AN ABSTRACT OF THE THESIS OF

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An inventor seeks to leverage his unique means in order to create and commercially exploit new technologies. Until new technologies are sufficiently developed, they have the theoretical potential for commercial exploitation in a wide range of markets. Those opportunities are limited by physical bounds that are often only discovered through costly development. Developing a new technology for all potential markets is impractical, so focusing development efforts is necessary. Large product development firms often predict the technology performance, and then execute a plan to exploit the greatest predicted financial opportunity. However, many small product development firms avoid such high-risk and high-stakes projects for a number of reasons. Fortunately, effectual entrepreneurship provides a proven alternative methodology to prediction-based methods that is favored by many expert entrepreneurs and small product development firms, especially under conditions of high uncertainty. In this thesis, effectual entrepreneurship is described in general and specifically to R&D, and prescribed for guiding a microfluidics R&D startup. This approach aligns the interests and means of collaborative stakeholders as they co-create new technologies and markets.

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Effectual Entrepreneurship and its Application to a Microfluidics R&D Startup

by Matthew E. Brown

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matthew E. Brown, Author

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1 INTRODUCTION

The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka" but "That's funny..." —Isaac Asimov (1920–1992)

This commonly cited quote captures the nature of many of the most important discoveries in science and technology: they started by stumbling on the unexpected, and not by confirming the predicted. The discovery of an unexpected phenomenon is exciting as it fills the mind with new opportunities for further exploring and exploiting it for practical and commercial ends. Many success stories start with highly-innovative technologists in labs, or garages, exploring what they can do with their unique means and discoveries without limiting themselves to any previous predictions as to what they *should* do.

The possibilities for a new technology are contingent on the imagination of the inventor within the bounds of physics. Until these inherent boundaries are revealed, the range of potential markets can appear far greater than will later prove to be physically possible, let alone economically possible. This wealth of potential opportunities can be exciting. However, considering all potential existing markets, let alone creating new markets, can be overwhelming.

Once the new technology is well understood, developed into a product, and demonstrated to provide a significant competitive advantage over existing technologies in existing markets, then causal prediction-based methods can be employed. For example market-analysis, segmentation, targeting, and positioning can be used to develop a business plan, raise capital, and execute the plan to exploit the opportunity and, with any luck, reap the rewards. These predictive approaches rely on the *causal* logic that prediction and control are coextensive and if you can predict the future you can control it. Such methods, although analytically intensive, can be most effective for established firms in existing markets when historical data can be leveraged to make accurate predictions and options can be considered on the comparative basis of risk-weighted net-present-values. Hence, business decision-making at least has the potential to approach objective rational choice. However, as uncertainty and complexity increase, in entrepreneurship and especially in the creation of new product markets or highly innovative technologies, the ability to predict diminishes and such methods start to fall apart until what appears to be objective rational choice becomes hindsight rationalization of subjective choices.

Expert entrepreneurs are well aware of the shortcomings of prediction based planning. According to serial technology entrepreneur and educator Steve Blank, "No one besides venture capitalists and the late Soviet Union requires five-year plans to forecast complete unknowns. These plans are generally fiction, and dreaming them up is almost always a waste of time" (Blank, 2013). Blank's statement may seem exaggerated, but it may not go far enough as few VCs require such plans as they are well aware of their limitations (M. Lieberman, personal communication, November 16, 2015). Such business plans may be appropriate for predictable projects in established companies or may be required for certain types of funding opportunities, but they are of little use in inherently unpredictable startups. Validated business models and entrepreneurial teams are far more valuable to a startup than business plans which are widely considered obsolete as soon as they are printed (Hamilton, 2015 etc...).

If causal prediction-based planning methods are rejected by many successful entrepreneurs, then what methods do they employ? The success of entrepreneurs has often been attributed to luck and intuition "or any other explanation for entrepreneurial action that suggests entrepreneurs have knowledge of things before they exist or happen. These myths, usually fueled by post-hoc rationalization by entrepreneurs themselves, are well overdue for debunking" (Wiltbank, 2010).

With the null-hypothesis of entrepreneurial action limited to such as luck and intuition, in 1997 cognitive scientist Saras Sarasvathy began a study of highly-successful expert serial entrepreneurs to find out if there was such a thing as an entrepreneurial method and to answer the question: "What makes entrepreneurs 'entrepreneurial'?" Under conditions of uncertainty, expert entrepreneurs favored an approach that is in many ways antithetical to prediction-based causal methods, an approach Sarasvathy describes as *effectual entrepreneurship* (2001).

Effectual entrepreneurs are determined explorers. They focus on staying in control by doing the doable, and co-create a future with their stakeholders using an iterative cycle of learning that is similar to the scientific method. Effectual entrepreneurship describes an entrepreneurial method that was distilled from empirical studies, is grounded in accepted theories, and is congruent with popular business methodologies such as Lean Startup methodology and agile project management. Effectuation is a relatively new area of study with a growing body of literature that will be subject over time to more refinement. Nonetheless, it provides a set of heuristics that can be readily applied, especially under conditions of high uncertainty as with a technology startup in search of a business model.

This thesis is a hybrid of practicum and academic research. This thesis describes effectuation, its empirical and theoretical origins and its heuristic principles, introduces other congruent literature, and prescribes and applies an effectual entrepreneurship strategy tailored for a real inventor for sustainably exploring a diverse range of highly-innovative R&D opportunities in the field of microfluidics.

This work draws upon both secondary and primary research. Secondary research sources range from academic literature, popular business literature, and internet sources. Primary research sources include a series of informal interviews and draws on the author's personal experiences in both entrepreneurship and R&D. Chapter two introduces and describes essential aspects of effectual entrepreneurship. Chapter three describes and augments effectuation specifically with respect to R&D. Chapter four introduces the inventor, his technology and aspirations as well as other background information viewed through an effectual lens. Chapter five prescribes specific recommendations for our inventor in the application of effectual entrepreneurship. Chapter six is a discussion and conclusion of this work.

2 EFFECTUAL ENTREPRENEURSHIP

Effectual entrepreneurship refers to a recently articulated but long established and popular approach to decision making under uncertainty favored by expert entrepreneurs. Effectual entrepreneurship is particularly useful in guiding early-stage opportunity identification and exploration, well before prediction-based planning and decision-making methods can be effectively employed. Effectual entrepreneurship is described by set of heuristics and an underlying logic of thinking that facilitates the control of an inherently unpredictable future.

2.1 Empirical origins of effectuation

Saras Sarasvathy sought to find out what makes entrepreneurs "entrepreneurial", and if there was such a thing as "entrepreneurial thinking" that guides entrepreneurs in the transformation of ideas to enduring firms. She started a journey in 1997 that involved traveling across the United States over several months and interviewing dozens of highly-successful entrepreneurs. She wanted to learn about their characteristics, habits, behaviors, and about how they explore opportunities and make decisions (Sarasvathy, 2001).

Sarasvathy created a study of twenty-seven of these expert entrepreneurs. Each of which had extensive successful track records that included playing key roles in the creation of multiple ventures, which grew to values between \$200M to \$6.5B. Additionally, each had seen at least one startup through to an Initial Public Offering (IPO). A control group of MBA students was selected, as they understood the necessary general business concepts, but had comparatively little to no entrepreneurial experience (Dew et al., 2009).

These subjects were given a hypothetical business opportunity to exploit while they were asked to think-out-loud. All of their communications were recorded yielding eighty hours of recordings and five-hundred pages of data. This think-aloud protocol was considered important; as such problem solving could easily be reimagined in retrospect. Protocol analysis showed that the MBA students displayed a high tendency to employ predictive planning methods as they are taught in many of their business classes, while the expert entrepreneurs approached the opportunity in ways that were remarkably consistent with each other, yet remarkably different from, and in many ways opposite to, the approach favored by the MBA students. Sarasvathy describes the methodology favored by the expert entrepreneurs as *effectual*, while in contrast, the familiar predictive approaches taken by the MBA student control group are described as *causal*, the antithesis of effectual.

The effectual entrepreneurs were generally well-versed in causal management approaches as favored by the MBA students and some employed them to varying degrees, but their clear preference was for effectual approaches. Such a preference was a conscious one and not due to a lack of understanding of what causal approaches can yield. Thus, the effectual method was not a replacement for a traditional causal approach, but rather an antithetical alternative that was preferred by the expert entrepreneurs under conditions of uncertainty such as with creating new markets. It was another mode of operation that they used to create a business model.

Researchers explored historical accounts of entrepreneurial action through an effectual lens. They found many more examples of effectuation in action to further refine and support their theories. Examples range from U-Haul (Sarasvathy, 2001) to the RFID industry (Sarasvathy et al., 2005). Because effectuation was not explicitly taught to the entrepreneurs per se, successful entrepreneurs learned this general approach through experience and perhaps from other entrepreneurs. The approaches these entrepreneurs took were clearly effectual and in some cases such as U-Haul, it can be shown that they would likely not have succeeded had they taken causal approaches.

Effectual entrepreneurship is a relatively new and developing area of academic research. Effectuation continues to be further explored in a variety disciplines including strategic management (Wiltbank et al., 2006), business ethics (Dew, et al., 2007)(Harmeling, et al., 2009), angel investing (Wiltbank, 2009a)(Wiltbank, 2009b), evolutionary economics (Dew, et al., 2009), management (Wiltbank, et al., 2010), psychology (Sarasvathy, 2003), marketing (Read, et al., 2009) and corporate R&D management (Brettel, 2012) and many more.

Effectuation could be viewed as an *entrepreneurial method*, analogous to the scientific method, for the discipline of entrepreneurship. However, as long as entrepreneurship is considered a subset of other disciplines it will be subject to category errors (Sarasvathy & Venkataraman, 2011). Formally describing effectuation through its heuristics can be challenging, while causation is intrinsically formal and readily lends itself to description. The study of effectuation will benefit from further research as the majority of the papers on the central theories are written by a small group of authors. Regardless of the academic development of effectuation, it is a highly effective and strategic approach that can be readily applied to practical entrepreneurship.

2.2 Principles of effectuation

Effectuation researchers have identified five interrelated heuristic principles routinely employed by expert entrepreneurs. In modern effectuation literature these principles are commonly referred

to as: the *bird-in-hand principle*, the *affordable loss principle*, the *lemonade principle*, the *patchwork quilt principle*, and the *pilot-in-the-plane principle* (Read et al., 2010).

2.3 Bird-in-hand principle: Start with your means

The bird-in-hand principle describes how effectuators start with their means. They start by considering their available means, envision what can be accomplished with those means, and then take immediate action. This is in contrast with the causal approach of first set a goal, develop a plan, acquire required means and then take action.

Expert entrepreneurs begin by considering the key means of: Who they are, what they know, and whom they know. Considering *who they are* includes personal traits, tastes, interests, lifestyle considerations and their passions. *What they know* includes education, expertise, and experience. *Whom they know* includes individuals and organizations in their personal and professional networks and the means they offer. Means also includes what they have in terms of assets such as tooling, instrumentation, production capacity and intellectual property; all of which can be key enablers in the exploration of technology opportunities. Effectuators continue to imagine what can be created with their present means. Thus, they are able to take immediate action to explore those imagined opportunities.

Means continue to evolve and expand, increasing opportunities for success. Means such as knowledge and tools will continue to increase. By routinely reconsidering their unique set of means, entrepreneurs can keep goals and means aligned to maximize their unique competitive advantages. Aligning goals with passions is intuitively a competitive advantage in itself. Stakeholder networks will tend to grow, even through temporary failures. The entrepreneur's unique means including those of collaborative stakeholders form a key competitive advantage.

Brettel et al. augments the effectuation bird-in-hand principle, by adding "What I have" e.g. financial means, and tangible assets like R&D equipment to fundamental means to consider. They describe the evolution of means by "absorptive capacity" (Cohen and Leventhal, 1990). This is when new means are gained and new competencies are built upon existing expertise as the firm continues to conduct R&D activities (Brettel, Mauer, Engelen, and Küpper, 2012). For example the accumulation of specialized knowledge, test, prototyping equipment, and stakeholders.

2.3.1 Affordable loss principle: Focus on the downside risk

Affordable loss is a strategy for sustaining the exploration for opportunities by limiting losses. Expert entrepreneurs focus on this downside potential and ignore the upside potential of an opportunity. This is in contrast with causal approaches, which tend to focus on upside potential such as risk-weighted projected returns.

Before an entrepreneur creates a great opportunity, they are likely to experience an unknown number of setbacks. Since they cannot predict when they will discover a great opportunity, they need to be able to afford to sustain the search indefinitely. To do so, they never wager more than they can afford to lose at any step of the process. This helps protect such individuals from suffering from the condition sometimes described as *gambler's ruin* whereby a failure bankrupts them rendering them unable to afford to stay in the game and continue as entrepreneurs.

Adherence to the affordable loss principle also helps protect entrepreneurs from escalations of commitment. Over-commitment to a goal can easily drive entrepreneurs to go broke committing more than they can afford with an escalation of commitment. By making pre-commitments to what they are willing to lose at each step, affordable loss provides entrepreneurs with a psychological commitment defense against such an escalation of commitment bias. This helps them cut their losses and move to other projects sooner (Dew et al., 2009).

Causal reasoning tends to focus on risk-weighted financial return projections, while expert entrepreneurs often avoid such predictions. Dew et al. found that expert entrepreneurs practically never use analytical methods such as real options analysis because such methods are viewed as being time consuming, unreliable, and fail to reasonably account for non-financial and more subjective considerations. These researchers also found that entrepreneurs do not need to be motivated by predicted returns as they are sufficiently confident that if they persist they will succeed (Dew et al., 2009).

While expert entrepreneurs limit their own resource commitments to what they can afford to lose, they work to augment their resources through growing their network of stakeholders. The extreme expression of the affordable loss principle can be described as 'zero resources to market', where the only resources committed to the venture are those afforded by its own revenues, but this can result in undercapitalization.

Affordable loss could result in undercapitalization more frequently than with pre-planned and financed projects. This can have positive and negative consequences. Limited funding can lead to more financial efficiency and lower losses. However, significant opportunities that require

more financial resources may be missed. However, a prudent entrepreneur would seek some sort of funding or even transition to causal approaches if such opportunities are recognized.

