8. Engineering and manufacturing: concurrent maturation of xRL

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WHY MANUFACTURING MATTERS

There is abundant evidence that manufacturing is a critical sector of a nation's economy for building wealth. A number of studies from governments, corporations, policy institutes and academic institutions support this assertion and indicate that "making things" is an important way to improve a society's standard of living (Duesterberg, 2013). The United States recently highlighted four key benefits of a robust manufacturing sector (Report to the President, 2012):

1. 70 percent of exports consist of manufactured goods;
2. one manufacturing job produces an additional six related supply chain jobs and ten jobs in the general economy;
3. 66 percent of scientists and engineers are employed in manufacturing; and
4. more than 50 percent of national research and development expenditures are made in manufacturing.

A robust manufacturing sector is also critical to a country's national security because modern militaries rely on advanced weapon systems and communication platforms to maintain superiority. In effect, high-tech manufacturing capacities in terms of technical knowledge and the ability and resources to manufacture high-tech weaponry are essential for national defense. If a nation relies on a military supply chain that extends significantly beyond its border, the ability of the country to obtain critical components during a time of conflict becomes increasingly risky. Often, the innovation required to conceptualize new products takes place in an industrialized country such as the US, and the manufacture of the products is then sent to another country that has lower labor rates in an effort to reduce the total cost of the product. When military supply chains follow this model that dominates civilian manufacturing, there can be national security and national competitiveness consequences.

In this chapter, we propose an engineering-oriented model aimed at increasing the domestic production of manufactured goods using the guiding principle: "Discover here – accelerate Translation – Build here" (DTB). In order to accomplish this goal, we propose a new Accelerated Readiness Level (xRL) model that accelerates the speed at which new concepts become products. This xRL model increases profitability by mitigating the time it takes to move an innovation to market. It also emphasizes the role of design and customization in advanced and high-tech manufactured goods that requires higher skills and will likely lead to more high-tech jobs.

