Manufacturing for Tomorrow

Building robust strategies to ensure a vibrant and resilient manufacturing sector in the face of the Fourth Industrial Revolution

by

Ron Memmel

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Author's Declaration

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Abstract

This project investigates how strategic foresight methodologies can inform and create robust, future orientated strategies for manufacturers. This project attempts to understand the rapidly changing and increasingly challenging landscape of the manufacturing sector on the verge of the fourth industrial revolution. Building on existing literature related to the continuing evolution of manufacturing, and combined with ethnographic data, the paper explores the historical developments and manufacturers' current strategies for moving into the expected future.

The author suggests that the current strategies of manufacturers may be inadequate in the face of the multivariant future; due to several reasons, such as temporal bias. Furthermore, the study proposes that implementing foresight methodologies increases the likelihood of developing robust future orientated manufacturing strategies. The project concludes, however, that these need to be bespoke solutions.

Key Words

Fourth Industrial Revolution
Industry 4.0
Manufacturing
Canada
Strategic Foresight
Three Horizons
Foresight Scenarios

To the men and women, past, present, and future, who manufacture our world.

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1.0 Introduction

Manufacturing is the central focus of my career; from the shop floor to executive management and everything in between. Over that time, recessions, credit crunches, offshoring, bitter competition, and wildly fluctuating exchange rates became every more frequent. Like waves of crisis, the manufacturing ecosphere became ever more turbulent.

Out of necessity, management seemed to move inexorably from crafting vision and strategy to firefighting mode. In what seemed an already challenging environment, came the early whispers of an approaching tsunami; the fourth industrial revolution. However, details of what the future might entail were limited to vague concepts and pithy sound bites. Even the much-touted Industry 4.0 initiatives seemed to be marketing hype. Under such circumstances, the challenge to build a robust, futureproof strategy in the manufacturing sector seemed impossible. However, for Canadian manufacturing to not only survive, but also to thrive, in the face of these hurdles was a challenge that must be addressed.

1.1 "You say you want a revolution"

The term revolution is often used to describe rapid, transformative change which overthrows (or at least fundamentally alters) the status quo. Historically, revolutions are often the result of new technology, social innovation, and political thought rising to meet new challenges. We tend to consider revolutions as violent and abrupt political upheaval; however, this is not necessarily always the case. In fact, de Tocqueville (1840) reminds us, systemically transformative revolutions can also be much slower paced, some taking many years or even generations. Frequently they disrupt and change economic and social systems in fundamental ways sowing the initial conditions for the next revolution.

2.0 Background: The Manufactured Landscape[1]

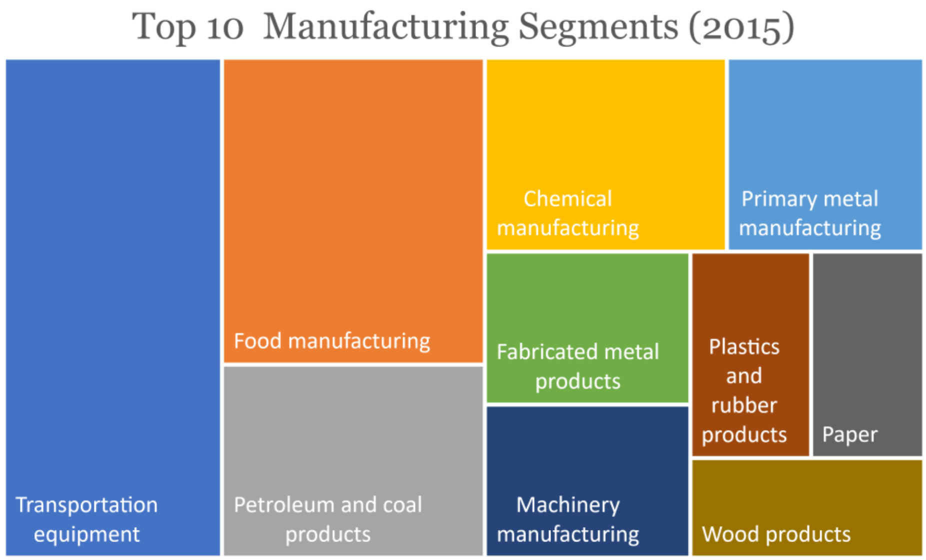
2.1 What is manufacturing?

The modern usage of the word 'manufacture' dates back to at least the 16th century and is based on the Latin 'manu factum' or made by hand. (OED, 2017). In the modern sense of the word, the manufacturing sector is comprised of establishments that are, "…primarily engaged in the chemical, mechanical or physical transformation of materials or substances into new products." (Statistics Canada, 2017).

Today, manufacturing has moved into a multiplicity of transformative activities. As with most industrialized nations, Canadian manufacturers have transitioned from low complexity – high labour products to higher complexity - high value products. This ranges from aerospace to power generation equipment, medical and leading-edge technology. However, a wide range of more traditional manufacturing, from iron working to metal fabrication, raw material processing as well as still some made-by-hand trades flourish in Canada.

[1] With apologies to Edward Burtynsky.

Figure 1: Top 10 Manufacturing segments Canada in 2015.



Data source: (Statistics Canada, Principal statistics for manufacturing industries, by North American Industry Classification System (NAICS), 2017)

Manufacturing in Canada - Key Metrics

Manufacturing is one of the pillars of the Canadian economy. Annually, manufacturing accounts for approximately $173 billion of our gross domestic product, which represents almost 11 percent of Canada's overall GDP.

Table 1: Key Metrics of Manufacturing in Canada

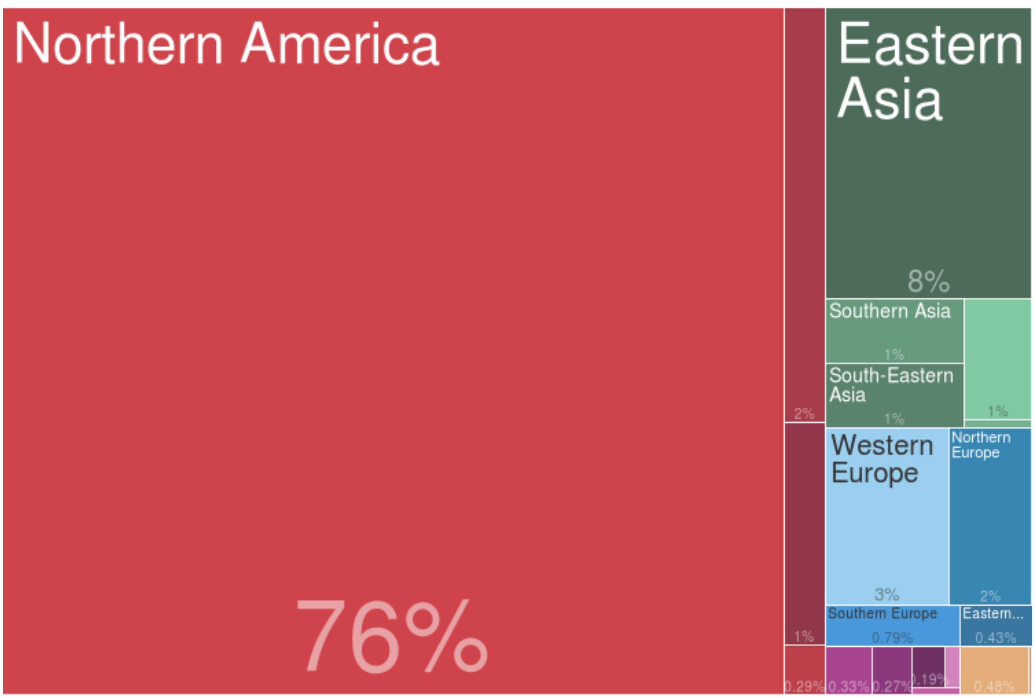
Shipments	$623 billion
Value added	$217 billion
Total wages	$84.6 billion
Total net revenue	$59.8 billion
Number of firms	89,885
Average firm revenue	$686,000
Percentage of firms with < 100 employees	93.3%

Data based on latest available full data sets 2014-2015 (Industry Canada, 2017), (Statistics Canada, 2017), (Statistics Canada, Principal statistics for manufacturing industries, by North American Industry Classification System (NAICS), 2017).

Export, eh?

In 2016, the manufacturing sector accounted for national exports valued at $354 billion, representing 61 percent of the country's exports. (Industry Canada, 2017). The largest export market for Canadian manufacturing was the United States, accounting for over two thirds of the volume at $238 billion. China ranked a distant second at $10.8 billion. Third was Japan with Canadian exports reaching just over $5 billion (Industry Canada, Canada's Manufacturing Sector, 2017).

Figure 2: Canadian Manufacturing Export Markets in 2016

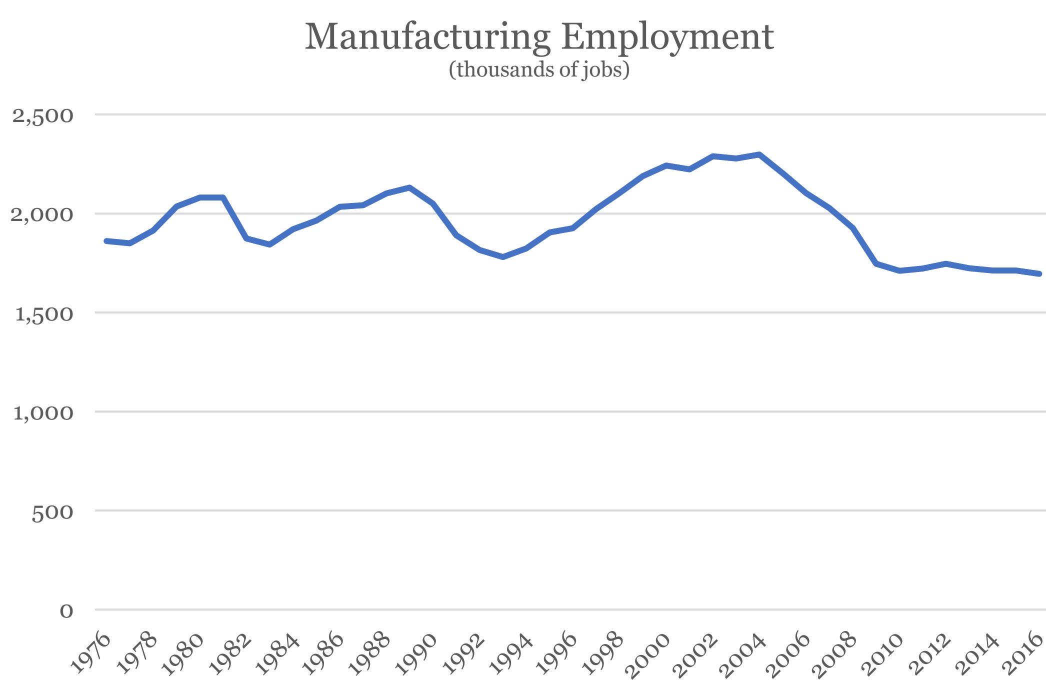


Data source:(Center for International Development, 2017)

Employment

Nationally the manufacturing sector employs 1.7 million people in mostly full-time, well-paying jobs. Perhaps surprisingly, "… the manufacturing sector pays $1.85 billion weekly in salaries to Canadian workers, more than any other sector in the Canadian economy" (Industry Canada, 2017). Additionally, almost 3 million people are employed indirectly by the manufacturing sector.

Figure 3: Manufacturing Employment in Canada

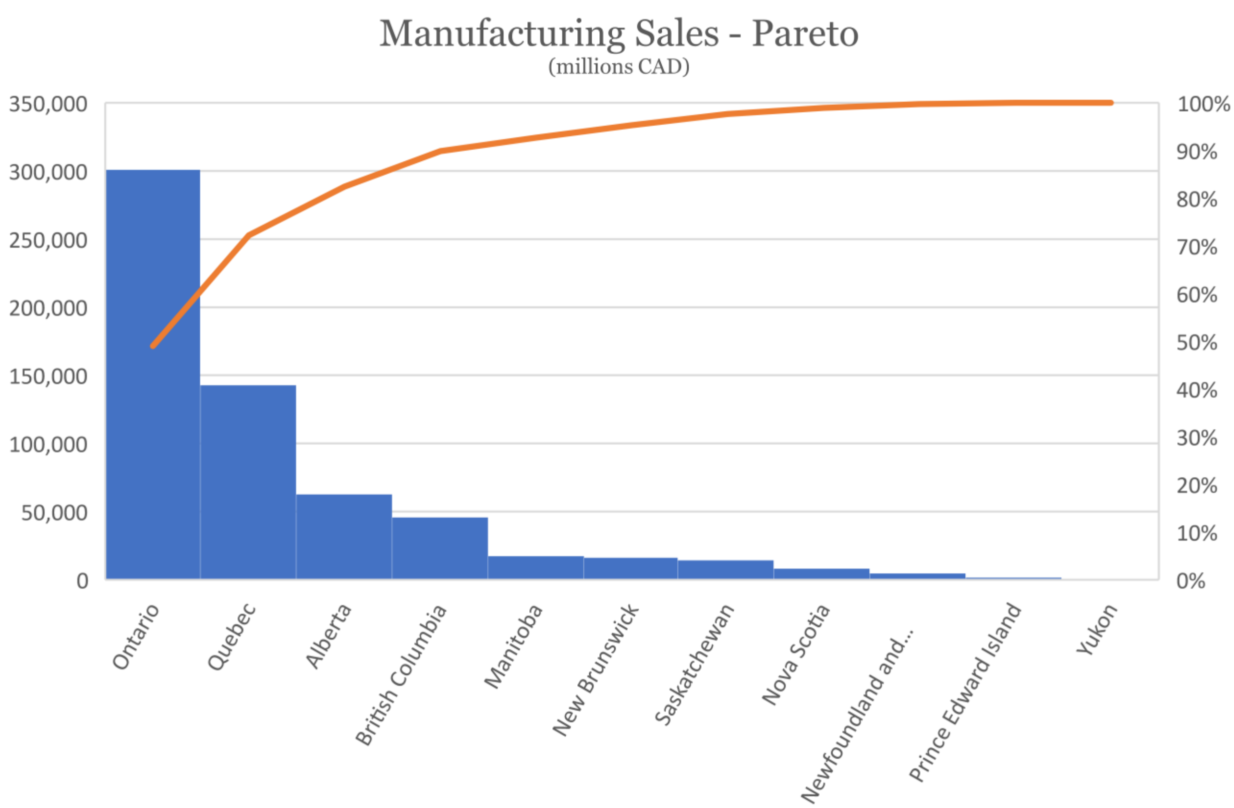


Data Source: CANSIM table 282-0008 (Statistics Canada, Labour Force Survey, 2017)

Where in Canada?

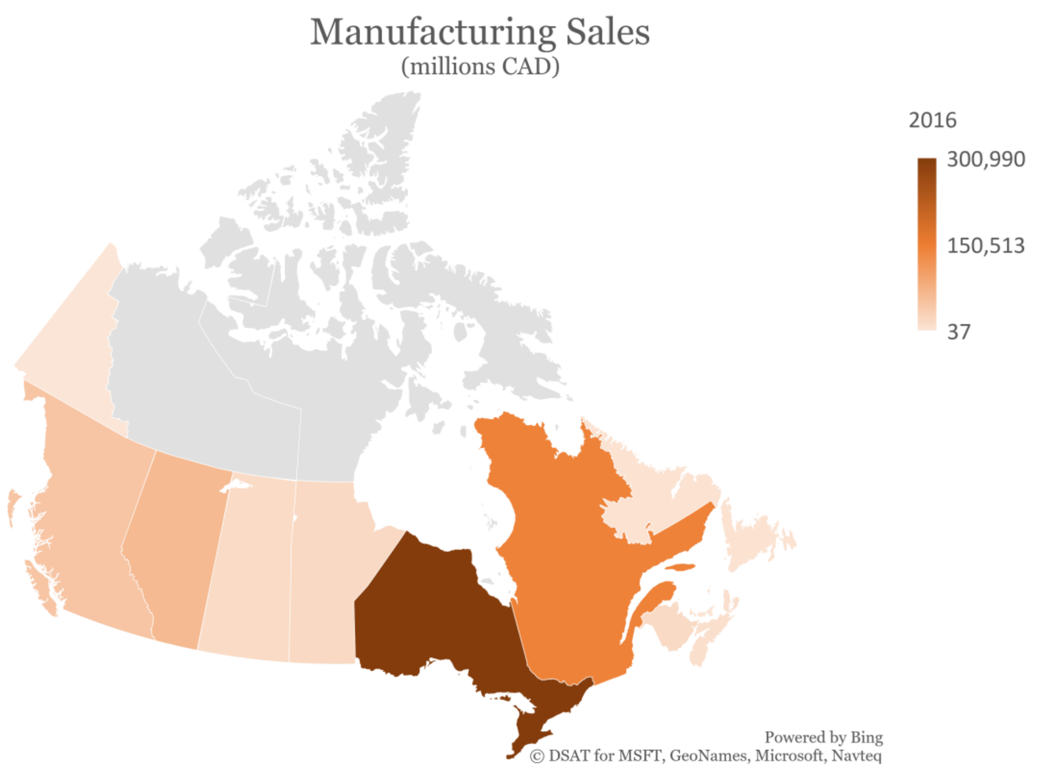
Geography and history have played the leading roles for the distribution of manufacturing in Canada. The proximity to markets, labour, infrastructure, and natural resources has traditionally meant that the majority of manufacturing was concentrated in Ontario and Quebec. The relatively more recent build up of extractive industries has lead to a corresponding development of manufacturing in Western provinces.

Figure 4: Manufacturing Distribution for 2016, Pareto Analysis



Data source: CANSIM tables 304-0014 and 304-0015. (Statistics Canada, 2017)

Figure 5: Map of Regional Distribution of Manufacturing 2016



Data source: CANSIM tables 304-0014 and 304-0015. (Statistics Canada, 2017)

All of these elements, when taken together, demonstrate that Canada's manufacturing industry has, and will continue to have significant impact on Canada's economic future. However, it is equally true that the world is changing rapidly.

A multitude of new technologies are changing not only the ways goods are produced but also quite possibly the dynamics of the marketplace and the very fabric of society. This is compounded by the need for manufacturing to address climate change in a meaningful way. Manufacturing must move towards sustainable, if not regenerative, practices. Such far reaching changes imply a paradigm shift for the entire system.

Revolutions imply a sudden and often violent change from the status quo into a new, unknown paradigm. No wonder that the notion of the fourth industrial revolution is unsettling for many manufacturers. In an era where uncertainty, confusion and a blindingly fast pace of change is already the norm, to envision a revolution in the manufacturing sector is indeed terrifying.

In order to plot a viable course through the turbulent times ahead we need to appreciate the main characteristics of the fourth industrial revolution. While it is impossible to predict the future, it is possible to construct a holistic understanding of the major characteristics shaping the future of manufacturing.

Our current manufacturing ecosystem and the productive forces within, are a product of historical circumstance. Therefore, before diving into the future(s), it is important to understand the historical context and underpinnings of industrial manufacturing.

2.2 Historical Context

A fourth industrial revolution implies that there were three previous revolutions. What can we learn about these revolutions? Are there analogies in the paradigm shifts and in the way that manufacturing has responded to these challenges? Moreover, what major historical characteristics are still influencing the manufacturers of today and which are vulnerable to disruption?

The term 'industrial revolution' is often used in an ambiguous manner. In general, the term describes a transitional period when more advanced systems displace traditional means of production. These advanced systems are often an amalgamation of previously enabled elements which are recombined into more complex systems. Theses new systems, in turn, generate their own set of challenges and also enable the next set of advancements.

Industry 0.1: Fiat Fabri

For most of human history, manufacturing was an artisanal endeavour complementing agrarian life. This form of manufacturing was heavily dependant on individual skills. Production was carried out by skilled crafts workers who learned their trade through apprenticeship type programs, and were often organized into guilds. Initially, tools were made from wood, stone, and later bronze. About 3000 years ago, iron tools allowed for a dramatic increase in productivity.

Production was generally household, or village based and broadly disbursed throughout rural areas. Relying on muscle power, biomass fuels, and hand tools, output was usually limited to small volumes of non-standardized production. This resulted in widely varying quality and relatively high product costs. Trade networks gradually evolved and provided distribution of raw and finish material alike.

Industry 1.0: Efficiency

The first Industrial revolution took place from the mid 18th century to about the mid 19th century[2]. At the centre was the transformation of the manufacturing process. Previously, manufacturing was primarily done by hand, in small workshops in tightly controlled guilds.