The affordable loss principle can be understood as essential for serial entrepreneurs, as they can expect to experience failures as well as successes. Affordable loss enables entrepreneurs to fail sooner, with lower losses, and continue their pursuits. They will be able to explore and learn from more opportunities as they grow their means and stakeholder networks, thus increasing their opportunities for success. One study showed that angel investors who employ effectuation, including the affordable loss principle, tend to experience a reduction in the number failed investments, without a reduction in the number of successes (Wiltbank, 2009). As Sarasvathy describes "...if homeruns are drawn from a random distribution, it is plausible to suggest that the effectual entrepreneur gets to explore more opportunities than does the causal entrepreneur" thus "effectuation gives the entrepreneur more shots at the jackpot" (Sarasvathy, Dew, Read, & Wiltbank, 2007).

2.3.2 Lemonade principle: Leverage contingencies

"Contingencies can be viewed as opportunities to be exploited rather than misfortunes to be avoided" (Sarasvathy, 2003) Surprises are often welcomed by effectuators who see them as opportunities that can lead the path to new, perhaps previously unimagined, opportunities. In contrast, causal contingency plans seek to minimize the probability and impact of unexpected outcomes. The ability to leverage contingencies and "turn the unexpected into the profitable" is the "heart of the entrepreneurial expertise" (Sarasvathy, 2001).

Rather than focusing on one specific goal that can obscure new opportunities, effectuators remain agile and readily adapt to any new information as inputs into the entrepreneurial process. Effectuation is a "method to use and exploit chance and contingency in the creation of novel and unanticipated effects. Effectuation is driven by agency and interaction, not by chance and contingency." (Wiltbank, 2010).

2.3.3 Patchwork quilt principle: Build strategic partnerships

Effectuation is a stakeholder-centric process. Effectuators continually seek to build partnerships with self-selecting stakeholders to expand available means, and explore new opportunities. Effectual entrepreneurs will tend to view outsiders as potential collaborators more than competitors, as with competitive analysis.

Effectual entrepreneurs seek out stakeholders who are potential or surrogate customers. In that sense, effectual entrepreneurs start with customers directly; rather than eventually segmenting, targeting, and positioning their way to hypothetical customers. Since effectuators are not tethered to a plan, stakeholders can help imagine, shape, co-create and constrain opportunities. Stakeholders help the entrepreneur imagine and explore opportunities in areas where they lack experience or expertise; this can be particularly valuable when exploring high-technology opportunities. An established network of stakeholders can also form a substantial competitive barrier.

Partnering with stakeholders who add to available means minimizes the entrepreneur's exposure to risk. Building and maintaining relationships with a growing network of diverse stakeholders can often yield benefits well beyond the expiration of any single imagined opportunity. As Sarasvathy observed, stakeholder relationships typically outlive failures and help create success over time (Sarasvathy, 2001).

2.3.4 Pilot-in-the-plane principle: Emphasize control and avoid prediction

The future is to be created, not found or predicted. Although the principles of effectuation are interrelated, this principle is perhaps the most central. The pilot-in-the-plane analogy refers to the effectuator's emphasis on continuously maintaining control of their venture rather than setting it on autopilot towards some destination predicted to be the best. Entrepreneurs emphasize controlling both their immediate and long-term futures.

Effectual logic is: "To the extent that we can control the future, we do not need to predict it." Effectual entrepreneurs progress by taking incremental steps and doing what is reasonably doable as they leverage contingencies and co-create opportunities with stakeholders. In contrast, Causal logic is: "to the extent that we can predict the future, we can control it". A causal approach is planning a course based on assumptions of inevitable trends and market forces that will cause the future to unfold (Sarasvathy, 2001).

2.4 The effectual cycle

The effectual cycle shown in Figure 1 is a heuristic and not an algorithm, but it does capture the iterative process followed by many expert entrepreneurs. It has much in common with the scientific method and other iterative discovery processes.



Figure 1: The effectual cycle (Society for Effectual Action, 2011)

2.4.1 First, inventory means and imagine goals

Following the bird-in-hand principle, the effectuator starts the cycle with considering their means by first asking: "Who am I?" "What do I know?" and, "Whom do I know?" These means include the means of collaborating stakeholders. Means evolve and tend to increase throughout the entrepreneurial process.

The effectuator then imagines goals and chooses to take action towards pursuing them within the bounds of the affordable loss principle. Here "goal construction and goal achievement are different sides to the same coin" (Wiltbank, 2010). As more is learned about envisioned goals, a compelling vision starts to take shape that can then be shared with others in the next step to gain feedback, validation, new stakeholders and new stakeholder commitments. This process is cyclical and iterative.

2.4.2 Then, interact with others and gather feedback and commitments

With opportunity ideas, visions, prototypes, and other information to share, the effectuator then seeks to interact with others to gain new information and to gain commitments from new and existing stakeholders. Stakeholder commitments could be anything from simply agreeing to continue to provide feedback, agreeing to purchase products or services once available, contributing to means, or even committing to joining the venture.

Following the patchwork quilt principle, these self-selecting stakeholders and partners augment the means and help morph and refine the vision to co-create an outcome that is desired by all members of the growing network of contributors. Building and managing this growing network of stakeholders is a key skill for an effectual entrepreneur.

2.4.3 Finally, leverage contingencies and repeat the cycle as needed

With new stakeholders come new means and new goals. Combined with other contingencies, both internal and external to the growing stakeholder network, the overall goals and vision are revised within the limits of affordable loss, and are further explored and pursued by the growing team. The cycle continues as goals eventually coalesce into well-defined stakeholder-verified sellable products or services, which may be ready for more causal approaches.

2.5 Comparing effectuation and causation

Effectual-reasoning and causal-reasoning describe the ends of a dichotomous spectrum of rational strategic approaches to entrepreneurship. Expert entrepreneurs use predominately effectual approaches to sustain a quest for creating business models, while expert managers use predominantly causal approaches to generate and execute business plans.

2.5.1 Causal reasoning

Causal reasoning is traditionally taught in business schools and frequently employed by established companies. First, market research and other data are used to determine options and predict future outcomes; then, decisions to select projects from amongst these options are made based on relative opportunity and risk predictions; detailed plans are developed; means are acquired; finally, plans are executed to achieve desired outcomes.

Causal Managers use predictions of the future to develop detailed plans to take a predictable risk in achieving clearly desired outcomes. Clearly defined options are considered on merits such as their risk-weighted Net Present Values. Business plans for a chosen project are fully developed and used to justify acquiring means such as financing before the plans are executed. The popularity of such planning in large corporations perpetuates the unfortunate belief that such plans are the best approach to starting a business.

2.5.2 The perils of prediction

In his book Obliquity -- Why our goals are best achieved indirectly (Kay, 2011), economist John Kay describes the perils of overreliance on prediction. He explains through examples how ignoring stakeholders and adhering to predictions and assumptions about the world can be disastrous: "It is hard to overstate the damage done...by people who thought they knew more about the world than they really did. The managers and financiers who destroyed great businesses in the unsuccessful pursuit of shareholder value."..."Acknowledging the complexity of the systems for which they were responsible and the multiple needs of the individuals who operated these systems would have avoided these errors" Kay claims there is no true scientific basis of making business decisions and there never will be. Tools such as weighted decision matrices are inherently subjective and only create the illusion of a scientific process. In his economic consultancy Kay surveyed corporate clients here he regularly developed causal economic decision models for corporate clients, but later found that they were usually not actually used to make decisions, but were rather used to internally or externally justify decisions they already made. Kay describes this hindsight rationalization as Franklin's Gambit after a 1791 quote by Benjamin Franklin, considered by many to be the father of scientific decision making, so aptly describes this phenomenon: "So convenient a thing is it to be a reasonable creature, since it enables one to find or make a reason for everything on had a mind to do".

2.5.3 Effectuation compared to causation

An ideal Causal-Manager gathers needed resources and executes a complete plan to achieve a well-specified and predicted goal with an acceptable risk, while the Effectual-Entrepreneur efficiently sustains the quest for goals worth pursuing. Causal reasoning emphasizes wagering on the prediction of the future, while Effectual reasoning emphasizes sustaining the unknown and unpredictable in search of what could be transformed into a predictable and desirable future. Causal logic is most effective when there is a predictable future and effectual logic is most effective at finding and creating such a predictable future. Correspondingly, expert entrepreneurs in the earliest stages in the creation of a startup tend to favor effectual approaches, while expert managers in more developed ventures tend to favor more causal approaches. Table 1: Comparing relatively effectual or causal associations. Table 1 lists a variety of expressions that are comparatively associated with either effectuation or causation.

Associations more effectual	Associations more causal
Stay in control to create the future	Stay on course to a predicted future
Angel Investor might invest	Venture Capitalist might invest
Agile project management	Waterfall project management
Work with existing means	Acquire means as needed
Stakeholder analysis	Competitive analysis
Start with customer	Market analysis to find customer
Embrace change as it shapes the path	Avoid deviation to stay on plan
Sustain business model quest	Execute business plan
Stay in the game	Reap maximum rewards
Open to new ideas	Laser focused on one opportunity
Not tethered to a plan	Dedicated to executing a plan
Versatile team readily adapts	Specialized team executes
Creative exploration	Disciplined exploitation
News on a wide range of markets	Focused market research

Table 1: Comparing relatively effectual or causal associations.

2.5.4 Appropriate products and markets

Many successful effectuators avoid market analysis and predictions completely as they distract from possibilities, and because predictable opportunities are likely to attract more and stronger competitors. Sarasvathy (2008) explains: "It is only when the market is truly unpredictable that

the small, lean and mean startup entrepreneur has a real chance of shaping it into something innovative and valuable." Products and markets which cannot be readily analyzed or which have yet to be created are more appropriate for effectual approaches.

Figure 2 compares opportunities in terms of the relative newness of products and markets. This is a variation of the familiar Ansoff Matrix (Ansoff, 1957), although that is typically used to describe growth strategies for existing companies. The upper left quadrant where existing products are positioned in existing markets is the most predictable, hence most appropriate for causal approaches. These predictable opportunities are usually best exploited by large companies as it is likely to attract competitors. The lower right quadrant, where both products and markets are new, is often referred to as the "suicide quadrant" as this is where risk is the greatest. Traditional marketing techniques do not work in this quadrant. This is where effectuation is most appropriate. These high-risk opportunities are often desired by entrepreneurs who seek to introduce new products and new markets in the absence of competitors.



Figure 2: Opportunities in terms of newness of products and markets (Sarasvathy, 2003).

2.5.5 Causal and effectual market sequences

Typical marketing sequences for causal and effectual approaches is shown in Figure 3. A causal marketing approach starts at the top with market definition; then the customer is eventually

reached through the sequential process of segmentation, targeting, and positioning. In contrast, the effectual approach starts in the middle of this diagram by collaborating with a customer. Then as new products evolve, segments and strategic partners are identified to reach those segments, resulting in the definition or creation of one or more from several possible markets. Products created through the effectual process could then be considered for the application of causal marketing approaches to target additional opportunities.



Process of Effectuation Used by Expert Entrepreneurs

Figure 3: Causal customer targeting vs effectual customer development (Sarasvathy, 2003)

2.6 **Summary**

Effectual entrepreneurship is an empirically observed methodology employed by expert entrepreneurs, particularly under conditions of uncertainty. While not a new way of thinking, formulation of it into a methodology that can be defined and researched is new. This body of effectuation research is now expanding into a wide range of academic disciplines. Effectuation was described in terms of its five interrelated heuristic principles and the effectual cycle. It was contrasted with prediction based causal approaches. In the next chapter, effectuation is further described, specifically in terms of R&D.

3 APPLYING EFFECTUATION TO R&D

In this chapter, effectuation is described specifically in terms of R&D as described in the literature and some additional implications are discussed.

3.1 Compounding complexities and the case for effectual R&D

Technology-based R&D-focused startups face complex challenges and have unique opportunities to create new markets. Some of the most commercially successful technologies started with technologists in labs exploring what they *can* do with their unique means and discoveries without limiting themselves to any previous predictions as to what they *should* do. The technologists must decide how to balance time between research explorations and development, including considering economic considerations, in order to commercialize technology.

The physical possibilities for a new technology are contingent on the imagination of the inventor within the bounds of physics. Until these inherent boundaries are revealed, the range of potential product markets can appear far greater than will later prove to be physically possible, let alone economically feasible. Determining these boundaries and what is physically possible with a fundamental technology can require significant time and resources.

Without knowing what is physically possible with a technology, it is impossible to accurately predict in which markets it will have a *Performance Competitive Advantage* (PCA) through superior performance. A PCA is described to make the distinction between the physical performance advantages of a technology and economic competitive advantages. A PCA is in itself complex as it consists of a host of comparative performance and reliability parameters. For example, the PCAs for a new spray nozzle could be smaller droplet sizes, better droplet size distribution, less energy required to operate, greater durability, etc..; but until these are measured, it will be difficult to consider which markets will accept it.

Even if a technology has a PCA over existing technologies, there are likely to be economic barriers such as patents, manufacturing costs, and Not-Invented-Here (NIH) syndrome. NIH is a common syndrome where a superior technology is rejected by a firm because it would replace their proprietary technology even if there were net-positive performance and economic incentives to adopt it. If a new superior technology renders an earlier technology obsolete, then this can be described as creative destruction. The PCA might be predictable in a lab, but economic barriers might not be revealed until a product reaches its market. Many technologies,

especially component technologies, often rely on the performance or availability of existing or emerging technologies in order to reach a market as a complete product.

This complex compounding of physical and economic unknowns makes prediction impossible. However, commercializing a technology eventually requires focusing on developing the technology for the specific requirements of individual markets, existing or created. A wellfunded corporation with teams of technologists may be able to afford to use a causal planning method, targeting opportunities before technologies and markets are fully understood. However, small R&D startups, with limited pockets and staff, cannot afford this risk. For a small R&D firm, effectuation is the best approach to developing products based on new technologies.

3.2 Effectuation is more effective with high levels of innovativeness

Malte Brettel et al. (2012) examined corporate R&D and related literature through the lens of effectuation and causation. They researched the historical impact of the application of effectual or causal principles to corporate R&D projects. Using a series of studies, including a survey of hundreds of R&D projects, they show that effectuation is positively related to success when there are high levels of innovativeness and the relative benefits of causation increase when there are "low levels of innovativeness", hence increased predictability.