THE DTB CONCEPTUAL MODEL

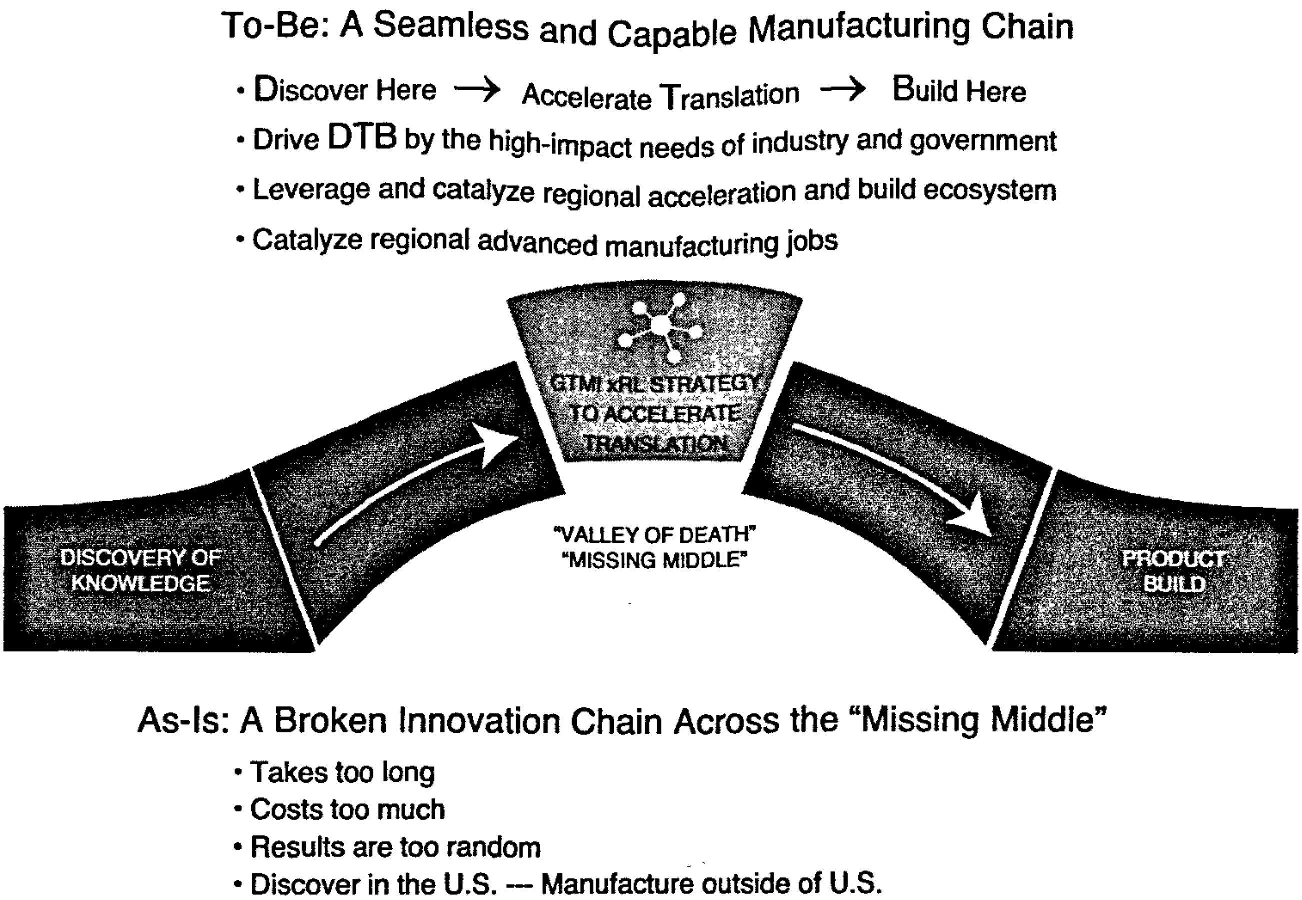
This chapter presents and describes our DTB model and how it methodically reduces risk, time and the cost of accelerating the translation of research to high-value, competitive products in the global marketplace. The DTB model of "Discover here – accelerate Translation – Build here" focuses on the concurrent maturation of xRLs – TRL (technology readiness level), MRL (manufacturing readiness level), BcRL (business case readiness level) and ERL (ecosystem readiness level). This chapter: 1) describes the critical and enabling role that universities have in the translation process in the US case; and 2) explains how the DTB approach meets two major challenges for industrialized countries, including the United States.

At the national level, there are two significant challenges to moving innovation into production. The first is a question of effectiveness and efficiency of innovation. Many analysts have pointed to the need to increase the speed of innovation and specifically the time it takes to turn research results into innovative products. Today's research translation takes too long, costs too much and the results are too uncertain. The second challenge is a question of geography, that is, location of manufacturing. Policymakers are increasingly convinced that what is invented in a place should be produced in that place. The DTB model accepts the premise that innovating and producing in place is a vital component of economic and national security policy for industrialized countries.

The DTB model for achieving these goals requires that the institutional actors, including research and development (R&D) centers like universities, stretch well beyond a successful research role to establish a capacity for focusing interdisciplinary research and provide translational leadership for seamless and capable DTB. In the US, research-intensive universities like the Georgia Institute of Technology, the Massachusetts Institute of Technology, the University of Michigan and Stanford have moved towards addressing the challenge of translational research capacity with the establishment of refocused university-level interdisciplinary institutes. These research centers have refocused to become more outward-facing, forming industry and government partnerships, and focusing the translation of interdisciplinary research to achieve real-world economic benefits and societal impact.

The DTB model we describe in this chapter requires capturing synergies of manufacturing-related expertise, aligning the regional economic ecosystem with the time and geographic challenges underscored in the DTB model, and establishing and enabling industry–government partnerships to accelerate the translation of manufacturing-related research to innovative products. This approach also requires the design and deployment of an Operating System to effectively institutionalize this future, or "to-be," manufacturing innovation process.

