Industry 4.0, the Future of Work & Skills

Building Collective Resources for the Canadian Aerospace Industry

Ted Rogers School of Management | Diversity Institute

Future Skills Centre

International Observatory on the Societal Impacts of AI and Digital Technology

CRIMT — Centre de recherche interuniversitaire sur la mondialisation et le travail / Interuniversity Research Centre on Globalization and Work

The CRIMT Institutional Experimentation for Better Work Partnership Project

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Future Skills Centre is a forward-thinking research and collaboration hub dedicated to preparing Canadians for employment success and meeting the emerging talent needs of employers. As a pan-Canadian community, FSC brings together experts and organizations across sectors to rigorously identify, assess, and share innovative approaches to develop the skills needed to drive prosperity and inclusion. FSC is directly involved in innovation through investments in pilot projects and academic research on the future of work and skills in Canada. The Future Skills Centre is funded by the Government of Canada's Future Skills program.

The research activities of the Interuniversity Research Centre on Globalization and Work (CRIMT) focus on the theoretical and practical challenges of institutional and organizational renewal in the areas of work and employment in the global era. Its *Institutional Experimentation for Better Work Partnership Project* - funded by the Social Sciences and Humanities Research Council of Canada and the Canada Foundation for Innovation - brings together CRIMT (funded by the Fonds de recherche du Québec - Société et culture) and an international network of leading partner centres (20) and coresearchers (180). This vast multi-year project seeks to build knowledge on and understanding of how to make work better. The focus is on actors from the world of work who – in a context of great uncertainty – engage in forms of social experimentation and on why these sometimes lead to better or worse work.

HEC Montréal is a French-language university institution offering internationally renowned management education and research. The School has been training future managers who contribute to our society's growth and prosperity since 1907.

With financial support from the Fonds de recherche du Québec, the Observatory helps communities, organizations and individuals maximize the positive outcomes of artificial intelligence (AI) and digital technology and minimize the negative effects of technology.

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Executive Summary

For decades, Canada has built a robust and competitive aerospace industry that plays a crucial role in the Canadian economy, with 700 aerospace companies employing roughly 90,000 people. Prior to the COVID-19 pandemic, demand for labour outstripped supply in the industry, resulting in labour shortages in many occupations. A major ongoing challenge is attracting a new generation of workers by offering good jobs and better work.

The adoption of Industry 4.0 (I4.0) is often presented as a way to increase the competitiveness of the industry, while improving the quality of work and increasing skills by reducing repetitive, routine tasks. Our research in the Montreal and Toronto aerospace clusters has two objectives: 1) to better understand the impact of I4.0 on work and skills; and 2) to identify the conditions that will enable the various stakeholders to meet the challenges of I4.0 and future skills. Four main findings emerge from this research.

First, there is much variation between firms in terms of I4.0 adoption. Some firms are fully engaged and are currently operating a virtual factory, whereas others have yet to begin the turn towards I4.0. In between, some firms sit at different stages, as they build their digital infrastructure to capture and organize the relevant data.

Second, the impacts of I4.0 on work and skills vary, and they do not affect all workers nor affect them all in the same way. While the adoption of I4.0 is in its early stages and its impact on future skills and work remains an open question, our findings suggest that it favours job polarization, creating some high-skill jobs but also many lower-skill ones. Thus, the industry is facing a real dilemma that the adoption of I4.0 could exacerbate: it has difficulty attracting talent due to the combination of fewer high-skill jobs and less high-quality work.

Third, in both clusters, the central challenge of I4.0 and future skills is the production of collective resources. In Montréal, at the cluster level, many collective resources are offered through regional mediating organizations in terms of training, knowledge, and material resources. These organizations also create space for low-power actors (e.g., small and medium-sized enterprises [SMEs] and unions) to participate in decision-making, agenda setting, and resource allocation. In Toronto, there are fewer cluster-level resources to support firms in adopting I4.0, yet there are more collaborative and experimental initiatives driven by individual firms and some colleges and universities. In recent years, intermediary organizations have also developed initiatives to encourage

networking and collaboration among various stakeholders. Nevertheless, large firms are in a better position to develop these initiatives and to access resources in comparison to SMEs. As such, each region has created resources through a distinct approach: a firm-centric approach in Toronto and a more coordinated approach in Montréal.

Fourth, firms cannot meet the challenges of I4.0 and future skills alone. It is important to establish mechanisms to foster collaboration and coordination among the various stakeholders, in order to produce collective resources that favour the development of a skilled workforce and technological innovation. Although our research in both Montréal and Toronto was conducted prior to the COVID-19 pandemic, this proposition holds even greater weight in the current time, with firms in a significant downturn that has caused many to make workforces redundant.

In the context of the COVID-19 pandemic—and the devastating impact it has had on the airline and aerospace industries—the recovery of the industry will have to rely more than ever on the collaboration of all stakeholders for the production of collective resources. It is essential for the industry to be at the technological forefront of product and process innovation. Canada needs a long-term strategy to achieve productivity and cost-cutting, while also creating good jobs and high-quality work through I4.0.

Introduction

COVID-19, I4.0, and the future of work and skills in Canada's aerospace industry

The COVID-19 pandemic has shut down global travel and crippled airlines. This has had a knock-on effect on the aerospace industry, as airlines are likely to put plans to purchase aircraft on hold (Srocki, 2020). This is bad news for the Canadian aerospace industry, which was already struggling to compete in a global market where other countries invest billions to support and retain their national aerospace industries.

Competitors' investments have only increased following the pandemic; in comparison, the Canadian aerospace industry has been starved for resources. The negative impact on the local industry is already being seen through high numbers of redundancies and layoffs. The pandemic is also likely to destroy the predicted industry growth and production backlogs that the global industry was facing. Additionally, some firms are gauging the benefits of moving their production to low-cost countries—a significant threat to local manufacturing and suppliers.

> *"We're on the brink of losing it all. Even prior to the catastrophic consequences of COVID-19, Canada's aerospace industry was losing ground... now, facing pressures and losses that are the biggest in aviation history, Canada has slipped even further."*
>
> — CHAREST (2020)

As of the end of December 2020, the federal government had not announced a strategy for aerospace and had provided government aid of only 1.3% of 2019 ticket sales to the airline industry, which is the primary purchaser of aircraft. This is incredibly low support in comparison to pledges by the US (32.7%), France (36.1%), Germany (19.5%), and the UK (7.1%) (Pearce, 2020; see also Leroux et al, 2020).

Additionally, the COVID-19 pandemic has placed an even greater spotlight on the role of I4.0.[1] The concept of I4.0 was launched at the Hannover Trade fair in 2011 and was heralded as a new production paradigm to revolutionize both manufacturing and services (Kagermann Wahlster & Helbig, 2013). Yet I4.0 is a contested concept, with multiple meanings (Mertens & Wiener, 2018), and more than 100 definitions have been identified (Moeuf et al., 2018). It has even been likened to a management "fad" or "fashion" (Madsen, 2019). In this report, I4.0 is defined as "a new approach for controlling production processes by providing real-time synchronization of flows by enabling the unitary and customized fabrication of products" (Kohler & Weisz, 2016). In a manufacturing context, I4.0 includes development of a virtual factory; virtual supply chain management; predictive maintenance; and real-time control of quality and production volume and flows.

However, I4.0 also operates as a frame that aims to institutionalize technological innovation and shape the future of work. It is a highly normative concept that provides a prescriptive view on how production processes can be controlled using new technological innovations, in order to improve productivity, flexibility, and delivery time while reducing costs. Global consultancy firms play an important role in shaping the ideational elements in the discourse about I4.0 through their reports and promotional materials (Pfeiffer, 2017). Data is considered to be the core driver of I4.0—the new fuel of the economy (Agrawal, Gans & Goldfarb, 2018). The ability of firms to learn from and adjust to data in real time is critical for the success of I4.0. It is expected that workers will have to become analysts of production-related data, with the ability to derive meaningful insights on process quality from a bulk of information. Hence, it is assumed that robotics and cognitive technology associated with I4.0 will transform the role of the workforce; however, it can be difficult to envision precisely what those new roles would be (Sniderman et al., 2016).

Beyond a general agreement that I4.0 is going to transform manufacturing industries and work, there is almost no consensus about the impacts I4.0 will have on skills. Will it augment and complement worker tasks and improve worker skills, or will it erode them? What types of skill sets will be needed in an I4.0 manufacturing environment? The combination of personal abilities and attributes, skills, and knowledge required to effectively perform a job in an I4.0 environment has yet to be defined.[2] However, it is likely that the existing training regimens will need to be updated, while the existing workforce will also require some re-skilling. This investment in skill will be expensive, in financial terms as well as in

1 In a recent report, the Organisation for Economic Co-operation and Development (OECD) (2020) argues that the pandemic is likely to accelerate the adoption of digital technologies and that automation is likely to replace tasks within jobs rather than replace jobs, which will have impact across the skill spectrum. New technologies are likely to make some skill sets obsolete and increase demand for new skill sets and jobs related to data management and information technology (IT).

2 We draw here on the definition of competency by Braham & Tobin (2020).

terms of human and technological resources. Data may be "the new oil," (Agrawal et al., 2018) but bottlenecks in implementing I4.0 are not related solely to data, as skills and training are also significant considerations (Brynjolfsson & McAfee, 2014).

In the absence of mechanisms to coordinate the needs of various stakeholders,[3] one of the outcomes is that firms may then tend to underinvest in training or invest more in firm-specific training (Crouch et al., 1999), which reduces the supply of skilled labour. Under these conditions, competition for (and poaching of) skilled workers is likely to flourish, as well as the pursuit of competitive market-based relationships between firms. These rivalries may also spread from firms to workers, unions, and even other organizations in the skill system (e.g., colleges, universities, private training providers, or industry bodies). In this business climate, individual firms are not well-suited to address future skill challenges and the broader challenge of I4.0.

Our main proposition is that a coordinated effort is needed to create collaborative spaces that enable firms and mediating organizations[4] to act together, pooling and creating collective resources while also sharing risk. Any benefits created by this collaboration should be equally accessible to the various stakeholders that need them.[5] An important contribution of Ostrom (1990) is to have highlighted that the nature of any good is defined not only according to its characteristics (exclusion and rivalry) but also according to the institutions that establish the conditions of its production and use.[6] We argue that while agility in skill development institutions can support the development of future skills (Organisation for Economic Co-operation and Development [OECD], 2020), these skills are likely to be best produced collaboratively as a collective resource.

3 A stakeholder is any actor (individual, group, organization) concerned with the activities of the aerospace industry. These include firms; trade unions; industry organizations; government representatives; and various actors involved in research and skill development, such as universities and colleges.

4 Following Cooke, Boekholt & Tödtling (2000:104) mediating organizations include industry organizations, technology organizations, public research organizations, education organizations, and employer and worker associations.

5 Economists often define different types of "goods" according to two criteria: 1) whether they are "excludable" (the goods can only be used by one person at a time or are available to all); and 2) whether they are "rival" (their use by one individual precludes their use by others) (See Crouch et al., 1999). We draw on the work of several scholars (e.g., Coriat, 2015; Ostrom, 1990) who put much emphasize on the institutions that enable the creation of collective resources.

6 Institutions shape actor behaviour and patterns of relationships through rule setting; formal sanctions and incentives; shared conceptions and taken-for-granted meanings; frames of interpretation; and binding norms (Scott, 2008). Institutions not only constrain, but also enable social actors within a particular field.

brief

Our report seeks to contribute to the literature by examining how ***regional institutions can enhance the creation of collective resources*** *to meet the challenges of* ***I4.0 and future skills development.***

The purpose of this report is twofold. First, it seeks to assess the use and development of I4.0 to determine its impact on work and skills. Second, it aims to understand the dynamics through which actors and organizations experiment with institutions to produce collective resources to meet the challenges of I4.0.The report focuses on two of the largest aerospace manufacturing clusters in Canada: Montréal, Québec and Toronto, Ontario. Québec and Ontario offer an intriguing comparison. Haddon (2015) argues that the two provinces have followed different patterns of development, leading to distinct social and economic policy choices. For instance, whereas Ontario has developed a firm-centric approach, Québec relies more heavily on a concerted form of interest intermediation between various stakeholders. Galvin's (2019) work on multi-level governance in the aerospace industry in Ontario and Québec also suggests that the two provinces rely on different types of economic development modelling. Several studies analyzing or comparing subregions and clusters in these two provinces reach similar conclusions (Rutherford et al., 2018; Warrian et Mulhern, 2009; Tremblay et al., 2012; Niosi & Zhegu, 2005). Our report seeks to contribute to this literature by examining how regional institutions in the two provinces can enhance the creation of collective resources to meet the challenges of I4.0 and the development of future skills.

The report is structured as follows: immediately following this introduction is a methods section, outlining the boundaries of this project. The second section uses Statistics Canada and industry data to illustrate the context of the aerospace industry, and the main demographics of the two regions under study. The third section draws on a combination of Statistics Canada data and qualitative data gathered through interviews with a variety of actors to examine the broader trends related to adoption of I4.0, and explores the impact that I4.0 is having on labour markets, work organization, and skill development. The fourth section briefly presents the framework used to analyze regional institutional configurations in both Montréal and Toronto and describes the current dynamics and the resources produced by these institutions to meet the challenges of I4.0 and future skills. Finally, the conclusion examines the wider implications of our findings on the development of a strategy to strengthen competitiveness and sustainability of the

Canadian aerospace industry.

Research design and methods

This study forms part of a research agenda on the aerospace industry.[7] During an early wave of research on the Montréal region (beginning in 2010), we saw a growing discourse around technological advancement and the challenges firms faced in implementing new technology and developing the skills of their workforce. A further wave of research started in Montréal in 2015, which we began to mirror in our study of Toronto in 2018, with interviews continuing until 2020.

We began our research by mapping the aerospace industry in each cluster (firms, trade unions, mediating organizations, etc.). Several resources were leveraged to do this, such as websites, reports, event information, previous research on each cluster, and various directories compiled by industry organizations. We conducted a total of 139 interviews between 2010 and 2020 (97 from 2015 onward) across the Montréal and Toronto clusters. For the individual interviews, we included managers, union representatives, representatives of industry or regional mediating organizations, government representatives, and various actors involved in the development of skills and new technology (refer to the breakdown of interviews in Appendix B). Through these semi-structured interviews, we wanted to understand: 1) how actors are implementing I4.0 in firms; 2) what are the challenges associated with I4.0 adoption; 3) how I4.0 is changing the organization of work and the skill requirements of the workforce; 4) how actors use the regional resources available to them. In May 2019, we also conducted four group interviews with 32 shopfloor delegates in the Montreal cluster in order to understand more fully the relationship between I4.0, work organization, and future skills.

All the interviews were recorded, transcribed, and anonymized. Where interviewees requested no recording, notes were taken instead. The interview data were analyzed and coded by several members of the research team. Unfortunately, our final fieldwork trips in Toronto were cancelled due to the COVID-19 pandemic. We had planned to do more visits in Toronto in March, undertaking group interviews with shopfloor delegates and conducting additional firm case studies. A small number were conducted via Zoom. Although the research design used in Montreal could not be fully replicated in Toronto, we are confident that the data collected provide a solid basis for comparison. An initial draft of this report was sent to a dozen key informants in Montreal and Toronto to validate our findings. This consultation gave us the opportunity to sharpen our analysis and gain insight on the impact of the pandemic on the industry.

7 This research was financed by the Social Sciences and Humanities Research Council (SSHRC), with the most recent phase being jointly funded by the Future Skills Centre and the Diversity Institute at Ryerson University's Ted Rogers School of Management.

We would like to thank all of the people who were interviewed and shared their experience with us. We are grateful to our key informants, who provided feedback on the first iteration of the report and gave us the opportunity to validate our results. We also want to thank the team at Ryerson and our broader research team: all of the students and colleagues who helped shape and frame this research project. Finally, it should be emphasized that our research team is solely responsible for the analysis and conclusions expressed in this report. Any omissions in fact or interpretation remain the sole responsibility of the authors, and the findings do not necessarily reflect the views of our research partners nor those of the many industry stakeholders with whom we discussed these issues. However,

The Aerospace Industry

we would be remiss if we did not emphasize how much we have benefited from their input.

This section outlines the evolution of, and trends within, the aerospace industry—with a special focus on Montréal and Toronto—and highlights several challenges that the industry faces.

The global aerospace industry

The global aerospace industry includes all in-country activities related to the development, production, maintenance, and support of aircraft and spacecraft, with a total valuation argued to be worth $838 billion (AeroDynamic Advisory & Teal Group Corporation, 2018). The industry is cyclical, experiences strong competition, and has a highly skilled labour force. It has a high dependence on R&D, as well as an international customer base and production capacity (Zhegu, 2013). The civil aviation manufacturing segment is a duopoly, with two major competitors and original equipment manufacturers (OEMs): Airbus and Boeing, who specialize in aircraft with 100 or more seats. Alongside these two, a handful of other OEMs of aircraft exist (e.g., private jets, smaller OEM competitors, regional aircraft), and they sit at the head of complex global supply chains. Beneath them reside four tiers of suppliers, including Tier 1 engine manufacturers and system integrators, who are responsible for work packages; Tier 2 suppliers, who manufacture and develop parts; Tier 3 suppliers, who manufacture components; and Tier 4 suppliers, who provide processing services or raw materials (Emerson, 2012; Supply Chain Working Group, 2012).

In the last five years, the global industry has seen significant consolidation. The role of the duopoly has been strengthened through Airbus acquiring Bombardier's C Series and Boeing's attempted partnership with Embraer (Hader et al., 2018). There has also been significant consolidation among Tier 1 and Tier 2 suppliers, with merger and acquisition activity between Safran and Zodiac, the formation of Collins Aerospace from UTAS and Rockwell Collins, and the emergence of Mitsubishi as an OEM with their purchase of the Mitsubishi Regional Jet program (Hader et al., 2018).

Until recently, growth projections for the industry have been strong (Deloitte, 2020). In 2018, the number of passengers worldwide reached 4.3 billion and the world fleet grew from 9,700 aircraft in

1986 to 30,300 in 2018 (Organisation de l'aviation civile internationale [OACI], 2018). However, the impacts of the global COVID-19 pandemic—and the associated reduction of global travel—will result in immediate and prolonged reductions in aircraft sales as airlines struggle to survive (Bruno, 2020). It is estimated that the industry will take between three to five years to recover (Chapman & Wheatley, 2020).

The Canadian aerospace industry

The Canadian aerospace industry is primarily oriented to commercial markets, as opposed to defence or space orientations, and ranks in the top three globally in the production of civil simulators, turboprop and helicopter engines, business jets, and regional aircraft (Innovation, Science and Economic Development Canada [ISED] & Aerospace Industries Association of Canada [AIAC], 2019). The industry includes firms from each of the supplier tiers, with each subsystem of commercial manufacturing being represented (i.e., landing gear, engines, aircraft structures, and final assembly) (Zhegu, 2013).

The majority (69%) of the industry's contribution to gross domestic product (GDP) comes from aerospace manufacturing activity, while the remainder (31%) comes from maintenance, repair, and overhaul (MRO) activities (ISED & AIAC, 2019). Aerospace manufacturing activity (NAICS code 3364)[8] has increased by approximately 88% from 1997 to 2017,[9] in comparison to aggregate increases in Canadian manufacturing activity across all industries of approximately 43% for the same time period. Figure 1 demonstrates the contributions of the industry to GDP over the past 20 years.

69%** of the industry's contribution to GDP comes from **aerospace manufacturing activity**, while **31%** comes from **maintenance, repair, and overhaul activities.

8 NAICS code 3364 includes the following industries: manufacturing aircraft, missiles, space vehicles and their engines, propulsion units, auxiliary equipment, and parts thereof. The development and production of prototypes is classified in this industry, as is the factory overhaul, and conversion of aircraft and propulsion systems. Our qualitative data focuses predominantly on civil aviation and all associated activities: manufacturing aircraft, engines, propulsion units, auxiliary equipment, and parts thereof.

9 This is the latest data point (released by Statistics Canada in 2020).

FIGURE 1

Contribution to Canada's GDP by aerospace and manufacturing industries

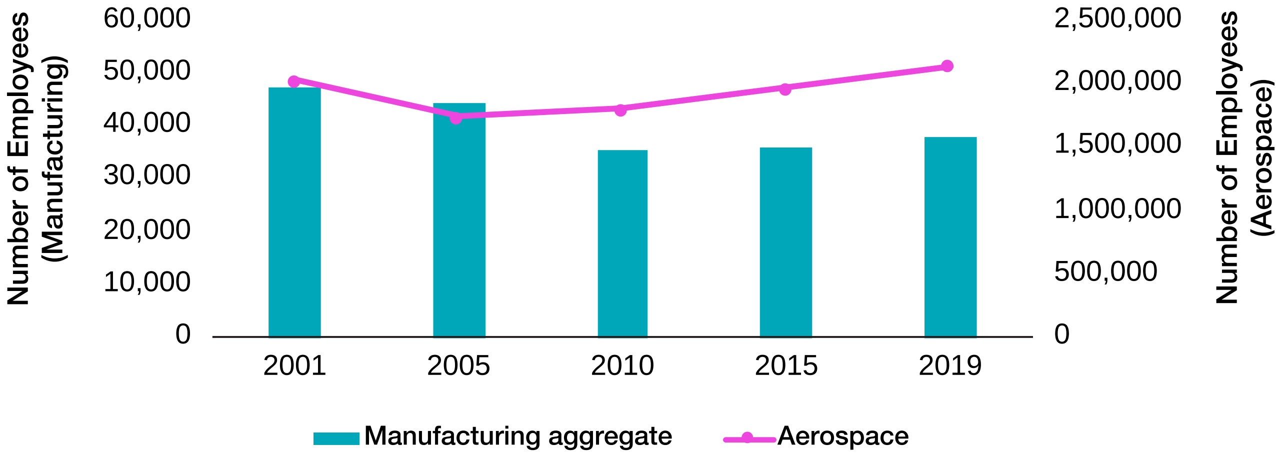
Note: "Manufacturing aggregate" refers to the Canadian manufacturing aggregate (across all manufacturing industries), while "Aerospace" refers to the aerospace industry (NAICS code 3364).