Brettel et al. explains that R&D projects are exposed to both technology-related uncertainty and market-related uncertainty. Market-related uncertainty is compounded for two reasons: First, with technology-uncertainty the inability to accurately predict which market segments an innovation will serve, "leads to *significant positioning uncertainty that makes it impossible to do conventional competitor or market analysis.*" Second, "market-related innovativeness can lead to customers using products in ways for which they were not initially intended" (Dew, et al. 2004). The compounding of technology-related and market-related innovativeness calls for effectual approaches. When employing the effectual logic to drive an R&D project with high-uncertainty and high-innovativeness, the top level goal may be as abstract as "eventual commercialization."

3.3 Causal methods can stifle innovation

Causal methods of R&D project planning can inhibit innovation because of the time required for such planning, a reduction in agility, and such plans can distract from the need to change. As Wiltbank et al. (2006) argue, that in "dynamic and uncertain situations planning slows adaptations" and "comprehensive planning can actually blind the organization to important

changes in the environment." Brettel adds "The likelihood of unnecessary data collection at the beginning of a project is increased when uncertainty in a R&D project is strong. Strong flexibility however allows a continuous adaptation to emerging circumstances which are hard to predict at the beginning of a project" (Brettel et al., 2012).

3.4 Small product development firms succeed by employing effectuation

There is a common misconception that successful small product development firms who do not employ causal approaches such as focusing on one goal, or performing upfront market research, are improvising or undisciplined (e.g. March-Chorda et al., 2002). Berends et al. found that although these firms do not apply causal approaches, they do employ effectual approaches; as they cannot afford to bet everything on one product and market and prefer short-term incremental developments they can control. Brettel also observed that their key competitive advantage is that they can adapt more readily than large corporations applying formal causal methods. Brettel suggests that approaches to innovation that may work for large corporations are not appropriate for small firms and that the distinction between large and small firms should be made for considered best practices. Even for a large corporation, creating "effectual cells" (Wiltbank et al., 2009) may be the best approach, at least when there are high levels of innovativeness (Brettel et al., 2012).

3.5 The importance of diverse R&D stakeholders

Stakeholder networks can be particularly important for discovering opportunities for a technology when they can exist in multiple applications and market. Research suggests that commercialization opportunities are more likely to be quickly recognized by those with specialized knowledge in a sector, than discovered by an outsider searching for opportunities in sectors in which they lack specialized knowledge (Shane, 2000). Building a network of stakeholders with unique experiences in diverse sectors thus increases the chances that more opportunities will be discovered. The value of diverse teams is highlighted by Brettel as "a major tenet of R&D research is that cross-functional integration is beneficial, especially in cases where high levels of uncertainty occur, since different functional perspectives provide different approaches to problem solving." Stakeholders contribute specialized means including contacts and help recognize opportunities and focus research.

Sometimes stakeholders other than the technology entrepreneur are better positioned to commercialize a technology for a specific sector. For example, a new component may help

create a new aircraft carburetor. Since aviation components must be produced by companies with specialized knowledge and certifications; carburetors consist of a system of many specialized proprietary components; and aircraft manufacturers are unlikely to purchase components from an unknown company; only established aviation companies can adopt the new technology. The developer of the new technology will need to form a strategic alliance or partnership, or license the technology to one of these established companies. If such an alliance were needed, then it would be good to leverage their capabilities and co-develop the technology early on. This will often be the best strategy when the entrepreneur lacks the specialized means to reach a particular segment or otherwise desires to continue to explore a wider range of opportunities rather than focus on one.

Diversity in teams is inherently effectual. In contrast with specialized teams that are appropriate for causally executing plans to exploit well defined goals, the freedom with which an effectual team can explore a diverse variety of potential opportunities benefits from a team with diverse skills, experiences, and perspectives. Diverse team members can greatly augment means including the ability to recognize and exploit commercialization opportunities. Members of a diverse team are also likely to have a more diverse range of contacts i.e. they can contribute a wider range of potential stakeholders and collaborators. The augmentation of means to follow the bird-in-hand principle, the augmentation of stakeholders to follow the patchwork-quilt principle, the ability to leverage contingencies as per the lemonade principle, and to stay in control in a wider commercialization opportunity space as per the pilot-in-the-plane principle all benefit from diversity in effectual teams.

3.6 Exploring a broad opportunity space

3.6.1 Collaborators and surrogate applications

Exploring a wide range of technology and market opportunities may increase the odds of identifying an opportunity that is worth further pursuing, but the balance between breadth and depth of focus must be carefully considered within available means. One way of efficiently exploring a wide range of envisioned market opportunities, particularly before the technology is understood, is to group potential applications according to technical similarities and then choose a representative application to explore that can serve as a surrogate for the other technically similar applications. The best choice of which specific application to pursue is likely to be the one for which an enthusiastic collaborator who will is available to contribute their means to the

effort, rather what is perceived as the best commercial opportunity. As the technology is advanced and characterized, its suitability for adjacent opportunities can be better predicted through quantifiable and comparison-based

3.6.2 Technical Competitive Analysis

At the early stages of technology R&D, the entrepreneur has not yet discovered what the technology is capable of; let alone what its markets may be. Before market suitability can be predicted, the technical performance potential of the new technology must be quantified such that it can be compared to competing technologies. Hence competitive analysis would best start from a purely technical rather than industry perspective. Existing markets and competitors will likely only present additional barriers to entry and such analysis is probably not warranted if the new technology is not understood to meet or succeed in terms of technical performance metrics. Prevailing wisdom dictates that performance of a new technology will need to offer substantial benefits over existing technology in order to enter existing markets. These advantages may be economic in nature. Even then, the technical performance is likely to be expected to be comparable with the existing solution for it to be accepted. A technical competitive analysis consists of a compiling performance metrics that are widely used across applications and markets, and then adding the new technology metrics as they are discovered. Once the technology can be compared on a technical basis, the range of potential markets can be more accurately determined.

3.6.3 Exploring multiple opportunities

Effectual entrepreneurship is inherently opportunistic. The effectual technology entrepreneur reduces exposure to risk by exploring a diversified portfolio of potential technology opportunities. This lack of a narrow product focus may not be aligned with the interests of investors such as VCs who reduce their exposure to risk by investing in a diversified portfolio of well-focused ventures. Until the technology entrepreneur is ready to focus on a single focused opportunity then the interests of the entrepreneur and investor may not be well aligned.

Some investors may require a controlling share of a startup which, amongst other things, gives them the ability to liquidate the firm if they consider progress unacceptable compared to their other investment options. However, the interests of founding entrepreneurs may differ from that of their investors. Some entrepreneurs may have a greater interest in such things as building a sustainable company, and maintaining control of their own direction and resources to the benefit of the founding stakeholders without being beholden to the interests of external investors. However, when the future can be well predicted to quickly provide large returns with an acceptable risk, then it may be in the founder's interest to raise venture funds as the interests of the founders and VCs may be sufficiently aligned.

Some angel and other early financial investors may be more comfortable with early investment once the entrepreneur has demonstrated the potential of technology. This is especially true if a disruptive PCA is demonstrated or if a competitive advantage is ensured through IP. However, since the ability to attract external investment cannot be relied upon, the ability to survive without can be key they survival and eventual success of the entrepreneur. This increases the importance of following the affordable loss principle and creating other sources of revenue.

3.7 Summary

This chapter further extended effectuation to R&D. As of yet, there is little effectuation research specific to R&D. However, research directly and indirectly supports the use of effectuation rather than causation for R&D. The compounding of new technology and market uncertainties creates conditions of extreme uncertainty where effectuation is particularly effective. The more innovative a technology, the greater the uncertainty and the more appropriate effectuation becomes. Effectuation is not only more effective for high levels of innovativeness, but causation can actually stifle innovation. Not surprisingly, some successful small technology product development firms, who were previously assumed to have been undisciplined as they avoid causal approaches, are actually applying effectuation. Diversity in teams is valuable for effectual entrepreneurship and particularly important for R&D; a wide range of means, experiences, and perspectives allows the effectual team greater freedom to explore a wider range of potential technology commercialization opportunities. Additional implications of applying effectuation to R&D were discussed. These including making the distinction between technical and market dimensions of new product development opportunities and the challenge of attracting investment while exploring a broad opportunity space. The next chapter introduces the microfluidics inventor, his technology and aspirations, as well as other background information viewed through an effectual lens.

4 INVENTOR AND COMPANY

This chapter introduces our inventor, his technology and aspirations and an historical account of technology development and commercialization activities viewed through an effectual lens.

4.1 Our technology entrepreneur: means and goals

Todd Miller is the principal inventor, entrepreneur, and stakeholder and his interests are prioritized in this work. Thus his personal means and goals including interests, preferences, abilities, resources, stakeholder network, and realistic availability to maintain what he considers an acceptable work-life balance define both means and constraints.

Mr. Miller is an engineer, inventor, and entrepreneur with undergraduate and graduate degrees in Chemical Engineering. His technical expertise includes Chemical Engineering and microchannel i.e. microfluidic devices including microreactors and micromixers, and he is presently focused on gaining expertise in micronozzles.

Mr. Miller is presently gainfully employed as the Operations Manager for the Microproducts Breakthrough Institute (MBI) and has been for the last decade. The MBI is a facility managed by Oregon State University (OSU) and is "committed to the development of micro- and nanotechnologies for sustainable energy, healthy environments and improved lives" (MBI, 2015)

As the MBI Operations Manager, Mr. Miller has implemented procedures and protocols for operation of the MBI facility and its equipment, as well as gained expertise in design and fabrication of microchannel devices. He has led development efforts of microreactor and micronozzle devices, as well as lab-on-chip and membrane separation devices.

Prior to joining the MBI, Mr. Miller spent 11 years at Hewlett Packard in supply chain management, new product development and introduction, and integrated circuit fabrication process engineering roles. Mr. Miller has extensive project management experience, is inventor on 9 issued US patents, and is founder and president of MicroFlow CVO, a startup company commercializing microtechnology (Todd Miller, personal communications, Spring 2015) (MicroFlow CVO, 2015)(Houtman, 2012).

Mr. Miller is highly motivated and well qualified to leverage his specialized skills for technology innovation commercialization without any preference for a particular application, sector, or industry. He is content in his current position at the MBI which, allows him considerable

freedom and means to continue to innovate and explore commercialization opportunities, albeit part-time and without considerable extra income to support those explorations.

4.1.1 Lifestyle firm and the implications for investment

As with any entrepreneur, Mr. Miller would love to discover and exploit an opportunity that yields great financial gains. However, like many technologists, he would be more than content with creating a firm that would provide for both a comfortable lifestyle with wages he is accustomed to, and the resources and freedom to continue to innovate in perpetuity, the type of firm generally described as a *lifestyle firm*.

A lifestyle firm is one that prioritizes providing a comfortable lifestyle for its owners, both personally and professionally, and typically generate modest revenues and growth. Many successful technology firms are lifestyle firms that contribute significantly to technology and the economy. Prioritizing the providing of a comfortable lifestyle in perpetuity increases the threshold for considering selling the firm or accepting the high-risks often associated with pursuing high-growth opportunities, as losing the firm means losing the lifestyle the owners enjoy. As attractive as owning a modest technology firm that is both financially and professionally rewarding may be to the entrepreneur, this type of firm is far less attractive to many investors. Many investors such as VCs, are only interested in opportunities for high-growth that also include an exit strategy. Hence, they would be unlikely to invest in entrepreneurs who would rather have a relatively good chance of creating a lifestyle firm than assume considerable risk and exit. Common advice is to avoid using the term *lifestyle firm* (Servo, 1992), but perhaps the best advice is rather to avoid seeking external investment unless a commercialization opportunity demonstrates a potential for growth that is enough to sufficiently align the interests of the entrepreneur and investor.

4.1.2 Todd Miller and Company (TMCo)

Although Mr. Miller is now the sole proprietor of MicroFlow CVO, more recent explorations have not necessarily been under the MicroFlow CVO banner, he has been working with others such as MBI employee Neill Thornton in a virtual company of sorts and will eventually either be officially founded or will become part of MicroFlow CVO. For economy and clarity in writing, TMCo (Todd Miller and Company) will refer to the virtual company that he is working with and has close ties, legal and otherwise, with the MBI and OSU.
4.1.3 Key Stakeholder: The MBI and Oregon State University

The MBI is tasked with helping Oregon companies innovate and they have many resources that will continue to be valuable to TMCo, not the least of which is employing Todd Miller and collaborator Neil Thornton while allowing them to pursue their entrepreneurial ambitions through commercializing OSU and MBI derived innovations. The MBI has additional lab space that can be leased by TMCo. This will allow them lease only the space required while in order to maintain a low overhead. The MBI and OSU derive significant public relations and other benefits from technology and commercialization success stories as well as potential financial rewards and thus have a vested interest in seeing TMCo succeed.

The Advantage Impact - Office for Commercialization and Corporate Development (OCCD) leads OSU's industry-sponsored research efforts and licensing of OSU innovation. The OCCD invests in OSU intellectual property by pursuing patent protection and then works to generate revenue through the licensing of that IP. The ability of TMCo to commercialize technology developed using OSU and MBI resources is allowed by OCCD in hopes of generating additional IP and subsequent licensing revenue directly or indirectly through TMCo.

Licensing royalties are divided between OSU, specific academic units, and the inventors according to a standardized formula. According to the OSU Research Dashboard, "in FY14, business payments to license patented technologies for product development reached nearly \$6 million, more than double what the university received in 2010. OSU patents for transparent transistors, wheat varieties and formaldehyde-free adhesives generated most of that income" (OSU, 2015). Historically, the majority of licensing revenues have been for wheat varieties and the OCCD is eager to see more growth in other areas such as TMCo's micronozzle technology where they have invested in seeking patent protection. However, the OCCD actively manages their IP investments and will limit them when commercialization progress is not made soon enough as they did when recently deciding not to follow through with seeking patent protection for TMCo's micronozzle technology in Europe.