Figure 8.1 identifies both the "as-is" and "to-be" characteristics for the DTB innovation, value-creation chain. Recent policy reports, including the White House Advanced Manufacturing Partnership Steering Committee's final report, have documented that although the "discovery of knowledge" and "product development" phases of the innovation chain have been, to a great extent, successful in the US innovation system, the "translation" phase has been characterized by unaddressed challenges known as the "valley of death" or the "missing middle" (Report to the



To-Be: A Seamless and Capable Manufacturing Chain

- Discover Here → Accelerate Translation → Build Here
- Drive DTB by the high-impact needs of industry and government
- Leverage and catalyze regional acceleration and build ecosystem
- Catalyze regional advanced manufacturing jobs

As-Is: A Broken Innovation Chain Across the "Missing Middle"

- Takes too long
- Costs too much
- Results are too random
- Discover in the U.S. — Manufacture outside of U.S.

Figure 8.1 *Framing the DTB grand challenge: Discover Here – Accelerate Translation – Build Here*

President, 2012). The DTB model of concurrent maturation of xRL includes the entire innovation chain but emphasizes the problematic "to-be" translational capabilities and focuses on an integral view of technology, processes, methods, tools, infrastructure, policies and skills.

To address these gaps and better integrate the innovation system with an emphasis on commercialization and production, the DTB model carefully articles each stage in the innovation to production process: 1) discovery, 2) product development, and 3) translation:

- *Discovery*: This is predominantly the area of university-based researchers. Universities treat manufacturing-related research in a siloed manner, differentiated by disciplines (e.g., materials, processes, design, modeling and simulation, quality, supply chains, logistics, economics, finance, business, public policy and economic development). Disciplinary incentives are generally structured towards individual accomplishments and prioritize intellectual property strategies that are not conducive to collaborations between universities or across firms and industries. A seamless innovation model requires an interdisciplinary and holistic approach to translating fundamental discovery to technology development. To facilitate this, universities must develop a value proposition for engaging the "missing middle" as a viable "knowledge creation" workspace, and some university policies and practices will require modification.

- *Product development*: This is predominantly the area of emphasis for industry. In many industrialized countries, including the US, vertically integrated firm structures began to erode in the 1980s, leading to vertical disintegration and distributed supply chains. This has had an effect both on innovation systems and production networks. Well-known industrial research centers such as "Bell Labs" and other similar organizations have been disbanded due to corporate restructuring and budget cuts. Newer firms with a production-oriented vision are increasingly populating the ranks of those willing to pursue the basic knowledge required for making products. As a consequence, it is these firms driving translational research collaborations. Traditional US-based companies tend to reach into the "missing middle" for information but rarely reach all the way back, strategically and systematically, to collaborate with basic researchers or collaborate in the Discovery phase. Again, it is new firms that may reach back into the Discovery phase or may rely on "entrepreneurial researchers" for new products to bridge the gap between discovery and product development. Although industry may occasionally expend effort to address the "missing middle," a seamless and capable innovation chain does not universally exist.
- *Translation*: In developing the xRL operating framework, our innovation chain analysis indicated a number of missing capabilities in the current system. These include: 1) the absence of an integrated and concurrent technique to eliminate technological, manufacturing and business risks across the "missing middle"; 2) no clear method to accelerate maturation in a "realistic product use and manufacturing" environment; 3) the absence of "an Operating System" designed to accelerate research translation; and 4) no model for collaboration among relevant stakeholders. What our research found was that integrated and concurrent maturation across the "missing middle" requires measurement of integrated readiness of technology, both the manufacturing and the business cases, and the clear identification of gaps in readiness and identified actions to close the gaps. Our research also identified the need for a "realistic" environment, also known as a "relevant" or "representative" environment, for accelerating translation that can replicate and assess both the product operational condition (for instance, altitude, humidity, pressures, temperatures, etc.) and the manufacturing environment (proper validation in lab, scale up, prototype, pilot production, low-rate production and full-rate production) to be incorporated at the proper maturity readiness level. In other words, the availability of a scientific or technical prototype development, testing and evaluation environment is critical. Similarly, a business environment capable of absorbing innovations is essential. In other words, an awareness and understanding of the regional manufacturing innovation ecosystem is required to enable acceleration across the "missing middle" through the alignment (space and time) of the institutional infrastructure in the regional economy: technical colleges, workforce development intermediaries, capital sources and regional governance agencies.