Source: Statistics Canada (2020a)

The Canadian aerospace manufacturing industry has a similar structure to the global aerospace industry in three ways: 1) it has a small number of aircraft and engine OEMs; 2) it has a limited number of Tier 1 engine manufacturers and system integrators; and 3) a larger number (around 670) of small and medium-sized enterprises (SMEs) are integrated into local and global supply chains (Emerson, 2012). The aerospace industry (including maintenance and repair operations) directly employs 89,500 people (ISED & AIC, 2019), with 51,349 of them employed in aerospace manufacturing (see Figure 2). Although, on average, manufacturing employment has seen a decline of approximately 14% from 2005 to 2019, aerospace has seen an increase of approximately 22% in employment numbers (see Figure 2).

FIGURE 2

Employment in aerospace and manufacturing industries in Canada



Note: “Manufacturing aggregate” refers to the Canadian manufacturing aggregate (across all manufacturing industries), while “Aerospace” refers to the aerospace industry (NAICS code 3364).

Source: Statistics Canada (2020b)

The aerospace industry in Montréal and Toronto

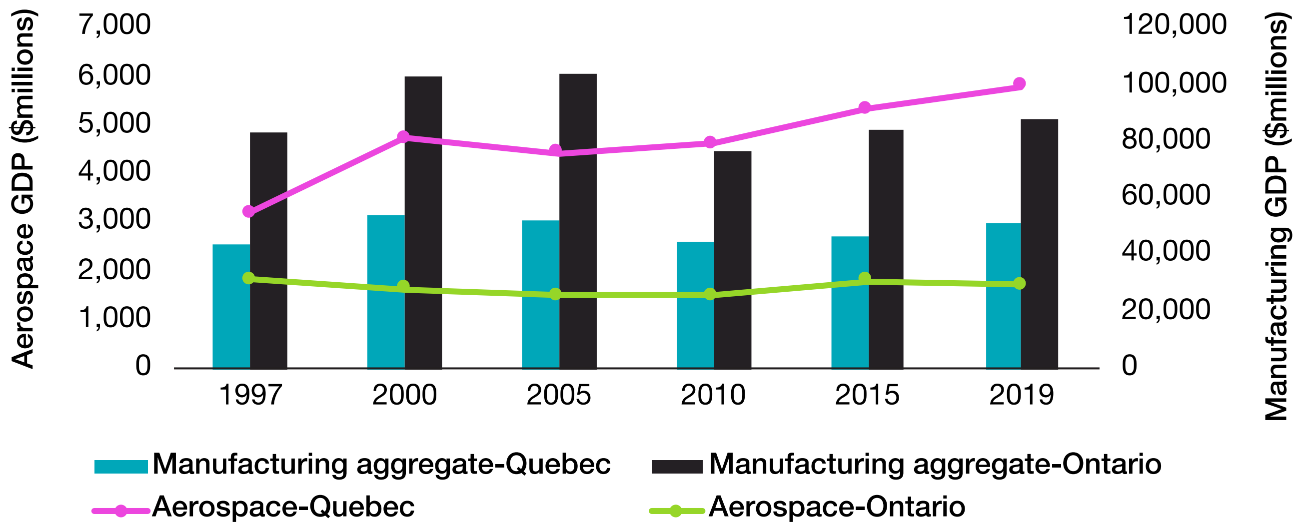
Two provinces make up 81% of Canadian aerospace manufacturing activity: Québec (51%) and Ontario (30%) (ISED & AIC, 2019). In 2019, the aerospace industry as a whole generated $17.8 billion in annual sales in Québec, and over $6 billion in annual sales in Ontario (Ministère de l’Économie et de l’Innovation Québec [MEIQ], 2020; Ontario Aerospace Council [OAC], 2019). The importance of the industry within each province differs—the industry’s GDP contribution is larger in Québec than Ontario—the impact of which is magnified when considered alongside the contribution of manufacturing to each province’s GDP (see Figure 3). In Ontario, the contribution of the aerospace industry is less pronounced because of the importance of the manufacturing sector overall, partially due to the prominence of its automotive industry, which reduces the relative contribution of its aerospace industry. In Québec, the contribution of the aerospace industry is more marked, notably because there is comparatively less manufacturing activity.

There are also differences between the two provinces in terms of industry composition. Of the approximately 700 aerospace companies operating across Canada, approximately 300 operate in Ontario (OAC, 2019) and 185 operate in Québec (MEIQ, 2020). The majority of aerospace manufacturing activities take place in two regions, concentrated either in the Greater Montréal Area (98%) or Greater Toronto Area (80%) (Canada 2020, 2012; Global Business Reports, 2017; MEIQ, 2020).[10] Pressure from OEMs for suppliers to become integrators, combined with their willingness to reduce the overall number of suppliers, has resulted in a declining number of aerospace firms in Canada overall (see Figure 4 on page 13).

10 The Greater Montréal Area and Greater Toronto Area will be referred to simply as “Montréal” and “Toronto” throughout this report.

FIGURE 3

Aerospace GDP versus manufacturing GDP by province



Note: "Manufacturing aggregate" refers to the provincial manufacturing aggregate (across all manufacturing industries), while "Aerospace" refers to the aerospace industry (NAICS code 3364).

Source: Statistics Canada (2020c).

In comparison to Toronto, the Montréal cluster is smaller in terms of number of overall firms, notably SMEs, but has a larger number of multinational companies, including four OEMs, and more than ten Tier 1 suppliers (e.g., CAE and Pratt & Whitney) (MEIQ, 2020). The cluster in Toronto is more geographically dispersed, has a far higher number of firms, most of which are SMEs, and has around ten Tier 1 suppliers (Canada 2020, 2012). Historically, the Toronto cluster has been dominated by one OEM: Bombardier (Niosi & Zhegu, 2005). Recent changes following Bombardier selling off some of its product lines have increased the number of OEMs to include DeHavilland and Mitsubishi.[11]

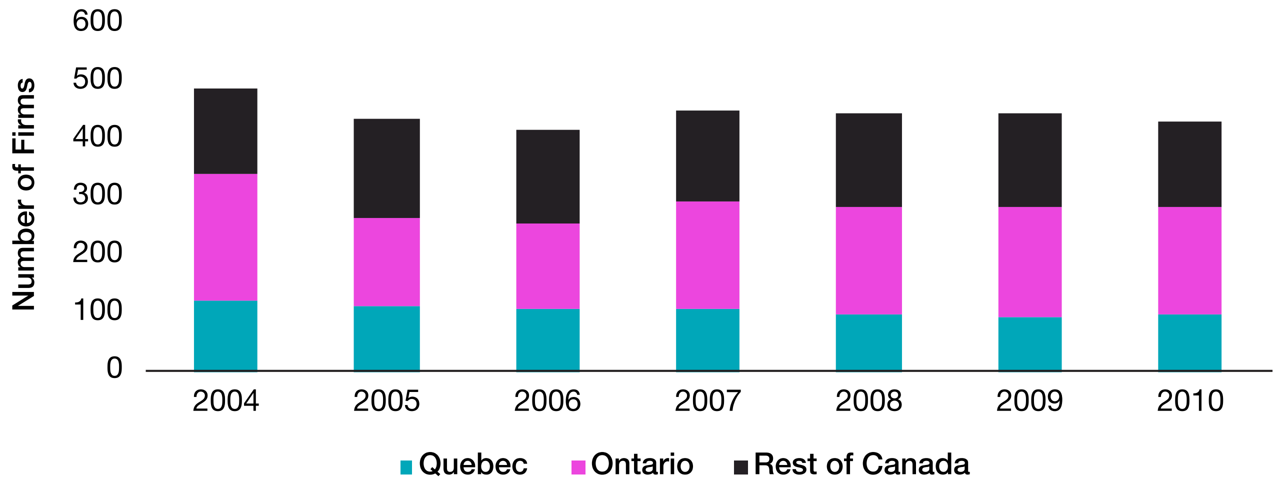
11 Although the composition of the clusters in Montréal and Toronto is different, it should be emphasized that there are many firms operating in both clusters, as subsidiaries of the same multinational company.

Most of the national employment for aerospace manufacturing is located within the Montréal and Toronto clusters (see Figure 5). Montréal captures the highest share of employment; however, comparing 2005 to 2019, Ontario has shown a higher overall percentage in growth rate (30%, compared to Québec's 22%).

Roughly 70% of workers in the aviation and aerospace industry are men, and 26% are immigrant workers (Canadian Council for Aviation & Aerospace [CCAA], 2018). These figures may overestimate the proportion of women in the aerospace industry. The latest data from Québec shows that women comprise 21% of the workforce, but that these employees are mainly (80%) concentrated in administration. Women represent only 12% of the workforce in trades, and roughly 20% of both scientific and technical staff (Comité sectoriel de

FIGURE 4

Number of aerospace manufacturing firms by province (NAICS code 3364)

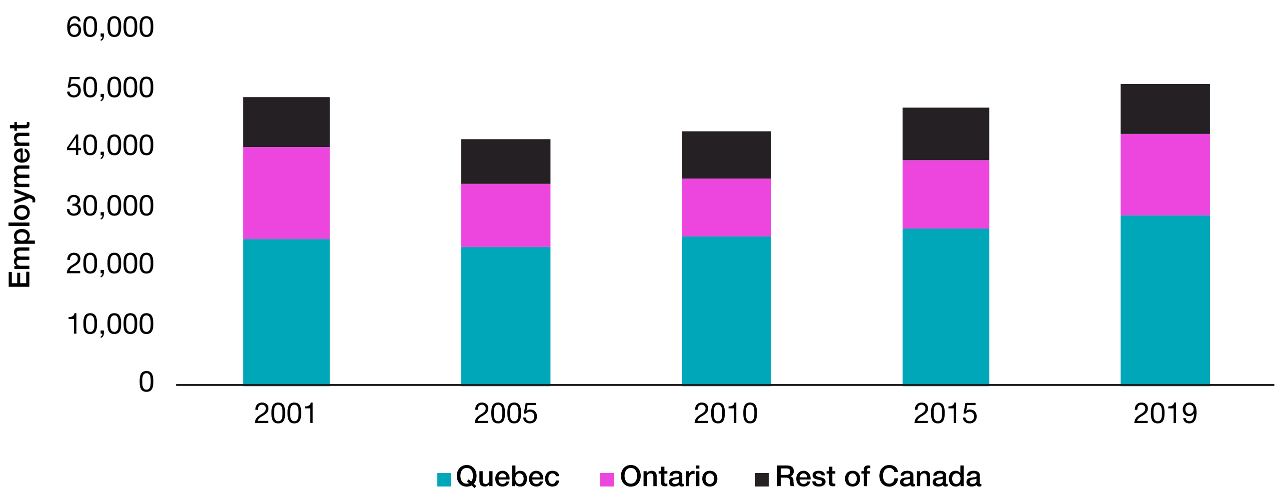


Note: Data for firm numbers was discontinued after 2010, and the data set was fully archived in 2012.

Source: Statistics Canada (2012).

FIGURE 5

Employment in the aerospace industry by province (NAICS code 3364)



Source: Statistics Canada (2020b)

main-d’œuvre en aérospatiale au Québec [CAMAQ], 2016, p. 7). There are several studies documenting that, even in fields with skill-scarcity, immigrants and women face barriers to entry (Braham & Tobin, 2020; Ng & Gagnon, 2020). Firms in both clusters report[12] that they have made inroads into achieving diversity of ethnicity in their workforce composition. However, many of these same firms argue that gender diversity is a bigger challenge due to low numbers of women graduates in science, technology, engineering and math (STEM) fields and trades.

The industry in both Ontario and Québec is also characterized by an aging workforce, with an average age of around 45 years (CAMAQ, 2016; CCAA, 2018). This is partially correlated to the difficulty of attracting a younger generation of workers to Canadian aerospace. According to the two dominant trade unions in the industry—the International Association of Machinists and Aerospace Workers (IAMAW)[13] and UNIFOR, who represent roughly one third of the workforce in Québec and one fifth of the workforce in Ontario (Castonguay, 2017)—this trend is exacerbated by the fact that firms are often recruiting experienced workers, as opposed to young people via apprenticeships. Both trade unions argue that the recruitment of younger workers is problematic and requires the provision of good, stable jobs with meaningful work. To address this issue, they have been pressuring the federal government to develop a national strategy for the future of Canadian aerospace (IAMAW, 2019; UNIFOR, 2019). However, the aerospace industry does have several qualities that make it attractive to workers, as it is a high-tech industry that offers competitive salaries. In 2016, average hourly earnings were roughly $33 per hour—40% higher than the Canadian average (UNIFOR, 2016).

*Roughly **70%** of workers in the aviation and aerospace industry are **men**, and 26% are immigrant workers.*

Women** represent only **12%** of the workforce in trades, and roughly **20% of both scientific and technical staff.

12 Via interview data.
13 Their acronym in French is AIMTA.

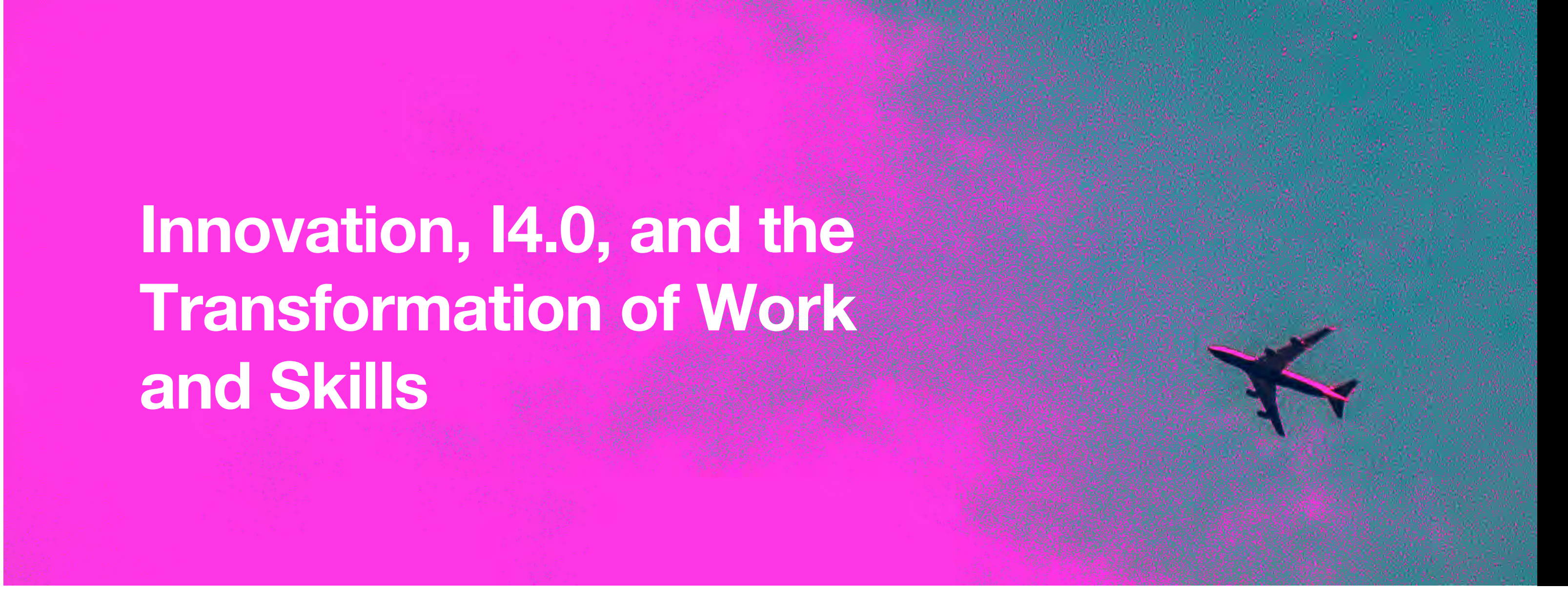
Looking ahead

The Canadian aerospace industry is still in a relatively good position, even in the context of the pandemic and other economic and financial hardships. These challenges will continue to place a significant amount of pressure on all labour market stakeholders—including employers, workers, and policymakers—but there are also other important trends that pose additional threats.

First, the concentration of Canada's industry in the commercial aerospace markets, as opposed to defence or space programs, significantly reduces access to federal investment; this contrasts with major competitors located in the USA, Brazil, or Europe. Business associations and trade unions have been arguing for a long time that the Canadian industry is at a comparative disadvantage, and have urged the federal government to invest more for the industry to compete at the same level.

Second, the acquisition of the C Series by Airbus—and, consequently, the withdrawal of Bombardier from the market of regional aircraft—has not only weakened the only Canadian anchor firm present in both Toronto and Montréal, it can also have a negative impact on Canada's employment potential and investment in R&D. As an illustration, the development of the Bombardier C Series, initially estimated at $3.5 billion, ended up costing nearly $6 billion (Dubuc, 2020).

Finally, the aging workforce—and Canada's difficulty recruiting youth to aerospace jobs—may reduce the capacity of the industry to make the shift toward I4.0. A successful transition will require not only investment in training, but also in the development of good jobs that offer meaningful and high-quality work.



Innovation, I4.0, and the Transformation of Work and Skills

This section draws on a combination of Statistics Canada data and qualitative data from our field work to examine the broader trends related to I4.0 adoption, identifying four stages that firms move through in their implementation of I4.0. The impact of I4.0 on labour markets, work organization, and skills are explored through the following questions:

> How are employment structures and occupations changing? What occupations are most affected by labour shortages?

> Are new technologies increasing worker autonomy and discretion over the organization of work? How are forms of control over work evolving? Is there an increase in monitoring and surveillance?

> How are the skill and competency requirements changing? Where are skills being upgraded and downgraded? What are the new skill requirements?

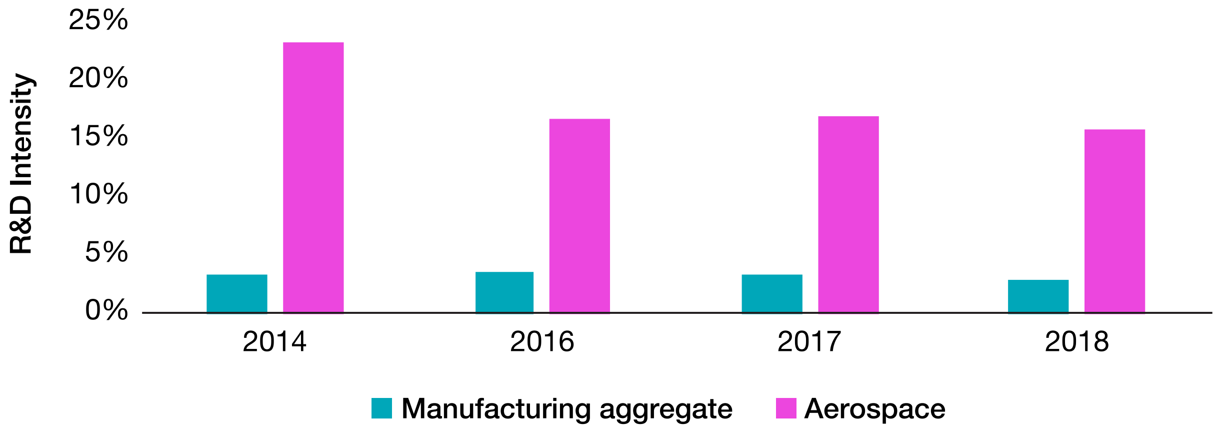
Technology and skills development in the Canadian aerospace industry

The global aerospace industry has a high dependence on R&D (Zhegu, 2013) and a high R&D intensity in comparison to other manufacturing industries. The industry is often perceived to be at the cutting edge of technological innovation (Hartley, 2014); however, the industry is not considered to be at the forefront in the adoption of I4.0. At a global level, some reports indicate that aerospace and defence firms are falling behind the curve in terms of implementing new technologies related to I4.0 and automation (Hader et al., 2018).

There are various reasons given for this underinvestment in emerging technologies. In some accounts, firms have reported being unsure of which areas of business the new digital technologies can be applied to and how to apply them (Hader et al., 2018). Other barriers slowing adoption rates

FIGURE 6

R&D intensity in aerospace versus manufacturing industries in Canada



Note: "Manufacturing aggregate" refers to the Canadian manufacturing aggregate (across all manufacturing industries), while "Aerospace" refers to the aerospace industry (NAICS code 3364).

Source: Authors' calculations completed for this study based on data from Statistics Canada for GDP (Statistics Canada, 2020a) and manufacturing R&D figures (Statistics Canada, 2020d), as well as data from ISED and AIAC for bespoke R&D figures (ISED & AIAC, 2015; 2017; 2018; 2019).[14]

include stringent safety regulations and associated compliance certification, as well as the immaturity of certain technologies such as artificial intelligence (AI) (Russell et al., 2019). Many of the major firms in the industry are not currently using the more radical or fundamental applications of I4.0, including the deployment of new business models (Hader et al., 2019). When adopted by firms, I4.0 technologies are predominantly being applied to improve existing processes within factory manufacturing and supply chain management (Hader et al., 2018). Additionally, there have been some applications of I4.0 in automated solutions and big data among Tier 1 suppliers, related to the profitable and growing aftermarket services segment (Deloitte, 2020).