Technology licensing is a complex, time consuming, and risky business. The OCCD is generally not interested in selling IP. Sharing of IP with private companies that do not have a direct connection with OSU is discouraged, but possible, while sharing of IP with other universities and OSU spinouts is preferred. Keeping these preferences in mind will help maintain and maximize OCCD support. Grant backs are generally expected to allow for non-commercial research at OSU, which is amongst the motivations for not selling intellectual property outright. At present either the commercialization of IP is pursued by the principal inventor or by an external party who contacts the OCCD and licenses the IP.

Beyond the OCCD, OSU has numerous resources and opportunities for the development of TMCo technology. Startup, technology, collaboration, and alumni success stories provide significant public relationship benefits to the College of Business, College of Engineering, and the overall university. Fundamental microfluidics technologies often have a wide range of potential applications and thus there a wide range of collaboration opportunity with research centers across the university. Amongst the OSU resources that can contribute to the commercialization of OMSA is the Advantage Accelerator, which offers many business and marketing resources to assist with commercialization activities and startups.

4.1.4 Key source of stakeholders: The Corvallis, Oregon region

Corvallis is a great location for a microfluidics startup, with unusually large number of potential collaborators and other stakeholders exploring entrepreneurial opportunities or otherwise with expertise in microfluidics. Corvallis is a technology startup town. It has twice the national average startup density (Hall, 2013), one of the highest educated populations, and has been ranked fourth in the nation in terms of patent applications per capital (Foden-Vencil, 2013). The majority of Corvallis patent applications are generated at the local Hewlett Packard site adjacent to the MBI, and a large number of those are related to microfluidics as Corvallis is considered the birthplace and R&D center for HP's cash cow inkjet printing and remains a center for microfluidics R&D. Many of the area startups involve former HP employees. Because HP Corvallis keeps downsizing (Rogoway, 2007) because there are few other area employment opportunities in microfluidic technologies, and because many former HP employees try to stay in the area because many consider it one of the best places to live in the U.S. (Bland, 2008), there is what may be an unparalleled supply of expert microfluidic and affiliated technologists eager to find local employment. There are also a large number of resources for startups, which tend to be welcomed and encouraged to form in the area. The conditions are right for Corvallis to be an ideal home for a microfluidic technology startup.

4.1.5 Key means: MicroFlow CVO

In 2011, Todd Miller and others founded microfluidics firm MicroFlow CVO (MFCVO) to commercialize a micromixer technology developed by Mr. Miller at the MBI. OSU pursued patent protection and granted MFCVO exclusive rights through a licensing agreement. The MFCVO micromixer, a.k.a microreactor, as shown in Figure 4, is a component technology (part of a greater system of components) which enables the efficient and consistent continuous-flow

mixing of two fluids as is often needed in industrial chemical processes. The technology is fully functional. The range of potential markets included just about every sector that mixes chemicals from pharmaceuticals to petrochemicals.



Figure 4: MicroFlow CVO micromixer (MicroFlow CVO, 2015).

The MFCVO team employed proven causal planning techniques and targeted the rapidly changing and growing life sciences market for an over \$2 Billion opportunity (Houtman, 2012). The team developed a detailed business plan and were successful in gaining grant funding. The technology performs well and is available for purchase, but unfortunately there was little demand. The predictions were wrong.

As Steve Blank often says "no business plan survives first contact with customers" (Blank, 2012). One hypothesis is that customers would have to replace their own technology with a micromixer that they would have to depend on and pay MFCVO for. Another hypothesis is that companies are resistant to replace any proven component technology with a new technology regardless of issues of control and finances. Hence, even though the technology performed well, it would have to perform disruptively better to motivate replacing presently existing technologies. Fortunately, much was learned through this experience and the now-patented technology still has the potential to be exploited.

Todd Miller is presently the sole owner of microfluidics company MFCVO. The first micromixer patent that was applied for (US 8,622,606) has since been granted and the OCCD has granted MFCVO exclusive rights to commercialize it. MFCVO won a 2014 TechConnect National Innovation Award (MicroFlow CVO, 2015) Orders for the micromixers trickle in, it has yet to be widely adopted enough to yield financial rewards, but it is still a great product from a technological standpoint that could still be adopted by an existing market, or perhaps a market opportunity created through effectuation.

MFCVO may have employed elements of effectuation in the beginning and were successful in building a team, attracting funding, and developing a novel microfluidics component technology. Since the technology essentially performs as predicted, the failure of this venture can be directly linked to reliance on causal market analysis and market predictions that proved to be wrong. Since this is a component technology, it relies upon adoption by system integrators in order to be sold as components of complete products and ultimately reach customers. This reliance on the cooperation of system integrators indicates an opportunity to apply effectuation and engage them as collaborative stakeholders by forming the likes of strategic partnerships. Now that Mr. Miller is the sole proprietor of MFCVO, applying effectual entrepreneurship may be more important than ever, as he will greatly benefit from creating a new team rather than attempting commercialization alone.

4.2 Stakeholder: Northwest UAV and the origins of OMSA

McMinnville Oregon based Unmanned Aerial Vehicle (UAV) propulsion system manufacturer Northwest UAV (NWUAV) is the largest UAV propulsion system manufacturer in the U.S. NWUAV was founded by Chris Harris in 2005 and started assembling UAV engines kits for Boeing. They now have annual revenues approaching \$20 Million and they continue to reinvest in a wide range of opportunities. Subsidiaries include off-road vehicle customizer RP Advance Mobile Systems, and manufacturing services provider NW Rapid Manufacturing. NWUAV was not built with large initial investment and a long-term plan to be where they are today, but rather from the ground up by building a growing network of strategic partnerships as they continued to develop their overall design and manufacturing capabilities. They receive revenue from research grants, product sales, and from engineering, manufacturing, and metrology services. In many ways, they appear to employ effectual entrepreneurship methods. NWUAV actively sought to collaborate with the MBI, and this which started the relationship with NWUAV and TMCo.

4.2.1 First collaboration with Northwest UAV and the origins of OMSA

Dominant UAV engine designs run on gasoline. NWUAV identified an opportunity to augment their competitive advantage if their engines could also run on a wider variety of heavier fuels such as JP5 and JP8 aircraft fuels and not just on gasoline. This would enable UAVs to run on fuels that were already readily available on military airfields -- a distinct advantage over competing propulsion systems. Effectively atomizing these heavy fuels would require new spray system including nozzle technology and NWUAV recognized the potential for microfluidics technology to solve this problem. They also recognized the potential for improved fuel atomization to improve engine performance, efficiency, reliability, and to reduce emissions for a wider variety of engines beyond the UAV market.



Figure 5: A NWUAV propulsion system in a running test fixture (Miller, 2014).

In 2009, NWUAV purchased a portfolio of Inkjet derived MEMS/microfluidic technology and acquired a portfolio of a portfolio of related patents from Hewlett Packard and Pico Jet (NWUAV, 2010) and approached the MBI for help in developing this technology. The MBI is tasked with helping Oregon companies innovate, and a collaboration with NWUAV would be a clear example of that. It was featured in promotional materials such as the promotional video "Northwest UAV Works with ONAMI to Develop New Fuel Injector" (ONAMI, 2010), and is still a featured product page on the MBI website (MBI, 2015).



Figure 6: Diagram of Pico Jet nozzle array fuel atomization technology (NWUAV, 2010).



Figure 7: NWUAV technologies including "MEMS Fuel Injection" from a (NWUAV, 2010).

The fuel atomizer product technology development deviated from the original concept of the inkjet derived IP portfolio and a new and improved novel micronozzle technology was developed as a result of the NWUAV/MBI collaboration. This technology will be referred to as OMSA for OSU Micro-Sprayer-Atomizer. An OMSA nozzle prototype was characterized for fuel droplet size distribution courtesy of Bend, Oregon based pharmaceutical company Bend Research who has the necessary specialized test equipment. An OMSA nozzle prototype was successfully demonstrated in a running UAV engine, although the fuel-air mixture was too lean to meaningfully characterize engine performance. Unfortunately, although the collaboration yielded early technology development success, the business relationship soon abruptly ended due to non-technical reasons and remained so until recently.



Figure 8: Droplet Size Controlled by Nozzle Design (Miller, 2014)

The Office for Commercialization and Corporate Development (OCCD), filed national and international patent applications on the new technology naming only Todd Miller and Neil Thornton as the inventors, to the exclusion of participants from NWUAV. Shortly thereafter, a representative from the OCCD then approached NWUAV for licensing fees in order to use OMSA technology. The collaborators at NWUAV were reportedly surprised and upset both by the exclusion of NWUAV collaborators as inventors on the patent applications, and the OCCD licensing demands, which they experienced as too aggressive -- particularly since NWUAV brought this project to MBI and had significantly participated and invested in this R&D. The NWUAV was clearly not happy. Regardless of the perceived affront over inventorship on the patent, the licensing fees may have negated the competitive advantage that NWUAV was hoping to gain by investing in developing this technology.

Although, the technology had been successfully developed to the point of initial demonstration in a running engine, NWUAV abruptly ended their collaboration with TMCo before the comparative performance of the engine, thus OMSA technology, could not be evaluated. This left NWUAV without achieving their goal of a UAV engine that could run on heavy fuels, OMSA without a customer or collaborator, and ending a committed stakeholder relationship. OMSA has since been *a solution in search of a problem*.

The disconnect between the OCCD can be viewed as a conflict of effectual and causal world views. NWUAV's CEO Chris Harris is a highly-successful expert entrepreneur who appears to apply effectual entrepreneurship principles to many aspects of his rapidly growing enterprises. Mr. Harris has relied on partnering with multiple stakeholders to develop multiple businesses that leverage a set a common means including engineering and fabrication capabilities. For example, his core UAV business is built on meeting the propulsion system needs of Boeing's UAV division. The means developed for that partnerships are further leveraged by affiliated enterprises Northwest Rapid Manufacturing and RP Advanced Mobile Systems.

Chris Harris approached the MBI to help co-create a new technology i.e. he viewed OSU as a collaborative stakeholder. Both the MBI and NWUAV brought unique sets of means to this collaboration and it successfully yielded promising results. From an effectuation standpoint or otherwise he could reasonably expect to gain a competitive advantage from this collaboration as compared to his competitors. OCCD's demanding licensing fees early in the collaboration without any guarantee of a sustainable competitive advantage for NWUAV may, from an effectuation standpoint, be poor stakeholder management at best. The OCCD at the time of this interaction may have had a more causal view. Their mandate can be seen making long-term investments in protecting OSU generated IP and then maximizing licensing revenue from that IP. Since effectual entrepreneurs such as Chris Harris may be key in developing and increasing the value of OSU IP, there is an opportunity for organizations such as the OCCD to incorporate effectuation into their strategic options and into how OCCD employees are held accountable. If this fuel spray technology proves to be commercially successful, then there are likely to be far greater sources of licensing revenue than NWUAV could ever provide. However, without the collaboration of NWUAV this technology would not have been developed in the first place and may never be developed. Fortunately, after a few years of separation, a resumption of the collaboration between TMCo and NWUAV is presently being rekindled.

4.2.2 Second and ongoing collaboration with Northwest UAV: A new hope

In April 2015, Neill Thornton, Todd Miller, OSU Mechanical Engineering Professor David Blunck and I travelled to NWUAV in McMinnville Oregon. The TMCo team met with NWUAV President Chris Harris, VP of Business Development Joe Gibbs, and CTO/Engineering Services Development Jeff Ratcliffe for the afternoon. The unfortunate falling out between NWUAV and the OCCD over licensing fees was discussed. Both NWUAV and TMCo want to resume collaboration and hope that the OCCD could better consider the value of this collaboration. Although the ability to run gasoline UAV engines on heavy fuels is still a motivation for this collaboration, NWUAV described a wide variety of other considerations and applications that the TMCo team was unaware of. An improved nozzle could significantly increase engine life. The problem is that at high altitudes fuel atomizers tend to coat the combustion chamber walls with fuel that washes away oil and thus increases the rate of engine wear. OMSA technology has the potential to solve this problem. If so, the value of the nozzle would be more related to the value of reducing the frequency of costly engine rebuilds rather than other considerations. The benefits of nozzle that reduces engine wear at high altitudes is not limited to military UAVs as they could be realized by the growing number of commercial UAVs such as those proposed for delivery services. Another benefit that could be realized with an improved nozzle is the ability to start UAVs that run heavy fuels without the need to preheat them. Another opportunity for an improved fuel nozzle is in 2-cycle engines, which are quickly being forced out due to stricter environmental regulations. If the quality of fuel atomization can have a significant impact on emissions, then the potential markets could be far greater than just small 2-cycle engines. The NWUAV team also described growing markets for portable generators that can run heavy fuels.

Although focusing on any subset of these products and issues would be inherently causal, the consideration of a wide range of opportunities can be seen as effectual, and these are clear examples of how diverse stakeholders can identify opportunities that may never have been discovered by the TMCo team alone. That is to say, by using effectuation to co-create a new product technology with diverse stakeholders, a greater range of potential opportunities will be identified thus increasing the chance of success. If an opportunity for commercial success is identified, then stakeholders such as NWUAV can add considerable means to exploiting the opportunity for the benefit of all participants.

A vision for TMCo as an R&D company that sustainably develops microfluidics technology platforms such as OMSA and microreactors; and which is initially funded by research grants and science-for-hire revenue, and eventually funded by licensing and product revenues was presented to NWUAV. This vision was well received by the NWUAV team and they offered to help by lending their established name, shared grant opportunities, and other resources including offering to have their website developer develop a website for TMCo. NWUAV regularly pursues grant funding opportunities and described some companies as "SBIR factories" that consisted of only two or three people and which are quite successful even without growth. NWUAV clearly recognizes the potential mutual benefits of conducting collaborative R&D with TMCo and offered their available means to help TMCo make that possible.

Much more was discussed during this long meeting, but the details described above are presented to illustrate how NWUAV augments TMCo's means in many of the ways described in effectual entrepreneurship literature. NWUAV provides TMCo with specialized technical and market insights that would not likely have been discovered by market research conducted by an outsider to their area of expertise. They also offer real performance targets and resources needed to explore the ability for the technology to meet those targets if a more causal focus is warranted.