Unfortunately, rebuilding such a successful corporate model as Bell Labs is likely to be far too expensive for most firms. However, replicating the techniques used by Bell Labs to commercialize research rapidly and effectively and in place could be recreated on a national or regional level through partnerships and consortium approaches like the DTB model shaped by the xRL operating framework. We have identified the need for four critical stakeholders to be involved to move the model forward: 1) universities possessing broad, interdisciplinary manufacturing-related research capabilities; 2) industrial and/or government entities that shape demand for new and high-impact products; 3) government and/or industrial entities that catalyze the translational process with sustained capital investments; and 4) a non-profit entity that can manage the overall process, act as a catalyst and unbiased broker, add value to the accelerated translation and assure that the appropriate space and environment are provided for the collaborators.

THE xRL APPROACH: OPERATIONALIZING THE DTB MODEL IN AN ENGINEERING RESEARCH CONTEXT

Our current research involves developing this framework to accelerate the commercialization of research conducted at the university level. The framework we have described in this chapter, xRL, focuses on establishing integrated technical, manufacturing, business and ecosystem maturity measures. The technical and manufacturing measures are based upon the TRL and MRL frameworks that have been developed primarily by the National Aeronautics and Space Administration (NASA) (Sadin, Povinelli and Rosen, 1988) and the Department of Defense (DoD) (Manufacturing Readiness, 2012; Rules and Regulations, 2011), respectively and are mature. The business and ecosystem readiness-level frameworks are in their preliminary development stages. In order to understand our proposed xRL model, it is important to understand the underlying characteristics of the TRL and MRL systems and the challenge of expanding and integrating these system models.

TRL

TRL is a method of classifying the maturity of a basic technology for use in a product or process. TRL defines a set of readiness levels from 1 to 9 that provide an efficient way of communicating a technology's current state along its development spectrum. A rating of 1 indicates that the technology is in a nascent state, just beyond the discovery phase. A rating of 9 indicates the technology is being used successfully in operations.

TRL was developed by NASA in the 1980s and is used by several large agencies throughout the world (Report to the President, 2012; Strategic Readiness, 2012; Department of Homeland, 2009; Technology Readiness, 2011). Fortunately, most implementations make use of the 1 to 9 rating scale, but the meaning of the ratings can vary based upon the primary mission of the user. NASA and the DoD are two large users of TRL. Table 8.1 shows the readiness levels used by NASA.

xRL makes use of TRL as one component of the overall readiness of a technology. Since TRL is well established and mature, xRL makes use of TRL without change. Currently, xRL makes use of the DoD readiness level definitions, but xRL may expand to use additional readiness level definitions to address various intents.

Table 8.1 *NASA technology readiness levels*

Level	Description
9	Actual system proven through successful mission operations
8	Actual system completed and qualified through test and demonstration
7	System prototype demonstration in an operational environment
6	System/subsystem model or prototype demonstration in a relevant environment
5	Component and/or breadboard validation in a relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof of concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

Source: Rules and regulations 2011.

MRL

MRL is another measure of overall readiness of a basic technology. As the name implies, it provides a way to communicate the readiness of a technology for use in a manufactured product or in a manufacturing process. It was initially developed by the DoD to improve the quality of procuring systems by the government. Specifics about MRL can be found in the "Manufacturing Readiness Level Deskbook" distributed by the DoD (Manufacturing Readiness, 2012).

