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Integration of Additive Manufacturing in the Aerospace Industry

by

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Résumé

La fabrication additive, plus communément appelée impression 3D, est une technologie émergente en pleine évolution qui a le potentiel d'offrir un avantage compétitif de taille aux entreprises qui sauront l'intégrer convenablement dans leurs processus. Grâce à sa capacité à produire des pièces métalliques plus légères, plus complexes, plus performantes, plus rapidement, l'industrie aéronautique sera un des plus grands bénéficiaires de cette technologie. Cependant, le développement d'expertise et son incorporation dans une chaîne d'approvisionnement traditionnelle représentent des défis de taille.

Ce mémoire de M.Sc. est issu d'une collaboration avec plusieurs organisations-clés de l'industrie aérospatiale canadienne en vue de répondre à la question suivante : *Comment intégrer avec succès la fabrication additive métallique dans la chaîne d'approvisionnement aérospatiale canadienne?*

La réponse à cette question sera présentée sous forme de recommandations basées sur des observations de l'état actuel de l'industrie obtenues grâce à des entrevues et un sondage. La participation de plus de 70 organisations à cette étude a mis en lumière des aspects préoccupants à propos de l'état actuel de l'industrie tel que la mauvaise compréhension de plusieurs parties prenantes quant au potentiel réel de la FA, le manque de demande de la part des donneurs d'ordre, la sous-estimation des opérations de post-traitement et le besoin d'adapter les programmes de R&D à de nouveaux types de modèles d'affaire.

Bref, ce projet de recherche innovateur est une réponse à un problème actuel, et ouvre le chemin aux chercheurs qui désirent participer à la prochaine révolution manufacturière.

Mots clés : Impression 3D, fabrication additive, aérospatiale, intégration technologique, technologie émergente, chaîne d'approvisionnement, innovation

Abstract

Additive manufacturing (AM), more commonly known as 3D printing, is a fast evolving technology promising a competitive advantage to the enterprises that will be able to correctly integrate it in their processes. AM has the ability to produce low volume, customized metal parts with complex geometries and improved functionalities in a cost-effective and time-efficient way. For these reasons, the aerospace industry will be one of the biggest beneficiaries of this technology. However, the development of expertise and its incorporation into a traditional supply chain are significant challenges.

This M.Sc. thesis has been done in collaboration with several key organizations in the Canadian aerospace industry in order to answer the following research question: *how to successfully integrate metal additive manufacturing in the Canadian aerospace supply chain?*

The answer to this question will be presented as recommendations based on observations of the actual state of the industry obtained using interviews and a survey. The participation of over 70 organizations to this study highlighted some concerns about the actual state of the industry such as the misconception of AM's true potential from multiple stakeholders, the lack of demand from OEMs, the underestimation of post-processing operations and the need to adapt R&D programs to new business cases.

In short, this innovative research project is a response to a current problem which will open the way to other researchers who wish to participate in the next manufacturing revolution.

Keywords: 3D printing, additive manufacturing, aerospace, technology integration, emerging technology, supply chain, innovation

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List of abbreviations

3DP: Three-Dimensional Printing

AM: Additive Manufacturing

ASTM: American Society for Testing and Materials

CAD: Computer-Aided Design

CARIC: Consortium for Aerospace Research and Innovation in Canada

CM: Canada Makes

CME: Canadian Manufacturers and Exporters

CRIAQ: Consortium for Research and Innovation in Aerospace in Quebec

CRIQ: Centre de Recherche Industrielle du Québec; Center of Industrial Research of Quebec

DFMA: Design For Manufacturing and Assembly

DMLS: Direct Metal Laser Sintering

EBM: Electron Beam Melting

FDM: Fused Deposition Modeling

FEA: Finite Elements Analysis

IM: Injection Molding

LMD: Laser Metal Deposition

NNMI: National Network for Manufacturing Innovation

OEM: Original Equipment Manufacturer

PLC: Product Life Cycle

SHS: Selective Heat Sintering

SLA: Stereolithography

SLS: Selective Laser Sintering

SME: Small and Medium Enterprises

TRL: Technology Readiness Level

Acknowledgements

The success of this exploratory research would not have been possible without the involvement of such a large number of experts and stakeholders. I am very grateful to everyone who shared their time and expertize during extensive interviews and to the 107 industry representatives who participated in the survey and contributed to its success.