Even if an external researcher has the required technical expertise, potential customers do not always advertise their "pain points" or freely share for a number of reasons including that they may point to product deficiencies that they themselves are seeking solutions. As Shane described, applications for a technology that might be difficult for an outsider to discover by searching, may be immediately obvious to a specialist within a given market (Shane, 2000). The interest of a successful firm such as NWUAV in collaborating in the development of a technology for opportunities in which they are confident, can hold more weight than a market prediction of upside revenue potential. This is particularly true for a technology that is not yet understood and when they bear a significant part of the risks and costs by contributing resources to the collaboration. This is also true for a small startup such as TMCo when just about any market or grant revenue opportunity is attractive; this is in contrast with a large company that might not be interested in diverting resources to a project unless projected revenues exceed some threshold e.g. \$5 million.

4.3 OMSA Technology

Oregon State Micro Sprayer Atomizer (OMSA) is a nozzle component technology that utilizes microfluidic design and specialized fabrication technologies. OMSA nozzles are *compound nozzles* in that they consist of arrays of individual micronozzles. The nozzles are constructed from a stack of flat machined layers. OMSA is a novel component technology that, although originally intended for a specific fuel spray application, could be potentially developed for a wide range of applications and industries in which nozzles are used.



Figure 9: Microscale features are machined in thin layers (Miller, 2014).



Figure 10: The thin layers are stacked to form fluid paths and create a nozzle (Miller, 2014)



Figure 11: Demonstration of an OMSA nozzle prototype spraying a fine mist of water (Miller, 2014)

4.4 Potential OMSA technical performance competitive advantages

The potential competitive advantages and disadvantages for OMSA nozzles are tied to the unique attributes of the micronozzle arrays. Unfortunately, little performance data is available for this technology, so we must rely on speculation.

Micronozzles may tend to provide better droplet control at closer working distances. Within twodimensions, OMSA nozzles can be arranged in arbitrary geometries thus the resulting spray pattern geometry can be arbitrarily designed. This is an advantage exploited by the NWUAV carburetor nozzle designs. Improved droplet control, a closer working distance, and custom spray pattern geometries are likely to reduce overspray when the compound nozzle is designed for a specific application, including non-planar extruded shape coating applications e.g. I-beam painting, where a custom nozzle can be designed to remain equidistant to the entire surface. Inward facing circular rings of OMSA nozzles have already been demonstrated for fuel atomization for NWUAV, where the analog of overspray is surface wetting.

Since the OMSA nozzles consist of a plurality of individual closely spaced micronozzles, alternate nozzles are not limited to spraying only one fluid and one gas. Multiple fluids and/or

gases could be sprayed simultaneously with their close proximity interdigitation contributing to the mixing of these materials. This could eliminate the need to premix multipart chemicals to be sprayed.

Some applications where OMSA technology may be unlikely to compete are those applications where high-volumes of material are sprayed at requiring large nozzle openings. For example, OMSA is unlikely to make a good large-scale pressure washer. Another type of application in which OMSA might not compete is those which, involve the spraying of fluids with significant amounts of suspended solids that could clog the microscale passageways. Clogging can be particularly problematic for a compound nozzle as any clogging or wear on one nozzle opening will cause uneven spray output. Reduced flow through a clogging nozzle may also tend to accelerate its clogging as the pressurized fluid is free to flow out other nozzles. Although the micro passages may be more susceptible to clogging, it is possible to allow for OMSA nozzles to be disassembled for field-servicing

The true competitive advantages and disadvantages of OMSA technology will only be validated through building, measuring, and learning about this technology and will also depend on customer requirements and other aspects of the spray systems in which these OMSA nozzles may be used.

4.5 Other development history and potential customer interest

After the initial collaboration with NWUAV had come to an abrupt end, TMCo sought to find a new market for OMSA. In search of new customers, TMCo exhibited OMSA at a trade show which, generated some customer interest including from three Fortune 500 companies: Illinois Tool Works, Nike, and Sherwin-Williams.

4.5.1 Illinois Tool Works

Chicago based Illinois Tool Works (ITW) produces engineered fasteners and components, equipment and consumable systems, and specialty products including spray systems for a wide range of industries and has annual revenues of over \$14 billion (Wikipedia, 2015). Although ITW has many potential applications for OMSA technology, they were specifically interested in the use of OMSA technology for paint spraying applications where improvements in efficiency in terms of reduced overspray and compressed air, thus energy, consumption would add to their competitive advantage.

A prototype OMSA nozzle was fabricated and sent to ITW for evaluation. TMCo was not present to assist with the evaluation which, reportedly produced mixed and non-quantified results. ITW interest was suspended reportedly due to company restructuring, although an ITW manager who regularly vacations near Corvallis, has expressed interest in visiting TMCo, but has yet to do so. The lukewarm response from ITW's may be in-part due to OMSA potentially replacing technology that ITW already owns as may have been a barrier to MFCVO. They may be more interested in exploring similar technology on their own or waiting until OMSA is further developed before considering it as an option. The motivations of ITW can only be speculated on, but their clear lack of commitment suggests that they would be a poor effectual collaborator. Effectual entrepreneurs seek pre-commitments from stakeholders and ITW is not yet up to that task. However, once the OMSA technology has been proven for applications that ITW may be interested in, then it might be advisable to contact them.

4.5.2 Nike

Portland based Nike is engaged in the design, development, manufacturing and worldwide marketing and sales of footwear, apparel, equipment, accessories and services and has annual revenues of over \$25 billion (Wikipedia, 2015). Nike's interest in OMSA technology is for the application of spraying adhesives for use in athletic shoe manufacturing. Some preliminary adhesive spraying tests have been conducted at the MBI. Nike is interested in a low-overspray spray system technology that could be used for well-controlled selective application of adhesives to shoe components which are presently manually coated with adhesive with small toothbrush-like brushes. Although an OMSA based spray system could theoretically be suitable for this application, existing spray technologies may be as well.

An OSU College of Business Integrated Business Project (IBP) student team was assigned to apply causal methods to commercializing OMSA technology. The team predicted that this was the opportunity most worth exploiting, developed a business plan and approached Nike about the prospect of licensing OMSA technology. Nike's response was to decline licensing OMSA, but indicated that they may be interested in acquiring OMSA IP for an amount that would not be acceptable to TMCo or to the OCCD who is generally only interested in licensing, and not selling, OSU technology.

Although considerable effort was placed into market research and developing a business plan as was required of the team, there was no real technical data to support the suitability of OMSA technology for this application and so the detailed analysis was built on top of conjecture. Nike's response is not surprising from the perspective that, although they may innovate in the use of

manufacturing techniques, they are not in the business of developing fundamental technology such as OMSA, so its value would likely only be to add to their defensive portfolio of IP. Nike is more likely to purchase a complete solution in which as technology such as OMSA could be a component. A system integrator who develops such manufacturing equipment is likely to be a better collaborator at this stage and perhaps the best use of a connection with Nike would be to help TMCo connect with such a collaborative stakeholder.

4.5.3 Sherwin-Williams

Cleveland based Sherwin-Williams (SHW) is in the general building materials industry and is primarily engages in the manufacture, distribution, and sale of paints, coatings and related products to professional, industrial, commercial, and retail customers, and has annual revenues of over \$10 billion (Wikipedia, 2015).

Like ITW, SHW is interested in new spray system technology that would reduce overspray. Their customers spend a considerable amount of money on the labor and materials required to mask buildings for spray painting. New spray system technology that reduces overspray would reduce these masking costs and provide SHW with a competitive advantage.

SHW has shown little more than cursory interest in OMSA technology. There may be some significant technical reason why OMSA technology would not be ideal in this market. Building paints tend to be of higher viscosity and compared to other paints and contain a large amount of suspended solids, while the micro-scale dimensions of OMSA nozzles may be better suited to lower-viscosity fluids with less tendency to clog. Additionally, a significant portion of building paint systems are airless and while an OMSA technology based paint system could require compressed air, thus nozzles that take full advantage of OMSA technology, would be incompatible with the dominant paint spraying systems resulting in high switching costs.

SHW is an innovative company but their patent grants indicate their research is focused on creating new coatings, not on the development of spray equipment. SHW sells spray equipment, but most or all of its products appear to be produced by other companies. Thus, they are not likely to be a good collaborator for TMCo to develop spray equipment with. However, like ITW they would likely be interested in new technologies once proven to work for their customer applications. As with Nike, ITW may also be a good means of connecting with system integrators who may prove to be better effectual collaborators.

4.5.4 Summary of observations

A diverse range of large companies confirmed that a disruptive new nozzle technology for the application of coatings would be of interest, but they did not offer pre-commitments as desired by effectual entrepreneurs. These companies might never make good collaborators from a technical standpoint as they likely rely on external system integrators for more complete spray coating solutions. Until TMCo has a proven spray nozzle technology, the best means that these large companies might offer TMCo is a connection to more appropriate collaborative stakeholders such as the system integrators they presently engage.

Traditional causal marketing approaches would likely consider these large customers as large market opportunities to target. However, without a proven nozzle technology working as part of a spray coating system, there is little value in causally targeting such opportunities and these companies are unlikely to become committed stakeholders as sought out by effectual entrepreneurs. The diverse range of customer interests for applications from UAV carburetors to painting houses does support one hypothesis: everybody wants a better nozzle.

4.6 Customer pain points: Everybody wants a better nozzle

Everybody wants a better nozzle. Spray Nozzles are critical system components that directly impact and often limit the performance, efficiency, and reliability of a vast array of processes, therefore practically everybody wants a better nozzle and nozzle technology continues to evolve. In light of that, there will be no shortage of industries that would welcome and encourage new nozzle technology, and this was reflected by the variety of companies which, are not in the nozzle business and yet expressed interest in OMSA.

Although customer pain points vary across applications and industries, they can mostly be grouped into two general categories: quality and efficiency. Quality describes the final product or result of the spraying process such as yield and the uniformity of a coat of sprayed paint, while efficiency addresses process waste such as overspray, and the energy consumed by the spray system.

Many spray technologies are mature and established. For well-established processes, the quality is usually already acceptable, and while there is always a desire for improved efficiency, switching costs and quality risks will tend to inhibit the adoption of new technologies until they are well proven. For example, although the automotive industry spends a significant amount of money on wasted paint and the related mitigation of environmental impact from overspray, they

would be unlikely to adopt a new low-overspray technology until it was proven not only in a production environment, but also in terms of paint reliability on actual cars over time.

Although practically all markets will eventually embrace innovative spray system technologies, with associated switching costs and risks, those with mature spray technologies will be slow to change. Thus, *the greatest and earliest opportunities for innovative nozzle technologies are likely to be in new nozzle applications as well as in those applications where performance requirements are increasing in ways that push the limits of established dominant designs.* The types of opportunities that may be best created through the use of effectual entrepreneurship

An example of where performance requirements are increasing in ways that push the limits of established dominant designs are in fuel sprays applications such as with NWUAV. Quality and reliability in fuel spray systems directly translate to engine performance, emissions, and reliability. Fuel that is not atomized and evaporated as intended will be wasted as toxic emissions. Analogous to paint overspray, wall wetting, i.e. fuel that reforms as a liquid on combustion chamber walls, washes away lubricants thus decreasing engine life (Hoffmann et al., 2012). Most internal combustion engine industries are pressured by some combination of increasing fuel efficiency, emissions, and reliability requirements, thus there are opportunities for new nozzle and spray system technologies and this is reflected by the significant amount of research in this area. However, new nozzle designs will often require spray system, fuel-air mixture, and control system advancements, and this combined with strict reliability and safety requirements, could take considerable time to for new nozzles to reach markets and start generating revenue.

An example of a new and growing application for spray systems that is not well served by existing technologies, is the application of electronic or optical thin-films to new materials that would not be compatible with the high-temperature requirements or size limitations of established semiconductor thin-film application processes. Example markets include wearable electronics, displays, and solar panels. Those attempting to solve this problem are approaching it with a diverse variety of spray nozzle and systems, thus there does not appear to be a dominant design. The lack of a dominant design presents both an opportunity and a risk as a competing technology could emerge as the dominant design. This was an opportunity to personally apply effectual entrepreneurship. Starting with what I know: electrical engineering including thin-film devices; and who I know: Dr. Nishit Murari, a post-doctoral researcher at OSU's School of Electrical Engineering and Computer Science, whose office happens to be a couple doors down from mine. We soon had a new collaborator.

4.7 Stakeholder: Nishit Murari and the CSMC

Dr. Nishit Murari is with the research collaborative Center for Sustainable Materials Chemistry (CSMC). The mission of the CSMC is to "conduct curiosity-driven and use-inspired research to enhance the sustainable chemistry toolbox with new methods and new techniques that will advance the scientific enterprise and transform the next generation of products, while preparing students to become the next generation of green chemists" (CSMC, 2012) Dr. Murari's work research includes applying thin-films with an experimental system from Finland-based thin film application equipment manufacturer Beneq, which reportedly cost over \$200 thousand. This system is for R&D use only as it is only capable of slowly coating one small substrate at a time. It is unclear as to what systems are available for production use, but they would likely cost somewhere in the range of a few-million dollars.

This spray coating process is referred to as aerosol coating. Droplet size and distribution are critical parameters. Beneq is interested in regular updates on Dr. Murari's work as they seek to improve this system. The nozzle technology employed in the Beneq system is very different from that of OMSA. It is imagined that OMSA technology would be far more suitable for production applications, yet still suitable for R&D applications. An alternative to Beneq technology would be advantageous to researchers such as Dr. Murari for a number of reasons. Perhaps OMSA could compete with Beneq and a new company could be formed or perhaps Beneq could become a strategic partner that licenses OMSA technology. Either way, there is already sufficient information to motivate TMCo and Dr. Murari to collaborate to explore this opportunity. Dr. Murari has the specifications, materials, and metrology equipment and is willing to help build a test fixture. TMCo will work on developing a nozzle design and coating system for this application. A significant benefit of this collaboration is that the knowledge gained through this collaboration will help TMCo further develop and characterize OMSA technology overall. This will help in the consideration and discovery of other coating applications such as painting.

4.8 Summary

The microfluidics inventor, his aspirations, his microfluidic technologies, key stakeholders, and a historical account of technology and business development activities were introduced and viewed through an effectual lens. Attempts at applying causal approaches such as targeting the greatest potential opportunities for revenues failed because the technology was either not sufficiently developed or because market predictions proved to be inaccurate. The greatest

successes can be seen as a result of collaborations that were essentially effectual in nature. Had effectual entrepreneurship been applied early on, then TMCo might have been more successful. The next chapter introduces some recommendations in the application of effectuation for future R&D efforts as well as some more practical strategic considerations.

