older products, a pressure switch was used to ensure that the air supply was connected. The 45XP instead uses intermittent "blips" of air to check for pressure which eliminates the need for a separate pressure switch. These DFMA efforts resulted in an assembly time reduction of over 15 seconds in addition to the cost reduction.

The main PCB Assembly was another area that was addressed by the team. By adopting a strategic supplier partnership and adapting the board design to their capabilities a higher manufacturing efficiency was achieved. Component-to-component spacing was adjusted to accommodate the supplier's pick-and-place equipment which reduced the need for hand placements. PCB component library foot prints and pad geometries were optimized to reduce pick-place errors during assembly. Large pad geometries were modified to reduce conformal coat masking needs. The interface connectors on the PCB were changed to handle wave solder re-flow oven temperatures which reduced secondary operations. These efforts helped reduce the cost of the board assembly by 12%.

Two major improvements in serviceability were achieved by redesigning how the air filter is mounted and accessed. Previously, changing out the filter element required the removal of the power supply cover to gain access to the filter bowl. The Powermax45 XP improves the serviceability of this part by placing the filter bowl outside the system. This also avoids safety and reliability issues by eliminating the potential for other system components to be impacted by the service. The second improvement is due to the push-to-connect bulkhead air fitting to which the filter is mounted. When changing air inlet adapters on the Powermax45, the internal piping to the filter would sometimes loosen as well. This caused the user to open the system and re-tighten the piping into the filter. The bulkhead air fitting on the Powermax45 XP eliminates this issue by being fully captured in the end panel so that it doesn't rotate when the adapter is turned. This design also improves assembly by utilizing a push-to-connect fitting rather than an NPT thread to mount the filter in the system.

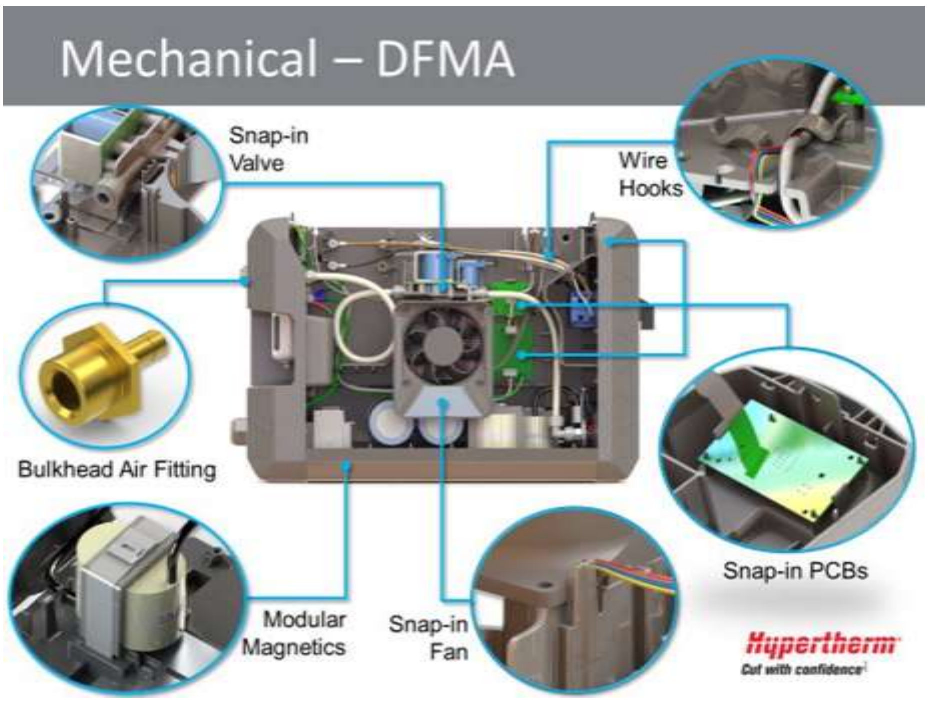

Figure 6. Examples of DFMA design improvements included in the project.

Perspective Gained Over Four Product Generations. To better put the new product in perspective with its predecessors we examined bills of material data for 4 generations of product mentioned in the introduction of this paper. Over the represented time span of 20+ years, we note improvements in product performance (i.e. cut speed) with substantial decreases in product weight (Figure 7). Over the same period, both informal and formal DFMA efforts have reduced the total parts count including both the number and different types of fasteners. For example, in the early generation MAX43 there were 38 different types of hardware used compared to 13 in Powermax45 XP (Figure 8). In addition, hardware count dropped 71% while total part count dropped 39%. This presents some interesting challenges to the design team moving forward with further effort to improve DFMA while enhancing product performance.