There were several key factors that fuelled this revolution. A growing body of scientific research was at it’s foundation. Secondly, the invention, and wide spread

---

[2] Historians still struggle with assigning firm dates to the industrial revolutions. This is due, in part, to the fact that these transitions display fuzzy logic amplified by different start times in different geographic locations. This paper will use the most common periodizations (Smil, 2014). For us, precise dates are of lesser importance than understanding the overall implications.

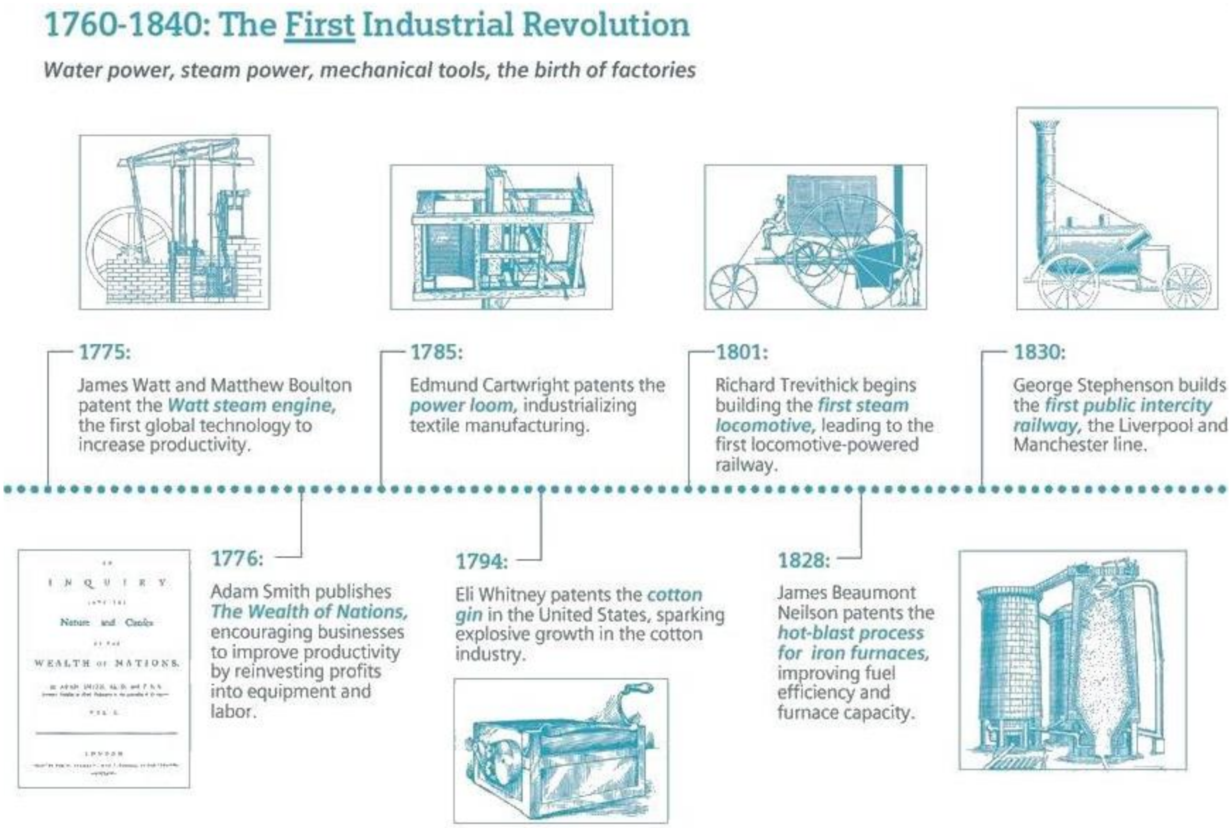
implementation of steam power began to replace human and animal labour at scale. Moving from muscle power to mechanical power was dramatic multiplier of efficiency. This allowed the efficient formation of rudimentary railroads, machine tools and wide spread iron production (Ashton, 1998). These factors combined to enable the significantly more efficient factory system and the mechanization of production. Scientific discoveries stimulated the new chemical manufacturing industries. Gasification and gas lighting allowed factories to extend the working day, and subsequently introduced nightlife to society.[3]

The sum of these factors enabled concentrated, factory based production which implemented both a division of labour in order to organize work in a more efficient manner; as well as the specialization of trade (Ferreira & Pessoa, 2016). At this point, time became a critically important commodity, as it was inexorably linked to profit by this form of production. Additionally, as manufacturing became industrialized, production volumes increased, cost decreased, and goods became more affordable.

The consequences of the first industrial revolution were (and still are) felt well beyond the boundaries of manufacturing. The results of these early developments were a massive paradigm shift as societies began to move from agrarian to urban systems. This was also the time during which our current economic model, modern capitalism, developed concurrently with the rise of the nation state to support the new economic paradigm. The primary objective for an industrialist in this model is to provide maximum return for the stakeholders' investments.

[3] Not coincidentally, the term *nightlife* was first used in 1852. (OED, 2017)

Figure 6: First Industrial Revolution



Source: (Siemens AG, 2016)

Industry 2.0: Effectiveness

The second industrial revolution began around 1870 and lasted until the early 20th century. This era ushered in many breakthroughs for manufacturing including the highly effective assembly line, mass production and the development of steel. Many of these advances required the concurrent development of standardization, the manufacture of interchangeable parts, operations management, and basic supply chain management. Electricity began to displace steam as a major source of industrial power and enabled the beginning of modern telecommunications. Again, this era marked major changes well beyond the sphere of manufacturing.

One of the most far reaching elements of the second industrial revolution was the application (or cross-impact) of the scientific method with production efficiency. The practice eventually became known as scientific management. It is also known as Taylorism[4] since it was based on the seminal work of Fredrick Taylor (Taylor, 1903). Scientific management is, in essence, a form of workplace organization and industrial engineering.

Although Taylorism was often criticized, such as in an article titled "A Scientific System of Sweating" (Lenin, 1913) who argued it was evidence of worker exploitation; Taylor went well beyond that. In fact, Taylor's intent was also to identify boring and repetitive tasks. These relatively simple tasks could then be more effectively mechanized. Thereby allowing workers to focus on more complex, skill dependant tasks (Taylor, 1903). Taylorism was the foundation for many of the developments of the second and subsequent industrial revolutions.

A subsequent advance based on Taylorism was a concept that lead to the development of the modern assembly line. Named after Henry Ford, Fordism introduced the moving assembly line to the automobile manufacturing– effectively bringing work to the labourers and introducing the standardization of manufacturing. In this way, unskilled labour could be used to supplement or replace the skilled labour that was previously required for "hand made" production (Tolliday & Zeitlin, 1987). At the time Fordism was attractive to many industrialists. It, "…promised to sweep away all the archaic residues of pre-capitalist society by subordinating the economy, society, and even human personality to the strict criteria of technical rationality." (Gilbert & Burrows, 1992).

[4] In the author's opinion, very few developments are the sole efforts of a single person. Time studies existed before Taylorism. Likewise, assembly lines existed before Fordism. However, both terms are well known historical constructs and as such aid in comprehension and readability.

Perhaps the most significant characteristic of Fordism is an exponential application of Taylor's work; Ford broke down automobile manufacturing into 7,000 separate tasks (PBS, 2013). The decomposition of complex tasks into simpler components is a critical enabler of many later developments, like numeric controlled equipment, and later by CNC machines and subsequently robotic automation.

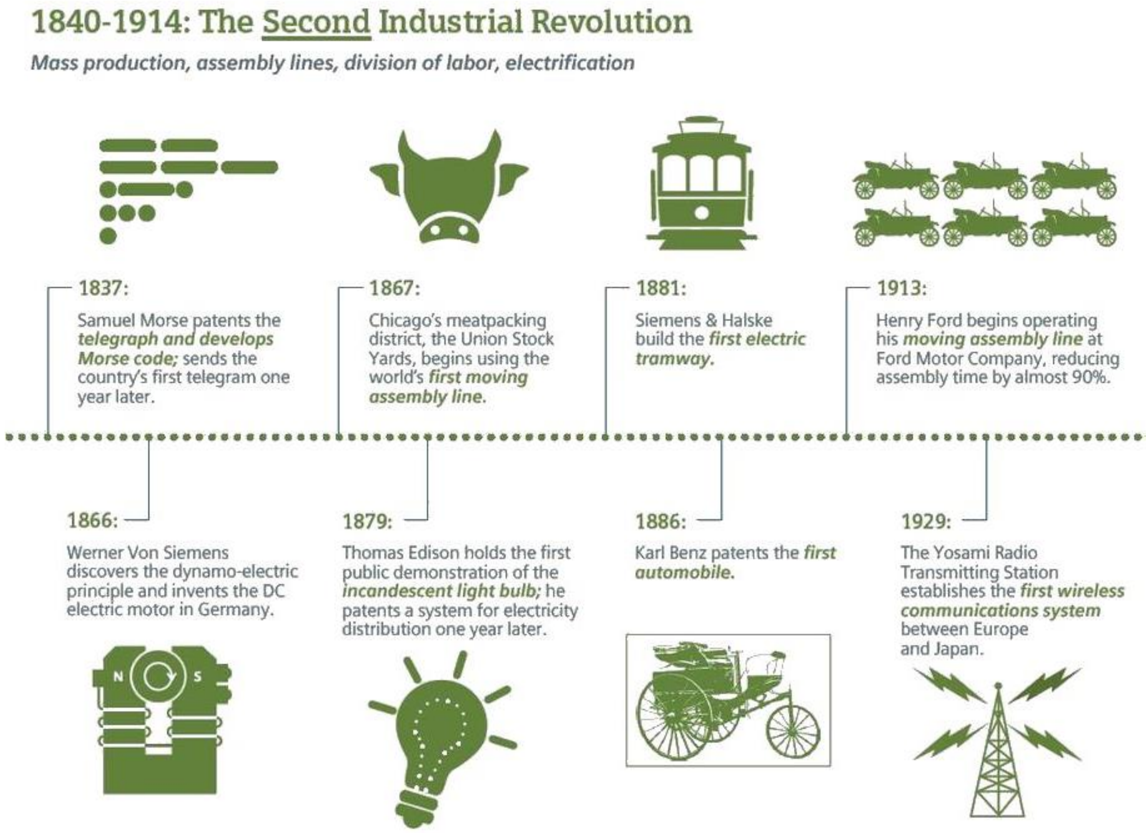
Although this paper narrowly focuses on manufacturing, it is important to note just how significant developments in this sector are to the broader society as a whole. This is vividly demonstrated in the response to the various industrial revolutions from non-manufacturing perspectives.

For instance, the principles Taylorism and Fordism are major targets of derision beyond the manufacturing sphere (Gilbert & Burrows, 1992). This is evident in Chaplin's film *Modern Times* and Huxley's novel *Brave New World*.

Additional significant societal impacts of the second industrial revolution are the widespread introduction of urban and national infrastructure; including water, rail transport, telecommunication, and electrification.

Sociopolitical responses to such developments are equally numerous. Perhaps most famously demonstrated by Karl Marx, first in his seminal work, *A Contribution to the Critique of the Political Economy* (1859) and later in his magnum opus of 1867, *Volume 1 of Capital - The Process of Production of Capital*, which analyzed the paradoxes and contradictions inherent in the capitalist economic system which had risen so dramatically from the first industrial revolution.

Figure 7: Second Industrial Revolution



Source: (Siemens AG, 2016)

Industry 3.0: Productivity

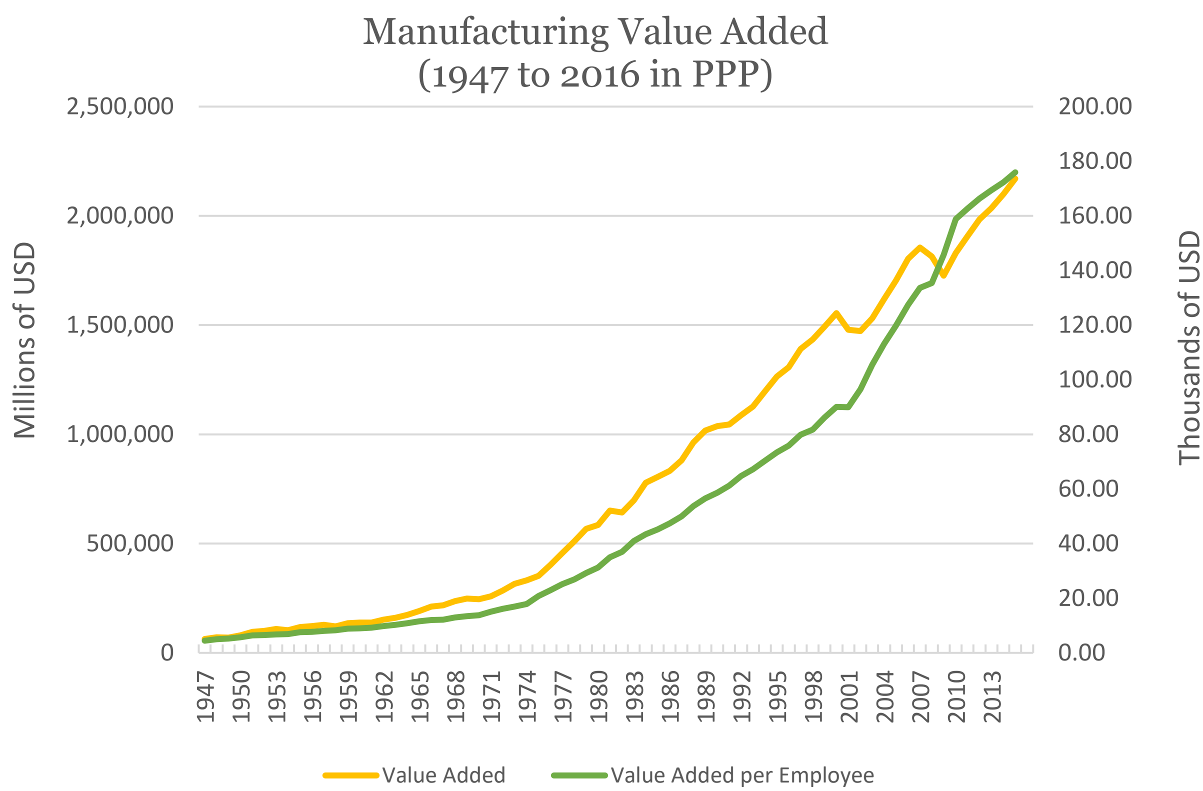
The Third Industrial Revolution began in the mid 20th century, again building upon the foundations of the previous revolutions. The advent of the transistor was the defining building block of this industrial revolution. Transistors were introduced in the late 1940s. By the 1960s, the wide spread use of mass produced semiconductor technology enabled modern digital electronic devices.

Semiconductor technology resulted in the production of the first modern digital mainframe computers. This would eventually lead to the manufacture of microprocessors, personal computers, and the software to run them. The mass production, and subsequent ubiquity of the computer leveraged the network effect (Shapiro & Varian, 2012). Subsequent digital technologies, in particular the internetworking ARPNET, became the precursor to the modern internet. Accordingly, Industry 3.0 is also referred to as the Digital Revolution.

The implication of the third industrial revolution was dramatic. Computers began to permeate manufacturing. Rudimentary computer numeric controlled (CNC) equipment dramatically improved the productivity of machine tools. While computer assisted design (CAD), and computer assisted manufacturing (CAM) was deployed in production. These breakthroughs allowed for the cost-effective production of better quality, high complexity products. Electronic enterprise resources planning (ERP/MRP) systems computerized administration, increasing workplace organization and productivity. Similarly, reliable telecommunications enabled just in time (JIT) inventory management and modern supply chain management, both of which contributed to leaner and more productive manufacturing.

The upheaval from the societal level changes that were enabled by the third industrial revolution are still being felt today. The widespread adoption of Keynesianism and monopoly capitalism are indicative of a broad shift towards a new macroeconomic paradigm for Industry 3.0 (Gilbert & Burrows, 1992). Taken together, the results of the third industrial revolution resulted in a massive leap in the productivity, effectiveness, and efficiency of production. From a manufacturing perspective, perhaps a more fitting designation for this era is the Productivity Revolution. Figure 8 illustrates the exponential growth of value added by manufacturing during this period.

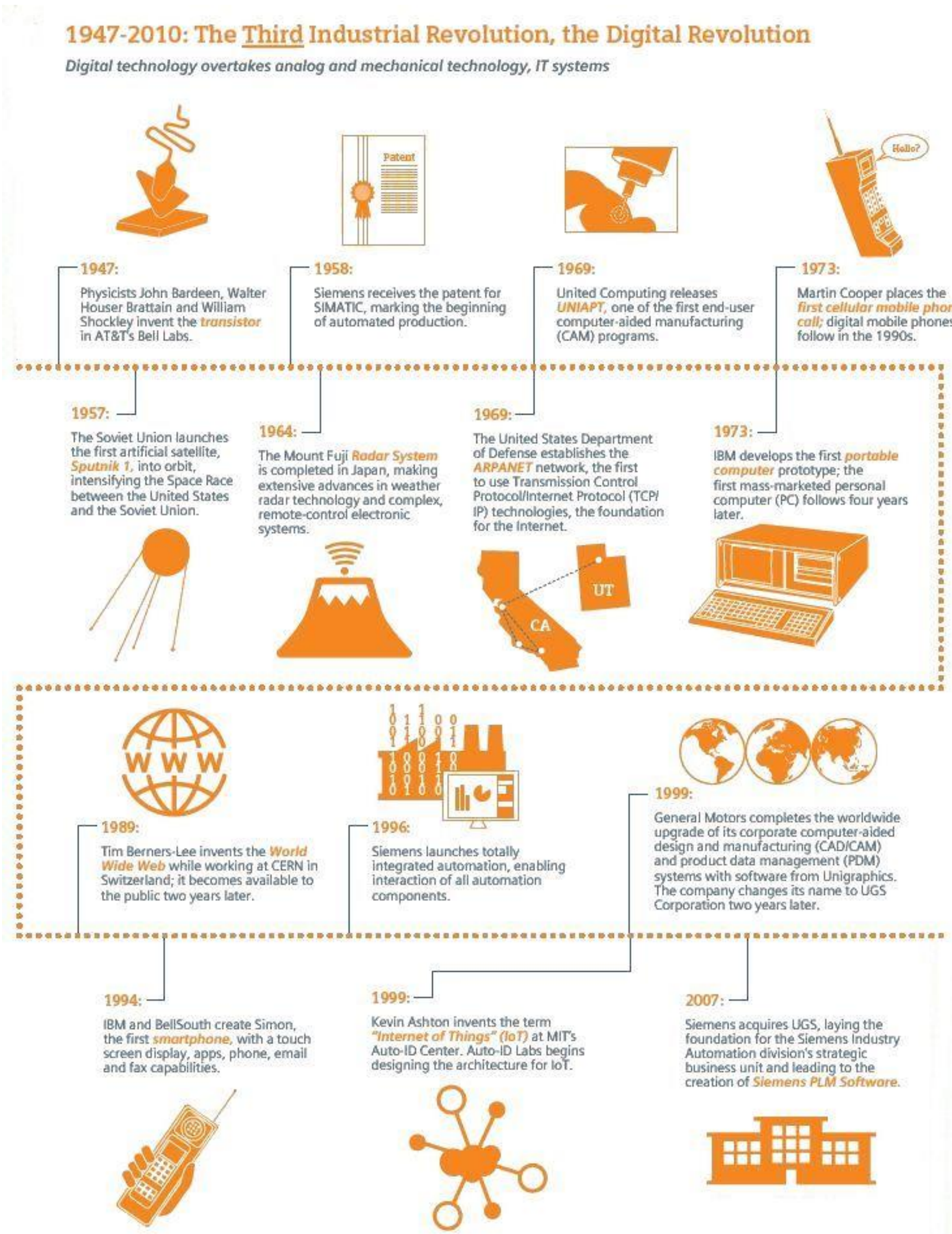
Figure 8: Manufacturing Value Added Trend Analysis



Data source: (U.S. Bureau of Economic Analysis, 2017) (U.S. Bureau of Labor Statistics)

The third industrial revolution enabled increasingly higher optimization, just-in-time inventory management, lean production methodologies and resource efficiency. In almost all of these cases, computers were an extension of human tools. However, manufacturing systems still require significant human presence to function correctly even within a narrow set of constraints and responsibilities.

Figure 9: The Third Industrial Revolution



Source: (Siemens AG, 2016)

Patterns

While this brief survey of the preceding industrial revolutions is far from complete, several interesting features can be detected. Firstly, there are numerous challenges and characteristics which drive each era (Bauernhansl, 2017). Some of these are highlighted in Table 2. However, the profit motive and the necessary push to reduce costs remains a significant driver throughout.