5 RECOMMENDATIONS

This chapter introduces some recommendations in the application of effectuation for future R&D efforts as well as some more practical strategic considerations.

5.1 Simple strategic planning

Common wisdom is that every business starts with a plan, and this is no exception. For most a business plan implies a long and complicated causal planning. Such a plan projects the future organization for three-to-five years into the future; product lines; financial projections; industry, market, and competitor analysis; a marketing and sales plan; and other information (SBA, 2015). TMCo is not such a business and, unless they are worth creating for grant and other funding opportunities or scalable business opportunities, making such plans will not only be a waste of time, but can distract from where the real opportunities lie.

The plans for TMCo are simple relatively static high-level strategic plans and short term action plans that are routinely created while progressing through effectual entrepreneurship cycles. The plan for TMCo is to apply effectual entrepreneurship and leverage unique means to build a sustainable world-class microfluidics R&D capability. TMCo will recruit collaborative stakeholders to co-create valuable microfluidics technologies that enable new levels of product efficiency and performance in wide range of industries. Strategic plans typically contain expressions of identity such as vision, vision, mantra, and values statements, strategic areas of focus, strategic goals and action plans. The high-level identity and objectives provide a reference point for a firm that is otherwise allowing itself considerable freedom to leverage contingencies and take shape as appropriate. Without long-term plans it is important to interpret and reinterpret these high-level statements when considering decisions.

5.2 Presenting a compelling vision and image

Conveying a compelling vision to stakeholders can be key to encouraging their participation. Identity statements are needed for internal and external use. A vision statement is aspirational, compelling, and describes a future desired state. For example, the vision statement for TMCo could be "Enabling a world of efficiency through innovations in microfluidics." The vision statement is intended to relatively static.

A mission statement defines the present state of what a company does; and typically includes who it does it for, and how it does it. At present the mission statement for TMCo could be "We create world-class microfluidics solutions through R&D for a wide range of industries that enable new levels of performance and efficiency" The mission statement is to be adapted as appropriate. Developing a firm that sustains a comfortable lifestyle for its owners and employees while providing the means to develop a world-class MEMS R&D capability may be the goal, but avoid any language in statements shared externally that would reveal that it is a lifestyle company as that could dissuade investment if TMCo decides to seek financing for a large opportunity.

5.2.1 Presentation of broader capabilities

The representation of TMCo as having an established world-class microfluidic capability is a valuable form of means. The better TMCo presents its brand as possessing an established world-class microfluidics capability, the more attractive TMCo will be to potential collaborators and licensees and the stronger TMCo's negotiating position will be. Attracting stakeholders who are willing to make pre-commitments is a key element of the patchwork-quilt principle of effectual entrepreneurship.

5.2.2 All microfluidics technologies under one company

If MicroFlow CVO is not encumbered it would be worth considering using the MicroFlow CVO business entity for other TMCo ventures, or otherwise establishing one company under one name as the earlier establishment year, broader technology offerings, and technical achievements will all add to the combined company's credibility as an established concern. This may also help with MicroFlow CVO product sales and attracting collaborators as more traffic is drawn to the combined website. The name could be changed from MicroFlow CVO if desired while preserving the business entity and 2011 establishment date. The name MicroFlow CVO could be maintained as a brand for the micromixers. However, the MicroFlow CVO name could lead to future problems in certain sectors as the name "MicroFlow" in itself is also in use for other products including a blood sample analyzer developed by the Canadian Space Agency (CSA, 2013).

5.2.3 Web presence and other image presentation opportunities

To present the image of a world-class microfluidics R&D company, the TMCo web presence, including advertising and search result positioning, will need to be considered. Chris Harris suggested doing this now and even offered his company resources to help if needed. Present the largest team, capabilities, and resources that can be honestly justified. Include bios on all individuals who are available to contribute and do not mind being listed. Include all patents from TMCo personnel in patent counts, even if they are not assigned to TMCo, to indicate the proven ability to innovate. List collaborators such as NWUAV who encouraged and agreed to this. List all resources controlled or that TMCo otherwise has access to. Advertise engineering services, manufacturing consulting, technology licensing and micronozzles and micromixers and any other service or product even if in early stages of development. Present the image of a stable company worth working with.

5.2.4 Needed means: droplet metrology equipment

In order to understand what OMSA technology is capable of and thus evaluate the markets in which it could provide a competitive advantage will require the ability to collect performance data. This is particularly important without performance modeling and simulation capability as many design variations will be evaluated by trial and error.

A critical capability that is missing from the TMCo and MBI toolkit is the ability to characterize the distribution of droplets produced by OMSA nozzle prototypes. Different droplet characterization technologies exist including direct imaging, phase-doppler and laser-diffraction system while the latter is likely most appropriate for OMSA.

Regular in-house access to an instrument such as a laser diffraction droplet measurement system is necessary for rapid development of OMSA technology and, assuming the ballpark of \$100k, this may be the greatest single capital expenditure required to develop an effective nozzle development capability. An example of such a system are those offered by Malvern (Malvern, 2015). External droplet characterization services are available from companies such as Spraying Systems Co. (Spray Consultants, 2015), but outsourcing such a critical function will significantly slow development time, there would be a significant loss of test flexibility, and critical IP developments could be exposed to competitors. If access to the droplet measurement system in Bend could be regained, then that may be a preferable alternative until a droplet measurement system could be acquired.

5.2.5 General sprays and application specific knowledge

Another critical capability that is missing is specific expertise in spray nozzles and spray systems and their applications beyond the realm of semiconductor manufacturing and inkjet printing and the experience gained from OMSA development to date. Present collaborators lack this expertise as well. This will likely require recruiting and external collaborator until it can be developed or hired in-house. Individuals who have this expertise could be found by searching for those who are members of the Institute for Liquid Atomization and Spray Systems (ILASS) where many specialize in fuel sprays. There are also consultants with this specialty. Faculty and consultants typically have the droplet metrology instruments that TMCo lacks.

5.3 Stay informed

Although detailed market analysis is typically avoided by effectual entrepreneurs, it is important to stay informed on a wide range of technology and other news which can help in the envisioning of new products and markets. It is also important to review technology literature related to the capabilities and interests of the entrepreneur.

5.3.1 Avoid patent searches

As informative as they can be, many technology entrepreneurs strategically avoid patent searches. Patent searches are avoided because they expose the entrepreneur to considerable additional penalties if they are sued for patent infringement. In the United States, willful infringement of a patent can result in the claimant being required to pay treble damages to a plaintiff. Treble damages are three times the amount of actual damages determined to have been caused by the infringement. This amplification of damages can and has resulted in putting even larger technology companies out of business. Any viewing of a patent can be argued as willful infringement; even if the individual did not actually read or comprehend the patent. Information that could expose viewing, such as internet search histories, can be subpoenaed as evidence.

Reviewing patents with the intent of avoiding infringement is futile as patents deliberately obfuscate technology and claims to enable their broadest interpretation. Thus, viewing patents is unlikely to help with avoiding infringement claims, but they will expose entrepreneurs to potentially catastrophic financial penalties. Similarly, co-developing technology with any individual who may be aware of patented or proprietary information may expose the entrepreneur to legal consequences. Protective barriers can be enacted by partitioning the

development of certain technologies from such individuals, even if they participate in other ways. Seeking legal guidance in such conditions is essential.

5.3.2 Get involved with the ILASS

One effective way to find stakeholders, promote TMCo capabilities, and to assess industry developments and customer pains, is by joining and participating in focused conferences. For OMSA, attending and potentially exhibiting as conferences held by the Institute for Liquid Atomization and Spray Systems (ILASS) (ILASS-Americas, 2015). ILASS is "an organization of industrialists, researchers, scientists, academics, and students engaged in professional activities connected with the spraying of liquids." Spray technology is used across a wide range of industries and is the focus of ongoing research at many distinguished institutions. From gas turbines, rockets, and diesel engines to agriculture, environmental usage, coatings and fire suppression, you'll have access to a technical community of 950 members dedicated to the science of sprays." According to the ILASS membership information, 'By becoming a member of ILASS, you'll gain a comprehensive view of what's happening wherever spray technology is used—and share in the collaborative nature of our Institute—one that embraces experimental, theoretical, practical, and computational models to advance innovation in this field. You'll have access to technical resources, networking opportunities, and a publishing channel with Atomization and Sprays; The Journal of the International Institutes for Liquid Atomization and Spray Systems." Membership in the ILASS only cost a one-time fee of \$20. In addition to the conference networking and exhibiting opportunities, there are advertising opportunities within **ILASS** publications.

As an example to gain an appreciation for the relevance of the ILASS research to TMCo, the 13th International Conference on Liquid Atomization and Spray Systems, held August 23rd-27th 2015 included a paper that, amongst other things, discussed fabricating "micro atomizers using Micro-Electro-Mechanical-System (MEMS) technology", "fabricating micro scale silicon carbide (SiC) fuel atomizers for gas turbine engines", and describes how "an array of simplex atomizers as parallel passages for the fluid can be exploited if one were able to miniaturize the spray nozzle" (ICLASS, 2015). This technology is too close to OMSA to ignore.

5.4 Adapt lean and agile business methodologies

Two popular business methodologies are recommended: The Lean Startup methodology and agile management. These are generally congruent with effectual entrepreneurship and offer

practical advice. These methodologies were initially developed in software and internet startups, and were adapted from lean manufacturing, which was adapted from the Toyota Production System. Agile software management has been adapted as a widely accepted general project management method. Agile is an alternative to the dominant sequential, and very causal, waterfall project management. Like the effectual cycle, agile project management is a stakeholder-centric process that involves making incremental progress towards flexible goals using short iterative cycles of development, feedback, learning, and setting goals for the next cycle.

Lean startup methodology offers actionable startup advice based on the personal experiences of the authors. As with effectual entrepreneurship, lean startup methodology rejects predictionbased business planning and advocates for an agile iterative discovery process in search of a viable business model. Lean entrepreneurs accept that all they start with is a series of untested hypotheses as to how they will create value summarized on a single page called a *Business Model Canvas* (BMC) (Osterwalder, 2008). Then, using agile project management methods of employing short iterative development cycles, they develop *minimum viable products*, gain feedback from potential customers, update their hypothesis and goals; they then repeat the iterative cycle as needed in the quest for a repeatable and scalable business model. There are several books related to the lean startup methodology; perhaps the most comprehensive is Bob Dorf and Steve Blank's *The Startup Owner's Manual: The Step-By-Step Guide for Building a Great Company* (2012).

The BMC is part of the lean startup methodology. It is a recommended tool to help envision and communicate business model ideas. The BMC is a graphical text-table format for presenting a business model in a clear and concise way. Concise lists pertaining to nine key business model areas are presented that represent four high-level aspects of the business model: infrastructure, offering, customers, and finances. The information subcategories are as follows: Infrastructure: Key Partners, Key Activities, and Key Resources; Offering: Value Propositions; Customers: Customer Segments, Channels, and Customer Relationships; Finances: Cost Structure, Revenue Streams.

Although much of the information contained in the BMC is causal in nature, the BMC can still be a useful tool early on for a couple of significant reasons. First, it can be valuable brainstorming tool that will encourage looking at all aspects of a business model; even when it may be too soon to plan in those areas, brainstorming may help generate new ideas and including what types of stakeholders might be worth contacting. Multiple BMCs could be generated for different imagined futures, but it will be important to not see them as complete plans to follow

during while in the effectual cycle. Second, the BMC is now ubiquitous enough to serve as an efficient tool to communicate with a wide range stakeholders, many of whom may be familiar with the BMC, and who may want to see some representation of a plan in order to be further engaged. Detailed causal analysis is avoided during the effectuation cycle, but the BMC allows simple presentation of all aspects of a potential business model without going into details.

Since the introduction of the BMC, other specialized derivations have been developed. The Lean Canvas (Maurya, 2012) may be a useful alternative form, as it is designed for the earliest stages of a venture. The Lean Canvas divides everything between two high-level perspectives: Product and Market, and the categories are: Product: Problem, Solution, Key Activity, Cost Structure; Both Product and Market: Unique Value Proposition; Market: Unfair Advantage, Customer Segments, Channels, and Revenue Streams. The way that the Lean Canvas separates the Product and Market aspects, may be more useful for early-stage idea generation, but it has less value as a tool to communicate with external stakeholders who are likely to be more familiar with original the BMC.

5.5 Performance Competitive Analysis

For each technology developed by TMCo, identify performance parameters and specifications that are important to stakeholders. Take measurements of as many of these parameters from as many prototypes as possible. This is particularly important when access to metrology equipment may be limited. Once a technology is proven to function for a particular stakeholder application, then it will be worth comparing TMCo technology performance to the performance reported on data sheets from potential competitors and as reported in the literature. This database of performance will be useful for considering potential applications beyond the initial stakeholder's application. This data set may also prove useful when the technology is understood enough to attempt to model it to better focus design work.

For example, for OMSA there are a number of nozzle performance parameters to consider depending on the application requirements. Nozzle performance parameters include: droplet size and size distribution; droplet pattern distribution; droplet velocity; fluid pressure and volume requirement; gas pressure and volume requirements, if required; materials compatibility; reliability and durability; and mechanical requirements. Nozzle performance can often limit overall system performance. The overall spray system performance includes parameters such as overspray, i.e. wasted spray materials, and volume or surface distribution and quality.

5.6 Commercialization of scalable technology

If TMCo continues to sustain R&D efforts, expand its means and stakeholder networks, then the odds of discovering a technology with a predictably large or scalable commercialization opportunity will increase over time. If and when such an opportunity is identified, then it will be important to recognize the strategic options available. Such an opportunity will likely be best exploited by shifting to formal causal methods of research and planning. This does not mean that TMCo needs to cease as an R&D focused lifestyle firm as such opportunities can also be exploited by forming a spinoff company focused on the opportunity in which TMCo maintains a share, or by forming a strategic partnership with a company far better positioned to exploit the opportunity. However after other opportunities have been sufficiently explored and exhausted, and the scalable opportunity is promises great returns for acceptable risk, then it may be worth shelving other R&D, focusing all TMCo resources on that opportunity and bringing in sufficient investment to exploit it.