The Canadian aerospace industry is important in Canada not only because the industry is a large contributor of GDP, but also because the industry makes large investments in innovation activities. These contribute to the wider Canadian innovation system and create highly skilled jobs. Firms in the Canadian aerospace industry collaborate with a variety of actors for R&D, including academia, government, other firms, suppliers, and customers (ISED & AIAC, 2018). Aerospace firms collaborate at a significantly higher rate than the manufacturing average: over three times higher with academia (73%) and two times higher with government (39%) (ISED & AIAC, 2019). In 2019, R&D investment for the Canadian industry was calculated at $1.4 billion (ISED & AIAC, 2019). As an industry, aerospace's R&D intensity[15] has remained significantly high—at least 15% more than

14 To produce comparable figures from industry publications, we used bespoke R&D figures for aerospace. The GDP figures were compared with the R&D figures from the same year of release, as per the formula utilised by ISED & AIAC (2015; 2017; 2018; 2019).

15 R&D intensity refers to the ratio of R&D investment to GDP for the industry.

the manufacturing average of 3% since 2014 (see Figure 6). In part, this is likely due to a combination of factors, including the industry's acquisition or integration of new technology, the development of new products such as the C Series, and the incremental innovation associated with the modular nature of this mature industry (Industry Canada, 2013).

I4.0 adoption

Aerospace firms (NAICS code 3364) in Canada are almost twice as likely (29% vs. 15%) to be involved in developing new technologies than the manufacturing average (Statistics Canada, 2014). Statistics Canada (2014) data indicate that they do so through partnerships, either with academia (15% for aerospace vs. 4% for the manufacturing average) or with the private sector (11% vs. 5% respectively). A recent Statistics Canada report focused on robotics[16] notes that between 2014 and 2017, adoption of robots has rapidly expanded beyond the automotive industry to a wider range of manufacturing and service industries in Canada (Dixon, 2020). Geographically, adoption is concentrated around major cities, including the greater areas of both Montréal and Toronto.

While there are no direct metrics on rates of I4.0 adoption in the Canadian industry, there are indicators of the diffusion of technologies associated to I4.0. Many of these I4.0 technologies are referred to as "advanced"—which firms adopt piece by piece without fully embracing the concept of I4.0—while some are considered to be "emerging" technologies. Figure 7 displays data from 2017, which indicates that all the technologies featured are more widely used in the aerospace industry than the manufacturing average, though the gap varies by type of technology.[17]

Aerospace firms in Canada *are almost twice as likely* ***(29% vs. 15%)*** *to be involved in* ***developing new technologies*** *than the manufacturing average.*

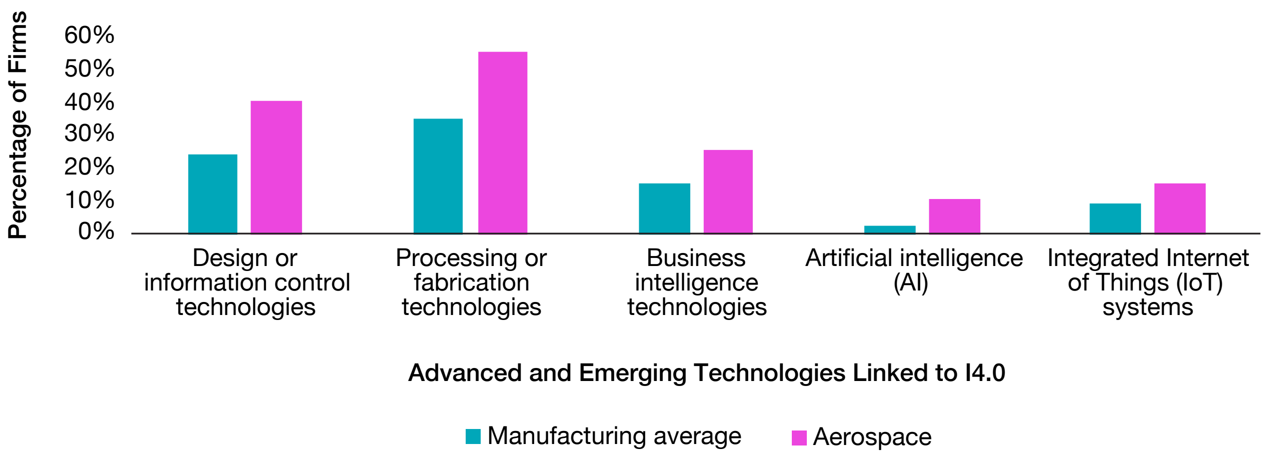
A recent Statistics Canada report focused on robotics notes that between 2014 and 2017, ***adoption of robots has rapidly expanded beyond the automotive industry*** *to a wider range of manufacturing and service industries in Canada.*

16 We refer to pre-I4.0 infrastructure as "Industry 3.0" (I3.0).

17 For full definitions, see ISED and AIAC (2019).

FIGURE 7

Use of I4.0 advanced and emerging technologies in manufacturing and aerospace in Canada



Note: "Manufacturing average" refers to the Canadian manufacturing average (across all manufacturing industries), while "Aerospace" refers to the aerospace industry (NAICS code 3364).

Source: Statistics Canada (2017).

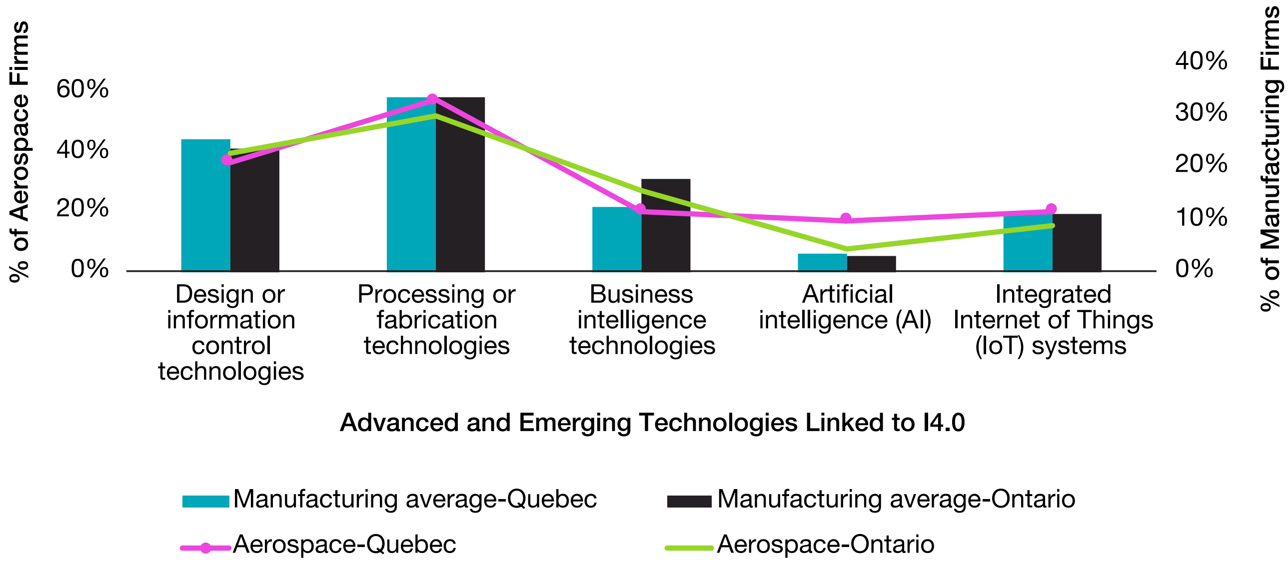
Some of these advanced technologies (e.g., processing or fabrication technologies) are widely utilized, with 56% of aerospace firms incorporating technologies such as computer numerical control (CNC) machining, additive manufacturing, and robots. For design and information control technologies, the figures indicate that, at most, 41% of firms have an enterprise resource planning (ERP) system (or a sensor network) to collect data from their machines. Furthermore, 26% have reported using business intelligence technologies, such as real-time monitoring and data displays for decision-making. This figure indicates that, at most, a quarter of firms have the technological infrastructure capable of operating a fully virtual factory. Finally, only 16% report having an internet of things (IoT) ecosystem operating, and just 11% use AI.

At a provincial level, adoption of the advanced and emerging technologies needed for I4.0 are similar for firms in the aerospace industry in both clusters (see Figure 8). Only two technologies demonstrate a 7% or higher provincial utilization gap: 1) business intelligence technologies, such as real-time monitoring and leveraging data for decision-making, which are used more widely in Ontario; and 2) artificial intelligence, which has been adopted more by Québec firms.

One report addressing I4.0 adoption in the Montréal cluster (CAMAQ, 2016) is quite consistent with these figures. Among the 163 aerospace firms that responded to the questionnaire, 47% have implemented a ERP system; 42% have an HR business intelligence system; 26% have robots; 19% have introduced a system of big data; 13% have implemented additive manufacturing; and 10% have implemented IoT (CAMAQ, 2016). These figures suggest that there is significant variation between firms in terms of the adoption of I4.0 technologies.

FIGURE 8

Use of I4.0 advanced and emerging technologies in Québec and Ontario



Note: "Manufacturing average" refers to the Canadian manufacturing average (across all manufacturing industries), while "Aerospace" refers to the aerospace industry (NAICS code 3364).

Source: Statistics Canada (2017).

Our qualitative data mirror these broader tendencies, highlighting that many firms—both large and small—have not begun to adopt any of the I4.0 technologies. These firms either do not see the relevance of adopting these technologies, do not have the resources and capacity, or have a niche that is secure enough to reduce pressure to implement I4.0. Some firms are clearly engaged in implementing I4.0, but at varying paces. Drawing on our qualitative data, it is possible to distinguish four stages of development in the shift toward I4.0, as illustrated in Figure 9.

Capturing and formatting data

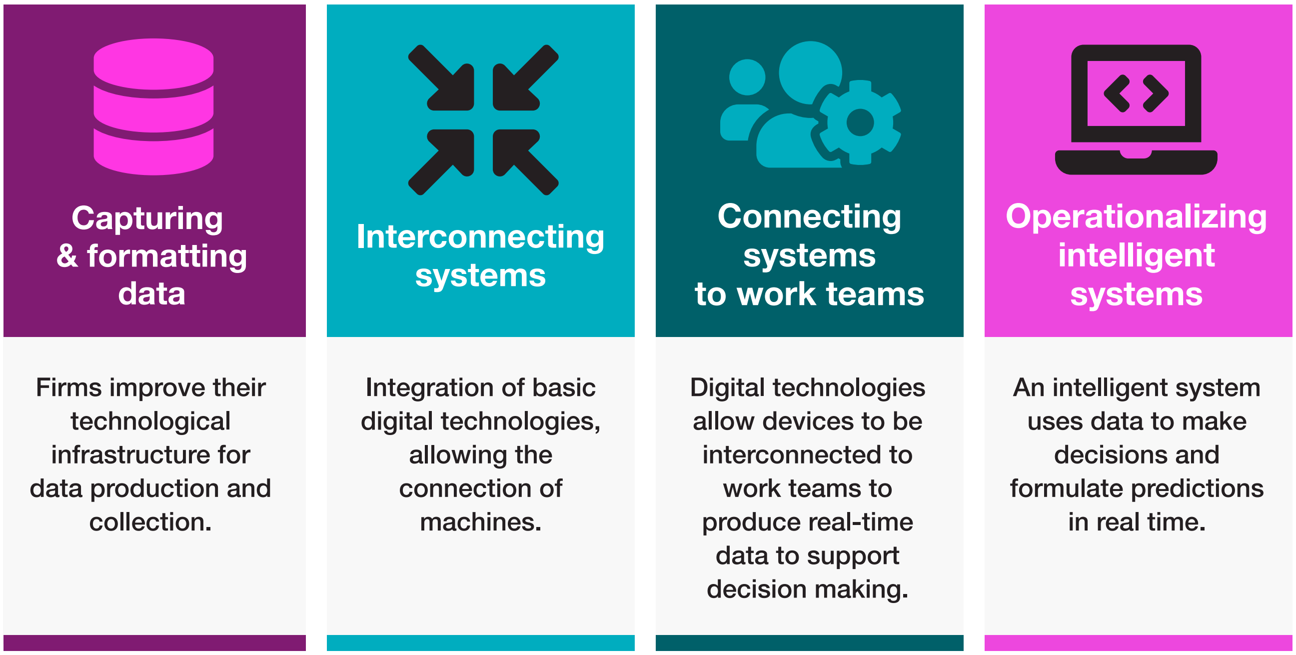
These firms are at the I3.0 stage of the implementation process but are implementing these technologies as part of a strategy to move toward I4.0. These beginning stages typically consist of firms improving their technological infrastructure, such as by purchasing robots, ERP systems, and sensors, or improving data production and collection. At this phase, firms generally have problems with the reliability of the data that they have gathered:

The machines can give us data on tool wear. For example, when to change and measure them, and adjust them automatically. That's already a big, big challenge. It's not easy to do that… I still have trouble connecting certain things. I don't have the real data. So, for example, the machine—it tells me it's running. I go to the floor, and it's stopped.

—MANAGER, SME, MONTRÉAL

FIGURE 9

I4.0 progression: Firms transition in a non-sequential manner



Source: Created by authors

Interconnecting systems

This phase is based on the integration of basic digital technologies that enable the connection of machines. These include digital control computers, touch screens, computer servers, and other management software (e.g., ERP, and manufacturing execution systems). This step allows machines to generate data related to, among other things, their productivity and/or operating status. Automated control also reduces manual data entry, but the data is not integrated or linked to decision-making. One of the major issues in this phase is data analytics. Firms generally gather a large amount of data, but experience difficulty in processing them:

The data exist, but we just don't use a tonne of it right now. So really, we have to spend more time using our data and acting on it… Once you know what you're looking for, then it becomes more attractive to pull the data out of the machine, or sometimes to create the data, because it's there, but it's not really made use of.

—MANAGER, SME, TORONTO

Connecting systems to work teams

This phase results in the interconnection of automated systems and work teams. New digital technologies (particularly process control systems and IoT) enable technological devices to be interconnected, allowing work teams to have real-time data at their disposal to support decision-making. This interconnection of technologies within the plant can also be coupled with an external integration dimension by directly connecting machines to suppliers and customers:

Enterprise synchronization is something big within [the firm] now… if you synchronize activities between those organizations, you can execute faster, but you can also leverage data between organizations better. So again, it's about competitive advantage. Data is the enabler. Data and the whole digitization of the data, so that the data isn't going through people—it's going through systems.

—MANAGER, LARGE FIRM, TORONTO

Operationalizing intelligent systems

The fourth phase refers to the operationalization of an intelligent system that processes the generated data to make decisions and then formulates predictions. These can be analyzed either by work teams or by an algorithm with autonomous decision-making capabilities. These decisions guide the actions of the machines, giving workers a primarily monitoring role. The responsibility of production managers and employees therefore lies in ensuring the optimal functionality and operation of the system when a problem arises:

Each machine has a control. We have people with different functions— supervisors, programmers, machinists—and we have programming systems like ERP and quality systems. All these systems, we direct them to a central office. The central office has a database; there are servers, applications, algorithms, analyzers. And analyzing that [data] gives feedback to all the different functions. I mean, it goes both ways… Everybody comes to talk to each other. So, it's really the interconnection between the different systems to use the data that's available.

—MANAGER, SME, MONTRÉAL

These observations from quantitative and qualitative data show ***significant variation in the stages of adopting I4.0****. While many firms are not even at the starting line, others are fully engaged.*

These observations from quantitative and qualitative data show significant variation in the stages of adopting I4.0. While many firms are not even at the starting line, others are fully engaged. Looking ahead, some of these firms will be operating a virtual factory, as they consider whether to alter their business models.

Some aerospace firms are even monetizing the data they produce, with the owners describing their firms as “IT firms,” as opposed to machine shops or component manufacturers. In between these two extremes, we find firms at different stages, with many of them building their digital infrastructure to capture and organize relevant data. Firms are transitioning

between stages in a non-sequential way (see Figure 9), often moving back and forth between the various stages. For example, a firm may move straight from data capturing and formatting into operationalizing an intelligent system. How firms move through the stages—and the time they spend at each point—depends on the scope of their I4.0 project.

One of the more difficult challenges, even for firms advanced in I4.0 adoption, is the incompatibility between different systems (e.g. product data managers and ERP).

One senior manager talked about having to “massage data to make things work.” This highlights how, to fully realize I4.0 and its promise of interconnecting systems, there needs to be work at an industry level to develop compatible architecture that supports this process. Without further coordination, I4.0 will not occur everywhere in the same way, nor at the same pace. Thus, its effect on work and the skill profile of the workforce will vary to the pace and trajectories of the I4.0 projects, which can range from ambitious to fairly limited in scope.

I4.0, the future of work, and skills

What will work look like under I4.0 in the Canadian aerospace industry? Will I4.0 augment and complement worker tasks and improve worker skills, or will it erode them? Can I4.0 create opportunities for the deployment of multi-skilled workers who master technology and data management, or will the whole workforce, from the managers to shopfloor workers, be governed by numbers? This section draws on quantitative data from various reports, and qualitative data gathered from managers and shopfloor delegates to explore these questions. Narratives from managers and shopfloor delegates share many commonalities and consistencies around the evolution of work and skills in the industry. They also contain some divergence, reflecting sources of contention about the meaning of work and skills under I4.0.

It has long been understood that the deployment of new technology and its implementation is a social process as well as a technical process, involving negotiation and compromise between workers, managers, technical, and scientific staff. It is also well-recognized that there are complementary relationships between types of technology, work organization, and skill deployment (Brynjolfsson et al., 2019). Investment in new technology can contribute to firms' performance, particularly when complementary changes in work organization and skills are made (Bresnahan et al., 2002). To examine the trajectory and impact of I4.0, this section draws attention to the importance of the intersection of labour market trends, work organization, and skills evolution.

Labour market trends

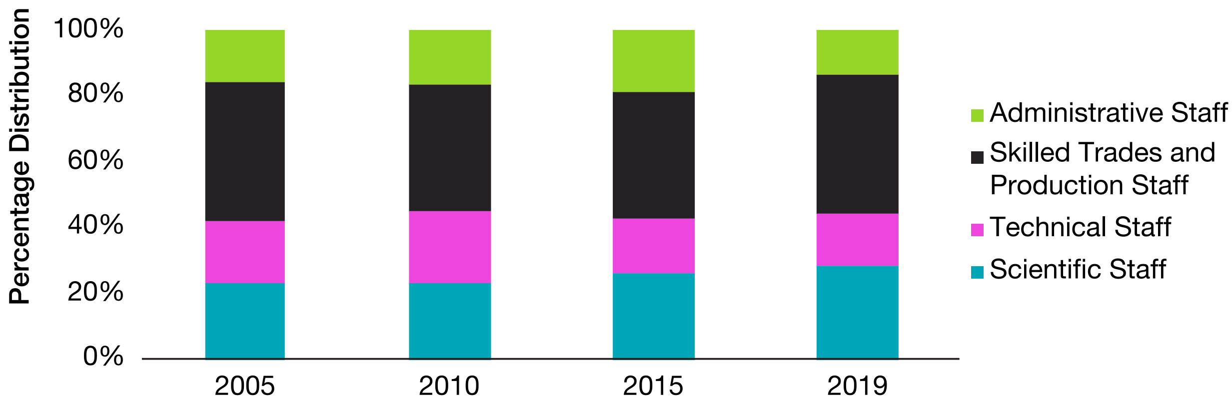
Until the COVID-19 pandemic, employment in both Ontario and Québec was increasing steadily. Although there is little data available at the national level by occupation, data from Québec shows that the aerospace industry employs a high-skill workforce. In 2019, over 40% of the workforce belonged to scientific or technical staff, and among the craft workforce, which represents roughly 40% of the total, 9 out of 10 workers had a qualified trade (CAMAQ, 2020, p. 7).

As highlighted in Figure 10, over the last 15 years, workforce composition has remained fairly stable in terms of percentage, with small changes occurring between 2005 and 2019 (CAMAQ, 2005; 2010; 2015; 2019). The trade category has only slightly decreased, while administrative staff and technical staff have decreased more significantly over the period. The only category that has increased is scientific staff. Additionally, the emergence of other occupations—such as cyber security technician, I4.0 analyst, and I4.0 integrator—although only relevant to a smaller percentage of firms, do indicate the ongoing impact of adopting I4.0.

It is clear that the demand for highly skilled occupations in the industry remains high. Québec has been gathering information on the evolution of the labour market, but over the last few years it has also provided data on labour shortages (CAMAQ, 2018;

FIGURE 10

Distribution of jobs by staff category in the aerospace industry in Québec



Source: Data gathered by the authors from CAMAQ (2005; 2010; 2015; 2019) reports.

2019; 2020).[18] These data suggest that machinists and programmers (both CNC and conventional) are the most difficult occupations to recruit: over 40 firms report that they are struggling to recruit this category of worker. There has also been increased difficulty in recruiting aircraft maintenance technicians, as well as electrical, electronic, and avionics engineering technicians. Some firms are also recognizing that they face challenges in the recruitment of aerospace engineers and IT employees.