Let me begin by expressing my gratitude to Sofiane Benyouci for helping me start this project from day 1, for inviting me to AM forums and conferences and for introducing me to relevant representatives of the AM and aerospace industry. Additionally, I'd like to thank Maude Théroux-Séguin and the team of Innovitech for providing me with an office, conference rooms and a stimulating work environment throughout the project duration.

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Special mention must be made to François Richard and Mathieu Fagnan for regularly sharing their time and their extensive expertise on additive manufacturing and on the aerospace industry. Their insights greatly helped me in understanding the real challenges faced by the industry towards AM and in focusing on the relevant aspects of the topic.

I am appreciative of the help of Martin Lavoie and Frank Defalco from the Canadian Manufacturers and Exporters for showing interest towards this study right from its beginning, sharing the survey to their network and introducing me to multiple industry experts who then contributed to the success of this research.

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Chapter 1
Introduction

1.1. Introduction

The following research project aims to facilitate the integration of different technologies of metal additive manufacturing (AM) into the Canadian aerospace logistics chain. When well integrated in the supply chain processes, AM can provide an important competitive advantage. It can allow its users to accelerate the commercialization of certain parts, improve their performance, reduce production costs and even make part designs that were once impossible to manufacture with traditional equipment. Canada is ranked as part of the global elite in the aerospace industry and the development of expertise in AM is essential for keeping local suppliers competitive and to keep shining on the international scene.

The objective of this research project is to understand the challenges and opportunities of the different segments of the logistics chain towards AM, in order to build recommendations adapted to their situation. The project is done in partnership with a consortium of aerospace enterprises in order to have a practical insight of the reality of the industry. During the first phase of the project, 15 interviews were conducted with professionals situated at every level of the value chain in order to identify their needs and particular views on the challenges to implementation. In order to have a representative picture of the actual state of the national industry, a survey has been sent to various stakeholders across the Canadian aerospace industry and 107 responses were collected from over 70 enterprises. Some of the needs and challenges that have been identified include: shortage of labor expertize, misunderstanding of the limitations and opportunities of AM, inadequate funding programs, inadequate certifications and standards, lack of demand from OEMs, lack of trust in the technology, underestimation of post-processing operations, and more. After analysis, some recommendations that could have the potential to fix one or many of these challenges have been brought up.

The whole analysis is presented to the stakeholders as recommendations on the next actions to undertake in order to better integrate additive manufacturing into the aerospace supply chain.

1.2. Relevance of the research topic

Even if AM is making its way into various sectors, the aerospace industry still struggles to additively manufacture metal parts. Rare are the manufacturers who own a metal AM machine, technical expertise is dispersed across the industry, certification is a work in progress and profitable business cases are exceptional. AM still is an emerging technology and its successful integration in the aerospace supply chain is within industry reach. If unable to adapt to evolving global manufacturing methods, the industry might not simply face a status quo, but rather, a steady decline of its industrial and innovative capacity, non-competitive products, and lost opportunities. The first step towards this goal of successful integration is to identify the many obstacles stakeholders are facing and to set strategies to overcome them.

The quality of the data collected during this study and the fact that it is quantitative instead of qualitative has a high value for the industry. The state of AM in Canada evolves quickly and is often based on the subjective point of view of experts in the domain. The trends that have been measured in this study are based on the answers from 107 participants with AM knowledge from over 70 organizations situated everywhere in the Canadian aerospace supply chain (from material provider and academia to OEMs and manufacturers). Given the relevance of the collected data, decision makers at the industrial and governmental levels will be able to use it to justify investments or build roadmaps based on facts instead of intuition.