Whereas TRL defines a single readiness level of a technology, MRL makes use of threads and sub-threads to provide a more extensive view of the readiness. Threads address nine manufacturing risk areas and consist of: Technology and the Industrial Base; Design; Cost and Funding; Materials; Process Capability and Control; Quality Management; Workforce; Facilities; and Management. Each thread is further divided into sub-threads that provide additional robustness and completeness to the analysis. MRL also defines a set of guiding/exit questions that are used to determine the readiness level of each sub-thread. The guiding questions are of great help to the users of MRL because they provide a systematic method of determining current state and provide semantics about the readiness definitions. xRL makes use of MRL without change to determine the manufacturing readiness of a technology within the xRL framework due to MRL's active user community and expanding use.

MRL provides a more robust view of readiness than TRL because MRL makes use of 22 topic areas versus a single TRL classification. This robustness requires additional analysis and is more challenging to communicate. Since xRL combines multiple readiness frameworks into an encompassing analysis, the challenges associated with MRL will be exacerbated in xRL's larger context. Therefore we propose that xRL be developed such that it can be applied without overtaxing resources and the results can be presented in a way that can be easily interpreted by the intended audience.

BcRL

No matter how innovative a product or process may be, if a firm cannot see the financial benefit then the new technology will likely be filed away. While engineers and researchers work within the realms of technology and manufacturing readiness – that is,TRL and MRL – corporate decision makers work within the realms of profits and earnings. To bridge the gap between innovation development and technology development, it is critical to incorporate BcRL and ERL into the process. Although very effective tools, TRL and MRL are not sufficient to guarantee successful and rapid commercialization of a new technology. Neither has gained such broad-based acceptance as Six Sigma – a doctrine that has gained tremendous popularity worldwide in manufacturing, services and the public sector.

Six Sigma is popular because it has a clear focus on achieving measurable and quantifiable financial returns by determining "product cost" – the metric of choice for firm decision makers. Executives can clearly see that when the quality level rises from Four Sigma to Five Sigma, the defects per million units produced drop from 6210 to 233. When the quality level reaches Six Sigma, another 230 defects per million units are eliminated. Decision makers prefer bottom line numbers, and Six Sigma readily offers these data where TRL and MRL do not. Although it is important from the new technology perspective to know maturity and manufacturing readiness, these metrics simply do not provide decision makers with the bottom line numbers they need to justify adoption of the technology.

This is where BcRL comes into play. As a companion measure to TRL and MRL, BcRL captures the "financial" or "business" reasoning for launching a new technology or manufacturing project. The intent of BcRL is methodically to build a business case and "market pull" as the technology matures, to shorten the time to market. It equips an integrated product and process design (IPPD) team with a disciplined maturation and evaluation process to bring the technology to market. Unfortunately, most technology projects ignore the importance of their business case until late in the development process. As a result, there is not enough market pull to justify the new technology insertion because associated benefits and risks have not been studied and articulated.

For this reason, it is critical to develop technology, manufacturing and business case readiness simultaneously. The IPPD effort was a significant step in the right direction. However, maturing technology and manufacturing concurrently without building a business case does not guarantee successful implementation of the new technology or manufacturing project. In other words, without the prospect of a solid financial return it is difficult to push a new technology into the marketplace, regardless of its level of innovation. A proper market pull – that is, sufficient business benefits – will ensure a smooth transition and insertion.

To build the business case, BcRL determines technology readiness for market transition (technology push), the targeted unmet needs (market pull), the product insertion timeline (technology road map), a market capture strategy and the financial benefits to the company. By incorporating BcRL into the process, a compelling business case is already in place when the technology reaches maturation.