There is less available data on workforce shortages in Toronto. A recent CCAA occupational standards report (CCAA, 2020)[19] focused on which occupations are seen as the most relevant in Ontario. This study indicates that firms consider all of the workers referenced above—particularly aerospace manufacturing technologists and CNC operators—either relevant or very relevant to their operations.

Several reports show that the Canadian aerospace industry has seen demand for labour outstrip supply (CCAA, 2018). While the COVID-19 pandemic is likely to continue to impact projected growth, prior to 2020, firms had been reporting labour shortages in several occupations. Many of these are shopfloor occupations, traditionally entered through some form of vocational education and training (VET), while some are technical or science occupations in both traditional and emerging fields (e.g., IT and data-oriented occupations). The more traditional occupations include CNC machinists, assemblers, technologists, non-destructive inspection technicians, the skilled trades, and engineers of various specializations. This was a recurring theme in all our interviews, both in Montréal and in Toronto. One SME manager in Toronto expresses the problem as follows:

18 See Table 5 in Appendix D for a breakdown of these data.

19 Our thanks to the CCAA for allowing us to use data from the report, which is not yet released.

*Firms continue to report **labour shortages** in occupations such as information systems analysts and consultants, computer network technicians, computer programmers, and software engineers and designers.*

[It's] very difficult [to recruit]. Especially in the machining areas, we are seeing the same problems as most other manufacturers. When you go to an industry conference, it's "front and centre."

—MANAGER, SME, TORONTO

This problem is not restricted to SMEs. Large firms are also confronted with the issue of recruiting machinists, and this shortage seems to favour investment in new technology:

It's hard to find good machinists… we always have [a] couple of years where we are struggling to find people that have that skill set. And that may be part of the driver of why we're moving toward the more automated solutions

—MANAGER, MULTINATIONAL COMPANY, TORONTO

The new occupations are related to data specializations, including data analysts and data scientists. Firms continue to report labour shortages in occupations such as information systems analysts and consultants, computer network technicians, computer programmers, and software engineers and designers (CCAA, 2018). An SME manager in Montréal describes the problem as follows:

Sometimes we have to find ways to get the data. It takes data architects… and I would say that these are very, very, very rare; very, very rare resources

—MANAGER, SME, MONTRÉAL

In addition to shortages in certain new occupations, industry surveys report a gap—or "skills mismatch"—between the skills that graduates have and the skills that firms need, due to "rapid technological advances" (CCAA, 2018). One production manager describes the difficulty as follows:

We're having a hard time finding people that have the crossover skills. Both IT and manufacturing engineering… they are skilled with technologies and have gone through school for manufacturing engineering. So, by coincidence they have both skills, and they are able to adapt. But it's not something that's taught… You can't go to a school and say: "I need somebody that has both these skills"… It's hard for us to fill those roles.

—MANAGER, LARGE FIRM, TORONTO

What is apparent from these data is the relative stability of the occupational structures within the aerospace industry. This may be related to the fact that the implementation of I4.0—as we discussed in the previous section—is being rolled out more slowly in practice than predicted (Stanford, 2020). It may also be linked to the fact that the full effects of I4.0 will not be realized until waves of complementary innovations are implemented (Brynjolfsson et al., 2019).

What becomes clear is that there is a need to consolidate critical traditional and emerging occupations, in order to position the Canadian aerospace industry for the challenges of the 21st century. Traditional skills, such as those of the machinist, are still important to the industry and require a more robust pipeline of new workers to fill shortages. Yet we are also seeing the emergence of new occupations related to data management, as well as hybrid occupations at the intersection of IT and manufacturing processes, which are integral to the future of Canadian firms.

Transformation of work organization

In the aerospace industry, there have been important changes in the ways that work is organized, but also much continuity in manufacturing processes. In most factories, you still find the "method agents" who prepare the work, the "machinists and operators" who do the work, the "inspectors" who review the work, and so on. These workers perform different tasks requiring various trades, knowledge, and training.

With the implementation of I4.0 and the integration of new technologies, there are associated processes of unbundling, re-composition, and hybridization of tasks both within and across various occupations. For example, in several firms, the function of inspection has been partly automated:

It's basically a robotic arm that will do an inspection of parts. So instead of having a human inspect something, this robot is equipped with all sorts of cameras and sensors to be able to do that inspection. For sure, now they're not at the point where they can actually do the inspection of a human. But it's getting there.

—SHOPFLOOR DELEGATE, LARGE FIRM, MONTRÉAL

The integration of robotics and automating technologies can also eliminate repetitive tasks, such as riveting or other work that is difficult and physically strenuous. One example is a series of "robotics modules" that the mechanic can put together to reach inside an airframe while remaining outside the structure, thus preventing tiredness and injury:

It's a reconfigurable robot.... it's a human hybrid with the automation, and they're not getting tired. Because they're on the outside, and they can play all day with this thing. And it actually becomes quite fun.

—MANAGER, LARGE FIRM, TORONTO

Closed-door machining and automated solutions have also increased production cycles, reduced the number of setups, and increased the number of machines that a worker can operate. These changes have had a significant impact on both the configuration of tasks and worker discretion—two important dimensions of work organization (Bélanger et al., 2002).

Another dimension of work impacted by I4.0 is surveillance and the role of supervision. Traditionally, frontline supervisors have often been former skilled machinists, and their role has required a deep understanding of the machining process. Under I4.0, we see a shift from in-depth knowledge about machining and manufacturing processes, to extracting and analyzing data. This shift from tacit knowledge about operations to extracting and analyzing data comes with its own challenges. Supervisors now need to understand and use statistics effectively, as highlighted by a production manager:

You have to be able to extract data, know how to ask people to extract the data you need, and then analyze it. And analysis is a skill, and sometimes it's difficult to teach. So that's where we're going to struggle.

—MANAGER, LARGE FIRM, TORONTO

In their narratives, both managers and shopfloor delegates acknowledge that supervisors have at their disposal various technological devices—e.g., laptops, tablets, or phones—which enable them to monitor production in real time and at a distance. Workers recognize that almost everything is digitally controlled and interconnected, and that the level of data management and collection has increased. This quote from a shopfloor delegate underlines the changes in the way data are gathered and analyzed:

It puts a challenge on everyone, because now people are able to monitor all the time it takes us to do a specific task; whereas we used to be able to take the time it took. They wrote it down on a paper—they probably had someone in an office somewhere compiling all this data, manually. Now they have everything done with computer, so it's a lot easier for them to try and put pressure [on workers]… to work faster, to get the job up quicker.

—SHOPFLOOR DELEGATE, LARGE FIRM, MONTRÉAL

In such a context, the supervisor role is to ensure that the recommendations generated by the system are enacted. This "digital supervisor" dictates the processes, the time they require, and the steps they should take; its role is to ensure that shopfloor workers follow these expectations. Some business managers even envisage that the role of human supervisors may become redundant:

Because humans need to be controlled, and processes need to be controlled. Doing that… that's quite a job. So the idea is, we want to eliminate [the human]; we want to put a digital supervisor... When I know that a setup takes 15 minutes, well, I'd need George at the machine at 8:00 so he has his game plan ready. [But] the machine [already] has his game plan. Everything is digitally synchronized.

—MANAGER, SME, MONTRÉAL

In this new configuration of work organization, the supervisors manage by data and numbers. Yet one of the major challenges that emerges—especially with supervisors hired without shopfloor experience—is that they do not have the in-depth knowledge of machining or manufacturing processes. As a result, some supervisors appear to lack the capacity to intervene on the shopfloor, or to engage in complex problem-solving, so decision-making becomes more centralized (e.g., in engineering departments).

Machinists report becoming increasingly frustrated after being given instructions from the engineering department that were ineffective, stating that supervisors did not always have the capacity to intervene or come up with alternatives. Workers argue that supervisors follow more "what the tablet says to do, than the guy who has experience and has been working for 20 years in the industry" (Interview with shopfloor delegate, large firm, Montréal). Managers in both Montréal and Toronto recognize that it is difficult for firms to find or develop supervisors with both manufacturing knowledge and data analytics expertise.

With these new technological devices, employee performance can be monitored, measured, and compared in more intensive ways. "Labour time" remains a fundamental focus of attention for supervisors. However, with these new technological monitoring devices, "slack time" has been shortened and work cycles tightened, reducing the opportunity for workers to cope with the unexpected. Time pressures can then produce unintended behaviour:

Given the cycle time we have, there is no room for repair. You have pressure to do it right, fast, and without mistakes. If you make a mistake, you try to find room to repair it, but you don't have time for that. It encroaches on your production time, and so you try not to make mistakes and it creates coverups. There are workers sometimes who want to hide it, because they're afraid they won't make their time.

—SHOPFLOOR DELEGATE, LARGE FIRM, MONTRÉAL

Data management increases time pressure while increasing opportunities to standardize work performance. A manager from an SME explains how data management has helped his firm to develop job descriptions that leave little space for deviation:

So, we build the entire referential [repository] to be able to retrieve the data—to make the link with all the data in our entire system. So, the employee is guided to that… [and that's] really a unique working model.

—MANAGER, SME, MONTRÉAL

This process of worker monitoring and work standardization often comes with a reduction in worker discretion. In both manager and shopfloor delegate narratives, it is recognized that workers have less control over their work—both individually and collectively. This quote from a machinist is quite representative of a more general trend of the impact of I4.0:

[As a machinist] you can make fewer decisions than before... you get cut off. Decisions have to come from the supervisor or the engineering department

—SHOPFLOOR DELEGATE, LARGE FIRM, MONTRÉAL

This reduction in workers' control over their work is acknowledged by both managers and shopfloor delegates; however, its impact is assessed differently. For some managers, this is the only way to increase the efficiency of the process, because human decision-making is seen to be inefficient:

Anything you can take away from a human's decisions, you have to take away from him... We are [still] asking the human to make decisions, [but] the human is not good at making decisions.

—MANAGER, SME, MONTRÉAL

In contrast, shopfloor delegates argue that the absence of a strong collective and individual worker voice—with influence in the implementation of technological change—undermines the logic of the manufacturing process, and results in decisions that are not adapted to the reality of the shopfloor. These contrasting assessments of managers and workers reflect sources of contention and power dynamics in the workshop around each other's role in decision-making processes:

The big mistake they make when they implement technological changes: most of them don't consult workers on the shopfloor. They make mistakes because they come up with proposals that don't work. When you put it into practice, and they come in to apply it on the shopfloor, the workers say, "What did you do there? This is not good for us." And then they stubbornly try make it work, because they have statistics.

—SHOPFLOOR DELEGATE, SME, MONTRÉAL

The picture that emerges from these narratives is that under I4.0, work is being reorganized and restructured in various ways. Although the implementation of I4.0 does not affect all workers and does not affect them all in the same way, several general trends stand out: 1) an increasing sophistication of monitoring devices, 2) an increase in work standardization, and 3) a reduction of workers' collective and individual control over work. Historically within the industry, a very different form of work organization has evolved, relying on tacit knowledge and skill. In direct

*This process of **worker monitoring and work standardization** often comes with a reduction in worker discretion. In both manager and shopfloor delegate narratives, **it is recognized that workers have less control over their work**—both individually and collectively.*

contrast, I4.0 builds upon processes of standardization and the codification of tacit knowledge and skill. Hence, the implementation of IT systems to capture data and monitor work activities introduces a significant shift in control mechanisms.

Within I4.0, for both managers and workers, standardization processes create a form of "governance by numbers," where the rules come from an impersonal source that is self-sufficient and functions without human intervention. However, the control mechanisms underlying governance by numbers are not flawless, requiring human intervention to ensure their smooth operation. Nor does I4.0 occur everywhere in the same way or at the same pace, so its effect on work and the skill profile of the workforce will vary. As will become apparent in the next section, one common challenge is how to fuse the old system of organizing work with I4.0. This is incredibly important, as the choices that firms make in transitioning to I4.0 will directly impact the future skills needed by their workforce.

Evolution of skills

At this stage, it is difficult to assess with certainty whether I4.0 augment, complement, or degrade worker tasks, and if it will improve worker skills or erode them.

Although it may be expected that I4.0 will impact most occupations, this section focuses on the machinist—a trade occupation that is central in the dominant forms of work organization within the aerospace industry. We will examine how I4.0 shapes the processes of unbundling, re-composition, and hybridization of machinist tasks, while also exploring how these processes impact other occupations (e.g., operators and data analysts). Traditionally, machinists have been described as "craftsmen," and are equipped with the skill set required to prepare the work, make setups, do edits on the machine's programming, and resolve problems with individual machines as they arise. One machinist describes his work as follows:

Before pushing the button, everything has to be in the right place. Everything has to look good. That's what we call a machinist. You'll never be able to remove him, unless it's a robot doing it, but then again, I doubt that's going to happen in the very near future.

—MACHINIST, LARGE FIRM, MONTRÉAL

In some workplaces, machinists have a lot of leeway in how they organize their work day:

If I'm doing a job and I know I have five different pieces… it's kind of the same job, but not in the same book, you know? [The information is] separated in different books. So if I took those three books, I can plan my day, and say, "Ok, I'm going to do all those things together, even if they're not in the same book." So it's going to be faster.

—MACHINIST, LARGE FIRM, MONTRÉAL

The movement toward I4.0 can lead to several trends that affect machinists' work and skill requirements: "job enrichment," which means more complex tasks are integrated into their work, resulting in upskilling; "job enlargement," where tasks of similar complexity are added, resulting in a reduction in the depth of skills and an increase in the breadth of skill sets; or "job degradation" where complex tasks are removed, resulting in a form of deskilling.

This movement of unbundling and re-integrating tasks can follow different trajectories and take various forms. Yet most firms fit somewhere in between two broad scenarios, which can be depicted and visualized at each end of a spectrum. In the first scenario, machinist jobs are enriched with more varied and complex tasks, including more autonomy to control the pace and sequence of work. These machinists are what we label "super machinists." In the second scenario, the tasks previously undertaken by the traditional machinist—such as programming and setups—are transferred to IT or data analysts, whose jobs are enriched. In both of these scenarios, the super machinists and IT or data analysts see their jobs *enriched*; whereas the majority of other machinists and operators see their job instead *enlarged* through the broadening of tasks of similar complexity, or *degraded* through a reduction of the scope and complexity of tasks. Figure 11 sketches out the trajectories of these two scenarios.

SUPER MACHINIST

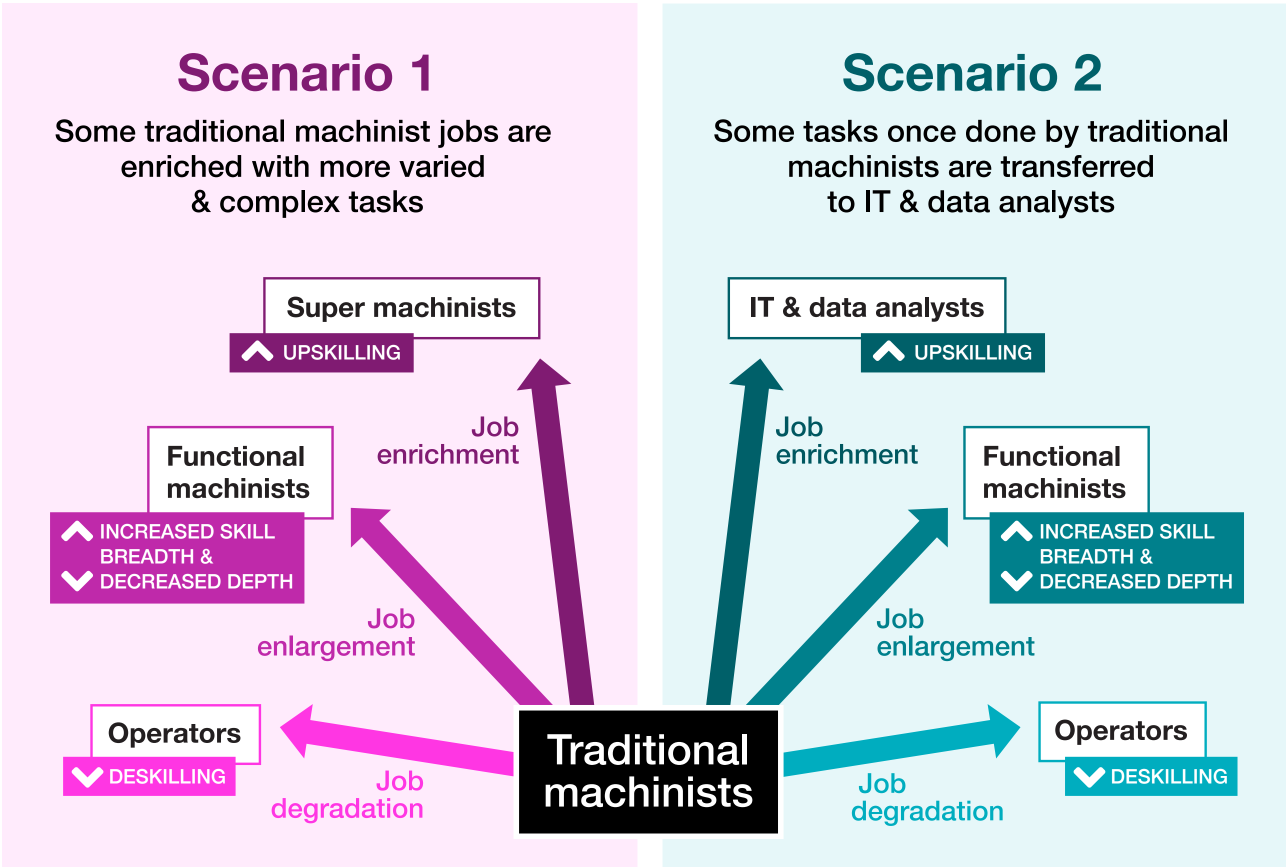
Previous technological shifts have moved machinists away from craftsmen who manually make the part, toward a profile where they master the technology and can undertake more complex tasks. One manager described these shopfloor workers as "machinists who think":

There's lots of demand for general machinists that have their Red Seal certificates, so that have gone through the apprenticeship program and are certified machinists… especially in our area, we're really IT savvy… We are looking for people who do full, complete setups; who can do minor programming edits; [and] who can take their machine and own it, with the tolerances that we need.

—HR MANAGER, LARGE FIRM, TORONTO

FIGURE 11

The transformation of the traditional machinist job



Source: Created by authors

With this technological shift of I4.0, firms are enriching some jobs, and we see the emergence of super machinists, who develop into subject-matter experts in relation to the new technology. In this case, the machinist is responsible for developing, editing, or writing complex code for automated machining, as well as testing longer run cycles. In other cases, firms were training their super machinists as programmers rather than recruiting people externally, who may lack shopfloor experience.

In some firms, super machinists become "cell captains" responsible for small teams, as well as the setups for the machines. These cell captains log on to the virtual factory to determine which jobs that their teams need to work on, while the machinists under them use the system to visualize the production process:

A "cell captain" will set up his section for the day… depending on the information that the guys need, they can go in and take a look at what tooling is required… So you can go in and see what that looks like; you can look at the part number, and look at the part drawing.

So we've used this type of technology to try and go to more of a visual explanation. Not only does this help with any skill gaps that we may have, but it also helps with language gaps.

—MANAGER, SME, TORONTO

This shift toward new digital skill sets raises challenges for firms, in terms of how they upskill their machinists. Teaching machinists to analyze and use data is considerably more difficult for firms, as it requires more in-house training and development; however, it does have the benefit of cultivating deeper problem-solving skills among shopfloor workers and developing cell captains who command respect due to their shopfloor experience. Overall, these shifts in machinist skills are clearly a form of upskilling, but in the Montréal and Toronto clusters, upskilling remains restricted to a minority of machinists.

IT AND DATA ANALYST OCCUPATIONS

Technical and scientific occupations such as technicians, programmers, methods agents, and engineers are also being transformed. The importance of these employees has grown substantially on the shopfloor in recent years. There are two dominant trends for these occupations: job enlargement and job enrichment:

The skill set is a lot higher. No longer is it no education or high school education—you've got to have a secondary type of education. And there are a lot of engineers. Whereas before the shopfloor would be a technical school-type training, now it's the engineer level on the shopfloor. So it's a definite shift.

—MANAGER, LARGE FIRM, TORONTO

Some of this transformation is directly related to the new technologies themselves (e.g., robots, automation, sensors, ERP). Engineers, technicians, and methods agents are seen to be the specialists and leaders of these technological changes. Technical staff are often seen to be responsible for designing and overseeing the implementation of new technologies—they are expected to not only plan adoption, but also to train and coach others in their operation.

I4.0 is also driving firms to hire staff with digital-related profiles and data specializations, such as data analysts; scientists and architects; information systems analysts; computer network technicians; computer programmers and software engineers; and designers. The demand for these occupations comes from the digitization of manufacturing, which requires the extraction, analysis, and application of data:

What I think companies often neglect, when they get into all these little Internet of Things projects… [is] the digital infrastructure able to take it? That means the server [and] the way it handles data security, data backup… it all adds up. Your data science becomes extremely important. You've got millions and millions of pieces of data, and sometimes it's not structured that way… [So we've hired] a lot of programmer-analysts.