Table 2: Drivers and Characteristics of the Industrial Revolutions

Industry 1.0	Major population growth and urbanization
	Factory system based on the division of labour
	Exploitation of manual labour, no work/life balance
	Industrialisation of textile, iron industry
Industry 2.0	Growing affluence in society, growing demand
	Taylorism, and Fordism enable Mass production
	Product-Dominant production and marketing
	Rise of automotive, chemical, and electrical industries
	Vertically integrated production
	Geopolitical tensions
	Trade Unions, Marxism, and social democratic movements
Industry 3.0	Globalization competition: sellers' market becomes buyers' market
	Multi-variant production using mechatronic systems
	Large, multinational conglomerates
	Cold war, arms race
	JIT and lean manufacturing, interlinked market economies
	Rise of digital electronics, cold war, and free trade

Sources (Bauer, Schlund, Marrenbach, & Ganschar, 2014) (Bauernhansl, ten Hompel, & Vogel-Heuser, Industrie 4.0 in Produktion, Automatisierung und Logistik. Anwendung Technologien · Migration, 2014) (Rifkin, 2015) (Sommer, 2015)

Secondly, it becomes apparent that many of the technologies, processes and ideas take a significant amount of time to develop. Even then, widespread adoption will still lag behind in other regions and countries. This could be described as uneven, yet combined development[5] across regions and between nations. Evidence for this can be readily seen throughout the world where, for example, manual looms are still used in textile manufacture. This is the 'long tail' of industrial revolutions.

Thirdly, there are widespread interdependencies in both technological and social developments. In this light, it is nearly impossible to say that development *x* is *the* cause of an industrial revolution. Hence the difficulty historians find in identifying definitive start dates for the industrial revolutions.

There is however a temporal hierarchy for industrial processes. Consequently, each subsequent revolution builds upon the previous one. In some instances, replacing elements but in co-opting others that are still useful. For example, many of the advances in the third industrial revolution required the technical, scientific, and social progress from the second industrial revolution to occur. In turn, those developments are themselves based on the first industrial revolution. Also noteworthy is the decreasing time *between* industrial revolutions, contrasting with exponentially growing complexity of the developments. This is represented diagrammatically in Figure 10.

Fourth, one of the more interesting patterns that emerges is that the revolutionary aspects of these upheavals are seldom *just* about an individual, a new technology or novel concept. Rather it is the *way* pre-existing methodologies and technologies (which evolved in fits and starts) are recombined that is revolutionary.

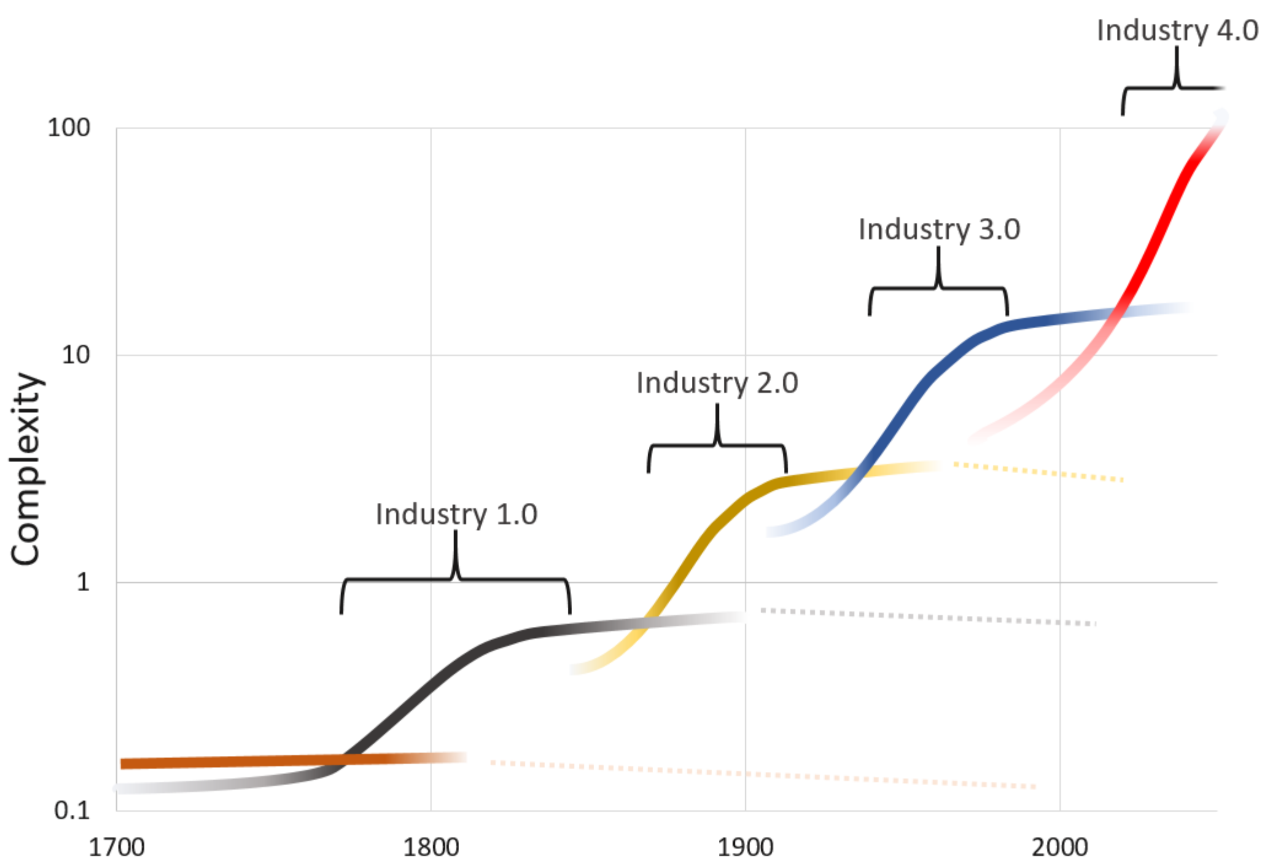
As McLuhan (1964) presciently noted: "The restructuring of human work and association was shaped by the technique of fragmentation that is the essence of machine technology. The essence of automation technology is the opposite. It is integral and decentralist

[5] *Cf.* Leon Trotsky, *The History of the Russian Revolution (1932).*

in depth, just as the machine was fragmentary, centralist, and superficial in its patterning of human relationships."

Historically, the *antecedents* of the next revolution are based on incremental change. In other words, the seeds of the next revolution are sown in the current era. Using foresight terminology, they would be referred to as weak signals.

Figure 10: Temporal Hierarchy & Interdependencies



2.3 The Fourth Industrial Revolution

"The 'fourth industrial revolution': everyone is talking about it, but no one seems to really know what it is." (Fell, 2017)

It is impossible to predict the future. However, there are many challenges in manufacturing that are well known. Manufacturing associations, trade publications (CITE), government agencies, NGO's, as well as the daily interactions from the author's private practice, are sources that are well versed in the challenges that face manufactures. Specific references are listed with Table 3.

As a sense making exercise, the challenges were categorized using the STEEPV framework (Loveridge, 2002).   With this framework, the challenges were identified and grouped in six dimensions. The six dimensions are composed of the following factors: Social, Technological, Economic, Environmental, Political and Values. Table 3 highlights some of these using the STEEPV categorization convention.

Table 3: Challenges for the Future of Manufacturing

Social	Aging demographic and loss of tacit knowledge, consumer trends/individualism and smaller lot sizes, skills gap.
Technological	Artificial intelligence, falling costs of increasingly powerful tech, human-machine collaboration, system security.
Economic	Economic sustainability, volatile markets, fierce global competition, fluctuating exchange rates, post-capitalism, deflation and changing nature of work.
Environmental	Climate change, regenerative manufacturing, resource constraints and depletion, variable energy costs.

Political	Instability, trade relations: nationalism vs globalism, populist vs technocratic agenda formation.
Values	Declining margins vs higher risks, work/life balance vs higher productivity, social responsibility juxtaposed with profit motive.

Sources: (The Association for Manufacturing Excellence , 2016), (Canadian Manufacturers and Exporters, 2014), (Baldwin & Macdonald, 2009), (Burt & Poulin, 2008), (Manufacturing.Net, 2017)

There are also indicators in the present that highlight the possible future characteristics of the fourth industrial revolution. Some of the key enablers of the fourth industrial revolution are listed in Table 4

Table 4: Enablers of the Fourth Industrial Revolution

Key Enablers
Advanced mechatronic systems and robotics
ICT, Network, TCP/IP and IPv6
Internet of Things (IoT) and Internet of Services (IoS)
Always on connectivity and internet access
Powerful yet affordable computational resources and sensors
Knowledge workers
Big Data analytics
Cloud computing
Artificial Intelligence
CAD, CAM, ERP/MRP systems

Sources: Author's personal practice and interviews, (Annunziata & Evans, 2012), (Pike, 2015), (Bungart, 2014), (Buerger & Tragl, 2014), (Dais, 2014), (Davis, Edgar, Porter, Bernaden, & Sarli, 2012) and (Herman, Otto, & Pentek, 2015), (Bauer, Schlund, Marrenbach, & Ganschar, 2014), (Kagermann H. , 2015), (Sommer, 2015)

Because of the importance of manufacturing to national economies, it is not surprising that there are advanced manufacturing initiatives that attempt to construct a future orientated framework.

Industry 4.0

One of the most influential efforts is the aptly named Industrie 4.0[6]. Although initially dismissed as purely marketing hype, research revealed otherwise. In fact, it is an initiative which was championed by the German government, business leaders and academia (Herman, Otto, & Pentek, 2015). This association recognized early on that there were tumultuous changes about to occur in the manufacture and landscape. With the knowledge that large segments of the German economy are heavily dependent upon domestic manufacturing, the association performed a thorough analysis of what that future might look like and possible strategies for coping with that future (Kagermann H. W., 2013). The intent is to position German manufacturers to shape and thrive in the fourth industrial revolution. However, it has also noticed by manufacturers, researchers, and governments worldwide. "Industrie 4.0 has attracted extensive attention in the world in recent years, which is believed to be a new paradigm to meet the ever-changing requirements of future manufacturing." (Zhang, Li, Wang, & Cheng, 2017).

Some of the key economic challenges identified by the Industrie 4.0 association facing manufacturing are the decreasing availability of natural resources, and the globalization of production. Additionally, the seismic demographic changes of an aging manufacturing workforce will result in a subsequent skills shortages. The rapid rate of technical and social change compound the challenges. For example, satisfying customers is becoming increasingly difficult. No longer content with just the lowest price. There is a growing demand for ultra short lead times, higher levels of product service, and increasing product novelty.

[6] The original German term is "Industrie" and widely translated as "industry".

To meet these challenges, manufacturers must understand and proactively manage their whole value-chain in a significantly more nimble way. This is a dramatic switch from traditional make-to-inventory or even make-to-order methodologies with which manufacturers are familiar. Manufacturers require new virtual tools and novel management structures to foster agile management, value chain cooperation and rapid development methodologies (Waters & Rainbird, 2007). These tools will be required throughout their processes all the way from design innovation, through production, product lifecycle, distribution, and support.

Furthermore, one of the most interesting characteristics of an Industrie 4.0 compliant manufacturer is to anticipate future demand more accurately (Hermann, 2014). This must be done utilizing sustainable processes; while managing the increasing variety and complexity of demands in a cost-effective manner.

These elements, taken holistically, suggest that Industrie 4.0 is in fact more than just an ambitious technological guideline. Rather the initiative should be understood as a paradigm shift in business operations, since it fundamentally alters the organization and control functions of the manufacturing organization. Indeed, this shift requires a holistic interpretation of product lifecycle and their associated value chain structure.

The key enabling technology for this model is the internet and associated ICT. The internet forms the virtual nervous system for integrating the elements of Industrie 4.0 together. The objective is to create highly agile value chain networks that cut across organizational boundaries. This is accomplished by linking together stakeholders, machines, processes, and objects across the internet, regardless of where they are located on the value chain. Such highly agile production systems enable profitable fabrication of ever smaller lot sizes; ultimately paving the way for mass customization production systems. A summary of the major concepts of Industry 4.0 is listed in Figure 11.

Other flavours of Industry 4.0

There are several similar initiatives to Industrie 4.0 that have since arisen throughout the world. In the United States, General Electric initiated a comparable concept which they branded as the Industrial Internet (Annunziata & Evans, 2012). This initiative resulted in the formation of the 'Industrial Internet Consortium' in 2013 (Pike, 2015). The group is narrowly focused on the build out of the internet of things (Bungart, 2014). Basically, its focus is, "…the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes" (Industrial Internet Consortium, 2013). Verisimilar concepts are illustrated by "Integrated Industry" proposal (Buerger & Tragl, 2014). As such, both initiatives could be understood as components of the broader focus of Industrie 4.0.

In the United States, the Obama administration laid the foundation of the first national industrial policy since the Carter administration (Frick, 2013). Essentially, this involves building a platform under the banner of the National Network for Manufacturing Innovation (Molnar, 2013).

The initiative links national laboratories[7] with newly created R&D institutes and private industry partners to work on advanced manufacturing techniques. This approach corresponds to an early call by the Brookings Institute for an American approach to advanced manufacturing (Helper & Wial, 2011).

Additional initiatives include efforts to develop smart factories. Broadly considered, the "Smart Industry" (Dais, 2014); or "Smart Manufacturing" (Davis, Edgar, Porter, Bernaden, & Sarli, 2012) in (Herman, Otto, & Pentek, 2015) initiatives are easily understood as components of Industrie 4.0.

Further initiatives have also been created internationally that are designed to address the fourth industrial revolution. For instance, there are two notable programs in Asia.

[7] Such as the Department of Energy's Oak Ridge National Laboratory.

The first is a South Korean program called ‘manufacturing innovation 3.0’ created under the auspices of Ministry of Trade, Industry, and Energy (Kang, et al., 2016). The second initiative originates in China and is based on the German Industrie 4.0 initiative. It was originally called “internet plus”. However, it was recently rebranded as ‘Made in China 2025’ (Kennedy, 2015).

WEF’s Perspectives on the Fourth Industrial Revolution

Considering that the impact of the fourth industrial revolution is of global consequence, it is not surprising that the World Economic Forum (WEF) is dedicating significant resources to understanding the impacts. Recently Klaus Schwab, chairman, and proxy for the WEF, summarized the Forum’s thinking (Schwab, 2016). The WEF also considers the fourth industrial revolution to be fundamentally different from its historical predecessors.

In addition to a laundry list of some of the major, new technological elements; the author discusses the convergence of digital, biological, and physical worlds. Schwab also offers a high-level outline of the associated risks and rewards of some of these developments. The explicit point being the necessity of stakeholders to adapt to the technological changes.

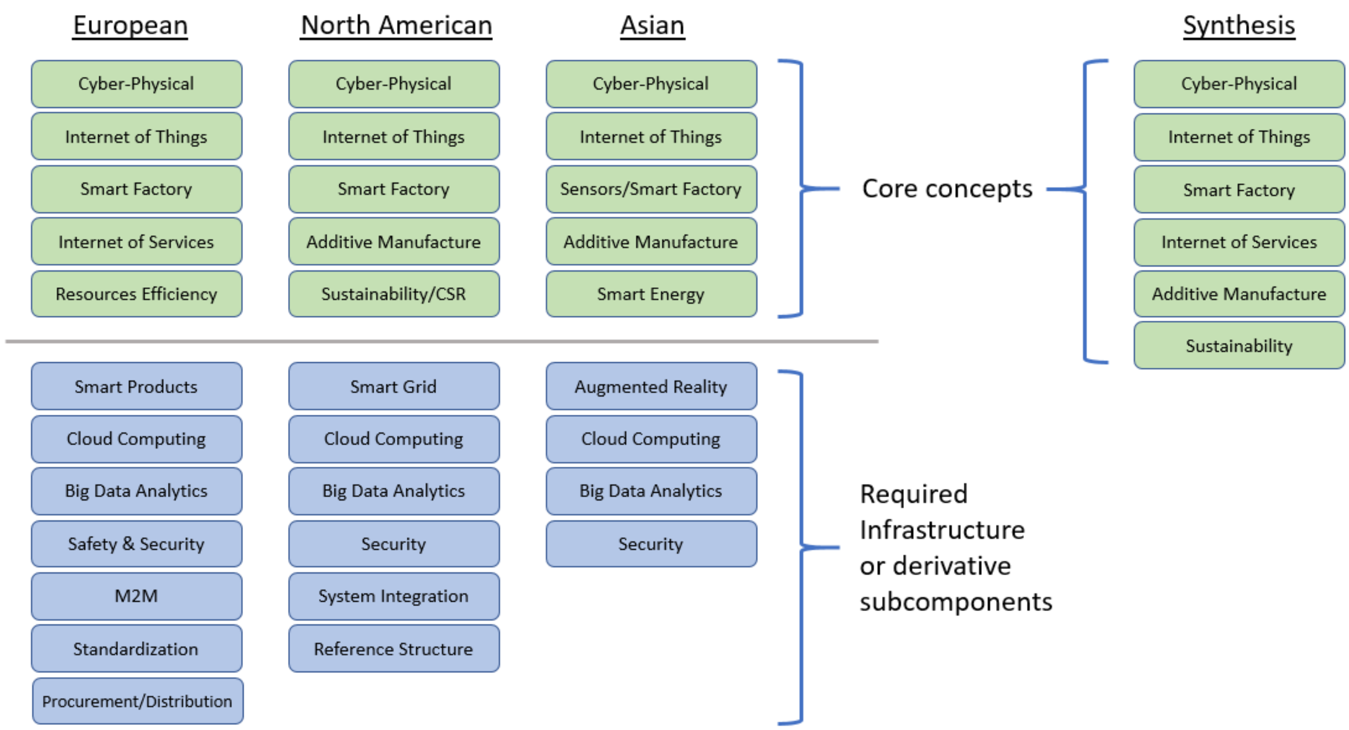
However, instead of providing a deep analysis or perhaps a roadmap to the massive changes, Schwab (2017) highlights some of the technological changes and challenges. This has also lead to a milquetoast summary as opposed to a thorough, cross-impact analysis. Critics, such as Poole (2017) argue that Schwab is much too vague and offers no solutions to the challenges presented. He furthermore suggests that the Schwab’s call to adapt “… is really a veiled update of social Darwinism, according to which the people who survive the coming robot deluge will by definition have been the fittest all along.” (Poole, 2017).

The WEF's work, as presented by Schwab, can best be understood as a quick snapshot that represents the broad thinking of the WEF analysts and crowdsourced opinions from Davos. As such it provides useful insight into not only *what* one of the world's leading trade institutions and its members are thinking but, also *how* they are thinking about the fourth industrial revolution.

Based on literature review, there are numerous, interrelated elements that form the conceptual foundation of the future of manufacturing (Bauer, Schlund, Marrenbach, & Ganschar, 2014), (Kagermann H. , 2015), (Sommer, 2015). Ranking these elements based on the frequency of occurrence within the literature (Herman, Otto, & Pentek, 2015) reveals that there are five main components that make up Industry 4.0. Further analysis and review of various papers (Annunziata & Evans, 2012), (Pike, 2015), (Bungart, 2014), (Buerger & Tragl, 2014), (Dais, 2014), (Davis, Edgar, Porter, Bernaden, & Sarli, 2012) and (Herman, Otto, & Pentek, 2015) uncovers very similar conceptual elements in both Asian and North American initiatives. Kang, et al (2016) confirm similar results.

The results of this distillation process yield six common core concepts that are critical to the future of manufacturing. They are: cyber-physical systems, the internet of things, smart factories, internet of services, additive manufacturing, and sustainability. The results are summarized in Figure 11. Details of the major concepts are discussed thereafter.

Figure 11: Major Concepts of the Fourth Industrial Revolution



Sources: (Annunziata & Evans, 2012), (Pike, 2015), (Bungart, 2014), (Buerger & Tragl, 2014), (Dais, 2014), (Davis, Edgar, Porter, Bernaden, & Sarli, 2012) and (Herman, Otto, & Pentek, 2015), (Bauer, Schlund, Marrenbach, & Ganschar, 2014), (Kagermann H. , 2015), (Sommer, 2015)

Cyber-Physical Systems (CPS)

A central component of the future of manufacturing is the concept of Cyber-Physical Systems (CPS). They are a fusion of physical objects (such as CNC machines) and digital technology (such as AI); as such they represent a convergence of the physical world and the virtual world. This merger is accomplished using sensor technology and actuators (Thiede, Juraschek, & Herrmann, 2016).

While traditional automation systems are organized in a hierarchical framework, CPS are designed to be decentralized yet networked and highly collaborative, computational entities.[8] Each entity has a unique network identity allowing imbedded and networked computer systems to monitor physical processes and assets. CPS processes are usually controlled with feedback loops so that "…physical processes affect computations and vice versa." (Lee, 2008). Intelligent inventory bins which can monitor their own stock levels and automatically reorder parts when necessary, would be an example of a very simple CPS.