BcRL is compatible with TRL and MRL because it is organized at nine readiness levels, as shown in Figure 8.2. The critical phases are BcRL 3–7, where the technology

Business Case Readiness Level (BcRL)

PHASE	BcRL	READINESS LEVEL DEFINITIONS
Phase 3: Reaching the "Tipping point" and on to Full Scale Market Insertion	9	*Full Rate Production into National Markets – Future Product Improvements Planned*
	8	*Full Rate Production into Local Markets – Confirmation of Financial Metrics Estimate*
	7	*Product Insertion into one Target Market – Positive Market Focus Group Response*
Phase 2: Bridging the "Missing Middle"	6	*Market Ready Research Prototype Vetted to Outside Entity and Key Customers*
	5	*Financial Issues Defined – Return on Investment Required, Margin, Funding Source (Internal, External, or Both)*
	4	*Research Concept/Target Markets Presented to Industrial Partners – Fit to Strategic Plan Goals*
Phase 1: Technology/ Manufacturing for Market Readiness	3	*Research Concept Vetted to Outside Entity (Advanced Technology Development Center, Incubator Board, etc.) for Review*
	2	*University Team Review and Validation of Potential Research Concept Market Insertion*
	1	*Research Concept Proven in Laboratory – Principal Investigator Defines Usage of Potential Market Value*

Figure 8.2 *Nine levels of business case readiness maturity*

development reaches a tipping point, and firm executives are convinced of the potential business value of the new technology, allowing it to move forward.

BcRL is meant to evaluate technology starting at a TRL of 2 or 3 and ending at the tipping point, at TRL 6 or 7. This tipping point corresponds to BcRL 6 or 7, where the technical concept initially developed in the lab is transitioned to initial market insertion. A tipping point may be characterized by a commercial success during test market evaluation. The overarching objective of BcRL is to transition a technology from an academic or industry lab to market in a timely fashion so that product insertion immediately results in significant market success for the company. An additional benefit is when the owner of the technology receives a revenue stream through continuing royalty payments from the successful translation of its intellectual property. Ultimately, BcRL is a win–win solution for all partners. Combined with TRL and MRL, the triad addresses the first challenge of ensuring rapid innovation and seamless transition from lab to pilot to production.

ERL

The second challenge of "discover here, build here," however, requires a different set of capabilities. To ensure that a new technology or product can survive once it has reached maturity and entered the marketplace a supportive production environment or manufacturing ecosystem is required. Manufacturing ecosystems, also called industrial commons by Pisano and Shih (2012), provide a cluster of localized, interdependent businesses that offer design, production, distribution, workforce, infrastructure and investment capabilities to help a business thrive.

Take for example two recent companies that had the potential to have a significant impact on society but ultimately did not survive. These two firms were Solyndra and A123. Each company had received hundreds of millions of dollars in US government assistance, garnered much press and raised the hopes of many US-based manufacturers in cognate fields. Both had highly innovative technologies in the clean energy arena, rechargeable batteries for hybrid/electric cars (A123) and crystalline thin files (Solyndra).

Analysts speculate that these firms failed because the infrastructure to support these technologies had declined and departed the United States years ago. Although the United States was once a leader in battery design and production, for example, that industry largely followed the move of electronics manufacturing to Asia in the previous few decades, forming an industrial ecosystem in a new region. For A123, the "hollowed out" ecosystem for battery manufacturing that this migration created, ultimately led to the company's inability to find the localized group of suppliers and collaborators necessary to design a new product using a new technology for a new market.

Solyndra's story took a very similar route. The design and manufacturing skills and know-how needed to process ultrapure crystalline into wafers and apply thin films of silicon onto large glass sheets were lost decades ago. This was because the United States outsourced the seemingly mundane manufacturing of semiconductors, power supplies, controllers and similar components to lower-labor-cost economies. The center of knowledge and skill sets, or the locus of R&D and manufacturing, had moved to lower-cost locations many years before (Pisano and Shih, 2012).

This migration of ideas, skills and knowledge was a firm strategy employed by many firms as a simple solution to improve the bottom line for the short term primarily by reducing the labor cost. However, the net result of these business decisions by many US corporations over the past few decades has been, at the national level, lost competencies, lost jobs, and lost capacities for the future rounds of innovation in the United States. In other words, the "graze land" for battery-making, thin film-fabrication and many more foundational technologies has eroded in the United States. For A123 and Solyndra, there was no support system to provide assistance and nurturing. Developed in isolation, without a manufacturing ecosystem, they did not have a chance to grow and prosper.