—MANAGER, SME, MONTRÉAL

***Technical staff** are often seen to be **responsible for designing and overseeing the implementation of new technologies**—they are expected to not only research and plan adoption, but also to train and coach others in their operation.*

Some firms have siloed these new occupations alongside their more traditional technical occupations. By doing so, more control over the actual manufacturing process is given to programmers and technical staff, while the the job of the traditional machinist is deskilled:

You need fewer people with a qualification. The word "average" is not good, but maybe a little less skilled trades, just like machinists. All the people who had a lot of know-how, and who were in the plant, and who applied their knowledge… it seems that this knowledge is moving to more [of the] programming, engineering, IT layer. [You take] your part, you design it, and then you make it almost virtually.

—MANAGER, SME, MONTRÉAL

One of the problems with this division of work is that programmers and other technicians do not always have in-depth machining knowledge, which may prevent them from effectively solving problems. Centralizing decision making within these technical occupations can result in machinists and shopfloor workers becoming frustrated when the decisions made by technicians do not solve the problems encountered on the shop floor.

Often in I4.0 companies, there are almost no machinists, and the person who does the programming doesn't even know how to make parts. They don't even know the raw material. They just add numbers. That's what is really changing... Machinists are artists, they are craftsmen… [IT analysts have] another vibe. They want to have a free spirit.

—MANAGER, SME, MONTRÉAL

Some firms, rather than centralizing decision making with technical occupations, choose an alternative form of work organization through the "hybridization" of skills sets. One firm referred to these as "crossover skills" in manufacturing, engineering, and/or engineering technologists. This combination of traditional manufacturing and IT skill sets are sometimes grouped together as "mechatronics"—a combination of mechanics, electronics, automation, and real-time computing.

Another strategy that some firms adopt is a type of "buddy" system. This entails recruiting new engineers with no experience and pairing them with manufacturing engineers who understand the production process extremely well. Through this arrangement, new engineers are then able to design new processes and products for the firm more effectively:

We've been hiring a lot of people, probably at least 50 in the last two years, in data specializations. They don't know what [the company products] are. They don't know how to design [them]. What they do know is how to interpret data, how to look at [company] data from the field. [And] also how to analyze customer data, analyze trends… [determining how] you develop features that you can sell to customers and operators.

—MANAGER, LARGE FIRM, TORONTO

Technical and scientific staff have grown in importance, particularly those employees with new digital skills. These range from the setting up of infrastructure (e.g., cloud computing systems) to programming and software development—including data gathering and analysis, as well as skills related to the use of engineering software.

One major issue lies in patterns of relations on the shop floor. When firms choose to keep IT and data analysts siloed, while broadening yet decreasing the skills of machinists, tensions can arise on the shopfloor. Workers often resist sharing their tacit knowledge and know-how about the actual manufacturing processes in order maintain some form of autonomy and control over their work, while IT and data analysts also seek to impose their expertise over the digital process. These types of tensions are not exceptional in the world of work, but the form they take in aerospace firms has evolved under I4.0.

FUNCTIONAL MACHINIST AND OPERATORS

What becomes apparent in the move toward I4.0 is the process of deskilling of many machinists. The expansion of closed-door machining and automation has resulted in fewer setups and adjustments and an increase in time and complexity of machining programs, thereby reducing the technical requirements of the machinist's job. This new work environment also restricts the number of interventions a machinist needs to do on the job:

I would say that there's less and less "hard skills" necessary for machinists. They still need to understand it, but it's only setup. Whereas before, they were taking measurements of the part. They don't do that anymore. The measurements are done by the machine.

—MANAGER, MULTINATIONAL COMPANY, TORONTO

The division of work between machinists and IT and data analysts not only reduces the scope and complexity of the tasks of the machinist, but also takes away much of the machinist's discretion over how to organize their work. In some workplaces, the span of control of the machinist has been reduced significantly, as highlighted by this manager:

Today, they say it's not your job to make decisions, to decide what to measure. It's the team that makes the decision... "What we want from you is for you to make good setups. What we want from you is for the machine to run. What we want from you is that you produce quality. What we want you to do is to tell us what to improve. What we want from you is to tell us what's going on, but… we don't want you to make any decisions about it. You're not the best at it."

—MANAGER, SME, MONTRÉAL

Work degradation and the associated deskilling often involves removing complex tasks such as setups, reducing machinist autonomy, and decreasing the depth of knowledge and skill required. In contrast, job enlargement involves increasing the number of machines a machinist is responsible for, while also requiring a good understanding of workshop operating methods (e.g., a flexible cell). For instance, instead of operating a single machine, machinists may now be assigned to operate four to six machines during the same shift. As such, the impact of I4.0 on the work of a functional machinist involves both a process of deskilling and of broadening in relation to machining tasks.

In comparison, operator roles require lower levels of skill. One of the advantages for some firms is that they can recruit workers with no special qualifications and train them in-house. Hence, while I4.0 may increase the skill sets of some workers, it may involve deskilling for the majority. As a result of technological changes, firms have replaced some skilled machinists with less-skilled, lower-wage operators:

We need the operators, that's our problem right now. We don't need people with qualifications. You have a high school diploma, we'll train you. And we'll accept people who have not completed high school, and we'll train them.

—MANAGER, SME, MONTRÉAL

Whether firms choose to utilise functional machinists or instead hire more operators with lower skills raises important questions about the future of several shopfloor occupations, as well as the overall quality of aerospace jobs. The implementation of I4.0 may lead to the integration of new skills (i.e., upskilling) and to new routes of progression (e.g., programmers and technicians) for some machinists. Yet there is also evidence that changes resulting from I4.0 technology and work organization are likely to contribute to job degradation with the erosion of skill requirements.

Previously, the skilled trades such as machinists have been seen as craftsmen: occupations "who think" and who are capable of problem-solving and complex decision-making. In some firms, the machinists have historically played more important roles in designing certain manufacturing processes than engineering departments. However, the more advanced stages of I4.0 herald a centralization of decision-making away from the shopfloor. How firms choose to design their work organization around these new technologies will have important implications for the future of these occupations and their associated skills.

The more advanced stages of I4.0 herald a centralization of decision-making away from the shopfloor. How ***firms choose to design their work organization around these new technologies*** *will have important implications for the future of these occupations and their associated skills.*

Understanding labour market trends, work organization transformation, and skill evolution

This section has sought to understand how I4.0 is shaping the world of work, through an analysis of the intersection of labour market trends, work organization transformation, and the evolution of skills. It highlights that aerospace is a highly skilled industry and that, prior to the COVID-19 pandemic, demand for labour outstripped supply. This created a shortage of labour, notably in traditional occupations such as machinists, but also in emerging occupations related to data management, including programmers and data analysts.

The emergence of these new occupations and the integration of data management have opened up new opportunities, enabling aerospace firms to monitor production processes in real time, to standardize work more tightly, and to reduce worker autonomy. In this new work organization—characterized by the unbundling, re-composition, and hybridization of tasks—some jobs are enriched, others are enlarged, while many are degraded. The transition toward I4.0 is not straightforward, does not affect all workers, and does not affect those it impacts

in the same way. This uneven process seems to favour job polarization, with an increase in a smaller number of high-skilled jobs (e.g., super machinists) and a greater proportion of low-skilled jobs (e.g., operators), at the expense of traditional “middle-skilled” occupations such as machinists.

The findings from our study support, illustrate, and provide a more in-depth understanding of claims in a recent Statistics Canada report on robotics adoption (Dixon, 2020). This report demonstrates that, at a Canadian cross-sectoral level, robotics adoption does not appear to reduce employment overall. Instead, increased robotics adoption is found to result in skill polarization; reductions in “middle-skilled” workers; increases in both higher- and lower-skilled workers; reductions in managers; increases in the span of managerial control; and transformation of managerial work and tasks. Our study identifies some forms that job polarization has taken in the Canadian aerospace industry following the adoption of I4.0 and how algorithmic management may further entrench these trends.

These trends also raise fundamental issues with regards to the future of the industry. On the one hand, the industry has been dealing with labour shortages and has had difficulty recruiting skilled labour, particularly among the new generation of workers. On the other hand, I4.0 is creating some very attractive jobs requiring high skills, but also many low-skill ones. The industry is thus facing a real dilemma: it has difficulty attracting talent because it has fewer attractive jobs Hence, the capacity of the industry to create a pipeline of talent is compromised. These are complex issues that a firm can hardly address at an individual level; they require a collective response from various stakeholders in the industry.

Cluster Dynamics and Regional Institutional Configurations in Toronto and Montréal

I4.0 adoption is challenging for firms and, in the context of the COVID-19 pandemic, is likely to become even more so. The current constraints on the global aerospace industry exert excessive pressure on regional institutions, leading actors to redefine the governance structure of these institutions, their boundaries, their collective resources, and even their identities. This redefinition is possible through processes of experimentation, mutual adjustment, and collective learning that allow actors to reassess and revise their objectives and the means to attain them (Heidenreich, 2005; Murray et al., 2020).

In these experimentation processes, actors can build “thick” or “thin” regional institutions[20] (Zukauskaite, Trippl & Plechero, 2017; Amin & Thrift, 1994). Regions with thick regional institutional configurations (RICs) have a variety of mediating organizations that support innovation and knowledge transfer. These organizations are well-connected to each other, with power being dispersed rather than concentrated. Actors and organizations also share a common agenda that focuses on the production of collective resources. These RICs generate experimentation processes based on networks or coordinated actions between firms and mediating organizations that are generally located at the cluster level. We refer to them as institutional experiments. In contrast, in regions with thin RICs, there are few mediating organizations; as such, interactions among firms and with mediating organizations are rather limited. Power is concentrated in a few dominant organizations and firms, and there is no collective agenda binding the various actors and organizations together. These RICs foster “firm-centric” experiments. We refer to them as organizational experiments.

20 To measure regional institutional thickness, we draw on the work of Zukauskaite, Trippl, and Plechero (2017) who have identified four dimensions: 1) The presence of a variety of different organizations such as firms, business associations, trade unions, and industry-mediating organizations; 2) the level of interaction between these organizations (i.e., the intensity of formal and informal interaction); 3) the dynamics and structure of power relations; and 4) the existence of a shared and common agenda and identity.

Drawing on the distinction between thick and thin institutions, this section explores the following questions:

> To what extent do actors have access to a resource-rich environment to experiment and cope with the challenges of I4.0? What type of resources are available, and are they the result of collective or individual actions?

> Are these resources distributed evenly, or are some actors capturing the resources for the benefit of their own organizations? What type of capabilities do actors develop to mobilize these resources?

> What are the dominant patterns of behaviour and relationships between actors? Are these relationships competitive or collaborative? Are they bilateral or multilateral?

> What are the main processes of experimentation? What role do large firms, mediating organizations and low-power actors such as SMEs and unions play in these processes of experimentation?

Toronto RIC

Institutional legacy of the Toronto RIC

The Toronto cluster has had a thin RIC, demonstrated by its small number of industry mediating organizations, with those that do exist having been established relatively recently.[21] There are several mediating organizations at the provincial level, including a large pool of colleges and universities that provide a highly skilled workforce. However, compared to other high-technology industries in Ontario (e.g., Bramwell & Wolfe, 2008), firm–university–college links have not been a driver of innovation within the aerospace industry, with minimal technology spillover from mediating organizations to Toronto-based aerospace firms (e.g., Niosi & Zhegu, 2005). In terms of skill development, there have been several cross-sectoral attempts by both the federal and provincial governments to encourage stakeholder involvement in the training system (Rutherford, 1998; 2001)—particularly during the 1990s—but these were unsuccessful in shaping the RIC in the long-term.[22] Industry mediating organizations receive minimal funding for operational and human resource costs, so their capacity to provide services at a cluster level is restrained by their levels of operational and human resources. As a result, actors such as

21 See Appendix C for a more detailed list of RIC actors.

22 Several of these attempts include labour unions. Examples include the Canadian Labour Force Development Board, the Ontario Training and Adjustment Board, and local training boards developed in Ontario in the 1990s.

firms tend to develop initiatives using either federal[23] or provincial[24] funding programs, or through collaborations with mediating organizations at a more individual or "firm-centric" level (e.g., between individual colleges/universities and firms) as opposed to initiatives at the cluster level.

Of the industry mediating organizations that do exist, the most influential is the provincial industry trade association: the Ontario Aerospace Council (OAC), founded in 1994. The Ontario Manufacturing Learning Consortium (OMLC) was established in 2013 by the OAC and offers a series of subsidized training programs for skilled trades (e.g., machinists and assemblers), though these are not consistently available to the cluster due to funding availability. The Ontario arm of the Consortium for Aerospace Research and Innovation in Canada (CARIC) was started in 2014 and provides funding for collaborative innovation projects. Firms and actors in Ontario have utilized the Green Aviation Research and Development Network (GARDN) to access innovation funding.

Downsview Aerospace Innovation & Research (DAIR) emerged in 2013 as a consortium of universities, a college, and several large firms, and focused on developing an innovation hub at Downsview (Emerson, 2012).[25] DAIR is currently in stage 2 of establishing a physical innovation hub, but further progress has been affected by Bombardier pulling production from the site. Additionally, established in 2014, the Women in Aerospace (WIA) Canada group focuses on diversity, inclusion, and mentoring for women. As part of the federal government's innovation super cluster initiative, aerospace firms are also involved in the cross-sectoral Next Generation Manufacturing Canada (NGen) project that started in 2018 (Innovation, Science and Economic Development Canada, 2020).

Firm relationships within the cluster are often competitive, with firms preferring to collaborate with actors outside of the cluster, though several prominent firms have raised the need for greater collaboration (Canada, 2020, 2012). Power has historically been concentrated in a few large firms, notably multinationals. While there have been several examples of initiatives aimed at common agenda and cluster-building, none have been very successful to date (Gavin, 2019).

How then does the institutional legacy of the Toronto cluster shape the development of skills and technological transfer and, more specifically, I4.0 implementation? The Toronto aerospace cluster has developed through the years a firm-centric model. This

23 Federal funding programs include the Strategic Aerospace and Defence Initiative (SADI); Scientific Research and Experimental Development Tax Incentive Program (SRED); and funding streams offered by the Natural Sciences and Engineering Research Council of Canada (NSERC) and Mitacs.

24 At a Provincial level, funding is often cross-sectoral. Examples include the Ontario Centres of Excellence (OCEs) and the Federal Economic Development Agency for Southern Ontario, for supporting innovation and skills development (FedDev Ontario, 2015).

25 As part of stage 1 of DAIR, Centennial College inaugurated a new aerospace campus in Dowsview Park in 2019. The project was funded by provincial ($26 million) and federal ($18.4 million) governments (Innovation, Science and Economic Development Canada, 2016).

is an RIC where technology transfer primarily occurs at a localized level. As a result, there is weaker coordination at the cluster level. This institutional legacy can reinforce or limit the deployment of various strategies and create openness or resistance to some forms of experimentation.

Cluster resources and current dynamics

In Toronto, due to the thin RIC, there are not many coordinated initiatives specifically targeting I4.0 and future skills, and where initiatives do occur, they are often at the level of the individual firm. One of the consequences of weaker coordination is that the nature of relationships between firms in the cluster continues to be competitive, due to perceptions that collaboration could impede securing contracts and work package distribution. Large firms display protectionist behaviours, while SMEs choose not to collaborate, even in commercial partnerships that would enable economies of scale:

My perception is that [collaboration] in Ontario [is] very weak. There's no glue; there's no incentive to work together… I could imagine that if the big companies want there to be collaboration, they could force that type of cooperation.

—MANAGER, SME, TORONTO

Horizontal collaboration (e.g., among competitors at a cluster level) is particularly challenging. Collaboration may be more readily achievable at a vertical level through supply chain relationships, but this would require OEMs or Tier 1 firms to drive such activity.

A notable consequence of the lack of cooperation between firms is that poaching is prevalent. Poaching occurs when larger firms ramp up their recruitment efforts and offer higher salaries than SMEs. Experienced workers or those with a specialist skill sets are the most likely to be poached:

Around 2013, there were a number of companies that were members of the OAC, who were coming to me and saying, "we're having a really hard time finding CNC machinists … The [experienced] ones, they're working for somebody else, my friend down the street is stealing my guys, now I have to go steal somebody else's."

—MEDIATING ORGANIZATION, TORONTO

Poaching emerges as a form of conflict at a firm-to-firm level and firms of all sizes have been affected. There are few means of regulating this behaviour at the cluster level but the OAC and OMLC have sought to mitigate its effects by creating training programs to expand the pool of skilled labour.

The initiatives firms have developed to access skilled labour and resources linked to the implementation of technological innovation tend to be firm-centric. Many firms choose to use private training providers (e.g., robotics, coding, data management), consultants (e.g., offering I4.0 expertise), and/or technology or machine manufacturers (e.g., Siemens, GE, robotics manufacturers), with less reliance on resources produced at the cluster level. Other firms also interact with other actors or with mediating organizations within the cluster, working collaboratively to develop skills or new technology.

One of the more advanced SMEs in the adoption of I4.0 has built many of the resources that they needed individually, purchasing training for programmers and super machinists through their software providers and using ERP consultants to improve the operation of their virtual factory. Less advanced firms draw upon a variety of consultancies, machine manufacturers, and service providers to gain information on how to implement I4.0. Sometimes, these connections are made through networking events organized by industry mediating organizations, such as the OAC:[26]

We've had discussions with [machine manufacturers] who are both supporting us and giving us information… There are other resources with the OAC group. There are [consultants] in there who do [I4.0 implementation] full-time. There's also support from our accounting firm, who offered to help us optimize the data; to look at the data and what it's telling us.

—MANAGER, SME, TORONTO

Multinational subsidiaries can also draw on their own networks and may lean on more advanced counterpart subsidiary sites in transitions from I4.0 (e.g., rolling out use of tablets, automated lines, and flexible cells). As an example, several subsidiaries from Toronto worked closely with their Montréal counterparts to implement new technologies or to develop internal training programs.

In Toronto, however, there are cases where firms are choosing to work collaboratively with other stakeholders to produce collective resources, and it is on these cases that we primarily focus in the below sections. When firms engage in cluster-wide initiatives related to skills development and new technologies, these initiatives typically involve the collaboration of a few firms and at least one mediating organization. Thus, they could lead to sustainable networks between firms and with mediating organizations. However, the deployment of such networks requires a strong commitment from the various stakeholders, particularly from mediating organizations and large firms.

SKILL-DRIVEN INITIATIVES

At a cluster level, the thin RIC results in large differences in terms of how large firms interact with RIC actors as compared to SMEs. Large firms benefit from a significant amount of flexibility and agility in their interaction with various stakeholders and have the capacity to access resources and develop cluster skill initiatives. In comparison, SMEs experience greater difficulty in accessing these resources and shaping cluster-wide initiatives. The thin RIC means that skill-driven initiatives are often market driven, in that they reflect the specific needs of individual large firms.

26 Events disseminating I4.0 through the OAC were run by an external consultancy, and several interviewees reported meeting firms offering services through OAC networking events. Other mediating organizations have explored similar types of arrangements, with DAIR considering partnering with one I4.0 specialist manufacturer to establish a demonstration space for I4.0 using the manufacturer's machinery.

Some multinationals collaborate with cluster stakeholders to address current (as opposed to future) skill needs. Their activities span from direct relationships with colleges, to collaborative initiatives through their supply chain or through industry-mediating organizations such as the OAC. Multinationals are often able to "capture" the resources of the RIC.[27] In one example, a multinational worked with a college to deploy one of their entry-level training programs for machinists as a short college course. The college and this multinational firm were able to access government subsidies to fund their entry-level firm-specific training program which is currently offered to other aerospace firms:

We have something called "[firm name] Fast Track," which is an intensive one-semester program ... on basic metal working and fasteners. And with [the multinational's] processes: working with their diagrams or drawings, [and] their processes for assembly lines.

—ADMINISTRATOR, COLLEGE, TORONTO

In another example, a Tier 1 is collaborating with a pre-existing college–university partnership and three SMEs in its supply chain. This group is developing three short "micro credential" training programs, which will be used to upskill shopfloor workers into robotics maintenance technicians.

Collaborations may also include industry-mediating organizations, particularly the OAC. Several large firms make contact directly with the OAC when suffering from labour shortages. In some instances, this resulted in a single-firm solution; but in others, a more collective approach emerged. For example, a series of intensive training programs for occupations such as CNC machinists and structural assemblers was developed in Ontario, with large firms in the cluster recruiting the majority of those trained or upskilled by these programs.[28]

For SMEs, the landscape is very different. On the one hand, SMEs are not able to individually negotiate with colleges or universities because they have more limited internal resources and are unable to develop a common agenda and operate collectively. On the other hand, SMEs are also dependent on multinational supply-chain initiatives that focus on skill development. Overall, SMEs are not in a position to capture institutions and access resources in the same way as multinationals.

Both multinationals and SMEs engage with formal VET initiatives offered by colleges and universities, such as taking interns and cooperative or work placement students. These VET initiatives are often funded by NSERC, and there is significant variation across colleges and universities in terms of how the various initiatives operate. Firms see these programs as a way to build a

27 Phelps (2008) argues that multinational firms (through foreign direct investment) may be able to "exert disproportionate influence" over education and training agendas and may be able to tilt local education and training strategies towards their specific needs (pp. 467-68). The term "institutional capture" is used more generally to refer to how multinational subsidiaries may be able to "capture" or "secure" resources at a regional level, in order to meet their individual needs.

28 A series of entry-level programs were developed, lasting approximately 6 months for new starters. These involved 4–7 weeks of classroom training and 2–4 weeks of upskilling and were the equivalent of half an apprenticeship. These programs were deployed through the OMLC.

skills pipeline—an opportunity to train, build a relationship with, and often recruit their placement students. Some firms used placements to run projects related to process changes. One SME manager at the I3.0 stage used cooperative placement students to oversee projects developing "smart processes" to make production more efficient:

For production control, the student is in charge of doing setups. The production manager noticed such an improvement in efficiency [that] he asked me to make it a permanent role.