1.3. Research Question

This thesis will survey and interview stakeholders from all the different segments of the aerospace supply chain in order to have sufficient data to give recommendations on **how to successfully integrate metal additive manufacturing in the Canadian aerospace supply chain.**

More precisely, this research will investigate the following sub-questions:

1) What are the perceived opportunities in AM for enterprises?

2) What are the perceived challenges and obstacles for utilizing AM?

3) What are the most influential cost drivers in AM?

4) Which type of AM-related initiatives could accelerate AM deployment?

1.4. Thesis structure

Chapter 2 explains what additive manufacturing is, its advantages, the related challenges and some considerations for cost analysis. Chapter 3 gives a brief overview of the aerospace industry in Canada and the effects that AM could have on it. Chapter 4 explains the methodological approach used in the research project, which is based on a series of interviews combined with a national survey. Chapter 5 presents the data collected during the survey and discusses the results obtained. Chapter 6 brings up a list of recommendations in order to successfully integrate AM in the Canadian aerospace industry. Finally, Chapter 7 concludes this study with a summary of all the subjects discussed during this thesis, the limits of the study and its contributions to the industry.

Chapter 2
Additive Manufacturing

Additive manufacturing (AM), most commonly known as 3D printing (3DP), has been around for over 30 years now and many authors wrote about it. The subject even caught the attention of the media who did not hesitate to describe it as a “third industrial revolution” which is about to change the whole world as we know it (The Economist, 2012). Since reality is always more complex than the newspaper’s titles, this report will help to break some popular myths around 3D printing and to better understand the possibilities and limits of the technology. The following section provides an overview of the different AM technologies available on the market, the opportunities, the limitations and various applications of AM. From there it will be easier to understand the real impact for the industrial domain. Once this section is completed, the reader will have the necessary knowledge to continue reading with a better understanding of the basic principles and limits of additive manufacturing.

2.1. What is additive manufacturing?

The American Society for Testing and Materials (ASTM) International Committee F42 defines AM as the “process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies” (ASTM International, 2009). AM should not be considered as a simple technology, but more as an industrial domain allowing for a different way to manufacture products. This new type of manufacturing technique, which has been commercialized in the United States in the mid-1980s, is still immature, but rapidly developing. It presents advantages that are pushing enterprises to choose it over traditional manufacturing for specific applications (Wohlers, 2014).

The main feature of AM is its responsiveness to the demand and its ability to allow more design flexibility. The downsides that come with it are the lack of repeatability of the process, difficult product certification and the limited range of materials. Weighting the pros and cons, AM is generally more cost effective for making one-off jobs with low volume of production (Aliakbari, 2012).

2.2. Overview of the different AM technologies

At the moment, on the AM market, there are 13 different sub-technologies which can be grouped into 7 different processes categories (see Table 1). Each of these sub-technologies uses different materials (mainly metals, plastics, ceramics and composites) and has different advantages and limits (geometry complexity, cost, printing speed, quality of the print, etc.) (Cotteleer, Holdowsky and Mahto, 2013). The table below lists the ASTM-approved system of process categorization for AM.

Table 1 : Main categories of AM processes

Powder bed fusion
AM process in which thermal energy selectively fuses regions of a powder bed
Directed energy deposition
AM process in which focused thermal energy is used to fuse materials by melting as the material is being deposited
Material Extrusion
AM process in which material is selectively dispensed through a nozzle or orifice
Material jetting
AM process in which droplets of build material are selectively deposited
Binder jetting
AM process in which a liquid bonding agent is selectively deposited to join powder materials
Sheet lamination
AM process in which sheets of material are bonded to form an object
Vat photopolymerization
AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization

Source: ASTM, 2009, ASTM International Committee F42 on Additive Manufacturing Technologies, ASTM F2792-10 Standard Terminology for Additive Manufacturing Technologies, ASTM, West Conshohocken, PA.