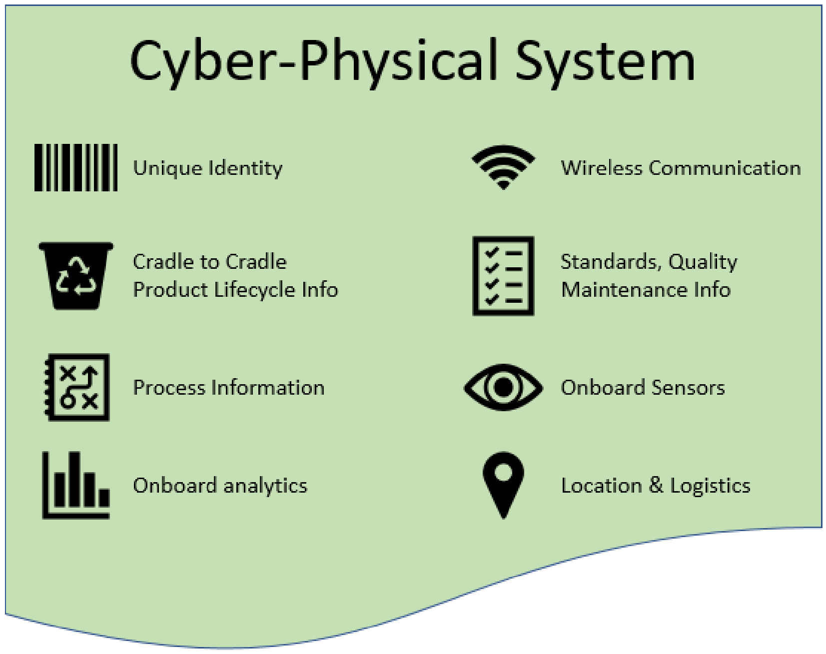
Another example of a CPS would be a fully autonomous vehicle integrated into a larger traffic system. In this case the physical elements of the vehicle are monitored in real time via vision, location, and telemetry sensors. The data would be analyzed in real-time to control the vehicle via actuators and simultaneously shared with the broader transportation ecosystem (and other cyber-physical systems) to prevent accidents, improve efficiency, and provide real-time information about traffic conditions.

Such advanced CPS, "…can store and analyze data, are equipped with multiple sensors and actuators, and are network compatible (Bauernhansl, 2014). In the manufacturing context, cyber-physical systems could not only operate autonomously but also self-optimize their own processes using machine learning techniques. Over time, CPSs would build a shareable knowledge library available to other CPSs on the network.

A more advanced CPS example might be an intelligent work piece sub-component that knows its own process routing, logistical constraints, and upcycling information – all of which is available online in real time for other cyber-physical systems to use. Characteristics of a CPS structure, based on Bauernhansl (2017) is summeraized in Figure 12.

[8] As such they are components of, and rely on, the Internet of Things(IoT) for their functionality. IoT is discussed below.

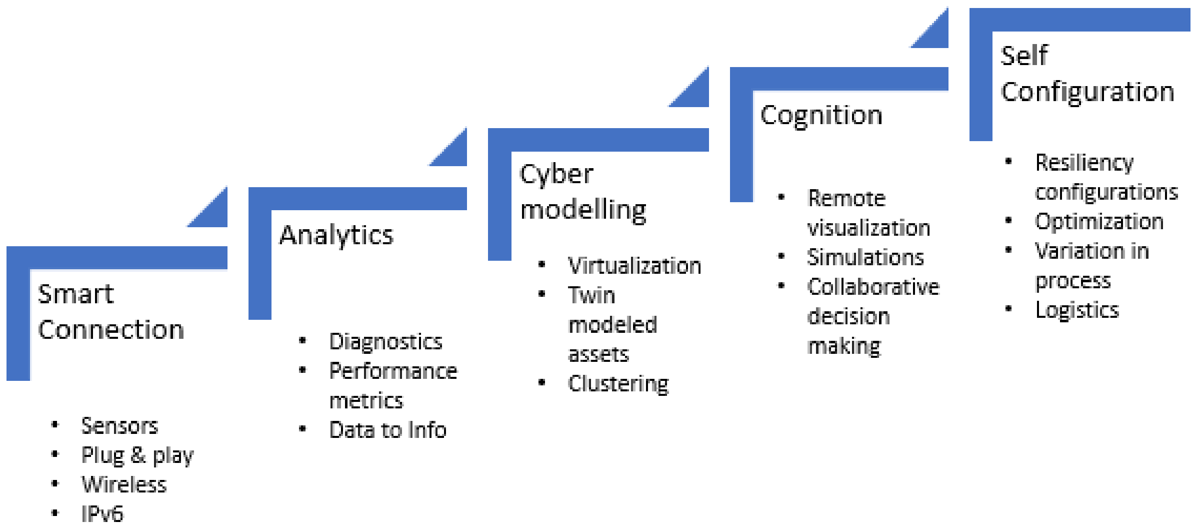
Figure 12: Characteristics of a Hypothetical Cyber-Physical System



Sources: Bauernhansl (2017), (Thiede, Juraschek, & Herrmann, 2016)

Cyber-physical systems describe the synthesis of the virtual world with the physical objects. The National Science Foundation states that, "*cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components. Advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security, and usability that will far exceed the simple embedded systems of today. CPS technology will transform the way people interact with engineered systems — just as the Internet has transformed the way people interact with information.* (NSF, 2017) Cyber-physical systems are a core enabling technology for the smart factory. A general construct of the CPS structure of increasing complexity, based on Bauernhansl (2017) is summarized in Figure 13.

Figure 13: General structure of a Cyber-Physical System



It is important to note that these technologies are not necessarily a prescription for a particular manufacturing segment or production line. Further, CPS does, "…not determine one particular or definite type of work organisation and production process model. Enterprises choose different kinds of work organisation because of their different markets and varying requirements of production processes, for instance." (Dworschak & Zaiser, 2014).

While cyber-physical systems are still in their infancy it is easy to imagine some of the many implications that such systems represent. In terms of the production and fabrication of goods, the impact of CPS will be dramatic. Machine learning will permit much higher quality fabrication while increasing manufacturing flexibility. Smaller lot sizes and highly tailored customization should be enabled with significantly more efficient processes. Cyber-physical systems networked in the broader context of smart factories (discussed below) will in some instances enable truly autonomous manufacturing.

There is a high probability that cyber-physical systems will have a major impact on manufacturing employment. Indeed, it seems reasonable to expect that the job loss typically associated with industrial robotics will increase proportionately as the capabilities of cyber-physical systems grow. Whereas robotic systems are usually purpose built for a narrow range of specific tasks, CPS could be orientated towards a more flexible approach encompassing a wider set of processes, thereby becoming an evermore viable substitute for human labour. As such, a broad move in manufacturing towards CPS raises serious concerns of potentially wide-reaching job displacement in areas which were traditionally sheltered from automation.

Internet of Things

A core enabling technology of CPS is the Internet of things (IoT). The IoT functions as the backbone for cyber-physical systems. In fact, "...the IoT can be defined as a network in which CPS cooperate with each other through unique addressing schemas" (Herman, Otto, & Pentek, 2015). In other words, the IoT is a network of connected devices which collect, exchange and process data. Devices are uniquely identified using TCP/IP protocols; which allows them to be accessed and controlled remotely (ITU, 2015).

The data collected in this process is then analysed to improve the process in terms of quality and efficiency. Given the effectiveness of this type of system, it is reasonable to assume that the automated CPS and IoT feedback loop will dramatically improve factory productivity.

For example, the operation and effectiveness of a production machine that is a fully cyber physical system, utilizes auto sensing feedback methodologies to significantly reduce manufacturing errors by recognizing and correcting for conditions that are out of tolerance. It does all of this in real time. Additionally, IoT connectivity enables real time monitoring, tracking, and control of assets. This has the potential to greatly enhance workflow and processing efficiency. In turn, this would result in substantial savings of material, energy, and time. For an industry 4.0 manufacturer, the estimated energy savings alone would amount to

10-20%. Although at this point, estimates of economic impact vary widely, even conservative calculations suggest the effect would be massive. McKinsey (2015) estimated that the global impact that CPS and IoT would have amounts to between $1 trillion to $4 trillion USD per year by 2025. If that is true, then based on the OECD (2017) projects for global GDP, the impact would be the equivalent to 1-4% of *global* GDP by 2025.

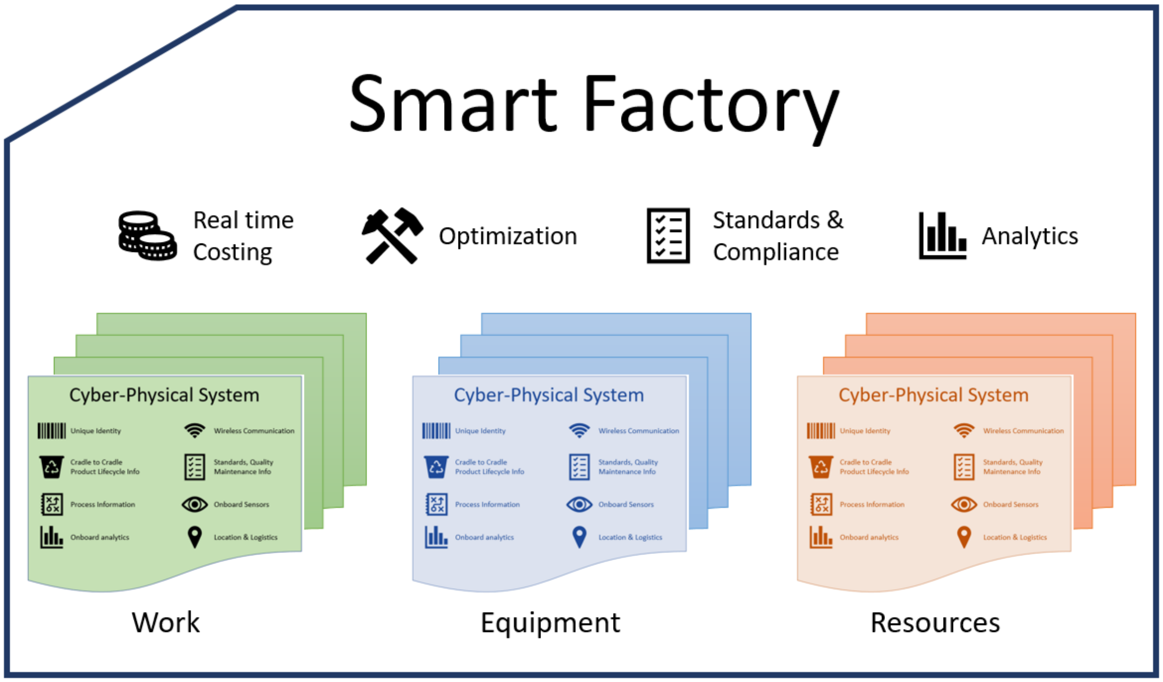
Smart Factory

Once production assets become cyber-physical systems that are interconnected and managed via the Internet of Things, the smart factory becomes a reality. The smart factory is basically, the entire manufacturing process fused together into an intelligent production system. Flexibility and agility characterize the smart factory (Kagermann H. , 2015).   It can rapidly adapt to changing requirements and processes in near real time.

The characteristics of the smart factory are the deployed CPS and IoT elements, discussed previously, viewed as a holistic system of humans, machines, information, and products networked together and communicating autonomously. In this framework, the cyber physical systems are context and environmentally aware components. This means that they can take aspects like the status or physical location of other CPS into consideration. Together they provide; quality, process, location, status, resource, and accounting information – all in real time. As such, "…the Smart Factory can be defined as a factory where CPS communicate over the IoT and assist people and machines in the execution of their tasks. " (Herman, Otto, & Pentek, 2015). Simplified, this decentralized intelligence is an element to control all processes, factory wide.

Consequently, the smart factory as envisioned in Industry 4.0 is a potential enabler for improving productivity by dramatically improving and optimizing lean manufacturing methodologies. In fact, "…committing into Industry 4.0 makes a factory lean besides being smart." (Sanders, Elangeswaran, & Wulfsberg, 2016).

Figure 14: A schema of functions in the Smart Factory.



Furthermore, the Smart Factory will be able to improve processes via autonomous decision making (Roblek, Mesko, & Krapez, 2016). This is similar to a scaled-up version of self-optimization discussed previously, but with holistic view of the entire production process.

In this regard, the role of artificial intelligence will play in the fourth industrial revolution is critical and difficult to overstate. Artificial intelligence as machine learning will, in general terms, dramatically increase rational, data-driven decision making (Schwab, 2016) across the entire manufacturing sector.

Perhaps one of the most interesting developments is the increasing use of AI in product development and design. Combining computer assisted engineering (CAE) with artificial intelligence allows the development of virtual models of products which are the rapidly iterated in an evolutionary like simulation. Additionally, multi-disciplinary optimization could simultaneously take into account a large number of considerations (such as user safety, product life cycle) to enhance a product's design (Hofmann, Neukart, & Baeck, 2017).

Artificial intelligence seems to be well suited to addressing the complex task of production scheduling (Zhang, Ding, Zou, Qin, & Fu, 2017). Production scheduling is a vital task for every manufacturer. It is a process which allocates resources to time-constrained tasks. Mass customization, decreasing lead times, and growing customer requirements dramatically increase the complexity of production scheduling. It seems that AI driven scheduling systems will be an important, if not required, component to effectively manage the growing complexity of an Industry 4.0 manufacturer.

Additionally, the impact of artificial intelligence will also extend into the areas of procurement and finance. In terms of procurement optimizing analytics allows for the generation of increasingly more accurate purchasing requirements tied automatically to the production schedule while taking in to account performance, quality, and supplier characteristics (Hofmann, Neukart, & Baeck, 2017).

Closely associated to issuing purchase orders, is the area of company finances. Here too artificial intelligence will have a significant impact in the long term. Continuous monitoring and data analytics are well suited to scrutinising key financial and controlling data while offering real-time predictive analytics (Hofmann et al. 2017). Taken further such a system would be ideally positioned to suggesting financial optimization strategies.

These factors when combined form a powerful vision of what the smart factory might become. With artificial intelligence optimizing and overseeing many management functions, autonomous vehicles providing logistics, and cyber-physical systems carrying out a large portion of production, it is possible to envision a manufacturing plant that is truly a "lights-out" facility with significantly less human intervention than is currently required.

The risk of job loss from automation is of course significant. A recent OECD study found that, in Canada about 9 % of jobs are automatable (Arntz, Gregory, & Zierahn, 2016).[9] However, if smart factories were to become truly lights-out facilities as described above, it seems reasonable to expect that job displacement would be significantly higher.

Internet of Services

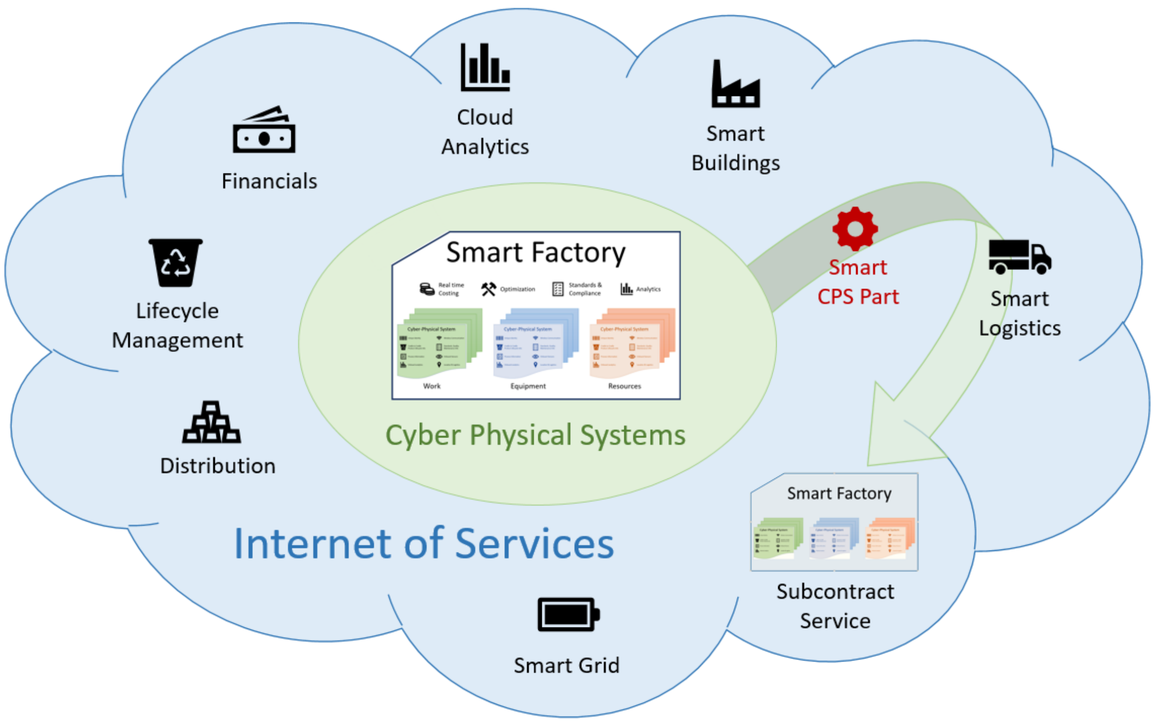
The connected Smart Factory, when viewed from a macro level, is itself a component of a much larger eco-system. It is part of the Internet of Services (IoS). Here the Smart Factory can be understood to provide a manufacturing service. A simplified version of this interconnected nesting of CPS systems sharing a common IoT backbone is illustrated in Figure 15.

It is interesting to note that this holistic view of services dovetails with the recognition of Service-Dominant (S-D) logic (Lusch and Vargo, 2004). S-D logic is a significant paradigm change from traditional goods-dominant logic which arose during the second industrial revolution. S-D logic, "...represents a shift from an emphasis on the exchange of *operand resources*, usually tangible, inert resources, to an emphasis on *operant resources,* dynamic resources that act upon other resources." Moreover,

> *"…in order to improve their individual and collective well- being, humans exchange the service—the application of specialized skills and knowledge—that they can provide to others for the service that they need from others. If goods are involved in the exchange, they are seen as mechanisms for service provision." (Lusch & Vargo, 2015)*

9 This varies significantly from earlier projections (Rifkin, 1995), Frey and Osborne (2013), Brynjolfsson and McAfee (2014) that where based on job classifications instead of job task.

Figure 15: The Smart Factory integrated within the Internet of Services.



It is important to realize that this nesting of service applies not only at the factory level but also potentially to the individual CPS unit. Robotic equipment could easily take advantage of this service orientated architecture. This would then be a Robot as a Service (RaaS) unit (Chen, Du, & Garcia-Acosta, 2015). The CPS enabled weld robot could offer its welding 'service' as a discoverable CPS element within the smart factory. In that context, a CPS work piece could dynamically request welding based on its shop routing. Thereby effectively enabling an autonomous pull of the service, based on real time capacity, requirements, and constraints. Beyond the factory walls, the weld robot could also broadcast its capacities externally, into the larger IoS ecosphere. This would be particularly useful to increase utilization of otherwise wasted machine time.

All together now

The innovations discussed above are critical components of the fourth industrial revolution. Even individual components like CPS would have a tremendous positive impact on productivity (Bauer, Schlund, Marrenbach, & Ganschar, 2014). Likewise, the self organization of CPS enabled resources combined with routing aware CPS work pieces would allow efficient production of very small lot sizes.

Therefore, when combined, it is difficult to overstate their revolutionary influence on manufacturing. The fusion of people, machines and objects networked vertically within the smart factory and horizontally within the larger internet of services enables myriad possibilities.

For most manufacturers, this is a major transformation. Traditionally, production is isolated not only between organizations but often to independent departments and even to individual work cells. Transitioning to the complete integration of production elements across silos will obviously be challenging. However, interconnectedness is a requirement for the agile production systems that future manufacturers require to be competitive.

This new architecture will impact the entire manufacturing process from design and engineering to operations and service; and of course, on the shop floor. Furthermore, the new paradigm further enables a new generation of customer relationship management which will enhance value creation for customers and manufacturers. The network effect of linking stakeholders, machines and products will make manufacturing systems faster, more effective, and efficient. Taken together, they enable the dynamic, decentralized management of complex manufacturing systems in real time.

2.4 Additional Considerations

In addition to the Industry 4.0 characteristics discussed above, there are several further considerations that may shape the fourth industrial revolution. They can be broadly classified as the macroeconomic landscape, organizational constructs, and some additional manufacturing concepts. These ideas are listed in Table 5 and discussed further thereafter.