—MANAGER, SME, TORONTO

All the actors and firms see these VET activities as beneficial for firms and students. Yet some actors voice concerns that a small number of firms use students only as cheap labour, as opposed to developing their skills, or as a way to cut costs by training students without paying them.

Firms of both sizes also engage in formal skill outreach activities organized by colleges and universities, such as by sitting on program advisory committees, providing feedback on formal course content, and giving industry guest lectures. Several of the colleges and universities have developed modules or courses around I4.0 or mechatronics as a result of these activities and outreach. The participation of managers to these outreach activities helps to address challenges encountered by colleges and universities, including those associated with delays in the approval of course curricula.

Partnerships between individual colleges and universities have become another route to overcome these challenges. These partnerships often produce non-accredited industry-oriented programs (e.g., Bachelor of Technology [B.Tech.] in Manufacturing Engineering Technology) or create transition routes from technician to graduate engineering programs. Colleges and universities also collaborate with various industry accreditation bodies to shape future skill initiatives. For example, some college mechatronics programs provide industry accreditation through Siemens, while other types of certification are linked to modules on robotics, I4.0, and automation.

INITIATIVES SUPPORTING TECHNOLOGICAL INNOVATION

Technology-driven initiatives follow the same pattern as skill-driven initiatives, with most of the initiatives being firm-centric. Where more collaborative initiatives do emerge, industry-mediating organizations play an important role in helping firms to overcome competitive relationships and in synthesizing information, such as helping firms to navigate the complex funding landscape. However, there are few initiatives that target I4.0 directly.

One of the successes of the Toronto cluster—and the Canadian industry to date—has been in exploiting technological niches within the global industry, and sometimes with less government support. Sustainable civil aviation is, at the cluster level, seen as a potential future niche for Canada, primarily pursued through the green aviation initiative GARDN in Montréal:

In Europe, yes, they have Clean Sky; and in the US, they have NASA. But I think in Canada, [the industry] can be agile… Canadian success, because of the size of our country, is often based on niches… I think sustainable aviation would be a wonderful niche for Canada.

—PROFESSOR, UNIVERSITY, TORONTO

Sustainable civil aviation is, at the cluster level, seen as a potential future niche for Canada, primarily pursued through the green aviation initiative GARDN in Montréal. Several of the OEMs and Tier 1 firms in the cluster have openly acknowledged that new technologies—including tablets, robotics, and other forms of automation—have typically been applied to the newest product lines. Therefore, rates of I4.0 adoption in multinationals appear to be linked to whether subsidiaries are producing the latest product lines (e.g., more sustainable aviation products).

Within the Toronto cluster, large firms benefit by leveraging their individual purchasing power with colleges and universities, funding highly applied research projects related to I3.0 or I4.0. These projects can include the installation and integration of robotics into existing manufacturing processes, the implementation of digital systems and/or cybersecurity, and developments in areas such as predictive maintenance. One notable example is an I4.0 project, a "build your own" robotics module for a reconfigurable robot, being undertaken as part of an NGen funding bid.

Collaborative initiatives involving large firms typically involve some form of intermediary. Universities and colleges spearhead a number of outreach activities,[29] while the DAIR consortium is currently focused on workshops and real estate (e.g., lab space) for existing innovation projects[30] (though none to date on I4.0). Recently, CARIC and NGen have offered project-based collaborative innovation funding—helping consortia to access other funding sources, and attempting to mediate conflict between participating firms[31]:

Working with organizations like Mitacs, Ontario's Centres of Excellence, NCERC… when you're working with industry, they have very little capacity. And so the extra work to put together a strategy… a lot of companies don't know how to do that.

—REPRESENTATIVE, INDUSTRY-MEDIATING ORGANIZATION, TORONTO

These organizations therefore play an important role in coordinating collective action, particularly in terms of their capacity to synthesize information, mediate conflict, make firms aware of the numerous sources of funding, and help them to exploit multiple resources, which can enable projects to operate over longer timescales.

29 Outreach activities include university research groups, informal firm workshops, and formal multi-firm research agreements.
30 One example is a landing gear electrification project.
31 Both initiatives are designed to be industry-led and require some form of industry co-funding (Industrial Technologies Office, 2014; CARIC, 2014).

For SMEs, the services offered by the various colleges are the primary means through which they can implement new technology. Contract research services at individual colleges provide support for short applied-innovation projects, with some funding subsidies through initiatives such as SONAMI.[32] These projects can include on-site I3.0 and I4.0 implementation; in one example, an SME purchased a (subsidized) collaborative robot, with a local college helping to integrate the robot into their production processes. However, many SMEs were unaware of these services; those that knew had been informed through various outreach programs developed by mediating organizations.[33] Some SMEs are involved with GARDN, CARIC, and NGen networks—but it is typically through either a larger firm or specific programs targeting SMEs. These various projects highlight the crucial role mediating organizations can play in supporting SMEs in the deployment of new technology (OECD, 2020).

One of the challenges with I4.0 implementation is that the process is very industry-specific. I4.0 technologies have to be translated and adapted to each industrial context. With more funding constraints than ever—with CARIC being defunded, GARDN only renewed until March 2021, and NGen corresponding more to cross-sectoral logics—there are not many industry-specific funding initiatives within the aerospace cluster. The lack of "translating" mechanisms between industries for technological innovation could have important implications for adoption rates of I4.0. As one senior manager from a Tier 1 firm explained, it requires considerable resources to translate process innovations into an industry context—a transition that is often easier when moving from more technologically complex processes (e.g., aircraft) to other industries with less complex processes, rather than the reverse.

While firms and actors in the cluster can be highly inventive when it comes to developing ways to generate technological innovations and future skills, many of these experiments remain localized and are difficult to scale. At all levels, there is often a danger of large firms "capturing" the resources and expertise developed at the cluster level.

32 SONAMI is a consortium of colleges and one university (of which we consider four to be operating within the Greater Toronto Area as part of the Toronto aerospace cluster). SONAMI projects are often small (approximately $50k value) and are half-subsidised by the scheme and half by the firm. The initiative received $7.3 million from FedDev to begin, and this funding has since been renewed (Canada Makes, 2017).

33 Outreach programs offered by colleges, universities, or local government agencies.

Power to set the agenda, produce collective resources, and experiment

The Toronto cluster is characterized by a thin RIC which reduces the opportunities to develop coordinated actions between the various stakeholders. Power dynamics remain asymmetric, with large multinationals having more influence to create, shape and access resources. Even though no actor or mediating organization is able to compel other actors to adopt their vision or understanding of I4.0, power within the aerospace cluster remains concentrated among a few large firms.

Firms and other cluster actors face difficulties and resistance in their attempts to develop a common agenda around skills or technological innovation. One of the challenges is that developing a common agenda requires a number of actors (particularly firms) to share information. Various mediating organizations have sought to develop a narrative around the need for collective approaches:

It's moving from the individual—from the "what's best for me"—to the "if I'm successful but my street burns down"… You have to move toward the Team Canada approach. And everyone has to be out there together.

—ADMINISTRATOR, INDUSTRY MEDIATING ORGANIZATION, TORONTO

Currently, one arena where this collective approach occurs is the OAC; however, they are somewhat restricted in the activities they can undertake, due to limitations in human resources and financing. Yet there are other common agendas being developed by a small number of larger firms who are trying to take a leading role. For example, a manager from Tier 1 firm explained how they are forcing collaboration between the actors they work with:

We aren't going to have ten meetings on the same topic. We're going to put together Team Canada. "Are you interested? Oh, and by the way, this college or university is over here, and we expect that you will work and collaborate with them. Are you willing to do that?" And if they say no, we're saying, "Ok, well, you're out of the game." Literally none of them say no.

—MANAGER, LARGE FIRM, TORONTO

Firms in the cluster are engaging more with colleges and universities in terms of research, gaining access to their research competence (both pure and applied). A number of initiatives (e.g., DAIR, CARIC, and informal workshops) were designed to develop these links—and they appear to be working. While the number of industry mediating organizations has also increased in the cluster, they do not appear to play much of a coordinating role, with several being limited by the broader scarcity of resources at the cluster level.

In terms of information and knowledge sharing, the collection, presentation, and availability of data on cluster demographics—e.g., the number of firms and workforce distribution—are limited and not available annually or consistently nor to all stakeholders in the cluster. Additionally, no cluster data are produced on I4.0

adoption rates, implementation, or impact on skills. Thus, at a cluster level, it is difficult to use comparable and consistent external data to make decisions or benchmark against other clusters. Provision of other collective resources—such as training, innovation, or new technology implementation—are increasing but remain limited given the need of the industry. When these resources are offered, they are typically project-based (instead of longer-term programs) and are often restricted to localized forms of organizational experimentation.

Large firms have a greater capacity to shape the agenda and pattern of relations in terms of I4.0 and future skills, and to capture the resources (including funding) that are being produced at a cluster level. These larger firms have derived considerable benefit from the flexibility and agility of the RIC—further demonstrating their capacity to shape the aerospace industry in Canada. In comparison, low-power actors such as trade unions and SMEs have far less capacity to shape cluster development and the types of collective resources delivered by mediating organizations.

Trade unions have produced reports to shape the agenda and pressure the federal government to develop a national industry approach. UNIFOR operates a national aerospace council, where trade union representatives meet to set the year's agenda and to propose solutions to the challenges that workers face. A lot of union activity is also emerging at the workplace level, particularly in developing new language in collective bargaining agreements around technological change. However, at the governance level of the cluster, unions are absent, without voice on the board of any of the industry mediating organizations.

SMEs do not have the internal and external resources to compete with large firms. They are also unable to act together and to develop a common agenda that puts forward their specific needs. In addition, there are few collective mechanisms or industry mediating organizations to help them share their vision or understanding of I4.0—nor to represent their interests by challenging other definitions of I4.0 (e.g., those put forward by large firms). Even SMEs who have implemented I4.0 do not appear to be able to shape the I4.0 narrative within the cluster. SME managers have to develop their own capabilities and social capital, and be imaginative in generating their own opportunities, to access the limited cluster-based resources available to them.

Thus, there have been significant shifts at a cluster level. Previously, the aerospace cluster had a RIC that adhered almost exclusively to a firm-centric approach. The growing number of industry mediating organizations, and initiatives by other mediating organizations (colleges/universities) have encouraged network building for both skill development and technology transfer. These initiatives are important because they can enable organizational experiments to be institutionalized and scaled up at the cluster level.

Montréal RIC

Institutional legacy of the Montréal RIC

One of the distinctive features of the Montréal aerospace cluster is its thick RIC built around regional industry-mediating organizations,[34] which provide stakeholders with various resources (Hassen et al., 2011; Tremblay et al., 2012; Warrian & Mulhern, 2009). These industry-mediating organizations benefit from government financial support, even though firms and other mediating organizations also contribute to them (either financially or in kind).[35] The first industry-mediating organization — CAMAQ (Comité sectoriel de main-d'oeuvre en aérospatiale), which was founded in 1983 — operates on a parity basis. Trade union and manager representatives have equal weight in the decision-making process.[36]

Through the 1980s and 1990s, CAMAQ was the primary locus of coordination within the aerospace cluster in Québec (CAMAQ, 2013), though now it shares this role with other industry-mediating organizations. CAMAQ participated in the development of numerous specialized training programs and has made a significant contribution to cultivating a pool of skilled workers. In addition to fostering management and trade union cooperation around common issues such as training, CAMAQ became an agenda-setter, leading various stakeholders to develop a shared understanding about the importance of investing in skill development. As highlighted by one union representative, trade union involvement in CAMAQ gave them the opportunity to address aerospace issues from a different perspective:

We had good discussions at the CAMAQ. Me, I liked it because I took off my label of "trade union representative." I was more looking at the whole context of the aerospace industry in Québec. How we can gain more work in Québec and shape the debates within firms.

—UNION REPRESENTATIVE, MONTRÉAL

In 1997, SMEs created their own association (Association québécoise de l'aérospatiale [AQA]) to voice their concerns and represent their interests before the various levels of government and multinational companies. Québec SMEs were under pressure from large firms that were transforming their procurement strategies by reducing the number of their suppliers, transferring risk, reducing costs, and choosing suppliers with more integrated services. Thus, SMEs were compelled to develop new forms of partnership in R&D and technological innovation, while also transforming themselves into manufacturing system integrators instead of parts suppliers. For AQA, one of their core issues was to enhance SME capabilities and facilitate

34 See Table 1 in Appendix A.

35 At the provincial level, the main sources of funding come from the Ministère de l'Économie, de l'Innovation et des Exportations (MEIE), the Fonds de Nature et Technologie du Québec, and the Caisse de Dépôt. For the period of 2016 to 2021, the provincial government (through the MEIE) is drawing on a financial framework of $250 million. Firms can also take advantage of sources of financing, complementary to traditional lenders, through venture capital companies (such as the Fonds de solidarité of the FTQ).

36 See Appendix C for a more detailed list of RIC actors.

relations with large firms in order to foster innovation and ensure the integration of SMEs into global supply chains. AQA was a pioneer in creating an awareness of common interests among SMEs and enhancing their capacity to act together with a common voice.

CRIAQ (Consortium de recherche et d'innovation en aérospatiale du Québec) was founded in 2002 under the impetus of several universities and large firms.[37] CRIAQ's activities focus on pre-competitive research. Since its creation, CRIAQ has organized various activities, notably annual research forums, aiming to highlight the most relevant research themes for companies and match them with the interests of academic researchers. These activities have reduced the traditional barriers between applied and fundamental research—as well as between firms and universities—while also encouraging further collaboration on open innovation initiatives between various stakeholders.

Drawing on the industrial cluster model established by la Communauté Métropolitaine de Montréal (CMM) and in collaboration with the provincial government (CMM, 2005), leaders of major companies and representatives of different industry segments created Aéro Montréal in 2006. Aéro Montréal stands out for its ability to bring together all stakeholders: representatives from large companies and SMEs, the labour movement, research and education organizations, CAMAQ, and CRIAQ.[38] The implementation of Aéro Montréal has led to a redefining of relations between the actors and organizations within the industry, as this interlocutor from Aéro Montréal points out:

At first it was difficult because, well, Aéro Montréal arrived... CRIAQ existed, CAMAQ existed... then we tell them: "Well there, come with us on the ice rink." You know, at first, people didn't like it. Especially since we have the decision-makers… [and] they do not have these people on their boards.

—REPRESENTATIVE, AÉRO MONTRÉAL, MONTRÉAL

37 CRIAQ's board of directors is composed of representatives from industry and the academic research community.

38 It is worth mentioning that in 2012, AQA merged with Aero Montréal, and that the six SME representatives on the Aero Montréal Board of Directors are selected through an electronic ballot.

In its latest strategic planning, Aéro Montréal has identified four key pillars for the industry: 1) growth; 2) innovation, competitiveness, and productivity; 3) workforce; and 4) image, influence, and marketing. Each of these pillars are structured around one or more working groups, committees, programs, or initiatives.

Over a 40-year period, various actors within the Montréal cluster have built the RIC through an emergent strategy by responding to unforeseen events facing the industry. This strategy was articulated around the resolution of concrete problems confronting the industry, such as increasing workforce skills, reinforcing open collaboration on production and technological innovation, and building the capabilities of SMEs.

Each industry-mediating organization (i.e., Aéro Montréal, CAMAQ, CRIAQ) is relatively autonomous, but they do operate in a complementary and coordinated way. Each of these organizations develop their own projects independently, while also engaging in joint projects depending on the issue at stake. This institutional diversity has created space for the involvement of a variety of actors: from large firms to SMEs, trade unions, and research and education organizations. Power is not distributed evenly among the various actors, yet low-power actors such as SMEs and trade unions have a voice and can influence the course of events. This enables less influential stakeholders to contribute to shaping cluster agendas and decision-making processes, as well as gain access to more material resources, expertise, and knowledge.

Cluster resources and current dynamics

In Montréal, skill development and new technology initiatives occur at both firm and cluster levels. One of the outcomes of a firm-centric approach is the prevalence of individualistic strategies, which can result, as one example, in poaching. In these competitive relationships, large firms exert huge pull effects and can draw on a greater pool of workers by offering superior working conditions. This is a recurring problem raised by SMEs, as highlighted by this HR director:

Because the big companies… when they hire, you take what's left. You have to accept that... These are all things that are difficult to handle, because at some point you tell yourself, yes, I can increase salaries. But we don't have [a large firm's] capacity; we don't make billions.

—MANAGER, SME, MONTRÉAL

There are also many firms taking action individually to cope with skill, production, and technological issues. They work regularly with labour markets and education organizations to meet their specific skill needs. They also collaborate with consultant firms to upgrade their practices, particularly regarding the implementation of new technology and production processes.

Even though firm-centric approaches toward skills development and technological innovation are still prevalent, mediating organizations have a unique capacity to foster collaborative networked and coordinated actions. It is often difficult to distinguish between network and coordinated approaches because they work in tandem, with actors tapping into both of them to meet their needs. In fact, in many instances, coordinated approaches lead to more informal types of collaborative network approaches, where actors develop new resources and capabilities.

Over the years, actors in Montréal have developed a variety of programs and initiatives to improve the competitiveness of the aerospace industry—far too many to fully cover in this report. In the following subsections, we analyze in more detail the approaches (firm-centric, network, and coordinated) put forward in Montréal to ensure workforce skills development and technological innovation.

SKILL-DRIVEN INITIATIVES

The aerospace industry cluster can draw on a large pool of training and education institutes. As early as 1964, the École nationale d'aérotechnique (ÉNA) was founded to train technicians in aircraft construction, aircraft maintenance, and avionics (ÉNA, 2011). In 1994—under the impetus of CAMAQ and in partnership with the Québec Ministry of Education—the École des métiers de l'aérospatiale (ÉMAM) was founded. The school provides high school training of skilled workers, based on the school-factory principle, through various specialized aerospace programs.

At the university level, as early as 1984, three Montréal universities created a master's degree in mechanical engineering with an aeronautical option. In 1989, these universities collaborated with industry to launch a master's degree in aerospace. This program, coordinated by CAMAQ, currently includes six universities. Since 2001, the Montréal Aerospace Institute (MIA) has been selecting first-year engineering students on the basis of academic merit, skills, and interest in aerospace. These undergraduate students (roughly 300 per year) are involved in various projects, such as local and international internships, mentoring, training courses, and industrial visits. The four Montréal universities—ÉTS (affiliated with the Université du Québec à Montréal), École Polytechnique (affiliated with the Université de Montréal), Concordia, and McGill—are involved in this project. CAMAQ has also participated in the creation of the Laboratoire d'enseignement des systèmes intégrés en aérospatiale du Québec (LESIAQ). In 2013, under a joint initiative led by ÉTS and McGill University, the CAPE Program (Centre aérospatial de perfectionnement) was created to meet the training needs of aerospace professionals and engineers.

Three Montréal universities *created a master's degree in mechanical engineering with an aeronautical option. In 1989, these universities collaborated with industry to launch a* ***master's degree in aerospace.***

One of CAMAQ's important mandates is to promote the constant management of labour flow within the cluster. Since 1984, CAMAQ has been producing sectoral balance sheets and annual surveys on labour force forecasts. Although the balance sheets contribute more to medium- and long-term planning, the surveys do provide some insights into the short-term needs of businesses. An annual census is also conducted to identify firm training needs, as well as flagging occupations for which recruiting is more difficult. CAMAQ also produces an aggregated annual report, which enables stakeholders to follow the evolution of the labour market and identify major trends in their industry. From year to year, roughly 90% of firms in the cluster participate in the survey, thus sharing information that then becomes a collective resource available to all relevant stakeholders.

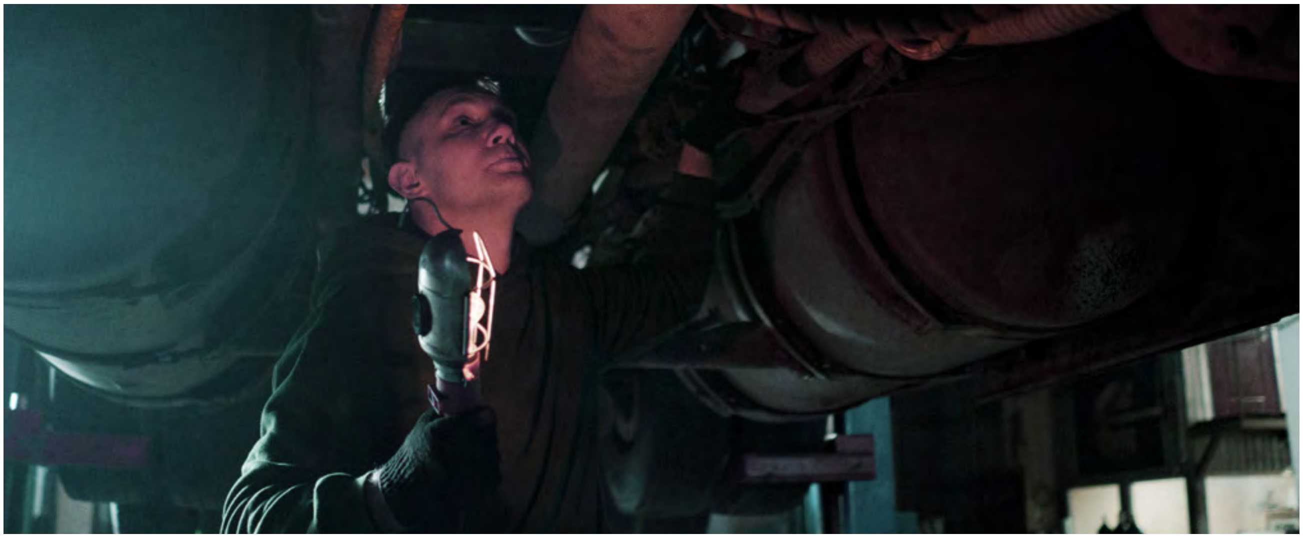
Recently, CAMAQ has developed various initiatives to ensure the development of a qualified workforce, including regional human resource committees to respond to the training needs of businesses—especially SMEs—on an ad-hoc basis. These regional committees have begun offering a more targeted service to firms. CAMAQ is also recognized as a training organization by Emploi Québec, supporting and advising aerospace SMEs in the development of training plans for their personnel.