It is important to note that, unlike other readiness-level tools, ERL does not remain constant once it reaches a certain level. A manufacturing ecosystem can ebb and flow as can any ecosystem. If certain pillars of sustainability begin to deteriorate, so does the ecosystem. That is why constant monitoring and upkeep is important in maintaining an existing ecosystem.

xRL: THE COMPILATION OF TRL, MRL, BCRL AND ERL

Some previous frameworks have been used to address specific areas of interest (i.e., technology or manufacturing); xRL addresses the meta-view of product readiness by providing a comprehensive view of product readiness status. It makes use of well-established sub-frameworks such as TRL and MRL and extends the overall readiness-level analysis by addressing BcRL and ERL readiness levels. Since BcRL and ERL are new concepts, these frameworks are being developed simultaneously with the overall xRL framework.

Our preliminary field tests of the xRL framework began with identifying the technology of interest and documenting exemplars (product emulators) chosen as tangible implementations of that generic technology. The exemplars were analyzed using the techniques defined in the various sub-frameworks. Each sub-framework defines a set of readiness levels that are used as ratings of maturity. Typically the levels range from 1 to 9 or 10 and are clearly defined so users of the frameworks know what is needed to achieve a particular level. Since the sub-frameworks address extensive areas of interest, the frameworks are divided into threads and sub-threads for a more granular analysis. Each of the threads and sub-threads is assigned a current readiness level so a more extensive view can be achieved. The current readiness level assigned to the threads and sub-threads is deduced from a set of exit or guiding questions.

Each question is associated with a readiness level and is answered true or false. The questions are applied from lowest to highest readiness level. If most of the questions relating to the readiness level are answered affirmatively, then the readiness level has been achieved. If most of the questions are answered negatively, then the readiness level has not been achieved. A comprehensive view of the readiness levels for the exemplars is determined by analyzing all the thread and sub-thread readiness levels of the frameworks. Currently, xRL makes use of radar charts to present the readiness findings. The xRL development team feels that determining more effective ways of presenting the xRL data is an excellent area for future development.

Once the overall readiness profile has been ascertained, the method to accelerate the technology used in products and processes is undertaken. Typically an inverse Pareto analysis of the readiness levels is used to determine the areas in most need of improvement. This is very similar to how a standard Pareto analysis is used to communicate, prioritize and address problems in a manufacturing facility. Identifying and documenting the comprehensive readiness view of a technology is one of the major strengths of xRL, for without knowing the complete deployment picture, knowledge of how best to deploy resources to accelerate technology adoption is hampered. Defining the specific actions required to accelerate technology adoption is also a major strength of xRL. Thus xRL provides a comprehensive view of maturity and the actions required to accelerate the change in maturity. Figure 8.3 contains a flowchart of the current xRL process.