Table 5: Additional Considerations

Theme	Consideration
Manufacturing concepts	Robotics
	Additive manufacturing
Organizational constructs	Business structures
	Post Fordism
	Vertical disintegration
	Hyper-specialization
Macroeconomic landscapes	Post Industrial, Information, and Knowledge economies
	Kondratiev Waves
	Zero marginal cost economy
	Post capitalist and circular economy

The Robots

Robots are an implied, yet critical, component of the fourth industrial revolution. Industrial robots have been a feature of manufacturing systems since the mid to late 20^{th}. Beginning with material handling tasks in the 1950's, robots quickly became a feature of modern factories automotive manufacturers adopted welding robots in the 1970's (Wallen, 2008). Since then robots have taken on tasks all manner of manufacturing tasks; ranging from welding and inspection to machine tending and precision semi-conductor assembly.

Robots are generally deployed in large batch or mass production environments. In some ways, these early systems could be considered the prototypes of CPS. However, robotics has undergone a major transformation since the turn of the century. This is due to a maturation of mechatronic and digital technology (Siciliano & Khatib, 2016).

One of the most important developments[10] are collaborative robots. They are designed to operate in semi-structured or even dynamic environments, working cooperatively with humans. Collaboration harnesses the unique skill sets of both humans and robots, thereby increasing efficiency, quality and improving ergonomics (Antonelli & Bruno, 2017). Human-robot collaboration is an important element for advanced manufacturing. This trend is illustrated in Figure 16.

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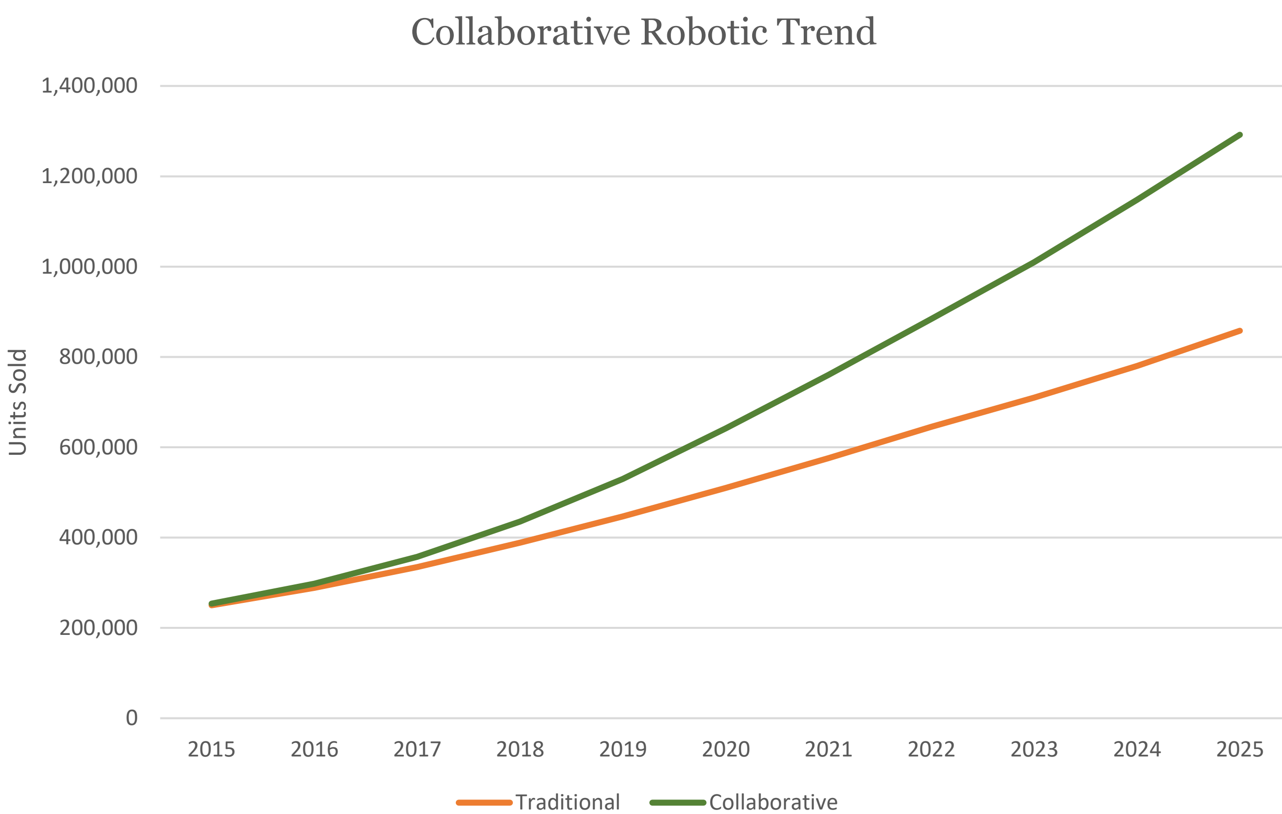
10. Within the time frame that this paper discusses. See also Norio Kodaira, *Expected innovation in industrial robots*. (2016) http://dx.doi.org/10.1080/01691864.2016.1197794

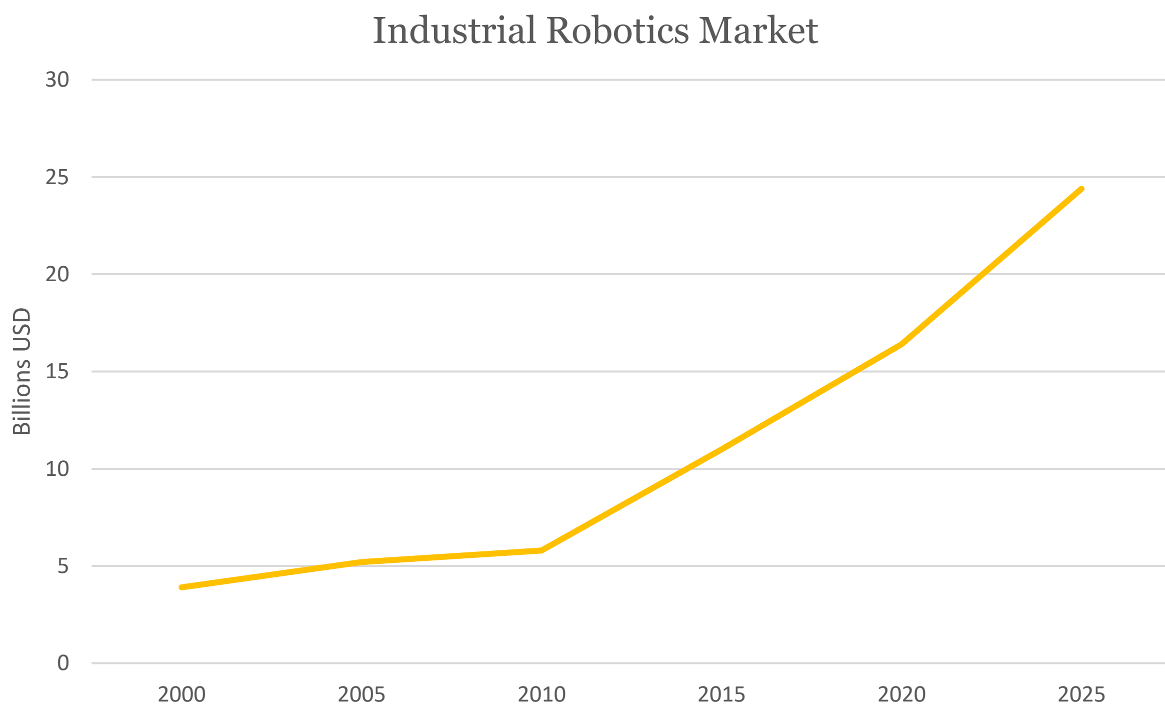
Figure 16: Industrial Robotic Trends



Data source: Loup Ventures, International Federation of Robotics

A second important observation is the adoption rate of industrial robots. Even conservative estimates suggest we are entering a period of exponential growth driven by falling costs and increasing capability (Wolfgang, Lukic, Sander, Martin, & Kuepper, 2017). The exponential growth of the industrial robotics market it illustrated in Figure 17.

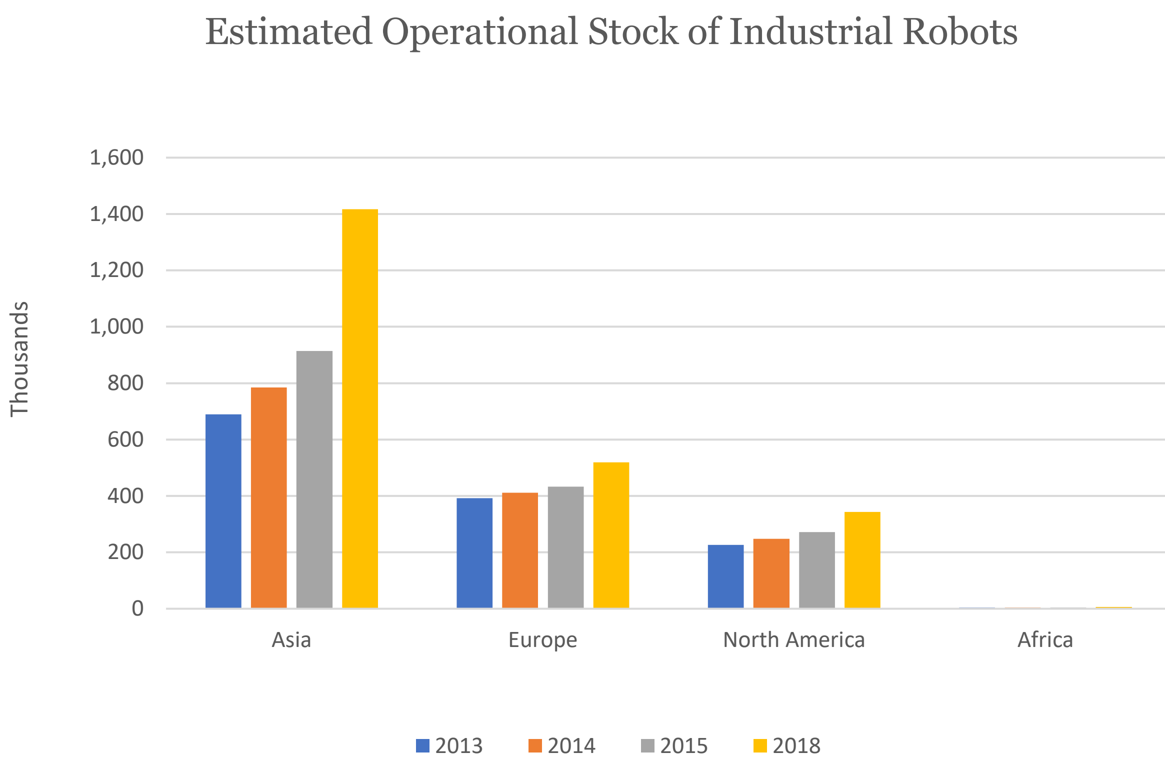
Figure 17: Growth in Industrial Robotics



Data Source: (Wolfgang, Lukic, Sander, Martin, & Kuepper, 2017)

An additional observation highlights the fact that the distribution of robotic stock is uneven. Growth is most aggressive in Asia where it is driven by mainly by China and weakest in Africa. This trend is expected to continue in the near future. Figure 18 illustrates the geographical distribution of industrial robots.

Figure 18: Estimated Operational Stock of Industrial Robots



Data Source: International Federation of Robotics, National Robotics Associations

Additive Manufacturing

There are two types[11] of manufacturing processes that are diametrically opposed. Subtractive manufacturing is a process where workpiece material is removed in a controlled manner. The opposite process, controls the addition of material to the workpiece. This is known as additive manufacturing. 3D printing, welding, and sintering are examples of this process.

The potential of 3D printing technology is still in its infancy. However, there are several interesting developments which are pertinent. The process is currently well suited for

[11] The third broad process is known as "non-additive" and includes forming etc.

rapid prototyping and specialized production. As such it functions as agile tooling and would be a significant contributor towards developing economies of scope.

Consequently, it is an amplifier of the fourth industrial revolution. More advanced systems have potentially more disruptive effect as they can replace other processes (Rayna & Striukova, 2015). The effectiveness and diffusion of this technology has the potential dramatically increase competition from SME's and prosumers[12]

2.5 Organizational Constructs

Business Organization Structures

Manufacturing (and most other) industries have typically been organized in a hierarchical structure. This is not surprising, because their power is astonishing: "It can direct and coordinate the actions of thousands of people making and selling thousands of products or services across thousands of miles, and do so effectively, efficiently, and profitably, week after week after week." (Kotter, 2011). Hierarchical control structures matured dramatically during the second and third industrial revolutions.

A well functioning hierarchy has several powerful characteristics. Foremost in terms of management, they offer top down control. In fact, recent data supports, "...a theoretical analysis which suggests that hierarchy is particularly beneficial for procedurally interdependent tasks" (Halevy, Chou, Galinsky, & Murnighan, 2012). Hierarchies tend towards rigidity and therefore predictability and uniformity. Such structures value adherence and compliance to internal and external regulatory requirements and standardization. Consequently, they satisfy a perceived need for order (Friesen, Kay, Eibach, & Galinski, 2014).

[12] *Cf.* the discussion on hyper-specialization below

There is also a well-established systems principle known as requisite hierarchy (Jaques, 2006). In general, a hierarchy is the most efficient decision to action structure; it is also ubiquitous in nature.

However, hierarchies almost by design, struggle with change (Kotter, 2011). This presents manufacturers with a problem. As discussed above the fourth industrial revolution is rife with change; in many cases the *rate* of change is increasing as well. There are however alternate models for structural organizations that do cope well with change.

Network structural models offer a different approach to hierarchies. These structures value adaptability and emergence over control and predictability. Instead of rigid structures, networks favour decentralization and self organization. The intent is to increase agility, adaptation, and responsiveness (Battistella , Toni, De Zan, & Pessot, 2017). A comparison of these two structures is illustrated in Table 6.

Table 6: Comparison of Business Models Structures

Hierarchy	**Network** ➔	**Intended Impact**
Command & control	Decentralization & self organization	Agility & adaptation
Compliance & repeatability	Flexibility	Resilience
Position in hierarchy	Contribution	Skill valuation
Stability & predictability	Emergence & novelty	Innovation
Efficiency	Ambiguity	Learning

The astute reader will recognize that many of the potential benefits of a network business structure directly mirror the objective of Industry 4.0 and those of S-D logic discussed previously. As such the design elements of the both physical and conceptual networks dovetail into a coherent paradigm.

However, it its worth noting that leaping straight into a network organization is a very risky endeavour. Such a move would potentially make things worse as it would conflict with the cybernetic theory of requisite hierarchy. In other words, "…relaxing too much hierarchy at one stroke may lead to the establishment of compensative hierarchy in some other form…" (Aulin, 1978)

Post Fordism

Post-Fordism is a move away from the mass production for mass markets, and economies of scale paradigm of Industry 2.0 and 3.0. Instead, Post-Fordism emphasizes the opposite (Amin, 2011). Production is focused on differentiated and diverse offerings manufactured in smaller lot sizes utilizing economies of scope[13]. Some of the general production characteristics (Goldhar & Jelinek, 1983) of Post-Fordism are illustrated in Table 7.

Table 7: Contrasting Production Characteristics.

Fordism	**Post-Fordism**
Flow production	Small lot sizes
Economies of scale	Economies of scope
Centralized production	Decentralization
Vertically integrated	Disaggregated production capacity
Efficiency & repeatability	Agility & flexibility

[13] Goldhar and Jelinek (1983) defined economies of scope as "efficiencies formed by variety, not volume".

Vertical (Dis)integration

Vertical integrated production combines all (or most) manufacturing activities "in-house". In other words, it represents the ownership of the entire production chain (Hsu & Kao, 2017). An early example of this was Ford's Industry 2.0 production facilities.

In contrast, vertical disintegration refers to the fragmentation of the production chain into smaller entities; where each entity specializes in a subset of the entire process. The benefit of this approach is to share risk, while increasing agility (Hsu & Kao, 2017). As such, vertical disintegration may be interpreted as signalling a broader move towards a Post-Fordism paradigm.

Vertical disintegration may result in the geographic clustering of mutually dependent companies for industries operating at scale or in tightly regulated industries such as aerospace. However, this concept also enables more flexible production chains to widely dispersed outsourcing. This, in turn leads to increasingly challenging management of complex value chains (Herrigel & Wittke, 2010).

Hyper-specialization

Speculating on the ultimate outcome of vertical disintegration taken to the extreme, is the idea of hyper-specialization. Here we can imagine the manufacturing facility focusing on a single element of a production chain.

As an example, consider 'uncle' Tat. Tat runs a one-man production facility based in Hong Kong. He specializes in manufacturing new parts for old Leica cameras built in 1930's - 1940's. Initially part of a much large (vertically integrated) organization, he now works out of a small shop in his apartment. His customers are global, and his work backlog exceeds 8 weeks.

McLuhan (1994) described the enormous impact telecommunication had on the interactions of people; essentially shrinking geographic distance. He termed this concept the global village. The internet and IoS reinforce McLuhan's theory. This, in turn, has potentially significant implications for manufacturing and Industry 4.0. In this light; hyper-specialization may well become the cottage industry in the global village.

2.6 Macroeconomic Considerations

Post-industrial economy

The concept of a post-industrial society is not new. In fact, Bell (1976) introduced the term to describe a societal move away from goods production to a service orientation. As a result, there is a decrease in blue-collar jobs and an increase in white collar jobs. Post-industrialism also places an increased emphasis on higher education. This is required to develop and build theoretical knowledge; with the ultimate goal of producing innovations and new technology.

In this sense, a post-industrial economy would occur in advanced economies like Canada. Three major characteristics highlight this shift. Firstly, there is decline in the relative importance of manufacturing in terms of percentage of GDP, employment etc. In an effort to control costs, processes which are labour intensive are offshored, resulting in a decline in blue collar jobs. Secondly, the service sector grows dramatically. Thirdly, the use and proliferation of information technology become a dominant component of the post-industrial economy. Combined, these three factors mark a switch from traditional processing and transformation of materials to a focus on knowledge and creativity as fundamental components of the economy.

Information Economy

The Information economy, is a closely related concept to post-industrialism. This is an economy that has an even greater emphasis on the central role of information and the information industry. This is considered a late stage of economic development and an adaptation of capitalism (Castells, 2010).

> *The "spirit of informationally" is the culture of "creative destruction" accelerated to the speed of the optoelectronic circuits that process its signals. Schumpeter meets Weber in the cyberspace of the network enterprise. (Castells, 2010)*

The primacy of the value of information, real time global information networks, and the blinding rate of change are key characteristics of this paradigm. An earlier manifestation of this model is the knowledge economy.

Knowledge Economy

As early as 1993, Peter Drucker explored the concept that knowledge and information is increasingly the new engine of economic growth. He argues that the knowledge economy emerged in the 1990s:

> *"That knowledge has become the resource rather than a resource is what makes our society 'post-capitalist.' This fact changes – fundamentally – the structure of society. The means of production is and will be knowledge." (Drucker, 1993)*

Drucker relates the seminal, role of F. W. Taylor's scientific management as a key enabling factor or perhaps even the foundation of the knowledge economy. This combines with the emergence of the knowledge creation as the competitive function of the firm (Penrose, 1959).This is implicated in the area of knowledge strategy.

Insightfully and eloquently written in the midst of the _**second**_ industrial revolution:

> *Nature builds no machines, no locomotives, railways, electric telegraphs, self-acting mules etc. These are products of human industry; natural material transformed into organs of the human will over nature, or of human participation in nature. They are organs of the human brain, created by the human hand; the power of knowledge, objectified. (Marx, 1857)*

In his often overlooked, yet truly revolutionary *Fragment on Machines*, Marx (in Grundrisse, 1857) envisioned the modern information economy where machines did most of the manufacturing while the human being becomes a "watchman" to the production process. Having arrived at these insights (fully 100 years before CNC machines were invented) Marx further asserted that information would increasingly become the main productive force of the economy. He called this "the power of knowledge". Furthermore,

> *The productive power of such machines as the automated cotton-spinning machine, the telegraph and the steam locomotive did not depend on the amount of labour it took to produce them but on the state of social knowledge. Organization and knowledge, in other words, made a bigger contribution to productive power than the work of making and running the machines.* (Mason, 2015)

Zero Marginal Cost

Jeremy Rifkin (2015) describes the potential cross impact of the Internet of Things and manufacturing. He correctly points out that most of the initial value of IoT in manufacturing is in reduced costs and increasing efficiency. This was later indirectly verified, and estimated to be valued at around two trillion dollars annually by 2025 (McKinsey 2015). The cumulative result of this unprecedented cost reduction pushes the cost of physical goods towards a zero-marginal cost paradigm originally pioneered by digital goods.