CAMAQ is also involved in improving human resources management (HRM) practices among firms, through an initiative aimed at sharing and disseminating best practices. This process starts by pooling notable experiences, and then selecting an SME or large firm that stands out through its innovative policies or practices. In some cases, this can be followed by firm visits, where managers from the selected firm are asked to explain its innovative practices to managers from other firms in the aerospace industry. This initiative promotes the sharing of concrete experiences and the transfer of innovative practices between firms, while also facilitating networking among SMEs. One manager from an SME acknowledged how the sharing of concrete experiences was beneficial:

But there's not an idea that can exist without being fuelled by what other companies are doing. As I mentioned, the visit to [redacted name of SME] really gave us ideas on how to do that, because they even suggested some kind of partnership.

—MANAGER, SME, MONTRÉAL

Aéro Montréal also contributes to the renewal of skills through various initiatives. In an initiative from one working group—"Le chantier relève et main d'œuvre"—Aéro Montréal has collaborated with CAMAQ on school outreach to attract young people to the industry. This initiative resulted in a project, called "Ça plane pour moi," which is aimed at elementary school students and tries to raise their awareness of STEM careers in aerospace. Aéro Montréal has also organized various working groups, notably on the intergenerational transfer of knowledge (Projet Héritage) and on inclusion of women and racialized groups within the industry.



In order to foster skills upgrading related to I4.0, Aéro Montréal has initiated a series of workshops, industrial visits, and interviews with managers to develop a skill set guide for the industry (Aéro Montréal, 2018). The guide is presented as a framework for firms to use to assess their current practices and future needs, identifying seven essential skills linked to the development and operation of I4.0.[39] These essential skills are then linked to more than 40 indicators for each main occupation in the industry (e.g., shopfloor workers, technicians, supervisors and managers). The guide highlights how the requirements for skill levels vary according to each occupation (e.g., noting a required level of skill for each indicator).

The crucial point, however, is that through this guide, Aéro Montréal is producing training and competency standards for the development of future skills for the industry. These standards are not enforceable, but they represent a first step toward the dissemination of best training practices for the implementation of I4.0.

INITIATIVES SUPPORTING TECHNOLOGICAL INNOVATION

There are many initiatives designed to foster technological innovation; as such, this section narrows its focus to production and technology-driven initiatives that foster the development of future skills and I4.0, notably the CRIAQ projects that encourage open collaboration, the MACH and MACH FAB 4.0 initiatives led by Aéro Montréal to upgrade SME capabilities, and the project Aérospatiale 4.0 created by AÉROÉTS[40] to foster the implementation of I4.0.

39 The seven essential skills are related to: 1) technology and the digital world; 2) relational and organizational skills; 3) mathematics and programming; 4) data leveraging; 5) integration, and automation; 6) process optimization; and 7) business management for I4.0 and co-opetition (cooperative competition).

40 Aérospatiale à l'École de technologie supérieure (AÉROÉTS) is a group aiming to promote and integrate the aerospace activities of the École de technologie supérieure (ÉTS).

CRIAQ activities are structured around three spheres of intervention: 1) strengthening the technological leadership of the aerospace industry in Québec; 2) supporting the co-evolution of the aerospace research and innovation ecosystem with other consortia, notably at the international level; 3) stimulating diversity, creativity and talent development of aerospace researchers. CRIAQ's open, collaborative model of innovation has the financial support of industry, universities, and governments, and is considered a unique means of heightening the competitiveness of the Canadian aerospace industry.

As an intermediary in an open collaboration system, CRIAQ encourages companies to work on a variety of projects. CRIAQ ensures synergy between the various stakeholders and requires certain minimum conditions to be respected for all its projects. For instance, each project must involve the participation of two companies and two research organizations, such as universities or colleges. This condition is also required for larger-scale projects, and the products of this innovation are usually commercialised by one or more of the partner firms. From 2002 to 2004, no research progress was made, even though some 20 projects had been launched. Discussions were stalled over intellectual property rights. To counter this difficulty, CRIAQ designed an agreement, in which it is agreed that while firms involved in the project retain ownership in the aerospace industry, universities can benefit by commercializing the technologies developed in other industries. Since then, some 155 projects have been completed or are underway (CRIAQ, 2018), and 85% of member firms are SMEs or start ups. These projects generally involve three or four companies, and an equal number of research centres.

All of the projects conducted at CRIAQ involve master's and doctoral students, with some including post-doctoral students as well. In this respect, CRIAQ is an incubator for young talent that generates specialized skill pipelines for companies in the industry, through the involvement of students in projects initiated by CRIAQ member collaborators. This type of collaboration promotes the transfer of knowledge, while also allowing students to integrate into professional networks.

CRIAQ has been very much involved in bringing together firms, universities, and research centres. Its open forums, used for planning research projects, help to articulate the aerospace industry's current and future skill needs. CRIAQ contributes to talent management and skill development through the networks that develop around Canadian research projects, as well as the culture of exchange and collaboration that it promotes. For instance, different connections between entities—inter-university, inter-company, or university-enterprise networks—can provide smaller actors like SMEs with access to R&D and the skills of the region's young talent. CRIAQ has also been a crucial contributor in the creation and development of CARIC, which focuses on collaborative research projects nearing commercialization. Finally, CRIAQ is involved in the GARDN project (sustainable aviation) and has taken a leading role with the support of Aéro Montréal in the greener aircraft catalyst project initiated by the Québec Government—known as SA^{2}GE (Système aéronautique d'avant-garde pour l'environnement).

In 2011, Aéro Montréal initiated the MACH program to foster the upgrading of SME capabilities and ensure their integration within global supply chains. The main idea behind MACH was to shift the conversation away from "SME productivity issues" toward "SME competitiveness." Hence, the program brought discussions about SMEs' capabilities, including management skills and abilities of leaders, human resources management, and project management practices:

What we wanted with MACH was not to help SMEs to be more productive. What we wanted was to help them to be more competitive… Operational management was already their strong suit; but HRM, leadership practices, and governance [fell short].

—REPRESENTATIVE, AÉRO MONTRÉAL, MONTRÉAL

MACH was innovative in terms of how Aéro Montréal fostered the upgrading of SMEs' capabilities and by strengthening the relationships between large firms and SMEs in the cluster. The MACH program seeks to establish sponsor relations between a large firm and an SME (usually one of its suppliers), with the sponsor committing to support the SME in various ways to increase its capabilities.

From the SME perspective, relationships with sponsors can vary (Pérez-Lauzon, 2021). In some cases, larger firms appeared less inclined to dedicate resources to the SMEs; in others, SMEs felt that their sponsors were trying through the program to take control of their operations. In yet others, the sponsor was committed, and the SME became a key supplier for them. In later iterations of MACH, SMEs initially sponsored by the program acted as sponsors with their own suppliers. Sponsorship relationships between two SMEs were found to yield more positive outcomes.

Overall, MACH experiences in which the sponsor was also an SME resulted in more positive outcomes. Both parties usually shared similar experiences; as such, the sponsor could act as a "role model" that was more attuned to the needs of another SME.

Even though the sponsor relationships took various forms, most of the SMEs recognized that the program did help them make some valuable changes and upgrade their capabilities:

There is no doubt that our evolution is related to MACH. There is no doubt about it. Because without it, we would have never attained this level of management, [and never] set our sights on what we are aiming for now.

—MANAGER, SME, MONTRÉAL

Participating SMEs are ranked on a five-level "MACH maturity" scale. Level five is the highest and is awarded to SMEs that Aéro Montréal considers to be world-class suppliers. As SMEs progress through maturity levels, they gain access to more

*As of 2019, the **MACH program** has had five cohorts, totalling nearly **70 suppliers and over 30 sponsors**. According to Aéro Montréal, these **SMEs were involved in approximately 900 completed and current projects,** representing approximately $13 million in total.*

financial resources to accomplish their projects. SMEs are evaluated annually to measure their progress and once a full cycle of projects is complete.

As of 2019, the MACH program has had five cohorts, totalling nearly 70 suppliers and over 30 sponsors. According to Aéro Montréal, these SMEs were involved in approximately 900 completed and current projects (Aéro Montréal, 2020), representing approximately $13 million in total (Aéro Montréal, 2019, p. 15).

SMEs who are active within MACH benefit from a recognized certification process, a mentoring relationship, financial support, and additional expertise through coaching in tailored projects. MACH also provides access to training and activities developed exclusively for the "MACH community" by Aéro Montréal. These activities provide opportunities to build social capital and networks, and offer a way for SMEs to exchange information and share best practices. These events also have a symbolic function, as Aéro Montréal considers its MACH SMEs to be either current or aspiring elite suppliers:

And MACH, just MACH… it's brought us into this kind of closed world. Because the [aerospace] industry really puts all the MACH companies on a pedestal.

—MANAGER, SME, MONTRÉAL

The MACH FAB 4.0 initiative—undertaken in 2016 by Aéro Montréal with various partners, including AÉROÉTS, Centre facilitant la recherche et l'innovation dans les organisations (CEFRIO), and Sous-Traitance Industrielle Québec (STIQ)—is a direct continuation of the MACH program and is directly in line with Québec's 2016-2026 Aerospace Strategy.

The objective is to support up to 50 SMEs in their transition toward I4.0 and advanced manufacturing. It is a "customized coaching program" for SMEs, aiming to support projects related to the implementation of I4.0: real-time production management; the optimization of the production cycle using simulation for machine sequencing; data mining for preventive maintenance of manufacturing equipment; and interconnecting ERP production systems across the value chain.

This program is a major driver in supporting and financing the digital transition projects of SMEs, with a horizon of between six months to two years. As of 2019, 37 SMEs were active in the program, 42 improvement cycles have been initiated, and 110 ongoing or completed projects have been established (Aéro Montréal, 2019, p. 16). According to one SME manager, the MACH FAB initiative comes at a timely moment:

MACH FAB was the logical continuation of MACH… The MACH program is great. It's great to audit; it's great to give a maturity rating; [and] it's great to move people through projects and all that. But… we want to add the digital axis to MACH too.

—MANAGER, SME, MONTRÉAL

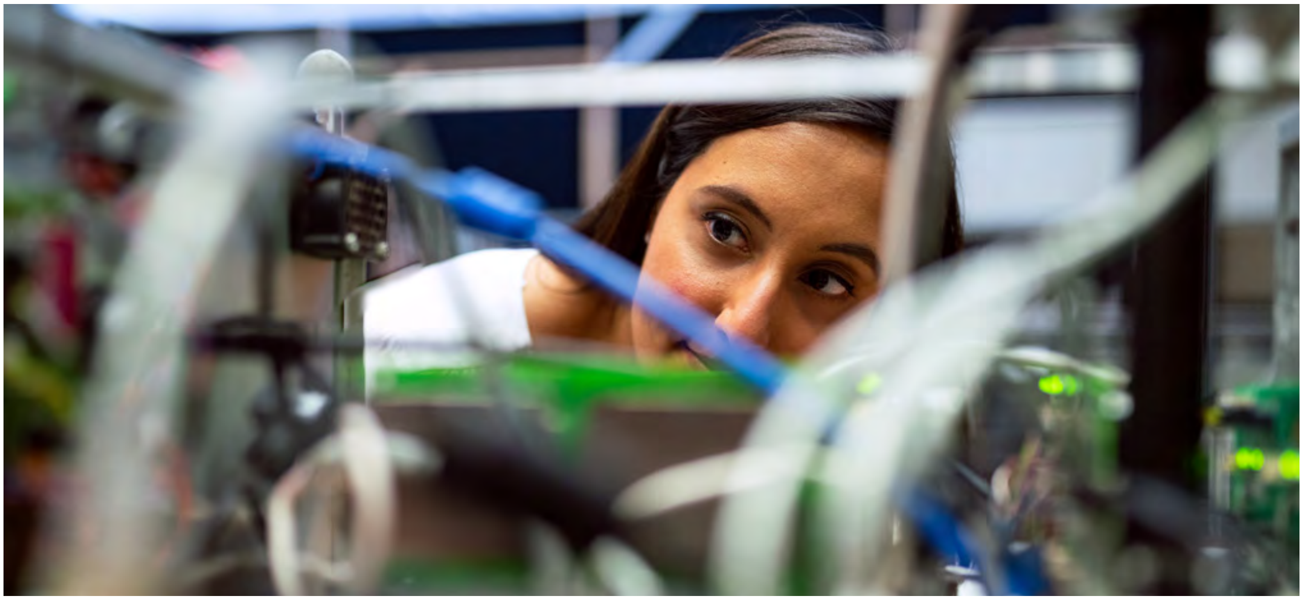
Finally, the last initiative fostering an upgrading of both technology and skills is Aérospatiale 4.0, created by AÉROÉTS. Launched in 2016, this initiative integrates research, education, and continuing education to meet the needs of I4.0 in the aerospace industry. The program includes education and training as well as R&D and pulls together several researchers and education actors to conduct studies on I4.0 in the aerospace industry. This program wants to help firms to achieve a "Smart Digital Enterprise." The education and training dimension mobilizes the resources of AÉROÉTS to develop various short-term training courses, which will prepare the aerospace industry to develop the new skills required by I4.0.

Each of these initiatives (CRIAQ projects, the MACH and MACH FAB 4.0 programs, and the Aérospatiale 4.0 project) involves a variety of actors and mediating organizations who work together to meet the challenges of I4.0. The initiatives—funded by a mixture of private and public funding—provide collective resources to firms, especially SMEs. However, these resources are not distributed evenly among firms and across organizations, as some are in a better position to access and take advantages of these collective resources than others.

Power to set the agenda, produce collective resources, and experiment

One distinctive characteristic of the Montréal RIC is the high level of coordination shared among various mediating organizations. Over the years, Aéro Montréal has become an essential organization with the capacity to exercise control over the allocation of resources and to set the priorities and agenda for the whole cluster. Other mediating organizations, such as CAMAQ and CRIAQ, are not powerless, but they do not have the same reach and cannot rely on as many resources—neither material, financial, nor organizational. Yet relations between these three predominant industry-mediating organizations are more collaborative than competitive, even though each of them is trying to frame the agenda around their specific field of action and protect their field of expertise.

The collaboration between these mediating organizations and other stakeholders has increased the capacity of the RIC to create and provide various collective resources for firms. These include training support, research competencies, information, and expertise on new technology implementation, all of which assist firms in dealing with the challenges of I4.0 and future skills. Hence, over the years, the RIC has been able to produce a resource-



rich environment for firms, combining both collective and private resources that support the development of the cluster.

Large firms not only play a predominant role in shaping the agenda and the allocation of resources, but are also able to capture collective resources produced within the cluster; however, there are various checks and balances that ensure power is not overly concentrated. Despite the strong presence of business representatives, trade unions have representation on the board of Aéro Montréal. On the board of CAMAQ, they have equal weight in decision-making to those of employer representatives. The presence of unions within these industry-mediating organizations offers them a space to shape the agenda and influence decisions concerning future skills and also, more broadly, the strategic positioning of the aerospace cluster.

SMEs are also not powerless, with six of their representatives on the board of directors of Aéro Montréal. Additionally, the official figures from Aéro Montréal, CAMAQ, and CRIAQ show that SMEs are very much involved in the various forums, workshops, committees, and activities organized by each of the industry-mediating organizations. This involvement allows them to obtain information but also to shape the content of the programs. SMEs have access to various resources (e.g., the MACH program) and can act collectively, share information, and collaborate on various projects. This manager highlights the change he has observed over a ten-year period in the relationships between SMEs:

For the last ten years, as I explained to you, it has been easier to share some things, because [before] we wanted to keep everything to ourselves, and we didn't want to share. But we realize that the competition is not between us. It's really global, and we can help each other. I think MACH had a lot to do with it.

—MANAGER, SME, MONTRÉAL

While collaboration between SMEs has increased, so has competition, which has taken other forms. SMEs are not only competing to increase their market share, but also to access collective resources. Although the RIC in Montréal is quite inclusive—with many SMEs having access to various programs and networks—subtle forms of exclusion persist.

If an SME is not part of "the elite" group of companies (e.g., firms in the MACH program), it becomes very difficult to be involved in the various networks within and the resources produced by the industry-mediating organization. To access these collective resources, SMEs have to play by the "rules of the game," and must also have already developed their own capabilities and resources. In other words, SMEs with specific capabilities can "play the game" and gain access to collective resources—but those who are relatively powerless are not able to engage in these networks or to access the resources. These SMEs are struggling and are often not able to start the turn towards I4.0.

Another dynamic reduces the capacity of firms to engage in experimentation: firms are strongly incentivized to follow the rules of the game established by industry-mediating organizations in relation to future skills and I4.0. These rules seek to reduce uncertainty and stabilize behaviours and patterns of relations. Firms are expected to follow and apply the rules defining the best practices for I4.0. For example, the MACH FAB program sets specific standards for the implementation of I4.0 and audits firms to ensure that they follow these guidelines. If firms deviate from these standards, they risk being excluded from participating in these programs or losing access to the resources that they provide. Managers in SMEs often feel that they are not allowed to experiment. As a result, these new rules of the game do not encourage experimentation outside the frameworks established by these programs and reduce the capacity of actors to challenge dominant practices and narratives associated with I4.0 and future skills.

Paradoxically then, a resource-rich environment favours institutional experimentation, yet appears to limit the capacity of actors to engage in organizational experimentation. In such a context, one of the challenges is for actors and organizations to avoid becoming locked-in (losing agility) when following the dominant pattern of practices, thus becoming overly path-dependent. As such, a central issue in meeting the demands of I4.0 implementation and future skill development is finding the right balance between organizational and institutional experimentation.

Experimentation processes and the development of collective resources

To what extent do thick or thin RICs create the conditions for actors to experiment and cope with the challenges of I4.0 and future skills? Our findings suggest that both thin and thick RICs create the conditions for experimentation, but, conversely, can also lock firms and mediating organizations into path-dependent behaviour that confines experimentation.

In the Toronto cluster, the RIC is thin, and there is weak coordination at the cluster level that restricts institutional experimentation but favours organizational experimentation. Firms in particular have more leeway to experiment, but to do so, they must build and rely on their own resources and capabilities. In such a context, large firms are in a more advantageous position and can experiment more extensively by capturing collective resources—particularly those produced by education and research organizations—to meet the challenge of I4.0 and future skills. Through experimentation, multinational subsidiaries strategize at the organizational level to reinforce the capabilities of the supply chain. On the other hand, SMEs are not in the same position and struggle to tap into these resources (e.g., accessing training offered by education organizations), since alone they do not have the individual resources and capabilities to do so. Some SMEs with skillful managers who have developed strong personal networks and social capital are able to access and utilize these resources, enabling them to experiment with new ways of dealing with the challenge of I4.0; however, they are exceptional cases.