5.7 Exploring and Exploiting Rich Technology Platforms

5.7.1 OMSA lends itself to parallel development

Resist pressure to focus on one application when stakeholders can help explore multiple applications simultaneously. The laminated nature of OMSA nozzles lends itself to low cost prototyping and manufacturing. OMSA nozzle prototypes are fabricated using laser and other readily accessible standard micromachining technologies.

Nozzles required to evaluate many potential applications can be constructed of common plastics and metals including stainless steel. Designs are drawn using CAD software and automatically translated via software to CAM files used to control machining. A sheet of machined material can yield a variety of nozzles design variations for the same basic price and batches of nozzles prototypes can be rapidly produced for only a few hundred dollars. Although final product material science requirements may differ, sheets of common materials can be used to cost effectively evaluate the suitability of OMSA technology for the wide range of potential opportunities.

Similar, or even identical, spray nozzle designs are used for similar applications across multiple industries, and the variations in nozzle designs mostly depend on the same fluid viscosity, droplet size and other fundamental design parameters. Therefore, from a design and prototyping

standpoint, it would be convenient and cost effective to simultaneously explore the wider range of potential applications for OMSA technology that require minor modifications to OMSA nozzle designs. The resulting data can be extrapolated to more effectively predict performance and eventually used for modeling and even design simulation as the technology matures.

The micromixer and OMSA technologies have the potential to provide sustainable competitive advantage in multiple applications and industries. The better any application aligns with the technical capabilities of TMCo technologies as compared to alternative technologies, the better the competitive advantage and thus chances of success in any particular market. The technical suitability for TMCo technologies for these diverse applications are already determined by physics, but have yet to be discovered. Effectively identifying and exploiting the breadth of these opportunities presents unique strategic challenges. Jenny Servo describes such a technology as a Rich Technology Platform (RTP) (Servo, 1992).

5.7.2 Rich Technology Platform

An RTP is a core technology affects multiple industries. The upstream activities involve the design and manufacture of the core technology such as TMCo's micromixers and OMSA nozzles, which can be applied to multiple applications. Each application is segmented in terms of technology and market and will demand a unique strategy and resources to gain and maintain a competitive advantage, thus the overall strategy of bringing an RTP to market will involve a constellation of individual strategies and collaborative stakeholders.



Figure 12: OMSA Rich Technology Platform (RTP).

A diagram of the OMSA RTP is shown in Figure 12. Upstream are the core technology and activities that can be applied to multiple downstream applications that are part of the OMSA Sprayer/Atomizer Nozzle RTP R&D capability. These would include R&D, design, manufacturing technology, metrology, and IP that can be applied to the overall technology such as the patent application in progress. The upstream activities are by default conducted by TMCo, but collaboration on some upstream activities are also possible, although retention of control of the upstream IP will be important as discussed later.

Four general simultaneous opportunities for upstream revenue generation are listed: Opportunity 1, Technology Innovation; Opportunity 2, Design Services; Opportunity 3, Metrology Services; and Opportunity 4, Fabrication Services. Although the primary objective is Opportunity 1, Technology Innovation, the other opportunities may help TMCo generate sustainable income by leveraging the specialized knowledge and tooling i.e. capacity that will be acquired during the

pursuit of technology innovation e.g. performing droplet characterization for others if TMCo acquires such equipment.

Downstream applications listed, but are not limited to, fuel sprays, thin films, and industrial coatings. Under Fuel Sprays are products including DOD heavy fuels, efficient turbine engines, etc..; under Thin Films are low temperature processes, optical, etc..; and under industrial coatings is spray finishes, e.g. paints, adhesive sprays, etc.... Practical delineation of the downstream applications will evolve over time and take into consideration the technology, market segmentation, and available collaborators who are already focused on specific pre-defined applications.

In practice, there are a wider range of potential applications and products than can be simultaneously pursued, and so the suitability of a potential application or product to serve as a proxy for similar applications or products should also be considered. For example, the ability to apply electronic device thin-film coatings for wearable electronics could serve as a proxy for other precision surface finishes applications such as optical coatings as much of the knowledge gained and data gathered would at a minimum provide greater insights into whether or not it would be worth exploring the similar applications.

5.7.3 Competitive barriers

Competitive barriers are key considerations when partitioning applications, products, and markets for a RTP, especially IP. For example, if the OCCD granted NWUAV preferential fuel spray nozzle licensing terms for their collaboration with TMCo, then those terms could be limited to their UAV and PPG markets; while another collaborator in, say, the automotive industry, could be given similar preference to be limited to the automotive industry in exchange for their continued collaboration. Another example is that such terms could also include IP grantbacks, such that if NWUAV patented their own refinement of OMSA, then *commercial* use of that IP for other segments by TMCo would be allowable under pre-arranged terms that perhaps distributed some of the licensing fees from other segments back to NWUAV as an incentive to continue such innovations.

The goal is to reward stakeholders for their collaborations and innovations, while retaining control of the core technology and enhancements which can benefit sectors other than the ones in which they originated. The default policy is that the OCCD retains grant backs for *educational* use, and there is no published policy for rewarding collaborators so this would require some negotiation with the OCCD. Regardless, stakeholders will reasonably expect to gain a

competitive advantage for their collaboration with TMCo and the OCCD will need to be onboard for helping make this happen. These sorts of issues would be good to discuss with the OCCD soon as they are in the process of redefining their organization and policies.

Upstream activities are those primarily performed or controlled by TMCo. Key upstream activities include: design, modeling, prototyping, manufacturing process development, exploration of potential applications, talking to potential stakeholders, providing microfluidics engineering and manufacturing services for hire, grant writing, and otherwise developing a world-class microfluidics capability. Some of these roles could be performed by others in the OSU community e.g. contracting with the Advantage Accelerator for grant writing assistance.

5.7.4 The application-specific collaboration value proposition

Collaboration opportunities need to provide a significant benefit for both parties. TMCo provides world-class microfluidic capabilities to collaborators that have significant opportunities to benefit from microfluidic technology. Application specific collaborators will provide application-specific means sufficient to at least build a minimum viable product using a TMCo component. TMCo will benefit by rapidly and efficiently exploring and expanding markets for its proprietary technologies and, through grant backs, expand its IP portfolio. Application specific collaborators stand to gain a competitive advantage in their specific markets to include early and preferential access to OMSA, micronozzle, and other TMCo technologies and expertise, while establishing barriers through application specific IP.

5.7.5 Downstream collaborators

Strategically seek collaborative stakeholders to most efficiently explore the range of possible applications for TMCo technology. Ideally, these stakeholders will sufficiently augment TMCo's means to explore a particular application. Desirable stakeholder means include: contacts, reputation, expertise, metrology resources, prototyping capability to build an MVP with TMCo technology, grant sharing or assistance potential, R&D expertise, and TMCo technology will not replace their existing technology. If collaborations may yield shared IP for upstream technologies, then university researchers are much preferred as collaborators as the OCCD has indicated that sharing IP with other universities is relatively easy and sharing IP with commercial entities not affiliated with OSU can be problematic. At first, companies that build systems in which TMCo would be a component and which do not have their own component technology, such as NWUAV, can be ideal as they would be able to develop the system with the component

and would be a first customer in their market if the technology proves worthy, and the technology would then be qualified for similar applications.

5.8 The importance of adjacent IP

One important source of revenue for TMCo and the OCCD is licensing fees. Licensees are important stakeholders to attract. However it is difficult to license a technology that is protected by only one patent as licensees frequently want more. They are relying on the licensed technology for a competitive advantage. Before they invest in adopting a new technology, they will want the IP landscape to be fortified by multiple adjacent patents that cover necessary components to the overall system. They will also want assurance that the patents will be vigorously defended by the licensor. To mitigate exposure to risk in adopting the new technology they will want to see performance data and that the licensor has established expertise in area of the patent. They will also prefer to license technologies from stable enterprises that will continue to innovate and generate more IP. Potential licensees may also want one or more of the patents in a portfolio to be granted before investment. This is a problem for OMSA as the OCCD recently decided to not follow through on gaining patent protection in Europe because of a limited progress in developing OMSA technology to date. Limiting the extent of OMSA patent protection reduced OCCD costs, but made the patent, if granted, less attractive so some licensees.

5.9 Caring for stakeholders

Stakeholders are the heart of effectual entrepreneurship. With NWUAV as a collaborator in exploring fuel sprays applications, and with Nishit Murari as a collaborator in exploring thin-film applications, TMCo is in far better positioned to further develop and qualify OMSA than would be possible alone. It will be important to taking good care of these and other stakeholders.

NWUAV is an eager collaborative stakeholder and has much to offer TMCo and OSU, thus restoring and maintaining the relationship with NWUAV should be a top priority. To that end, it is important for TMCo to work closely with the OCCD to make sure the interests of collaborators and of the OCCD are as aligned as is possible and that any expectations are discussed well in advance of any demands. If a stakeholder initiates a project and contributes considerable resources as NWUAV did with OMSA, then they will reasonably expect to receive a sustainable competitive advantage or other compensatory benefits in return. For example, OCCD licensing fees could be waived or greatly reduced for them within the niche military

markets that they operate in for at least a period of time beyond the five years it will likely take to get to market. This would still allow the OCCD to impose fees on their competitors or otherwise derive benefits from the wide range of other opportunities for OMSA technology.

5.10 Summary

Some recommendations for the application of effectuation to TMCo R&D efforts as well as some more practical strategic considerations were described. These were presented in part due to a relative lack of detailed practical guidelines for the application of effectual entrepreneurship in general, and very little to guide the application of effectuation to R&D. Popular business methodologies such as *Lean Startup* and agile project management are generally consistent with effectuation and provide a wealth of practical advice. However the advice offered by these methodologies tends to be biased towards software development from which they were mostly derived, and needs to be reinterpreted as appropriate for physical technology R&D. Neither the academic effectuation literature nor the popular business methodologies provide answers to important practical questions such as how to determine when to apply effectuation versus causation and how to hold effectual entrepreneurship teams and individuals accountable. These questions are considered in the following final chapter.

6 CONCLUSION

A motivated and capable technologist seeks to leverage his unique means to sustain R&D efforts to create and commercially exploit new microfluidics technologies. As with many technologists, he would be more than content in creating a modest R&D firm while searching for greater commercial opportunities. Until new technologies are sufficiently developed, they can appear to have the potential for commercial exploitation in a wide range of product markets. Those technology product opportunities are limited by the bounds of physics that are often only discovered through costly development and by practical economic limitations that might only be discovered after commercialization is attempted. Developing a new technology for all potential markets is impractical, so focusing development efforts is often necessary. Key challenges the technology entrepreneur faces include determining which product opportunities to focus R&D efforts and determining which technology, product, and business development methodologies to employ.

A considered best practice for new product development in large product development firms is to predict the technology performance, predict the market with the greatest financial opportunity, develop a detailed plan to exploit that opportunity, acquire resources, and then execute the plan. However, many small product development firms avoid such high-risk and high-stakes projects for a number of reasons including: the compounding of technology and market predictions results in unacceptable uncertainty and risk; focusing on one large project alone presents unacceptable exposure to risk if that project fails; and because small firms view their agility and ability to create markets that cannot be predicted as key competitive advantages. When a small firm is developing a new technology, the casual approach has many problems as outlined in depth throughout the body of this thesis. Fortunately, effectual entrepreneurship provides a proven alternative to prediction based methods that is favored by many expert entrepreneurs and small product development firms and which is appropriate for our microfluidics entrepreneur.

Effectual entrepreneurship was described in general through its heuristic principles and short incremental development cycle. Then, effectuation was further described in the context of R&D. Mr. Miller and his recent attempts at technology commercialization were described and provide real-world examples of effectuation. Finally, effectual methods were prescribed for his R&D firm. Mr. Miller is already employing effectual methods as were prescribed in this thesis. He will continue to do so as he co-creates new microfluidic technologies and markets with collaborative stakeholders, without the requirement of external investments.

Although the study of effectual entrepreneurship is a relatively new academic pursuit, it was derived from empirical studies of methods long employed by successful entrepreneurs, and has a

growing body of literature to support it as a valid methodological approach. It is perhaps no surprise that effectual entrepreneurship is in many ways congruent with methodologies described by expert entrepreneurs in popular business books such as those in *The Lean Startup* series (Blank, 2013), and with the popular agile project methodology. These methodologies reflect the practical insights of trial-and-error learning by practicing entrepreneurs and are well aligned with effectual entrepreneurship literature. Thus, they provide practical advice and further support for the academic theories of effectual entrepreneurship. Both academic effectuation researchers and practical business book authors would benefit from considering developments in both types of literature on what is essentially effectual entrepreneurship. Academic effectual entrepreneurship literature has yet to fully develop practical guidance for practicing entrepreneurs. Important yet unanswered questions discovered through this research include determining when effectuation or causation are appropriate and if they can be simultaneously employed. As well as how to hold effectual individuals and teams accountable in the absence of the likes of familiar causal plans and milestones. These are areas for future work, but the beginnings of their solution are described as follows.

6.1 When is effectuation or causation appropriate?

Research makes a compelling case for the application of effectuation to search for a business model, while causation is best used to execute a business plan once a scalable and repeatable business model has been validated. This implies an all or nothing approach to applying either effectuation or causation. However, both are intuitive and natural modes of operation, and decision makers can simultaneously employ elements of both effectuation and causation. For example, traditional causal methods of market analysis may be needed to recognize if and when a business model is scalable and repeatable, thus when to shift to a more causal approach. As an aside, Maslow (1970) describes the ability to resolve such dichotomies, including that of freedom and determinism, as essential traits of self-actualized individuals. A conscious awareness of these two general modes of thinking and how and when they are best applied is advantageous to any decision maker.