Perhaps surprisingly Marx also touched on this concept as early as 1857 in the Grundrisse where,

> *Marx imagined the end point of this trajectory: the creation of an "ideal machine", which lasts forever and costs nothing. A machine that could be built for nothing would, he said, add no value at all to the production process and rapidly, over several accounting periods, reduce the price, profit and labour costs of everything else it touched. (Mason, 2015)*

As the price of manufactures goods falls, the cost of socially necessary labour falls as well. This has a spiralling effect in that the cost of labour is now also less, thereby reducing the price of goods. Lower cost goods are able to cascade into other market sectors (such as energy and finance) as well; over time, this has a knock-on effect on their input costs. This, in turn, eventually further lowers input cost to manufacturing. Keen eyed systems thinkers will recognize this pattern as a series delayed reinforcing loops, which are part of a larger "race to the bottom" archetype systems dynamic.

Kondratiev Waves & Post Capitalism

Kondratiev wave theory posits that the economy can be understood to follow wave like patterns, with each wave cycle lasting many decades. A technological/economic paradigm characterizes each of the cycles (Kumar, 1995). Mason (2016) effectively summarizes Kondratiev's (1925) seminal work in wave theory. The theory describes the sine curve-like cycles of capitalism; where each cycle ends in a crisis phase. In the past, the technological and social adaptation resolved crises.

Mason presents a strong argument that we are at the crisis phase of the current, fourth wave. Kondratiev wave theory suggest that the long upswing of the fifth wave should follow. However, Mason argues that we are stuck in a period of stagnation, prolonging the continuation of this downward portion wave cycle rather than moving forward.

The primary theme in Mason's work argues that capitalism has succeeded in the past due to its ability to adapt. However; it is this very ability to adapt which Mason argues will render this approach untenable because the fourth industrial revolution destroys the principle foundation of capitalism; namely scarcity. As marginal costs approach zero, the price mechanism corrodes and loses its ability to function correctly. Without scarcity, the supply and demand dynamic drifts towards meaninglessness.

3.0 Methodology

3.1 The Research Question

The concepts discussed above, suggest a starting point for developing a strategic foresight framework to envision the future of manufacturing. Using this lens, the fourth industrial revolution will have a seismic impact on the manufacturing landscape.

Are Canadian manufacturers ready for this change?

How might we evaluate current initiatives and discover robust, future orientated strategies to ensure a vibrant and resilient manufacturing sector?

3.2 Project Structure

The introductory survey highlighted the scale and complexity of the manufacturing domain. To ensure robust results, the project required the development of a solid organisational structure. During each step of the project, findings and observations were reviewed and discussed with Dr. Jones, the project's principal advisor. Table 8 provides an overview of the project's methodology.

Table 8: Project Research Methods

Procedure	Method	Objectives	Key References
1	Scoping Review	Define boundaries & conceptualization of the domain	(vom Brocke, Simons, Niehaves, & Reimer, 2009)
2	Expert Interviews	Verify & build out understanding of domain, elicit weak signals.	(Sanders & Stappers, 2013)

Procedure	Method	Objectives	Key References
3	Literature Review	Develop research agenda; antecedents, and characteristics future developments	(Cooper, 1998) & (vom Brocke, Simons, Niehaves, & Reimer, 2009)
4	Three Horizons	Elicit stakeholder input and deeper understanding of Canadian SME future orientated strategies	(Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016) & (Curry & Hodgson, 2008)
5	Data Analysis	Interpret findings	(Ladner, 2014)
6	Scenarios	Develop multivariant test conditions	(Dator, 2009)
7	Wind tunnel	Evaluation of findings	(van der Heijden, 1997)
8	Analysis & Synthesis	Conclusions & next steps	-

3.3 Scoping Review

The project began with an preliminary literature review based on a variety of academic journals, trade publications and news articles. The primary objectives of the first stage were to determine the foundational concepts of industrial revolutions, the boundaries of the manufacturing domain and the developments in that space. Additionally, primary knowledge regarding the fourth industrial revolution, and Industry 4.0 was established. At this stage, an appreciation of the future challenges facing Canadian manufacturers was developed.

3.4 Expert Interviews

With the preliminary understanding of the future of manufacturing established, the project moved on to expert interviews. This second stage had two objectives. Firstly, to verify the findings of the first stage; possibly revealing future oriented manufacturing strategies which may not be available in the published literature. Secondly, to elicit weak signals and characteristics that might be early indicators of the fourth industrial revolution. The findings would inform the subsequent, in-depth literature review.

The second stage consisted of primary research in the form of semi-structured, expert interviews. The interviewees were required to be subject matter experts in their respective fields. They were selected according to their relevance to the purpose of the study. The sampling frame included six participants; a mix of professionals from the manufacturing sector and academic researchers.

Industry experts were required to be employed at a senior management or staff level in the manufacturing sector. Academics and research experts, were required to hold an advanced degree and employment in a recognized institution, and research or industry experience in manufacturing processes and or advanced technology (e.g. robotics, AI, advanced materials).

3.5 Literature Review

The third stage consisted of an in-depth literature review, built upon the framework developed in the first stage, which was verified and expanded in the second stage. The structuring of the third stage took research design cues from vom Brocke et al (2009). The review accessed journal publication databases (JSTOR, Sage, etc.) and Google Scholar. Preference was given to articles orientated towards manufacturing, engineering, ICT, business, and economics.

The main objectives of the third stage were to discover the:

- Context of Canadian manufacturing
- Historical underpinnings and context
- Characteristics of the fourth industrial revolution
- Exploration of weak signals
- Organizational constructs
- Future macroeconomic models

The general taxonomy of the literature review process follows Cooper (1988) and is summarized as illustrated in Table 10. The findings of this stage are discussed in detail above: see Section 2.0 – Background

Table 9: Taxonomy of the Literature Review process

Characteristic	**Categories**
Focus:	theories; applications
Goal:	integration; central issues
Organization:	conceptual; w/historical foundation
Perspective:	neutral representation
Audience:	general scholars; practitioners/politicians
Coverage:	representative

3.6 Three Horizons Workshop

The fourth stage consisted of primary research that was conducted in a foresight workshop. The workshop was based on the Three Horizons model (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016) and also (Curry & Hodgson, 2008). The methodology was adapted to the target audience by incorporating the modified Three Horizons workshop model developed by Jones and Dye (2016).

At its core, the Three Horizons model is a framework that prompts thinking about the future – with the understanding that evidence of possible futures is embedded in the present. As the name implies, there are three distinct time horizons which correspond to the short, medium, and long-term future. However, in the workshop setting, the short and long-term horizons are discussed first to enable a more meaningful discussion of the medium-term future.

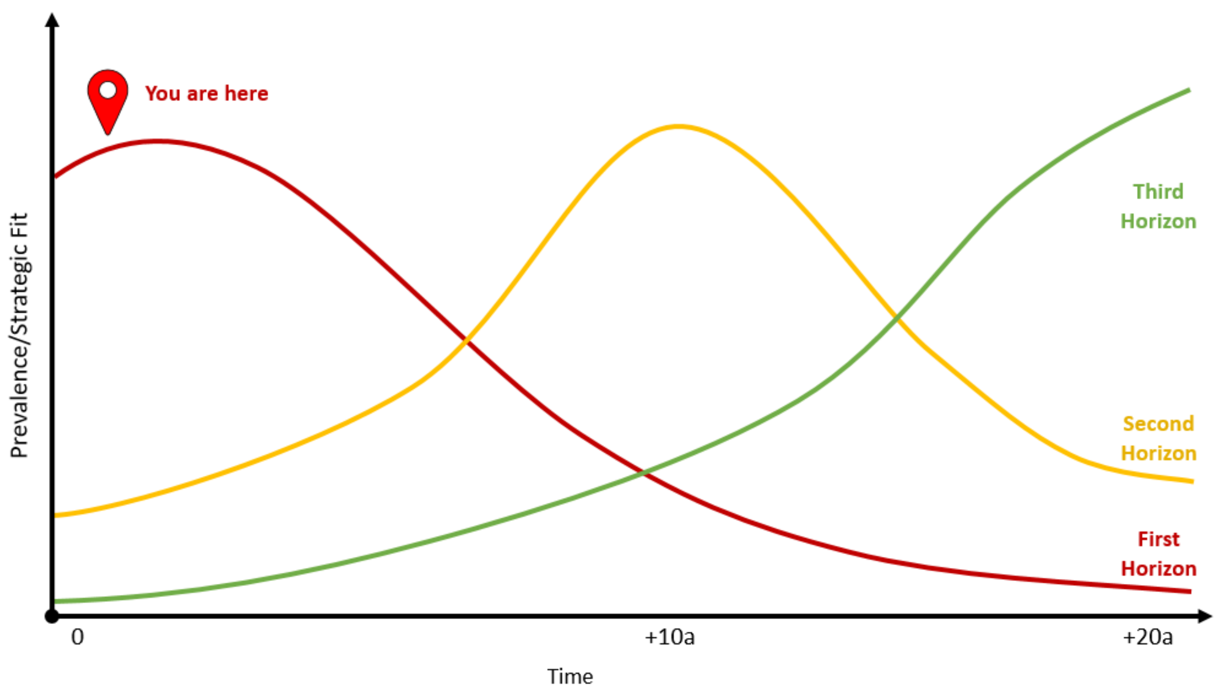
The first horizon (H1) is a snapshot of the current manufacturing paradigm. It represents 'business as usual'. However, complex systems are not static. As the metaphorical landscape changes, certain elements of the current manufacturing paradigm fall out of alignment and lose their strategic appropriateness. In fact, "the starting point of a three horizon conversation is the recognition that the first horizon pattern is losing its fit with emerging conditions." (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016).

The long-term future is represented by the third horizon (H3). It emerges from the weak signals, or "pockets of the future" which already exist today. The third horizon emerges as the successor to the turbulent second horizon. H3 describes a new paradigm which has a much tighter fit to the changing macro-scale manufacturing ecosystem than the current H1 system.

It is important to note that Horizon 3, actually represents a number of future states. As such H3 can be considered as a proposed future: "It fumbles towards utopia" (Curry & Hodgson, 2008) . In a workshop setting, many different and at times conflicting characteristics and possibilities emerge. While the actual transformative changes are open to discussion, H3 represents the impending descendant of the H1 paradigm.

Between these two different paradigms lies the tempestuous second horizon (H2). Stuck between a failing paradigm and an uncertain future, this horizon is inherently dealing with ambiguity. Here innovation plays one of two roles. It seeks to enhance the strategic fit of the H1 standard or to move towards a completely different model represented by H3. In this light, H2 is the short to medium term future. The prevalent mindset of H2 has been described as entrepreneurial (Hodgson & Sharpe, 2007). The Three Horizons framework is illustrated in Figure 19.

Figure 19: Three Horizons Framework



As Figure 19 illustrates, time is shown along the x-axis, the present time is located at the origin. The strategic fit of the system or paradigm in regard to the external environment is mapped on the y-axis. The strategic fit can also be described as the prevalence of a system, or as the overall adoption rate of a paradigm. When plotted over time, the prevalence or strategic fit of a system, maps to a standard bell curve distribution. This pattern is consistent with Schultz (2006) and emerging issue analysis.

The current, widely accepted manufacturing paradigm is indicated by the location marker positioned near the top of the first horizon. The curve tailing off to the right, expresses

the decreasing strategic fit of the maladaptive paradigm to the broader ecosystem. As discussed by Curry et al. (2007) a declining S-curve is consistent with model failure in open systems theory as described by Kahn (1966).

The objective of the fourth stage of the project centred on engaging frontline Canadian manufacturers directly to elicit their views and strategies on the future of manufacturing. Realizing that the workshop participants are not necessarily formally trained or engaged in the praxis or theory of foresight presented a challenge. The Three Horizons model provided an ideal method to co-create a foundational appreciation of foresight methods and build a shared understanding of the future of manufacturing and the associated challenges. The challenges from the Three Horizons workshop were analysed and are summarized in Table 11

A strength of the Three Horizons method is the way it presents: current state, future state, and transition state in a series of three interconnected curves that represent the arcs of innovation and value change over time sequence. This allows participants to grasp the various future horizons with a metaphor that is intuitive. In this manner, Three Horizons helps to deal with the inherent complexity change (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016).

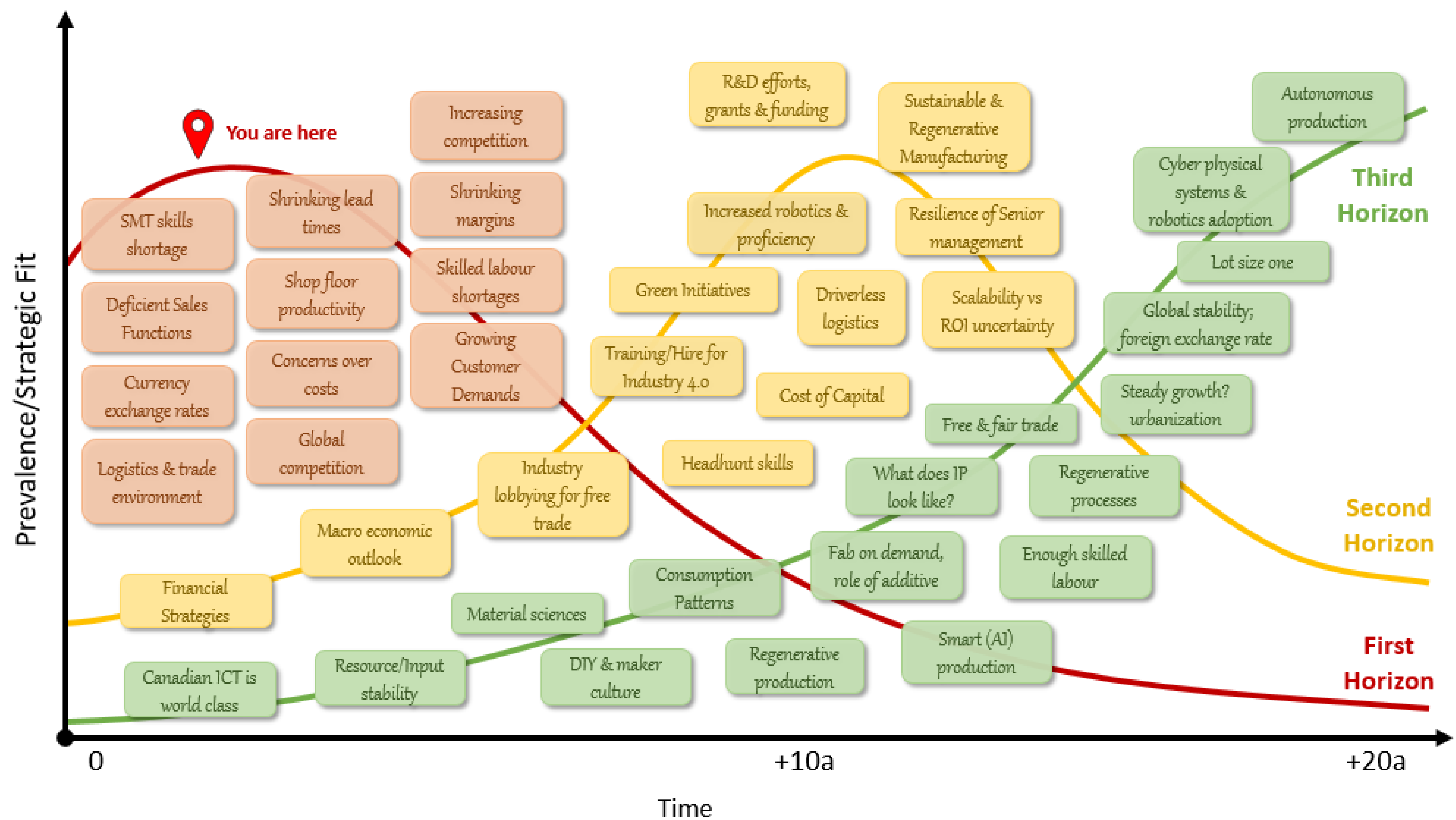
It also allowed the author/facilitator to highlight the connections between at the current system state and possible future system states and key factors that arise. As such:

> *We have found that Three Horizons can help participants situate the present moment in relation to the future. This is because it helps them regard each horizon as a quality of the future in the present, with each horizon characterizing a distinct way of acting in the present with a qualitatively different relationship to current and future patterns. (Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016)*

Additionally, this process illuminates and, also stimulates a discussion of the perceived critical uncertainties that might define the future. In this sense, a Three Horizons workshop is also a useful sense-making activity which prompts deep thought and forward looking strategic action. According to Sharpe et al. (2016), “It is the experience of being involved in the process that helps participants reframe their understanding of the relationship between the present and the future.” Consequently, Three Horizons could be considered a practice rather than a theory.

The results of the Three Horizons activity are briefly summarized in Figure 20.

Figure 20: Map of Workshop Results



A typical implementation following Sharpe et al. (2016) is for Three Horizons to initially assist in defining project scope while also framing the strategic output. To accomplish this, the scenario process is used to play-out and bring to life, the future uncertainties and also to highlight tensions between horizons. The scenario process is discussed in section 4.6.

At the end of the workshop, participants were asked to reflect and record any existing and future strategies, objectives, and initiatives for their organizations. This was done in private as an individual exercise. Thereby ensuring participants the freedom to express themselves outside of the group setting and to safeguarded confidentiality. The strategic initiatives and objectives were subsequently analysed and are summarized in Table 13.

The workshop was conducted, with a group of six participants. The recruitment process required participants to be sector stakeholders. As such, all the participants were employed in senior management positions and staff levels within a manufacturing organizations or related academic and research institution.

Table 10: Workshop Participants

Participant	Role	Sector
1	Assistant VP	Machining
2	Head of Engineering	Aerospace
3	Director, strategy	Automotive supplier
4	General manager	Power generation equipment
5	Managing Director	Construction equipment
6	Senior Director	Metal fabrication

3.7 Data Analysis

Following Sharpe et al. (2016) the primary driver for implementing a Three Horizons workshop was for problem finding and the identification of future drivers. A subset of critical uncertainties was then identified and further explored with foresight scenarios describe in detail below.

The Three Horizons workshop resulted in a large volume of data that was aggregated (and anonymized) and compiled into a spreadsheet for analysis. Using an iterative process, the data was further refined and sorted into numerous thematic categories. Common themes and patterns emerged. The categories were then grouped according to their original horizon (1 to 3).

Table 11: Current Challenges – First Horizon

Current Challenges
Control/reducing costs
Shop floor productivity
Skills shortages
Deficient sales functions
Increasing competition
Logistics
Growing customer demands

As outlined above, the second horizon is a transitional space. The characteristics of H2 innovations are a response to the changing strategic fit of H1 and the aspirational H3 perspectives. As such, H2 does *not* represent a smooth progression between the two paradigms.

Rather H2 reflects the inherent tension and conflict between H1 and H3. Consequently, there are two categories of H2 innovation.

The first H2 category consists of innovations which seek to extend, reinforce, and strengthen the H1 paradigm in the face of decreasing strategic fit. The second H2 innovation category is the opposite. Here innovations are enablers for the new H3 paradigm. These are the transition activities which foster the emergence of value driven third horizon futures. Following Sharpe et al (2016) these two categories will be referred to as H2- and H2+. The analytical process is illustrated in Figure 21.

Figure 21: Second Horizon Innovations

The Second Horizon results were group according to the perceived challenges of the participants and the subsequent innovations required to move towards the third horizon. The innovations were then further analysed for their contributions towards the H2- and H2+ or H2+/- after Sharpe (2016). The results of the analysis are sorted into Table 12.

Table 12 Challenges and Innovations of the Second Horizons

Transitional Second Horizon challenges	H2 Innovations	H2 Category
Macroeconomic outlook	Resilience of leadership team/best of best	H2+
Skill shortage – management/leadership	Hire/headhunt Industry 4.0 SMT	H2+
Skill shortage –shop floor	Formal/inhouse training programs	H2-/+
Cost of labour	Increase robotics	H2-
Cost of (new) capital equipment	R&D grants/tax rebates/depreciation	H2-/+
Currency exchange fluctuations	Financial strategies	H2-/+
Risk/uncertainty of ROI	Scalability	H2+
Logistics	Driverless vehicles	H2+
Energy & resource costs	Green initiatives/Recycling	H2-
	Sustainable/Regenerative initiatives	H2+
Protectionism/Nationalism	Industry lobbing	H2+

While there are several H2+ there is also an indication of the mindset firmly rooted in not only the current third industrial revolution but also still in the second.