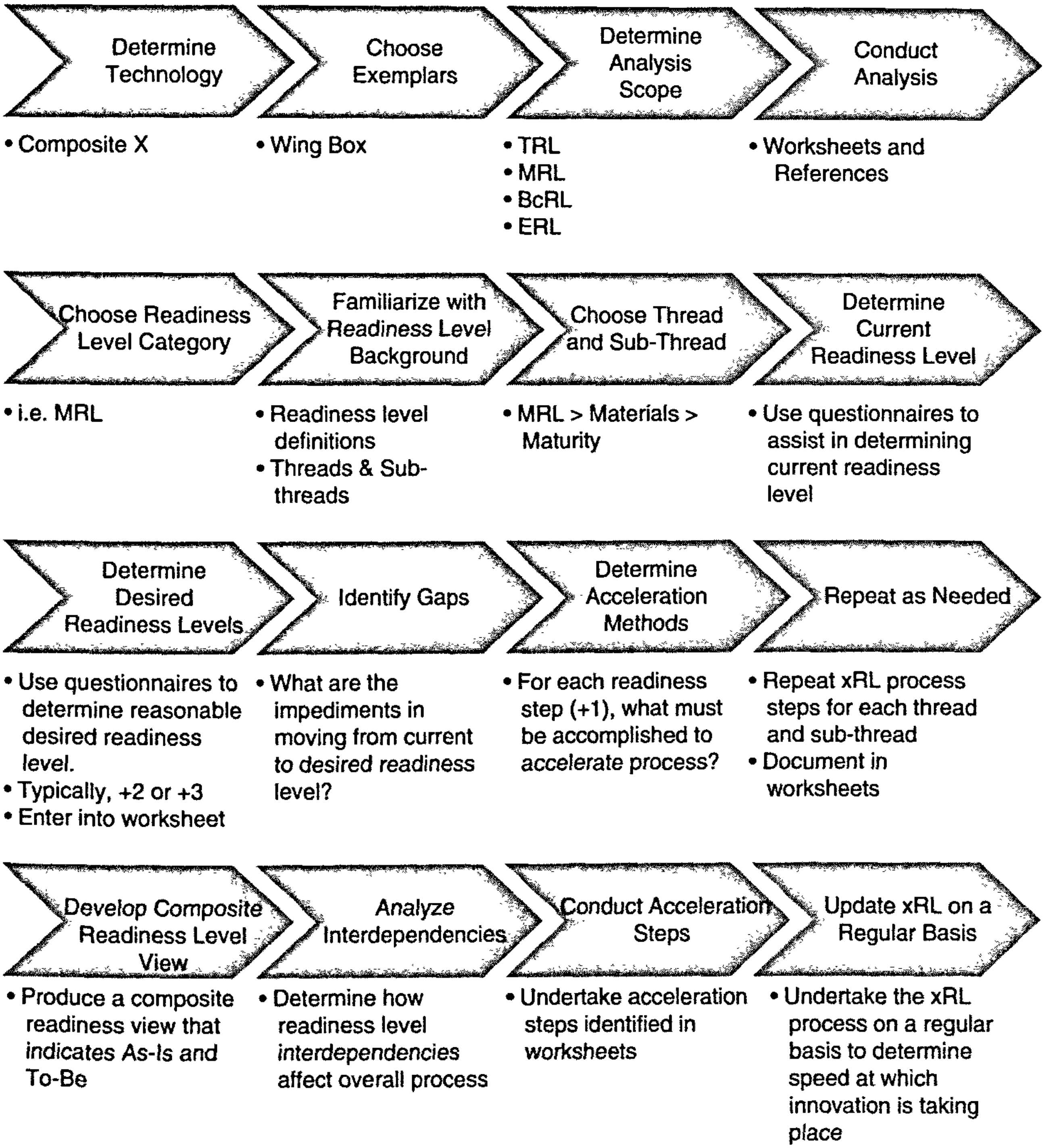


Figure 8.3 *The xRL process*

MOVING THE DTB MODEL FORWARD: THE FUTURE OF THE xRL FRAMEWORK

As the two firm cases demonstrate, it is critical for economic sustainability that innovation systems are not seen as distinct or divorced from a more nuanced, complex and dynamic manufacturing ecosystem. Although innovations have moved away from industrialized countries to emerging economies with lower costs, taking with them skills, ideas and talents, that trend is beginning to shift. As the recent 2008 recession has highlighted, industrialized economies have allowed the manufacturing base to dwindle, creating an economy based on services. The recession has reminded analysts and policymakers that regions that do not balance their industry mix do not stay in the lead and are extremely vulnerable to economic downturns.

Therefore, not only does the United States need to move its technologies to market rapidly, but it also needs to make sure that existing, localized production networks can absorb those technologies. Already, engineers have made crucial first steps by combining TRL and MRL. Now it is time to expand the model and incorporate the business and regional development elements into the framework used to evaluate, understand and invest in new technologies. Incorporating BcRL and ERL into the innovation chain can help move the process and the country in the right direction. The Discover here – accelerate Translation – Build here model begins to realign analytical processes to meet these persistent challenges and policy priorities.

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