Further, SMEs cannot rely on any collective mechanisms within the RIC to express their needs and concerns. Over the years, they have been unable to develop any form of collective action or sustainable patterns of collaboration among themselves. This situation has limited SMEs' capacity to develop horizontal networks in the industry, undermining their capacity to access collective resources, shape decision-making processes in the cluster, and participate in agenda setting about I4.0 and future skills. As a result, the dominant dynamic within the RIC favours bilateral relations over multilateral relations, and competitive relations over collaborative relations. However, mediating organizations have developed a number of network-building initiatives that are encouraging firms to work more collaboratively with other actors in the cluster. A number of collective resources related to skills (OAC, OMLC) and new

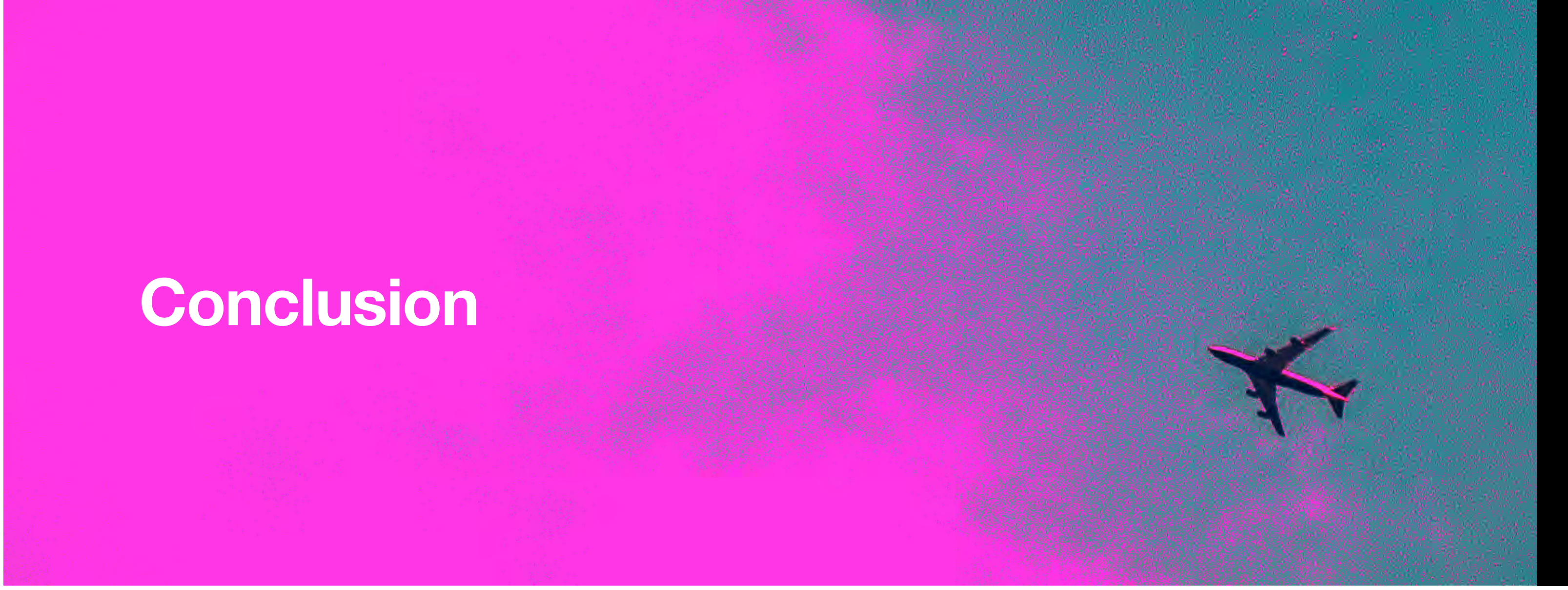
SMEs** have access to various resources (e.g., the MACH program) and can **act collectively, share information, and collaborate on various projects.

technology (university research groups, DAIR, CARIC, NGen) are emerging that could support firms in the cluster, and could be adapted to I4.0. Increasing the resources and, by extension, the role of various industry-mediating organizations (particularly the OAC) is important to accelerate the shift from a firm-centric towards a network approach.

The Montréal cluster rests on a different RIC. Over time, actors have built up a thick institutional configuration that offers many collective resources to the various stakeholders in terms of training, knowledge, and material resources (e.g., financing). These stakeholders can tap into an environment that is rich in collective resources to cope with the challenge of implementing I4.0 and future skills. This RIC thus creates the conditions for actors and mediating organizations to coordinate their action and experiment with new institutions at the cluster level.

The Montréal RIC provides many collective resources to large firms, SMEs, trade unions, research organizations, and educational institutions, while also fostering collaborations among these various organizations. The RIC also creates spaces for trade unions and SMEs to express their concerns at the regional level, providing opportunities for them to shape decision-making processes, the content of the agenda and how resources are allocated. Over the years, SMEs have also a collective capacity to act and collaborate among themselves. The net result is a dynamic within the RIC that encourages multilateral connections and both competitive and collaborative relations. The downside, however, is that institutional experimentation in this RIC seems to restrict some forms of organizational experimentation.

To access this resource-rich environment, actors and organizations need to play by the rules—including best practices, standards, and the cognitive frames established by the RIC. This environment thus enables firms, particularly SMEs, to cope with the challenges of I4.0, but also limits their capacity to experiment within their organization and to engage in more “out of the box” innovation projects. This is the trade-off that SMEs must accept to access collective resources produced by the RIC and be part of the aerospace business community.



Conclusion

Over the last few years, mediating organizations in Canada (e.g., Aéro Montréal, OAC, and trade unions) have published reports pressing the federal and provincial governments to develop a comprehensive policy and strategy for the Canadian aerospace industry. These reports rightly highlight the importance of: 1) attracting new investment; 2) supporting the development of greener aircraft; 3) investing in innovative technologies; 4) strengthening the capabilities of SMEs; and 5) fostering the creation of good jobs and a highly skilled workforce. In the context of the COVID-19 pandemic, these same mediating organizations have been urging the federal government to support the industry in its survival and recovery efforts. This involves immediate financial assistance, as well as a more long-term agenda to help the industry move forward with product and process innovations, so that it can remain competitive internationally.

This report on I4.0 and future skills seeks to contribute to this ongoing conversation in four distinctive ways.

First, the aerospace industry is not at the forefront of I4.0 adoption at the international level, while at the national level, the uptake of technologies that form I4.0 is higher in the Canadian aerospace industry than the manufacturing average. There is, however, much variation across firms, with some operating a fully virtual factory whereas other have yet to start. There are several factors explaining the uneven adoption of I4.0. One common challenge for firms in the Canadian aerospace industry is the codification and standardization of tasks necessary to implement I4.0, in an industry traditionally reliant on tacit knowledge and skills. While the adoption of I4.0 is in its early stages and its impact on future skills and work remains an open question, there is enough evidence to suggest that it favours job polarization, creating some very attractive jobs but also many lower-skill ones. Job polarization is not specific to the aerospace industry and appears instead to be driven by the technologies themselves (Dixon, 2020), but the divergent strategies of Canadian firms indicate that actors have room to maneuver in the implementation of I4.0. The widespread diffusion of I4.0 across the industry will require special funding from governments, as well as the development of proactive programs to support firms in making the transition.

Second, firms cannot not meet these challenges alone. By themselves, firms do not have the capacity to create the conditions to bring together all stakeholders in collaborative partnerships, or even encourage them to act in concert. To produce these conditions, thick regional institutional configurations must be developed to foster collective action amongst the various stakeholders to create collective resources.

Both clusters create space for collaboration and produce collective resources, but in an uneven way. In Toronto, there are few resources at the cluster level to support firms with I4.0; however, there are many collaborative and experimental initiatives driven by individual firms, mainly with colleges and universities, to create resources to meet the specific needs of a firm. In recent years, intermediary organizations have developed initiatives to encourage networking and collaboration. Nevertheless, large firms are in a better position to develop these initiatives and to access these resources in comparison to SMEs. It follows that in the absence of collective resources, SMEs, which typically have fewer internal resources than large firms, find it difficult to deal with the challenges of I4.0 adoption. In Montréal, at the cluster level, many collective resources are offered through mediating organizations in terms of training, knowledge, and material resources. These collective resources act as a substitute for SMEs’ lack of internal resources, in comparison to those available to large firms.

Future policy *will need to be* ***tailored to the needs of the various aerospace clusters*** *and the specific features of the RICs. However, some* ***essential collective resources need to be available*** *for all the stakeholders within the Canadian aerospace industry.*

Third, given the institutional legacies of both clusters, a one-size-fits-all strategy is neither desirable nor feasible. Future policy will need to be tailored to the needs of the various aerospace clusters and the specific features of the RICs. However, some essential collective resources need to be available for all the stakeholders within the Canadian aerospace industry. To take just one example: integrated labour market information should be available and accessible to all, but this is currently not the case. In Québec, in contrast to Ontario, this basic information represents a collective resource produced through the sustained involvement of almost all firms (90% participation in CAMAQ survey from year to year).

Fourth, to produce these shared resources, aerospace clusters need to establish deliberative spaces and mechanisms for fostering collective action and collaboration. We echo calls for developing agile and dense RICs (OECD, 2020) that strengthen the agency of low-power actors such as SMEs, unions, and workers. Mediating organizations have a crucial role to play in this respect, as they can support low-power actors in accessing resources and participating in agenda setting within their regions.

In contrast to Toronto, Montréal creates more spaces and opportunities to foster collective action and collaboration for the various stakeholders, notably for low-power actors. However, much more can be done in each cluster in this regard. In both Ontario and Québec, there are no specific mechanisms at the firm level to ensure worker and trade union participation in the design and implementation of I4.0 and future skills. They can then only be addressed later in the process, through collective bargaining or firm human resources policies. In terms of worker and trade union participation in the implementation of I4.0, Canada lags behind the most advanced countries in the world, like Germany (see for example Bosch & Schmitz-Kießler, 2020).

The creation of deliberative spaces and mechanisms also needs to go beyond each cluster, to foster collaboration between clusters. If Canada seeks to compete on the international level in the development of special projects, such as green aircraft, the country will have to mobilize all of its available expertise and foster mutual adjustment and collective learning across the Canadian aerospace industry. Programs favouring collaboration between clusters—such as CARIC and GARDN—have been, or will be, defunded. Yet in the current industry context, these types of programs seem to be a valuable way of increasing Canada' competitiveness. This leaves CRIAQ as the only permanent mediating organization that is attempting to create connections between clusters in the Canadian aerospace industry.

The time is now to decide what the future of the Canadian aerospace industry will be and what work and skills will look like in the era of I4.0. In the aerospace industry, with its pre-existing skills shortages and aging workforce, it is important to consider how I4.0 can be implemented optimally, in ways that not only enable productivity gains, but also increase the quality of work.

The industry must be able to attract the next generation of aerospace workers. To attract young people into the sector, Canada's industry needs to prioritize ensuring that I4.0 creates good jobs that enable workers to have a significant degree of autonomy and to express themselves while exercising their creativity. It is feasible to achieve productivity and cut costs, while also creating good jobs and high-quality work through I4.0; however, it will require firms to actively seek this outcome through an implementation process that creates space for the involvement of those directly impacted: the workers.

These are difficult times for the industry as a whole—for entrepreneurs, workers, and managers alike. However, this moment of crisis has also opened up opportunities for the Canadian government to reinvest, and for all stakeholders to reimagine the future of this crucial industry for the Canadian economy.

Appendix A: Tables of industry-mediating organizations in each cluster

TABLE 1

Main industry-mediating organizations in the Montréal aerospace cluster

Organization	Staffing	Mission	Remit and activities	Governance
Aéro Montréal **(2006–)**	16 people	Defined as strategic think tank, it has a role coordinating at the cluster level.	Activities structured around cluster competitiveness via supply chain development, innovation, human resources	Board: large firms and SMEs, unions, educational and research centres
Comité sectoriel de la main-d'œuvre en aérospatiale (CAMAQ) **(1983–)**	8 people	Promote workforce skills in the aerospace industry.	Coordination, planning, and strategy development for the aerospace labour market	Board: mainly firms and union representatives equally represented
Consortium de recherche et d'innovation en aérospatiale au Québec (CRIAQ) **(2002–)**	12 people	Develop and stimulate collaboration between industrial specialists and researchers on pre-competitive aerospace research projects.	Encouraging, supporting, and funding collaborative R&D projects	Board: university representatives, large firms

TABLE 2

Main industry-mediating organizations in the Toronto aerospace cluster

Organization	Staffing	Mission	Remit and activities	Governance
Ontario Aerospace Council (OAC) **(1994–)**	4 people	The provincial industry trade association; to foster relationships	Participation in trade events, key annual seminars and networking events, ad-hoc programs depending on firm needs	Board: large and small firm managers. Some college/ university members on steering groups
Downsview Aerospace Innovation and Research (DAIR) **(2012–)**	1 full-time, 1 based at college	A consortium designed to increase collaborative research and development	Fostering collaboration and providing physical infrastructure for events, R&D activities, and workshops and seminars	Board: in the process of being updated (interview). The consortium is made up of 3 universities and 1 college, and 8 large firms
Consortium for Aerospace Research and Innovation in Canada (CARIC) **(2014–2020)**	1 person	Fund collaborative R&D projects	Encouraging, supporting (through application process), and funding collaborative R&D projects	Board: Ontario branch managed within the OAC, so share the same governance structure
Ontario Manufacturing Learning Consortium (OMLC) **(2013–)**	2 people	Provide training programs for industry-specific occupations	Recruitment, selection, and provision of training for industry-specific occupations (e.g., machinists/structural assemblers)	Board: the OAC, and other manufacturing trade associations
Next Generation Manufacturing Canada (NGen) **(2018–)**	Approx. 4 people	Fund collaborative R&D, technology adoption, or skills improvement projects linked to advanced manufacturing	Funder; also appears to offer some forms of matching service for new innovation projects	Board: managers for large and small firms, OAC

Appendix B:
Tables of interviewee distribution

TABLE 3

Distribution of interviewees: Montréal

Level	Interviewee group	Number of interviews (2010–2014)	Number of interviews (2015–2019)
Regional and/or cluster	Institutional actors: research centres, industry association, training centres, government representatives	10	20
	Sectoral/provincial union representatives	4	4
Firm	Firm managers in SMEs and large firms: general managers, human resources managers, operation managers	18	35
	Workplace union representatives	10	5
Total		**42**	**64**

Note: In addition, four group interviews were conducted with 32 trade union shopfloor delegates

TABLE 4

Distribution of interviewees: Toronto

Level	Interviewee groups	Number of interviews (2018–2020)
Regional and/or cluster	Institutional actors: research centres, industry association, training centres, government representatives	14
	Sectoral/provincial union representatives	2
Firm	Firm managers in SMEs and large firms: general managers, human resources managers, operation managers	16
	Workplace union representatives	1
Total		**33**

Appendix C:
List of actors in each cluster

It should be noted that there are a number of important industry-mediating organizations that operate at a federal level—such as the sector trade association, Aerospace Industries Association of Canada (AIAC)—as well as a number of other associations that represent segments of the industry (e.g., Canadian Council for Aviation & Aerospace [CCAA]). These bodies are not be included below unless they are located within one of the clusters. Neither list of actors is intended to be exhaustive. Instead, we hope to provide a snapshot of some of the central stakeholders in each cluster, as well as the supporting RIC, providing resources for readers to check the most up-to-date industry resources.

The Montréal cluster

The following is a non-exhaustive list of actors in the Montréal cluster, with references and website links for further information.

Mediating organizations (see Table 1 in Appendix A)	Aéro Montréal: https://www.aeroMontréal.ca/home.html
	Comité sectoriel de la main-d'œuvre en aérospatiale (CAMAQ): https://camaq.org/
	Consortium de recherche et d'innovation en aérospatiale au Québec (CRIAQ): https://criaq.aero/
Other industry bodies based in the cluster	The Green Aviation Research and Development Network (GARDN): https://gardn.org/
	Projet mobilisateur de l'avions écologique (SAGE): https://www.sa2ge.org/
	Projet stratégique Aéro 21: https://www.aero21.org/
	International Air Transport Association (IATA): https://www.iata.org/
	Société internationale de télécommunications aéronautiques (SITA): https://www.sita.aero/
	International Business Aviation Council (IBAC): https://www.sita.aero/about-us

Firms	Many of the firms operating in the Montréal cluster are listed in the following resources: Aéro Montréal. (2020). Business Search. Montréal: Aéro Montréal. Retrieved from https://www.aeroMontréal.ca/business-search.html Aéro Montréal. (2020). Industry. Montréal: Aéro Montréal. Retrieved from https://www.aeroMontréal.ca/industrie.html MEIQ. (2020). Présentation de l'industrie de l'aérospatiale. Québec City: Ministère de l'Économie et de l'Innovation / Government du Québec. Retrieved from: https://www.economie.gouv.qc.ca/bibliotheques/secteurs/aerospatiale/presentation-de-lindustrie-de-laerospatiale/
Actors in the RIC	Skill and training programs relevant for Montréal's aerospace industry complete list available from: CAMAQ. (2020). Cartographie de la formation en aérospatiale au Québec. Montréal: CAMAQ. Retrieved from https://camaq.github.io/camaqMap/ MEIQ. (2020). La formation en aérospatiale. Québec City: Ministère de l'Économie et de l'Innovation/Government du Québec. Retrieved from https://www.economie.gouv.qc.ca/bibliotheques/secteurs/aerospatiale/financement-et-formation/la-formation-en-aerospatiale/
High school	École des métiers de l'aérospatiale (ÉMAM): https://ecole-metiers-aerospatiale.csdm.ca/
CÉGEP	École nationale d'aérotechnique (ÉNA) https://www.cegepmontpetit.ca/ecole-nationale-d-aerotechnique
Universities	Concordia University/Concordia Institute of Aerospace Design & Innovation (CIADI): https://www.concordia.ca/next-gen/aerospace.html https://www.concordia.ca/ginacody/ciadi.html
	McGill/McGill Institute for Aerospace Engineering (MIAE): https://www.mcgill.ca/ https://www.mcgill.ca/miae/
	École de technologie supérieure (ÉTS)/Institut de conception et d'innovation en aérospatiale (ICIA): https://aeroets.etsmtl.ca/pages/fr/home/ https://aeroets.etsmtl.ca/pages/fr/icia/presentation.php
	École Polytechnique de Montréal/ Institut d'innovation et de conception en aérospatiale de Polytechnique (IICAP): https://www.polymtl.ca/ https://www.polymtl.ca/iicap/

Research centres	Centre de technologies en aérospatiale (CTA): https://www.cegepmontpetit.ca/cta
	Centre de développement des composites du Québec (CDCQ): https://www.cdcq.qc.ca/
	Centre des technologies en fabrication aérospatiale (CTFA) - Aerospace Manufacturing Technologies Centre (AMTC): https://nrc.canada.ca/fr/recherche-developpement/recherche-collaboration/centres-recherche/centre-recherche-aerospatiale
Local government	At the provincial level, the Ministère de l'Économie et de l'Innovation du Québec is responsible for Québec's aerospace strategy. Other government bodies, at the provincial and municipal level, have complementary roles.
Additional funding bodies	Québec has workers investments funds, such as the Fonds de solidarity FTQ, that directly support firms in the aerospace industry: https://www.fondsftq.com/fr-ca/financement/fonds-siege-social/aerospatiale.aspx

The Toronto cluster

The following is a non-exhaustive list of actors in the Toronto cluster, with references and website links for further information.

Mediating organizations **(see Table 2 in Appendix A)**	Ontario Aerospace Council (OAC) - Provincial industry trade association: https://theoac.ca/
	Downsview Aerospace Innovation and Research (DAIR): https://www.dairhub.com/
	Consortium for Aerospace Research and Innovation in Canada (CARIC) (now defunded): https://caric.aero/
	Next Generation Manufacturing Canada (NGen) – the Advanced Manufacturing Super Cluster: https://www.ngen.ca/
	Ontario Manufacturing Learning Consortium (OMLC): https://www.omlc.ca/
	Women in Aerospace Canada (WIAC): https://wia-canada.org/

Firms	A large number of the firms operating in the Toronto cluster can be identified in a consultancy report of the Ontario industry, and in the following reports and directories from the OAC: Global Business Reports. (2017). Ontario Aerospace 2017. Toronto: Global Business Reports OAC. (2019a). Ontario Aerospace Research & Technology 2019 Source Book. Retrieved from https://theoac.ca/page/2019SourceBook OAC. (2019b). Ontario Aerospace, Space, Defence, UAV and MRO 2019 Capabilities Directory. Retrieved from: https://theoac.ca/page/2019Directory
Actors in the RIC	Colleges in the Toronto cluster sourced via OAC. (2019). Ontario Aerospace Sector Toronto: OAC. Retrieved from: https://theoac.ca/page/ONAerospaceSector
Colleges	Centennial College: https://www.centennialcollege.ca/programs-courses/full-time/aerospace-manufacturing-engineering-technology/
	Mohawk College: https://www.mohawkcollege.ca/
	Conestoga College: https://www.conestogac.on.ca/
	Georgian College: https://www.georgiancollege.ca/
	Canadore College: https://www.canadorecollege.ca/
	Humber College: https://humber.ca/
	Seneca College: https://www.senecacollege.ca/home.html
Universities	Universities in the Toronto cluster sourced via OAC. (2019). Ontario Aerospace Sector. Retrieved from https://theoac.ca/page/ONAerospaceSector
	Ryerson University/Ryerson Institute for Aerospace Design and Innovation (RIADI): https://www.ryerson.ca/ https://www.ryerson.ca/riadi/
	York University: https://futurestudents.yorku.ca/program/space-engineering
	University of Toronto/University of Toronto Institute of Aerospace Studies (UTIAS): https://www.utoronto.ca/ https://www.utias.utoronto.ca/
	University of Waterloo: https://uwaterloo.ca/
	McMaster University/McMaster Manufacturing Research Institute (MMRI): https://www.mcmaster.ca/ https://www.eng.mcmaster.ca/mcmaster-manufacturing-research-institute-mmri
Local government	Provincial and district government representatives. There are representatives at the provincial and municipal level who may be involved in various aerospace initiatives. Information about these representatives are available on local government websites.

Appendix D:
Workforce shortages in Québec

TABLE 5

Occupations considered difficult to recruit in the Québec aerospace industry

Occupations	Number of workers needed, 2017–2018	Number of workers needed (number of firms), 2018–2020	Number of workers needed (number of firms), 2020–2021
Machinists and programmers (CNC and conventional)	217	188 (41)	217 (43)
Assembler	194	341 (11)	58 (12)
Electrical/electronic/avionics engineering technicians	62	113 (5)	104 (12)
Aircraft maintenance technicians	54	289 (10)	199 (12)
Method agents	67	64 (11)	48 (7)
Inspectors and quality control officers	100	105 (18)	61 (11)
Engineers	n/a	234 (33)	107 (16)
Engineering specialists (aeronautics, mechanics, software, etc.)	155	n/a	n/a
Software designers/developers	64	n/a	n/a
Academic informatics (Software Engineer/IA Developer)	n/a	n/a	73 (11)
Computer programmers	n/a	n/a	54 (15)

Source: Data gathered by the authors from CAMAQ (2018; 2019; 2020).

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