The post workshop data was similarly compiled using a spreadsheet. The format of the initial data was mixed, and blended both official and possible strategies. The concept was to elicit current strategies as well as any new strategic perspectives that may have resulted from completing the proceeding workshop. The result is essentially a first pass effort at establishing objectives for strategy development.

Table 13: Possible Strategic Objectives and Initiatives

Strategic Objectives and Initiatives (nascent roadmap objectives)	**Percentage**	**Frequency (n=6)**
Investigate Industry 4.0 concepts	100	6
Implement or Improve Lean/5s techniques	100	5
Implement/Improve shop floor data collection	83	5
Green initiatives	67	4
Downsizing employees & cost cutting	67	4
Strengthen/increase senior management team	67	4
Improve office administration	50	3
"We have no official future strategy"	50	3

Perhaps one of the most striking finding was that 50% of the participants revealed that their organizations had no official strategy for the future.

Furthermore, the strategic objectives and initiatives listed in Table 13, reveal a mindset which is again dominated by the continued influences of the second and third industrial revolutions. Considering the impact and historical success of concepts such as Taylorism, Fordism, lean etc. this is an unsurprising temporal bias. For this reason, participants tended to exhibit a managerial mindset rooted firmly in the 20th century.

There was however an awareness of this temporal bias within the participants. Specifically, participants identified a major second horizon challenge; namely, a skills shortage at the level of the senior management team, resulting in the inability to define and lead Industry 4.0 initiatives. Arguably, this is may also be a near-term concern for senior managers who have the responsibility for succession planning.

3.8 Scenarios

This stage of the project focused on exploring and appreciating myriad possibilities for the future of manufacturing – particularly at the macro level. The previous sections are well grounded in upcoming developments within the meso level of the manufacturing sector. Yet the sector depends intrinsically on numerous external macro scale variables as well as the general unknowable uncertainty of the future.

Foresight scenarios are designed to address future uncertainty by presenting multiple possible futures for thoughtful consideration (Bishop, Hines, & Collin, 2007). Consequently, they are well suited for strategy development and evaluation of strategic initiatives. Furthermore,

> *Scenarios are devices for improving our perception. They fit into a different thinking paradigm, which defines strategy making not as a one-time decision, but as an ongoing process. This is the logical consequence of introducing unknowable uncertainty, which invalidates the idea of a single "best" strategy. Strategic decisions are not made once-and-for-all, but must be constantly revisited and tested. (van der Heijden, 1997)*

Taken in this regard the scenario process output has the ability to function as test conditions for the evaluation of strategic objects.

In order to facilitate this, simple, exploratory, strategy intervention scenarios were developed. The process follows a topology described by Notten et al (2003) which was initially derived from Kahn (1963) and subsequently elaborated by SRI and Hawken (1982). The main methodological characteristics of the scenarios are presented in Table 14.

Table 14: Characteristics of Scenario Development

Category	**Characteristic**
Time scale	~20 years
Temporal nature	Snapshot end state
Data	Participatory and literature review
Spatial scale	Macro level
Variables	Heterogenous

This form of simple scenario was chosen as a relatively accessible way for empowering stakeholder participation and as a building block to enable a future elaboration of deeper, macro scenarios. For this study, four exploratory scenarios were developed. They are based on Dator's (2009) archetypes which are: Business as Usual, Regression, Discipline, and Transformation.

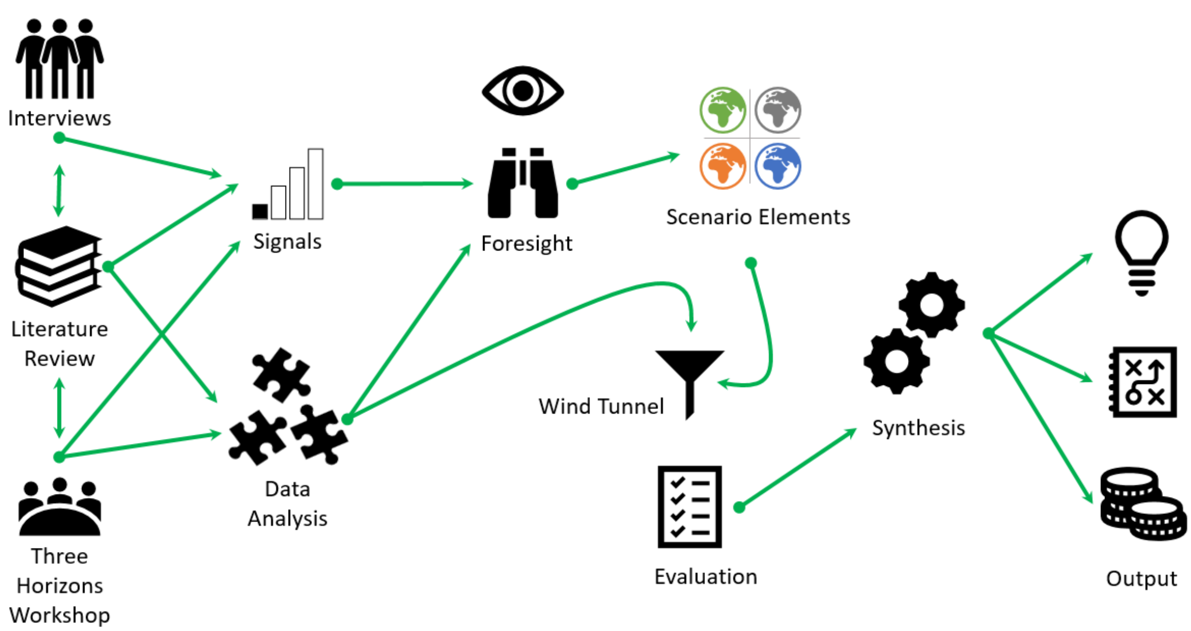
Bishop (2007) correctly suggests that a there is danger of scenarios to be interpreted as best and worst-case perspectives. Therefore, it is relevant to point out that the scenarios function as test conditions for the evaluation of strategic objectives as opposed to hard predictions. The scenarios are also a preliminary exploration of myriad possible futures. Consequently, the scenarios developed at this stage should be regarded as a starting point in an iterative process of strategy development.

3.9 Wind tunnel

The objective of this stage of the project is to provide a framework with which to evaluate the strategic objectives discovered through primary and secondary research. The purpose is to identify the desired subset of validated, robust strategic objectives which might then be further developed and elaborated by stakeholders in a future strategy development project.

In aerospace engineering a wind tunnel, is used to test various aircraft designs under a variety of test conditions, an apt metaphor for this process. This stage of the project implements the wind tunnel method developed by van der Heijden (1997). Here the previously derived strategic objectives are tested against the scenarios which represent the test conditions.

Figure 22: Overview of the Project's Workflow



4.0 Foresight Design Proposal

The primary objective for developing the foresight scenarios was to develop a set of four lenses to use in the wind tunnel evaluation (See below). The scenarios provide a critical lens for the evaluation of the strategic objectives derived from the Three Horizons workshop.

Scenarios have long and successful tradition in the domain of strategic foresight. They are well suited to explore possible futures and validate the strategic objectives to those futures (Saritas & Aylen, 2010). This is an essential component required for developing strategy that is robust in highly uncertain environments and involving systems of increasing complexity.

The scenario process is ideal to describe complex, often (hopefully) radical or at least surprising visions of a future state. In practice, I have found them to be particularly useful in building a shared understanding for the diversity of possible futures.

However, the creation of these exploratory scenarios requires the generation of critical uncertainties to frame the scenarios. As discussed in detail in section 4, the Three Horizons workshop was the initial foresight method employed to elicit the initial futurescape objectives of the Canadian SME manufacturing sector. Additionally, workshop participants identified important factors/uncertainties that were perceived as obstacles for envisioning the future.

This data set was then combined with the data collected from the subject matter expert interviews and the literature reviews. The result was a broad list of factors/ uncertainties which shape the future manufacturing landscape. These factors are the driving force of future change.

Once the resultant drivers were sorted, combined, and analysed, it was then used to build a portfolio of macro level uncertainties. To make sense of the information, the drivers were categorized using the STEEPV framework (Loveridge, 2002). Using this framework, the key drivers can be identified and grouped in six dimensions. The six dimensions are composed of the following factors: Social, Technological, Economic, Environmental, Political and Values.

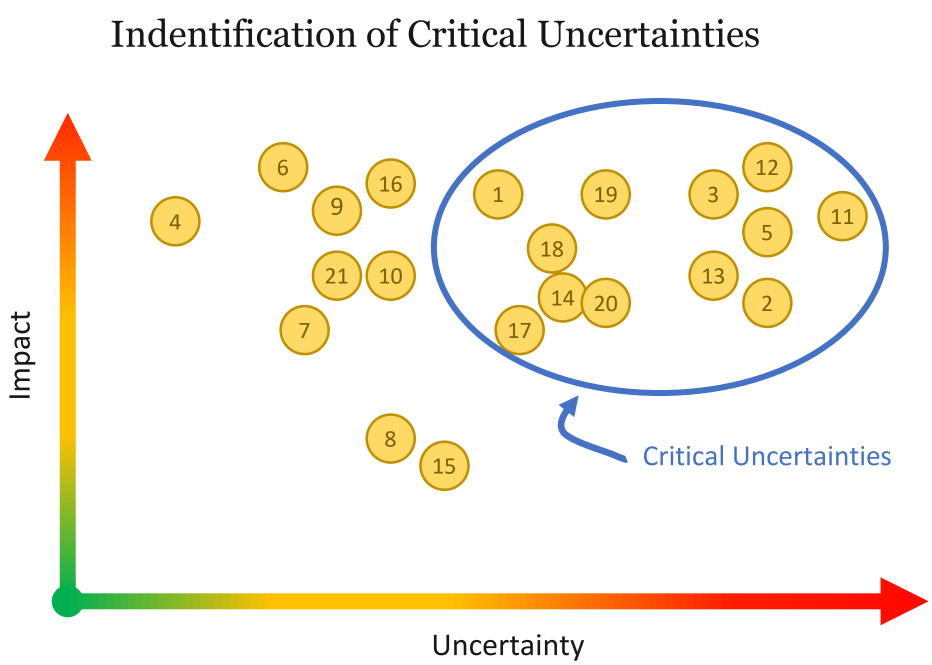
As a multidimensional method, STEEPV provided a deeper understanding of the findings and facilitated the creation of the scenarios. The drivers, sorted by STEEPV methodology, are presented in Table 15. These drivers are the forces of change that will consequently shape the development of the following scenarios.

The drivers were then evaluated according to impact and uncertainty as they pertain to manufacturing. The resulting scatterplot analysis yields a subset of *key* or critical uncertainties. This is illustrated in Figure 23; the data points are referenced using the ID numbers from Table 15.

Table 15: Drivers and Uncertainties Categorized by STEEPV

STEEPV	ID No.	Drivers and Uncertainties
Social	1	Consumption patterns, Individualism
	2	Maker-ism
	3	Skilled Labour availability
	4	Urbanization
Technology	5	Additive Manufacturing diffusion
	6	Artificial Intelligence development
	7	Canadian ICT
	8	Material Science
	9	Robotics development and adoption
Economics	10	Cost of Capital
	11	Economic growth
	12	Foreign Exchange rate
	13	Energy cost
	14	Resource availability
	15	Supply chain profile
Ecology	16	Climate change
	17	Environmental regs
Politics	18	Global Stability
	19	Trade agreements
Values	20	Intellectual property rights
	21	Production facilities localization

Figure 23: Identification of Critical Uncertainties



This subset of factors represents the important variables, that are characterized as having both a potentially high impact on manufacturing in Canada <u>and</u> are considered to be highly uncertain in outcome. They are the critical uncertainties. For example, factor 12, foreign exchange is considered a highly significant variable because of the impact on Canadian manufactured exports and the cost of imports. Foreign exchange rate policy can either amplify or negate a Canadian manufacturing productivity advantage relative to other international manufacturers. Additionally, the exchange rate is also subject to large variability due to macro economic determinants.

The critical uncertainties are used as an entry point for the subsequent foresight exploration and are therefore used as variables in scenario analysis.

4.1 Four Scenarios

The strategic objectives listed above in Table 13 are starting point in developing strategic vision for moving towards the future. However, they must be evaluated to determine their long-term value and to validate them against possible future events ahead of strategy formation. Foresight scenarios are useful in developing metrics for such evaluation.

The scenarios process is ideal to describe complex, often (hopefully) radical or at least surprising visions of a future state. In practice, I find them to be particularly useful in building a shared understanding among stakeholders of complex, multivariate challenges. When creating scenarios, it is worth bearing in mind that;

> *Scenarios are neither predictions, nor forecasts, in that they make no explicit claim to represent a single most likely path or destination. Rather they are developed as a set of multiple divergent stories extending outward from a specific, framing research question in order to help planners foresee possible futures. (van Alstyne, 2010)*

Table 16 highlights the critical uncertainties derived from the key factors. It is important to state, while perhaps somewhat counterintuitive, that in all the futures there are both winners and losers. Even in the most dystopian visions there will be people who thrive in such an environment. Therefore, it is useful to consider the scenarios as also presenting a diverse set of opportunities not just obstacles.

The scenarios were created following the four major archetypes initially conceived by Dator (2009). The scenarios are also influenced by Schultz (2001) and Hines (2014). In keeping with broad timeframes laid out for the Three Horizons workshop, the H2 is considered to be about +10a while the scenarios are in the +20a timeframe.

Table 16: Critical Uncertainties

Critical Uncertainty (Key Factors)	**Explanation**
Consumption patterns	The dominant purchasing paradigm
Maker-ism	The role of the DIY/marker movement in society
Skilled Labour	The availability, skill, and suitability of labour
Additive Manufacturing	The role and diffusion of Additive technology
Economic growth	Change in market value of goods and services PPP/GDP
Foreign Exchange	The value of CAD relative foreign currencies
Resource & Energy costs	The costs of manufacturing inputs
Resource Availability	The obtainability of raw inputs (titanium, rare earth)
Environmental regulations	Relative strength of environmental protocols
Global Stability	Uncertainty due to potential or actual conflict
Trade agreements	International trade integration paradigm
Intellectual property rights	Strength & value of rights granted to IP creators

Scenario: 8 Days a Week

Archetype: Business as Usual

This scenario is grounded on a business as usual mentality. The foundational framework is a continuation of the current paradigm without any major system shocks. The scenario was constructed on an extrapolation of the existing trends and forecasts of first horizon (H1) concepts. Significantly, a business-as-usual scenario is often cited (Dator, 2009), (Hines, 2014) as being the least likely to actually occur.

The scenario describes a world where manufacturing plays a critical role enabling unchecked materialism. Consumers' unsustainable lifestyles requires high velocity manufacturing to meet ever-growing demand. Feral consumption drives uncheck exploitation of natural resources. While economic power has shifted towards Asia, global trade flourishes with open markets.

Table 17 illustrates a condensed version of the scenario. The critical uncertainties are addressed as headlines from the future.

Table 17: 8 Days a Week

Critical Uncertainty	Today's Headlines
Consumption patterns	Fashion news: Single charge, disposable smartphones – a new look every week!
Maker-ism	Maker-fest draws hobbyists from across the country
Skilled Labour	CPS technicians demand top dollar
Additive Manufacturing	3d printers blamed for worldwide price drop of Yoda figurines
Economic growth	The OECD forecasts growth at 0.5% for next year
Foreign Exchange	The Canadian dollar closed steady at .85 USD
Resource & Energy costs	PV panel tax rebate extended as OPEC refuses to cut production
Resource Availability	Titanium futures set new record as demand skyrockets.
Environmental regulations	Acme Co registers anvil production line to ISO 14001-2025
Global Stability	G20 agree to global minimum wage
Trade agreements	TPP 3.0 negotiations set to conclude next week
Intellectual property rights	Equipment dealers lock in customers on proprietary raw materials

Scenario: Yesterday

Archetype: Regression

This scenario is based on the collapse archetype. Despite the menacing name, it is not intended to be representative of a “worst case” for manufacturing. Rather, the scenario is intended to reflect a drift or regression into a systemic dysfunction. This follows Hines (2014) as opposed to the more apocalyptic scenario archetype suggested by Dator (2009). This scenario draws on regressive second horizon (H2-) trends and perspectives. The cross-impact analysis of the critical uncertainties further develops the trajectory of this regression.

This scenario describes a manufacturing ecosystem characterized by a sputtering economy, deflation, protectionism, and growing nationalism. While defense industries flourish, other manufacturers struggle with dwindling margins as a cheaper-is-better consumer mentality drives a race to the bottom. Although rising resource costs are slightly offset by falling wages; many manufacturers are caught in a vicious, reinforcing cycle of falling profits, lower reinvestment and shrinking R&D budgets at a time when IP piracy is pervasive.

Table 18: Yesterday

Critical Uncertainty	Today's Headlines
Consumption patterns	"Cheaper is better" mantra drives record growth in dollar stores
Maker-ism	#1 on the Times Bestseller list: "DIY Everything: Build your own Appliances"
Skilled Labour	Unemployment surges again after decline in first quarter
Additive Manufacturing	City landfill full as home users' 3d printer waste increase four-fold
Economic growth	OECD report: Deflation expected to continue for most G20 nations
Foreign Exchange	Currency markets halt trading for the second time this year due to volatility
Resource & Energy costs	Airlines adopt multifuel jet engines as hedge on erratic fuel prices
Resource Availability	Wanted: scrap steel - we pay top bitcoin!
Environmental regulations	Acme Co denies allegations of illegal dumping of explosive waste in local waterway
Global Stability	UN Security Council attempts to defuse latest regional nuclear standoff
Trade agreements	Parliament approves next round countervailing duties
Intellectual property rights	WTO downplays failure to harmonize global patent laws

Scenario: Can't Buy Me Love

Archetype: Discipline/New Equilibrium

This scenario is modeled following the new equilibrium archetype (Hines, 2014). It is based on the concept that complex dynamic systems adapt to challenges and tend towards some form of self-preservation.

Although consumerism is still pervasive, environmental concerns moderate consumption. Dramatic climate change has impacted the reliability of global supply chains forcing reshoring and a move away from JIT and lean inventory management. International tensions run high in the face of uncontrolled migration and high resource costs. Ubiquitous 3d printing and an overly strong dollar threaten Canadian manufacturers by simultaneously increasing domestic competition while eroding relative productivity advantages. Risk mitigation and adaptation strategies take precedence over efficiency.

Table 19: Can't Buy Me Love

Critical Uncertainty	Today's Headlines
Consumption patterns	Local Manufacturer says: "Customer design input makes every product unique!"
Maker-ism	New #1 on Times Bestseller list: "Victory Gardens for Condo Dwellers"
Skilled Labour	Government ends foreign worker visa program
Additive Manufacturing	Local print shop booming with introduction of 24h, 3d printing service.
Economic growth	Bay Street profits up, as high frequency boom-bust cycle keeps foreign investors hopping
Foreign Exchange	Canadian dollar hits 1.40 USD on export strength
Resource & Energy costs	Energy prices higher on continued Gulf instability
Resource Availability	Rare earth prices up again on news of new PRC export quota.
Environmental regulations	Acme Co denies exporting defective anvils to avoid Canadian disposal fees
Global Stability	Standoff continues between Gulf states
Trade agreements	New NAFTA becomes bilateral deal on Tuesday
Intellectual property rights	Estimated 35% of imports violate new Canadian IP regulations.

Scenario: Tomorrow Never Knows

Archetype: Transformation

The archetype for this scenario is transformation; and portrays fundamental change to the overall system. The transformation is driven by technological innovation and societal values following (Dator, 2009) and (Hines, 2014) respectively.

Highly automated and responsive manufacturing systems enable effective production of both customer and AI developed designs. Nanoscale production techniques allow fabrication at the molecular level. The resulting revolution in material science unleash myriad new materials; however, their unknown impact on human health and the environment is a major regulatory challenge.

The dominant consumption paradigm is moving increasingly toward a responsible service dominant logic favouring use-value over ownership.

In this scenario product design and regenerative manufacturing emphasize cradle to cradle lifecycle methodologies enabling a circular material flow. Global stability further increases value chain fragmentation as hyper-specialization becomes commonplace.