Depending on the chosen technology and the equipment manufacturer, the price of AM equipment (3D printer) varies from less than $1000 to over $1 million (Wohlers, 2014). Given these characteristics, there are no best-overall AM technologies; only trade-offs between one and the other. The following table classifies the 13 sub-technologies by process, materials, advantages, disadvantages and prices.

The table below gives a quick overview of the different materials, advantages, drawbacks and price range associated with each AM technology. It is not meant to provide detailed specifications of every technology, but to give the reader a general view on the different processes trade-off. For example, metal processes are generally more expensive than those working with plastics. None of the processes offers to print rapid, accurate and cheap parts with a wide range of materials. All technologies are different and the trade-off they require will decide the applications for which they are more suitable. In the table below, the first 7 technologies can use metal as input material. However, this study will mostly focus on the first 3 technologies (DMLS, EBM and LMD), since they are considered as the most promising ones for aerospace metal part manufacturing.

Table 2: Characteristics of the Main Sub-Technologies of Additive Manufacturing

Technology	AM process	Typical materials	Advantages	Drawbacks	Price range ($USD)
Direct metal laser sintering (DMLS)	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Complex geometries; dense components	Small parts; finishing needed	$130K – $1,6M
Electron beam melting (EBM)	Powder bed fusion	Titanium powder, cobalt chrome	Fast build process; low distortion of parts	Finishing needed; difficult machine maintenance	$130K – $1,6M
Laser metal deposition (LMD)	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; large parts	Expensive; post-processing required	$350K – $1,5M
Ultrasonic consolidation	Sheet lamination	Metals and metal alloys	Suitable to print large parts quickly	Low accuracy; inconsistent quality; post-	N/A

(UC)				processing required	
Laminated object manufacturing (LOM)	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Cheap; suitable to print large parts quickly	Low accuracy; non-homogeneous parts	$36K - $48K
Selective laser sintering (SLS)	Powder bed fusion	Paper, plastic, metal, sand, ceramic, composites	High speed; no support structure required; heat and chemical resistant material	Rough surface finish; accuracy proportional to powder quality	$350K - $850K
Powder bed and inkjet head printing (PBIH)	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	High build speed; cheap; full-color print	Poor surface finish; low accuracy	$130K - $1,6 M
Stereolithography (SLA)	Vat polymerization	Liquid photopolymer, composites	Complex geometries; smooth finish	Post-curing required; support structure required	$5K - $600K
Digital light processing (DLP)	Vat polymerization	Liquid photopolymer, composites	Complex shapes and sizes; high precision	Limited product thickness; limited range of materials	$9K - $240K
Multi-jet modeling (MJM)	Material jetting	Photopolymer, wax	Accuracy; good surface finish; wide variety of materials; allow colors	Limited wax-like materials range; slow build process	$20K - $600K
Fused deposition modeling (FDM)	Material extrusion	Thermoplastic	Complex geometries; strong parts	Poor surface finish (possible post-treatment); slow build process (vs. SLA)	$500 - $500K
Selective heat sintering (SHS)	Powder bed fusion	Thermoplastic powder	Complex geometries; quick turnaround	Limited track record of this new technology	$140K - $984K
Plaster-based 3D printing (PP)	Binder jetting	Bounded plaster, plaster composites	Cheap; full-color print; high build speed;	Fragile parts	$16K - $114K

Sources: Adapted from Deloitte University Press, 2013 and Wohlers Associates 2014.