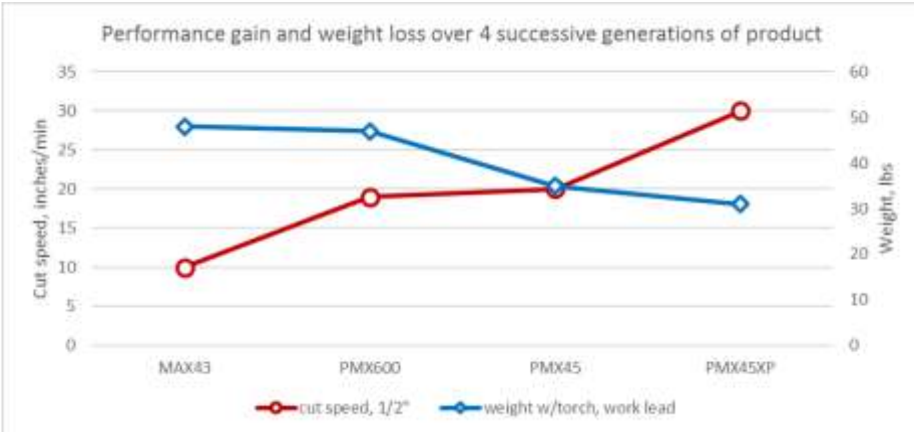

Figure 7. Performance improvement and weight decrease over 4 product generations.

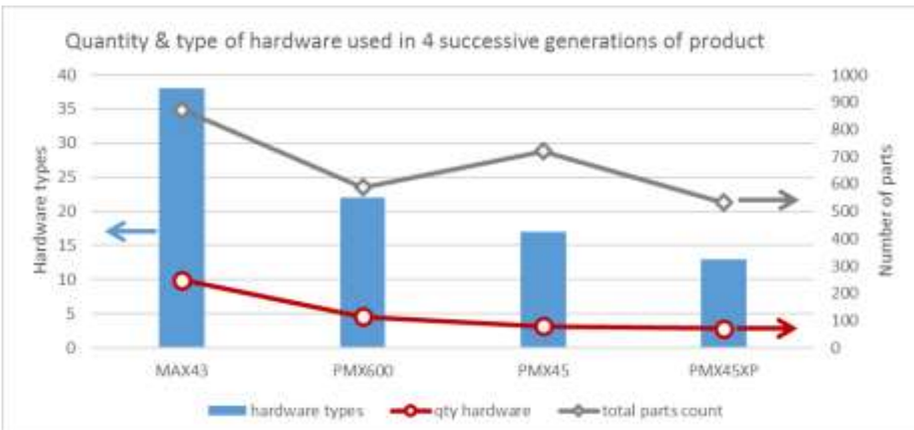

Figure 8. Parts count and hardware trends over 4 product generations.

Lessons Learned. *Early Value Engineering and DFMA is better.* It is nearly impossible to do DFMA too early in a project; it is possible to attempt it too late. The costs associated with making or changing design decisions increase markedly as time passes. Once the key functions of the product are defined DFMA can be given a green light.

Form a cross functional team. An effective DFMA team has broad representation from operations, supply chain, quality, marketing as well as engineers from outside the product team. Throughout the Powermax45 XP project, the team was reminded of how important it is to include non-engineer associates such as assemblers and supply chain managers to help wring out issues that could have otherwise gone unnoticed. Their input during the DFMA workshop was invaluable and the relationships that were fostered because of it made for a more collaborative environment. Timely cross functional meetings were successful in ensuring that the design would not only retain its functionality but that it would meet the expectations of the manufacturing, technical service, and procurement teams as well.

Team building. The workshop approach promotes a learning environment as well as serving as a team building experience where the benefits extend well beyond the end of the workshop. We find the 6D's methodology to be a useful model for a learning program that produces business results.

Structure without bureaucracy. It can be a delicate balance between employing DFMA project management structure to help the team stay motivated towards DFMA goals but not so much that needless waste is incurred. In addition to 30/60/90 day reviews of the DFMA opportunities list we believe we can take advantage of a DFMA balanced scorecard that can be used to capture outcomes of each project.

Lean manufacturing and DFMA are complementary. Reduced parts count leads to lower direct and indirect costs. Reduced assembly complexity leads to shorter cycle times and greater throughput in the value stream. Hypertherm will continue to employ Lean and DFMA in our OpEx strategy while exploring additional synergies.

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