Table 20: Tomorrow Never Knows

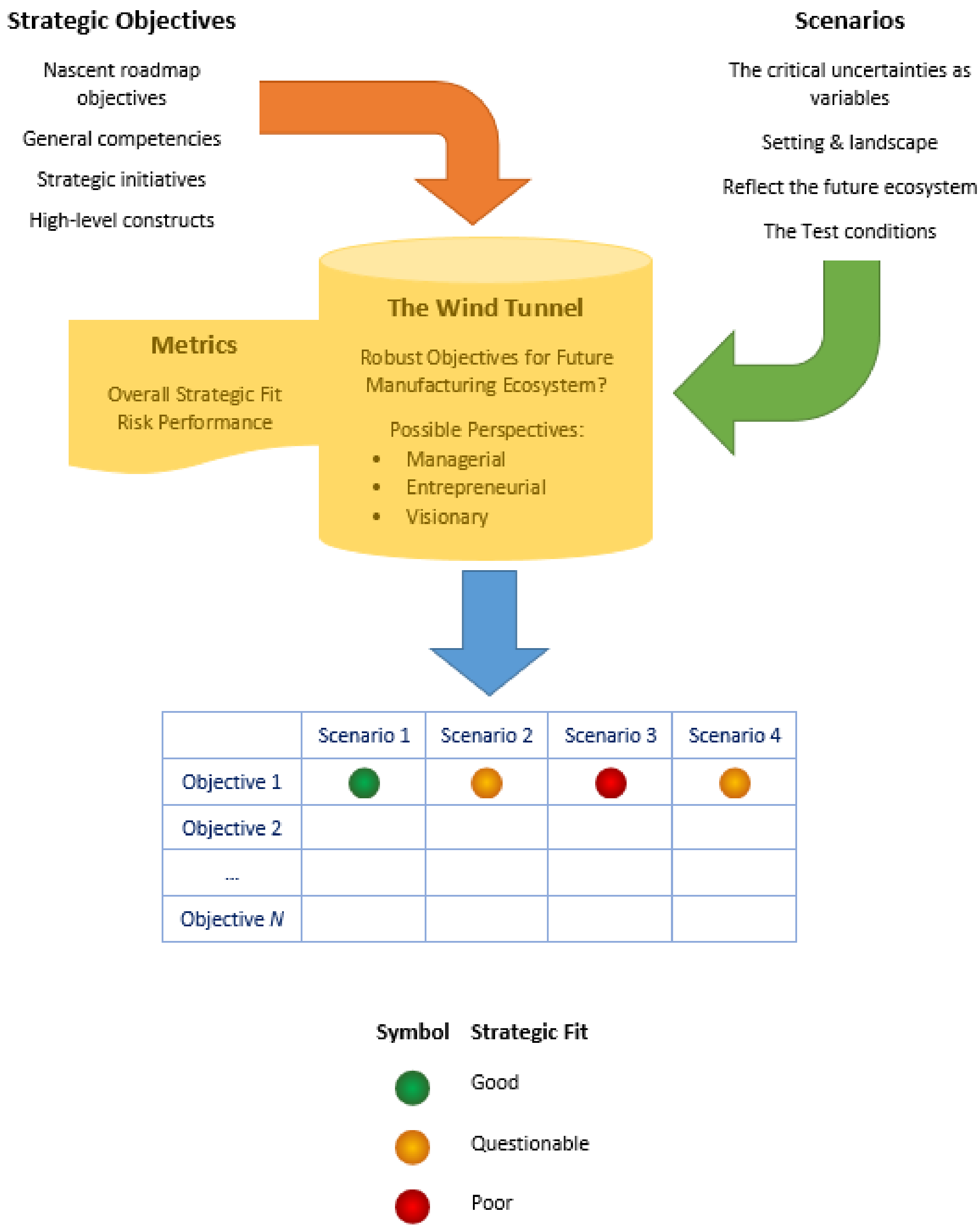
Critical Uncertainty	Today's Headlines
Consumption patterns	Automaker says customers want quality over quantity; offers scalable, guaranteed mobility packages, not vehicles.
Maker-ism	Aviation industry turns to crowdsourced engineering analysis using AI driven open source software.
Skilled Labour	CPS Apprenticeship program hits 90% job placement
Additive Manufacturing	Industrial 3D printers: layering value with molecular fabrication
Economic growth	Guaranteed Minimum Income program keeps growth steady at 1%
Foreign Exchange	CAD expected to hold firm against global currency reserves
Resource & Energy costs	New wind tower project scrapped as electricity prices flatline
Resource Availability	Investment in circular economy pays off as rare earth prices fall
Environmental regulations	Acme Co leads world in upcycling waste by-products
Global Stability	New budget slashes defence spending
Trade agreements	Trading blocs' competition heats up for African resources
Intellectual property rights	The new Creative Commons 5.0 standard comes into effect on Tuesday

4.2 Enter the Wind Tunnel

The goal of this stage of the project is to provide a framework with which to evaluate the strategic objectives discovered through primary and secondary research. The purpose is to identify the desired subset of validated, robust strategic objectives which might provoke subsequent bespoke, strategy development projects that could then be elaborated into roadmaps.

In aerospace engineering a wind tunnel, is used to test various aircraft designs under a variety of test conditions is an apt metaphor for this process. This stage of the project implements the wind tunnel method developed by van der Heijden (1997). Here the previously derived strategic objectives are tested against the scenarios which represent the test conditions. The specific test conditions are derived from the previously developed scenarios. Figure24 illustrates the wind tunnel process.

Figure 24: Wind Tunnel Analytical Framework



As this stage is a preliminary effort encompassing a wide range of participants, the performance metrics are different from the standard wind tunnel approach. Whereas, usually we would be considering cultural and financial performance among other factors those criteria are specific to individual organizations. For the high-level perspective presented here, the criteria are therefore also abstracted to a higher level namely: overall strategic fit and risk performance profile.

4.3 Evaluations

The wind tunnel testing yields some interesting results. Perhaps the most striking is the general lack of preparedness for the future. Most of the strategic objectives evaluated poorly in the scenarios. However, those that were the most robust are also the nascent steps towards a better appreciation of moving towards an Industry 4.0 framework. This is hopeful, yet shows the relative immaturity in approach of SME Canadian manufacturers towards the future. The evaluation results are summarized in Table 21.

Table 21: Evaluation Results

Strategic Objectives	Scenario 1 8 Days a Week	Scenario 2 Yesterday	Scenario 3 Can't Buy Me Love	Scenario 4 Tomorrow Never Knows
Investigate Industry 4.0 concepts	🟠	🟠	🟠	🟠
Implement or Improve Lean/5s techniques	🟠	🟠	🔴	🔴
Implement/Improve shop floor data collection	🟠	🟠	🟠	🟠
Green/Sustainability initiatives	🟢	🔴	🟠	🔴
Downsizing employees & cost cutting	🔴	🟠	🔴	🔴
Strengthen/increase senior management team	🟢	🟠	🟢	🟢
Improve office administration	🔴	🔴	🔴	🔴
"We have no official future strategy"	🔴	🔴	🔴	🔴
Implemented Industry 4.0 paradigm	🟢	🟢	🟢	🟢

4.4 Highlights of the results

Investigate Industry 4.0 concepts. On its own this initiative is a starting point and would be of little value without consequent strategy development and subsequent implementation. If the initiative is considered as a first step of many it would however rate as a robust initiative in all scenarios.

Implement or Improve Lean/5s techniques. These initiatives are clearly rooted in the 20th century. As such they are valuable in their own right but after initial gains provide diminishing returns in the foresight scenarios.

Implement/Improve shop floor data collection. This is a creditable initiative only if it lays the groundwork for a more intensive shift to a full CPS implementation.

Green initiatives. Current green initiatives are of course a commendable development. However, they are merely a starting point and not necessarily indicative of a more radical move towards sustainable or regenerative manufacturing required in most future scenarios.

Downsizing employees & cost cutting. This initiative appears to be a remnant of a Taylorist/Fordist mindset taken to the modern extreme of profit engineering. In this case the downsizing is motivated more by a short-term profit taking and an effort to make the quarterly targets instead of a long term investment strategy. While it may prove useful in race-to-the-bottom paradigm, it is a poor strategy in most scenarios.

Strengthen/increase senior management team. The evaluation has revealed that this is the most purposeful strategic option mentioned by the respondents. The research presented above strongly suggests that a strong and skilled workforce is a critical component of future orientated manufacturing.

Improve office administration. This option is not a robust future oriented strategy. While any improvement strategies are useful, in most cases the impact of this approach may be marginal.

"We have no official future strategy", while this day-to-day, noncommittal approach offers flexibility it evaluates poorly across scenarios. In a critical light, this is basically an admission that: "there is no business strategy."

Implemented Industry 4.0 paradigm. Surprisingly, a full implementation of Industry 4.0 evaluates well across all four scenarios. Far from being a mere marketing hype, this offers a viable model for manufacturers. This is due to dramatically improved agility and enhance effectiveness, and efficiency. This suggests that an Industry 4.0 based approach to manufacturing is a robust and resilient strategy.

This however, raises the question as to whether Industry 4.0 also address the more immediate first horizon challenges facing Canadian SME manufacturers. Based on the previous discussions, the initiative does prove comprehensive solution to the needs of manufacturing today. This is summarized in Table 22.

Table 22: Does Industry 4.0 address First Horizon Challenges?

Current Challenges	Industry 4.0
Control/reducing costs	Increases efficiency, machine learning optimization
Shop floor productivity	Increases productivity, decentralizes decision points
Skills shortages	CPS, IoS, collaborative robotics extends skills
Deficient sales functions	IoS, IoT, global connectivity
Increasing competition	CPS increases efficiency and productivity
Logistics	Geolocation, smart products, autonomous coordination
Growing customer demands	Smart Factory, small lot sizes, IoS, co-op design

5.0 Conclusions

The initial finding of this study suggest that Canadian SME manufacturers have not yet developed robust, future orientated strategies. Consequently, many of the participants in this study may not be ready for the challenges and changes of the fourth industrial revolution.

Fortunately, and contrary to initially held beliefs, this study suggests that the Industry 4.0 paradigm is a valid approach to addressing the immediate, first horizon challenges facing Canadian SME manufacturers today. More importantly, the study also confirms that Industry 4.0 initiatives are robust and resilient solutions for tomorrow as well.

However, most manufacturers seem to be ill prepared to develop future oriented strategies. This is a major obstacle to successfully transforming their manufacturing practices to an Industry 4.0 paradigm.

For many manufacturers, the Industry 4.0 model is highly abstract and incredibly complex. Together with a general lack of awareness, knowledge and understanding of the paradigm; these elements combine to form a significant barrier to entry. Consequently, this suggests a desperate need for an awareness and education program. As a starting point, such a program could initially target senior management teams, within an holistic strategy development initiative. This would be a significant contribution toward a developing robust, future orientated strategic dialogue.

Although, there are nascent strategic objectives that are aligned with building a positive fourth industrial revolution experience and organization; most initiatives are not resilient. In fact, many initiatives are grounded in 2^{nd} and 3^{rd} industrial paradigms. This seems to be due to a managerial mindset. This is understandable; since, in the past second and third horizon strategies were the success formula that worked well in the past. At that time, such strategies had good strategic fit. However, as the strategic fit declines over time, clinging to previous success formulas will provide diminishing returns.

The desire to hang on to 2nd and 3rd generation industrial paradigms is understandable; 'keeping the lights on' is of course a primary concern to, for profit organizations. However, this compounds a near term temporal bias. This bias makes it difficult to think about a long-term future viability of the organization. Again, an educational approach, which might include customized Three Horizons workshop, among other foresight orientated activities, would be beneficial. Such a tactic would be a relatively straightforward method to balance the observed temporal bias with a sustainable, long-term outlook. Such an approach would ensure 'keeping the lights on' today while building towards a progressive, *and* profitable future.

Considering these conditions, it is perhaps unsurprising that fully one half of participant organizations expressed the fact that they did not even have a future oriented strategy. This is a serious problem for three reasons.

Firstly, these organizations are in danger of falling behind very rapidly in the future as developments in the ecosystem are occurring at exponential rates. Secondly, trying to catch up at some later stage, hoping to leapfrog competitors, is risky and may not be feasible with dwindling economic resources. Organizations employing such a strategy may well get caught in a negative reinforcing loop of dwindling resources. Thirdly, deliberately employing a hedging strategy, in an effort to keep all options open, by deliberately not committing to a focused strategic approach is very expensive tactic. Again, this may result in playing a very costly, time-sensitive game of catch-up. However, even more critically, such an approach may result in the loss of organizational momentum and competitive advantage.

Another significant and, frankly concerning, observation is that none of the participant organizations are using any form of consequent strategic planning beyond a rudimentary forecast level. Informal discussions with participants suggested that the time horizon considered for current strategic planning initiatives is one year or less.

Consequently, it is no surprise that their strategic objectives are very much in the fire-fighting mode as opposed to well reasoned formulations. This points to the need for formalized initiatives towards development of comprehensive, long-term strategy development. This could be a deliverable of a highly customized strategic foresight initiative.

An additional surprising observation is that many participants and their organizations are rooted in initiatives which are very limited in scope. Not a single participant listed initiatives that considered business models, marketing platforms, service dominant logic or distribution channels as an opportunity – even though Industry 4.0 is an incredible pathway for the development of innovation along these lines. Rather innovation was regulated to mainly to technical or third generation operational elements. The application of advanced foresight techniques would assist identifying innovative opportunities.

5.1 Recommendations

1) Build your team & your industry

One of the most robust strategic objects relates to the development of human resources. The importance of building awareness of Industry 4.0 is an additional area which should be high on the list of priorities for Canadian manufacturers.

Developing a community of practice, and leveraging existing industry groups is a potential pathway for building a deeper understanding of the fourth industrial revolution. The development and sharing of best practices in moving towards an industry 4.0 paradigm is a beneficial undertaking for building a robust and resilient manufacturing base in Canada, it is especially important for SMEs to consider this approach as it is a proven way to minimize learning costs by sharing knowledge.

2) Think broadly and beyond old Industry 3.0

The analysis of the second horizon work strongly suggests that the mindset of many Canadian SMEs is firmly rooted in a managerial mindset. This is understandable, as the importance of "keeping the lights on" is critical to every business. However, equally important is the fact that the Three Horizons workshop participants overwhelmingly agreed that the current paradigm is losing its strategic fit. Consequently, it is imperative to consider options which go beyond the current industry 3.0 paradigm.

Indeed, it seems imperative to harness a more entrepreneurial approach towards the challenges of the second horizon. In fact, these challenges should be viewed as opportunities. Ideally, developments in this area would (and should) move beyond the usual technological solutionism. For forward thinking organizations, this would be a perfect topic for further exploration.

3) Risk Awareness & Assessment

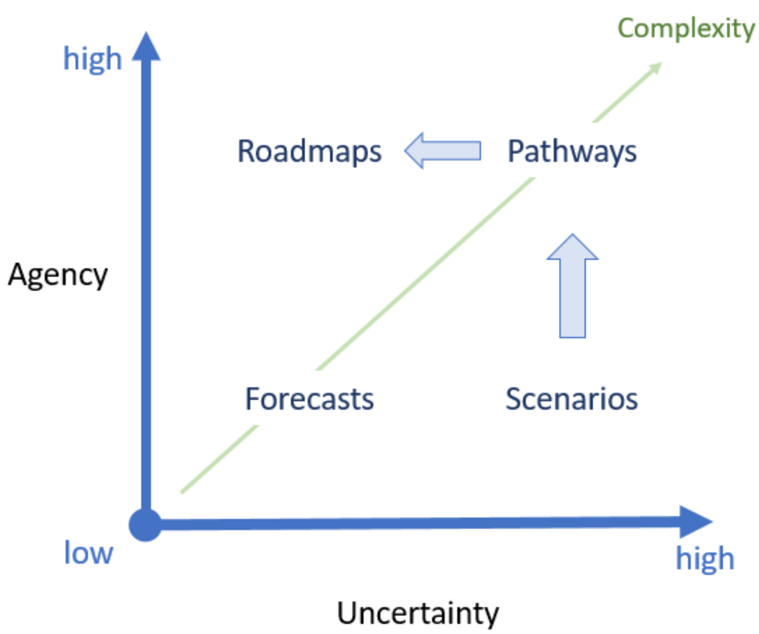
A key weakness of the industry, drawn out from the current analysis, suggests that the risk profile is not fully developed. Most critically, cyber system security, process supervisory control, and unforeseen problems are not being presented in the push towards the fourth industrial revolution. For example, "..., the performance of a CPS system is inevitably undermined by various physical uncertainties, which include stochastic noises, hardware biases, unpredictable environment changes, and dynamics of the physical process of interest." (Tan, Xing, & Yao, 2015)

However, progress is being made in addressing potential pitfalls. Tan et al. (2015) mitigate the aforementioned uncertainties with a system level calibration approach that relies on collaborative data fusion; however, the overall risk profile is still complex and difficult to ascertain. For the small subset of Canadian SME manufacturers that are actively considering moving towards Industry 4.0, this presents a major hurdle towards adoption. An effective measure towards understanding the inherent hurdles in moving towards Industry 4.0 is to undertake a comprehensive risk assessment as part of an individualized strategic foresight project.

4) Customized strategic foresight

While the preceding foresight design intervention represents a significant, ground-breaking work for raising awareness of Canadian SME manufacturers, it is critical to remember it is only the first step. The foresight process is dynamic as well as being highly iterative. The real value add is found through individually tailored strategic foresight solutions. Such a comprehensive project will assist in developing robust and resilient, future orientated strategic plans.

Figure 25: Scenarios to Roadmaps



(Sharpe, Hodgson, Leicester, Lyon, & Fazey, 2016)

Additionally, risk identification, assessment and mitigation are a vital element of such a project. Successful, all-inclusive foresight solution and are inherently dependant on the understanding and harnessing the unique circumstances of individual manufacturers. Consequently, a holistic, bespoke strategic foresight engagement is a valuable strategic asset, which can guide manufacturers through the turbulent second horizon.

5) Public policy & the role of government

There is a major role that the government could play to develop a resilient, future orientated manufacturing sector. In fact, many of the roadblocks facing manufacturers on the road to Industry 4.0 could be addressed with a comprehensive national manufacturing strategy. Furthermore, when developed with strong horizontal linkages to a holistic national innovation strategy, such an approach could help Canadian manufacturers take on a leadership role in the fourth industrial revolution.

Furthermore, the development of centres of excellence for Industry 4.0 specializations could be a major step towards building a strong, future orientated manufacturing base. Such knowledge centres could serve as hubs for research and development, best practices, training, risk identification and mitigation.

Additionally, the government could address SME manufacturers' concerns over the cost and capital required for embracing Industry 4.0 through tax policy initiatives that more aggressively support future orientated investments.

Specifically, in human terms, a strengthening of government's role in relevant skills training, retraining and life-long learning would be especially beneficial to the SME community. Furthermore, a renewed push towards a guaranteed minimum income would assuage the potential hardship and social upheaval that might accompany taking on a leadership role in the fourth industrial revolution.

5.2 Limitations

This research project is a small, qualitative study of Canadian manufacturing SMEs. However, it would be extremely useful to repeat the study with other manufacturers to verify and enhance the findings. This would provide addition guidance for manufacturers while clarifying the readiness and impact of the fourth industrial revolution.

Similarly, this research project highlighted a glaring need for an holistic Industry 4.0 maturity model. The development of such a model would be a critical step toward conducting a gap analysis for individual manufacturers. This would provide an incredible useful tool in developing a strong awareness of Industry 4.0 initiatives and provide a general entry point into the development of comprehensive strategy.

The framework developed for this project would also useful in research projects in a global setting. Indeed, it would be illuminating to conduct similar research with SMEs engaged in manufacturing abroad. Specifically, a study centred in an country with high perceived understanding of Industry 4.0 initiatives (such as Germany); and a potential competitor and significant market for Canadian manufacturers such as the United States.

Taken further, the construction of a broader model of larger firms and global corporations that might be useful to Canadian SMEs. Particularly interesting would be the development of an entire series of case studies which could be published and used to develop a library of best practices and lessons learned of moving to the new Industry 4.0 manufacturing paradigm. Case studies (and publish) would be amazing.

Additionally, building on this project's framework and initial findings, a series of Three Horizons workshops tailored to the manufacturing sector could be developed. These could be used as nexus points across the country to build awareness of the Industry 4.0 paradigm while also serving as an and entry point for creating community of practice. In essence, the workshop participants could become the initial members of regional peer groups for manufacturers interested in moving towards Industry 4.0

A final thought, beyond the factory

The coming changes in manufacturing are truly revolutionary. And ultimately it is a revolution that will, for better and for worse affect people across the planet. At its core, the fourth industrial revolution is essentially a human endeavour. It is worth appreciating the effects of this revolution in the human terms - whether job loss, displacement, migration, urbanization, and climate to name but a few.

In this regard, McLuhan (1964) is more applicable than ever: “For the “message” of any medium or technology is the change of scale or pace or pattern that it introduces into human affairs. The railway did not introduce movement or transportation or wheel or road into human society, but it accelerated and enlarged the scale of previous human functions, creating totally new kinds of cities and new kinds of work and leisure.”

For us today, the declaration of a revolution a priori provides us with an immense opportunity, nay, obligation to shape the “message” of the next industrial revolution which is unfolding before us.

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