6.1.1 Bounded rationality

Sarasvathy's earliest work on effectuation was guided by the late Nobel laureate Herbert Simon. Of his many contributions to political science, economics, sociology, psychology and computer science, he is perhaps most famous for his work on bounded rationality. According to Simon, the
principle of bounded rationality is based on the observation that "the capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problems whose solution is required for objectively rational behavior in the real world — or even for a reasonable approximation to such objective rationality" (Simon, 1947). The rationality of decision makers is bounded by constraints including limitations on available information, the cognitive abilities of the decision maker, and the time available to make a decision. Decision makers who intend to make rational decisions do so with a restricted view of the world and simplify problems until they are solvable with available resources. Thus, whether they are conscious of it or not, decision makers settle for suboptimal solutions that can masquerade as optimal. Where objectivity is lost, subjectivity is free to take its place and decisions can also be based on ulterior motives or implicit biases.

By justifying the application of effectuation over causation based on the limits of prediction, effectuation researches are essentially recognizing that rationality is bounded under conditions of uncertainty such that prediction cannot be applied to objective rational decision making. Bounded rationality provides a frame which can be used to consider the appropriate application of elements effectuation or causation.

Effectuators can be viewed as being particularly attuned to their own rational decision making limitations. Following the pilot-in-the-plane principle, they reject predictions when they recognize they are unreliable. Following the bird-in-the-hand principle, they regularly reevaluate their own means, capabilities, and limitations. They recognize their own cognitive limitations and, following the patchwork quilt principle, actively seek to collaborate with others who add to available information and cognitive abilities. They recognize that they will fail before they succeed and, following the affordable loss principle, they follow a strategy that allows them to continue until they succeed. Although entrepreneurs can excel at rationalizing and articulating compelling visions, effectual entrepreneurs are rather pragmatic in practice. Regularly considering and accounting for realistic cognitive limits can be an effective way to determine the appropriateness of applying varying degrees of effectuation and causation.

6.1.2 Simultaneous application of elements of causation and effectuation

Pure effectuation and pure causation describe theoretical endpoints of a spectrum of possible approaches to decision making. However, conditions of extreme uncertainty or extreme certainty are only hypothetical; real-world situations present the decision maker with a variety of inputs, each with varying degrees of certainty. In conditions of extreme uncertainty prediction may be useless at best. In conditions of extreme certainty, applying effectuation in general could be

grossly inefficient. In real-world situations, elements of causation and effectuation can be simultaneously employed as appropriate.

For example, when considering options for a fundamental technology that has the potential to be a rich technology platform with applications spanning a wide range of markets, it may be possible to conduct a reliable and objective comparison of the new technology with competing technologies on a purely technical specification basis. Competitive analyses are avoided by effectuators in general, but when the information is reliable, it can be used to consider the types of strategic partners to attempt to recruit and at least temporarily narrow the focus to areas in which the technology stands a chance of being competitive.

Sometimes elements of causality are imposed such as pre-defined goals, but that does not exclude the application of many elements of effectuation as appropriate. For example, agile project management can still be used effectively to develop software even if it its functionality and appearance is defined at the beginning of the project. Short effectual iterative learning and planning cycles are used to reach the end goal one step at a time as the team charts new territory in software development i.e. the details of how the goal was achieved may not have been predicted up front, but elements of effectuation can be effectively employed to reach the goal. If there are major flaws with the original specifications, then an effectual approach might reveal them sooner such that the end goals can be renegotiated.

Sometimes detailed causal business planning is required as a condition for gaining funding or other support. In such cases, the effectual entrepreneur will need to consider the net benefits to be gained after the costs of such planning and future constraints are accounted for. If the entrepreneur will not be tethered to such plans, then much of the planning can be outsourced, and the entrepreneur will need to be conscious of not being overly influenced by such plans or may choose to ignore them altogether. If the entrepreneur will be held accountable for following the plans, then the entrepreneur will need to consider if there is sufficient certainty that there is a validated, scalable, and repeatable business model worth focusing on executing i.e. the time is right to shift to mostly causal methods. Otherwise, it may be a good opportunity to convey a compelling high-level vision and that the plans may need to change. If the entrepreneur will be required to be tethered to a plan despite an uncomfortable degree of uncertainty, then the funding opportunity may be best declined.

Elements of causation and effectuation can be simultaneously employed. When an entrepreneur first starts to brainstorm for business model ideas, then predominantly effectual approaches are likely most appropriate. When a customer-validated scalable and repeatable business model has been developed, then predominantly causal approaches are likely most appropriate. In between

these two extremes there are opportunities, and perhaps requirements, for the simultaneous employment of elements of causation and effectuation. Regular consideration of the particular bounds on rationality can help determine when they are appropriate, as well as consideration of whether or not the entrepreneur has settled on a business model or is still searching for one.

6.1.3 Effectuate a causal vision

Effectual entrepreneurs benefit from a high-level vision, even if such a vision is inherently causal in nature. Following the bird-in-hand principle effectual entrepreneurs always start with considering their means which can be expected to increase over times. They also manage stakeholder networks which expand over time. R&D activities may require significant investments in specialized design, fabrication, and metrology resources. These means and stakeholder networks can evolve somewhat randomly as contingencies are leveraged and new opportunities are explored. However, the entrepreneur may be better served by crafting a high-level strategic vision to help guide the expansion of means in support of that vision. This is particularly relevant for technology entrepreneurs where the entrepreneur's unique set of means is in itself a key competitive advantage. This is true for TMCo where the scope of entrepreneurial opportunities are likely limited to microfluidics or adjacent technologies.

In such a case, there is an opportunity to apply aspects of causal planning, not necessarily to pursue a predicted market opportunity, but to develop, expand, and promote a technical capability. For TMCo, this vision can be to develop a world-class microfluidics capability. The consideration of design, fabrication, and metrology resources that would help achieve this vision; consideration of how and when to acquire them, finance them and alternative ways to profit from these means will benefit from the application of causal planning techniques. This vision can also guide the types of stakeholders to engage and may help choose between potential projects. Regardless of the outcomes of individual entrepreneurial explorations, the technical capabilities can increase as guided by the vision.

6.1.4 Predict within the foresight horizon

E.L. Doctorow once said that 'Writing a novel is like driving a car at night. You can see only as far as your headlights, but you can make the whole trip that way.' You don't have to see where you're going, you don't have to see your destination or everything you will pass along the way. You just have to see two or three feet ahead of you. This is right up there with the best advice on

writing, or life, I have ever heard. — Anne Lamott, Bird by Bird: Some Instructions on Writing and Life (1994)

Effectuation literature in general makes the distinction between the appropriateness of effectual and causal strategies based on the assumption that prediction and control are not coextensive. Causal logic states that "if I can predict the future, I can control it", while effectual logic states that "it I can control the future, I do not need to predict it". By presenting prediction and control as independent variables, Wiltbank et al. (2006) provides a useful framework for comparing a wide variety of different strategies. Wiltbank mentions the concept of foresight horizon, i.e. the temporal extent to which prediction can be made with reasonable certainty, in order to help distinguish between these strategies, but does not elaborate on how this concept can be further applied. However, considering foresight horizon, rather than thinking in terms of embracing or rejecting prediction, provides insights into resolving the dichotomy of effectuation and causation.

The foresight horizons implied or assumed in effectuation literature appear to be for relatively long periods of time comparable to those traditionally used in causal business planning e.g. three to five years. However, another way of considering the appropriateness of effectuation or causation is in terms of determining appropriate foresight horizons which could be considerably shorter. Within the appropriate foresight horizon prediction and control can be considered coextensive; beyond the foresight horizon prediction and control diverge. Considering the appropriate foresight horizon may help the decision maker choose between elements of effectuation.

Effectuators stay in control through "doing the doable." This can be seen as doing what task is predicted to be achievable and is predicted produce desirable outcomes, even if the specific outcomes are not predicted. In a quest for a business model or to develop a new technology, desirable outcomes include testing hypotheses and producing prototypes to engage stakeholders. They may not be predicting years into the future, but they may predict days or weeks into the future, which still employs some degree of prediction. For example, effectual agile software development cycles are typically two to four weeks in length and this could be considered the foresight horizon at which time the team reconvenes to plan the next short cycle to reach the next foresight horizon. At each planning step, the team sets reasonable goals i.e. they are predicted to be achievable.

As another example, TMCo predicts that they and their collaborators can produce an aerosol thin-film coating machine prototype. Based on the collective means and dedication of TMCo to that task, they believe with certainty that they can produce a simple coating machine. A nozzle will produce an aerosol which is directed to a substrate that is moved past the nozzle on a

conveyor-belt-like system. The technology required for such a system is well understood and TMCo already knows how to produce such a system for minimal cost. The performance and suitability of the system for any particular market is not predicted, but there is a significant chance of gaining valuable insights from the experiment. If it can passably apply any type of coating, it will make a valuable demonstration to engage stakeholders. If it cannot be used to apply any coating, then it may be best to focus on exploring other innovations. All of these predicted outcomes have a foresight horizon of a few weeks or about the time it would take the team to fabricate such a prototype and test it with a range of nozzles and other parameters.

For some technologies, the time required to test technical hypotheses may far exceed the foresight horizon in terms of market and other predictions as to what business model may eventually crystallize from the effort if any at all. For example an experiment that requires the integration of microfluidics layers and integrated circuit layers on the same substrate may take as long as a year to design, fabricate, and evaluate. This would likely require a significant amount of technical planning and expense when there is considerable uncertainty. In such a situation, the effectual entrepreneur would likely first attempt to break the experiment into simpler problems such as constructing and evaluating the microfluidics layers without the integrated circuit layers. If that is not possible, then the entrepreneur may wish to consider options such as treating the foresight horizon as aligned with the technical schedule and assume more risks in planning farther ahead than would otherwise be advisable, or alternatively devote efforts to exploring other potential opportunities while waiting for the long-term technical results.

6.2 Effectuation and accountability

Practical application of effectual entrepreneurship would greatly benefit from the development of appropriate methods of holding individuals and teams accountable for making progress. However, best practices of holding individuals and teams accountable when applying effectuation have not yet been developed in effectuation literature. Even independent individual entrepreneurs would benefit from objective methods of measuring progress. Such measurable progress may be invaluable to gaining early investments or stakeholder commitments, especially from individuals unfamiliar with effectuation, who may have only experienced accountability through causal-only metrics such as the achievement of well-defined goals according to predicted schedules and budgets.

Because effectuators are searching for a business model rather than executing a business plan, and since effectuation is antithetical to causation in many ways, a new set of performance metrics is needed. Learning to fail faster and in less costly ways as a variety of opportunities are

explored is an important component of effectual entrepreneurship. Performance metrics that place too much emphasis on rewarding individuals for solely discovering the best opportunities can encourage hero syndrome, distract from the contributions of those who helped narrow the focus to enable such discoveries, and diminish teamwork and collaboration overall. Fortunately, the principles of effectual entrepreneurship, the effectual cycle, and a vision of developing a technical capability together provide a framework from which meaningful performance metrics can be derived. Individuals who routinely document their activities will be able to demonstrate how attuned they are to their own bounded rationality, how effectively these principles are applied, and measure progress towards realizing the team's vision.

The bird-in-hand principle describes how effectuators regularly consider and make the best use of available means. How well an individual or team does this within the constraints of the affordable-loss principle provides a basis for accountability. Considering the absorptive capacity of means and the team's high-level vision, such as creating a world class microfluidics capability, contributions to augmenting means directly or through expanding the network of stakeholders as described by the patchwork-quilt principle, also provides a basis for measuring performance. The ability to recognize, communicate, and leverage contingencies according to the lemonade principle and the way those new inputs are used to shape goals according to the pilot-in-the-plane principle as the effectual cycle is followed also provides a basis of evaluating performance.

The time of an effectual cycle may be short relative to traditional causal projects, e.g. one month rather than one year, and goals may be need to be less specific. However, there is still ample opportunity to establish documented short-term goals and hold team members accountable for either delivering on those goals as described or providing clear reasoning based on the above described effectual principles. Goals may be highly specific such as to design, fabricate, and test a prototype conveyor belt system for aerosol coating substrates according to critical specifications. They may also be highly generalized such as finding new collaborators who have means to share that are needed to achieve the high-level vision. With a highly-diverse entrepreneurial team, individual roles and contributions are likely to shift as projects evolve e.g. the ability of some individuals to contribute in deep technical ways may increase or decrease. For example, if goals crystalize to focusing on electronic thin-film coating, than a team member with an electronic devices background, may shift to a more technical role, than if the goals evolve to focus on fuel sprays.

6.3 In closing

Effectual entrepreneurship embraces maintaining a pragmatic awareness of one's own bounded rationality. Things do not always go according to plan, and effectual entrepreneurship provides a methodology to create new business models rather than relying on the likes of luck, intuition, and improvisation. As many business schools today teach only traditional causal approaches to commercialization, there may be great value in moving to teach both effectual and causal methods. Effectuation researchers speculate that teaching students to frame entrepreneurial problems with a causal frame alone can actually "hinder entrepreneurial learning" as "it is far more difficult to unlearn something than to learn it" (Dew et al., 2009). Effectuation and causation are not only antithetical approaches, but their applications require different skills e.g. coursework in psychology and managing stakeholder networks may be far more valuable to an effectual entrepreneur than coursework in advanced analysis and statistics.

Effectuation is a relatively new area of research and its lack of familiar plans and analyses make it an easy target to be discounted i.e. it can appear "hand-wavy" compared to algorithmic causation for which formality is a cornerstone. The idea that a business starts with a detailed plan is so ingrained in the common perception of startups, that the idea of starting without such a plan can seem preposterous to many, even if the data supports that this is precisely what many of the most successful entrepreneurs do. Whether or not they were formally taught these methods, the ability to essentially employ both effectuation and causation as appropriate may be the key distinction between novice and expert entrepreneurs *and* managers.

This thesis describes effectual entrepreneurship, why it is often a superior approach to entrepreneurship than the traditionally taught approach of causation, and why it is particularly valuable under conditions of uncertainty. Effectual entrepreneurship was further detailed for its application to R&D in general and specifically for its application to a real technology startup. The entrepreneurial failures and successes of this startup were viewed through an effectual lens and this further supports the application of effectuation over causation. Although effectuation has been long applied by expert entrepreneurs, it is a relatively new and growing area of academic research and many questions as to its practical implementation remain. This thesis contributes to answering some of these questions, but significant opportunities for research and validation remain as the study of effectuation continues to develop. However, given its proven effectiveness and clear advantages over causal approaches under conditions of uncertainty, I propose that the study of effectuation be adopted as a core component of business education and accepted as a valid approach to starting new ventures.

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