2.3. Process Performance Measures

In order to define the performance of metal additive manufacturing processes, the multiple advantages and limitations of AM have been classified into four metrics that are commonly used in logistics and operations management: cost, quality, lead time and variety (Anupindi *& al.* , 2006). Additional topics have been categorized in a fifth category called "other". Acknowledging and understanding the advantages and limitations of AM will help the reader to grasp the essence of the results and analysis that will be done in the upcoming chapters of this report. The questionnaires of the semi-structured interviews and the survey, which have been used to collect the data for this study, are built according to these advantages and limitations.

As more AM R&D projects are launched, more profitable AM applications are being discovered. However, additive manufacturing still is an emerging technology (mostly metal AM) on its way to a plateau of maturity and those profitable business cases are exceptional. Even if the advantages of AM are attractive, they are sometimes still outweighed by its limitations. To reach maturity, AM requires more than machines with the expected technical performances; there is also a need for a democratization of the technology over the manufacturing industry, the creation of standards, the qualification of part manufacturers, and an adaptation of the product designers. The table 3 regroups the main advantages and limitations of AM. A more extensive description of each point is available in the next section.

Table 3: Advantages and limitations of AM processes

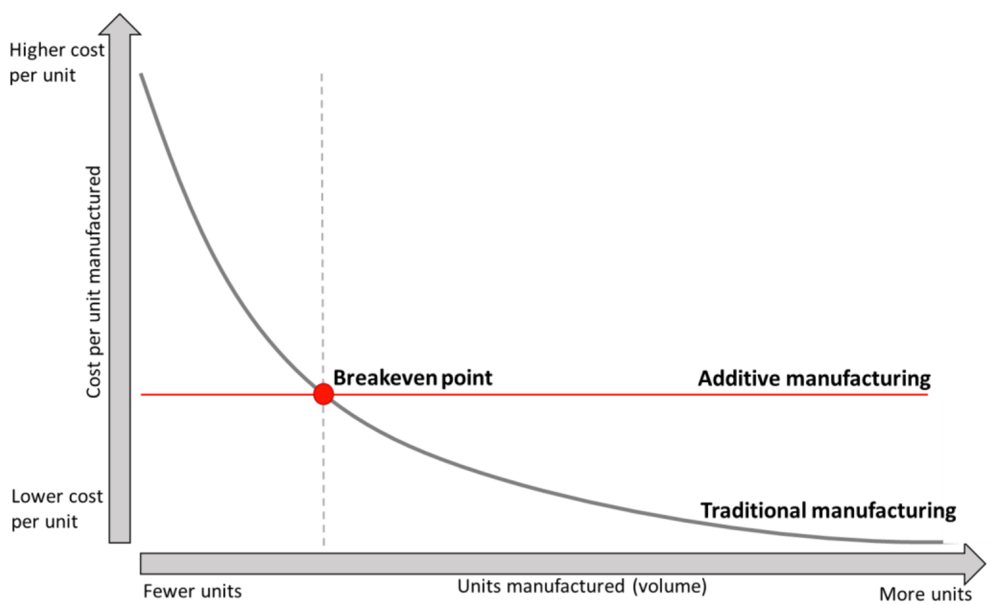
Performance measure	Advantages of AM	Limitations of AM
Cost	• Lower minimum efficient scale of production • Cheaper tooling and jigs • Reduction of logistics and transportation cost • Lower labor cost	• Expensive AM equipment • High material cost
Quality	• Weight reduction	• Low quality consistency • Talent and expertise shortage • Certification and material characterization
Lead time	• Lower inventory • Faster product development • Simplification of the supply chain network and logistics	• Slow build time - does not compete with mass production for large volumes
Variety	• Design flexibility • Manufacturing functional assemblies • More accessible mass-customization • Allows economies of scope	• Limited size of product • Limited range of materials
Other	• Improved process sustainability • Contribution in Lean manufacturing • Contribution in Agile manufacturing • Reshoring manufacturing jobs	• Low general understanding of the technology • Intellectual property protection

2.4. Cost

2.4.1. Lower minimum efficient scale of production

Economies of scale gave rise to modern industrial production facilities able to manufacture large quantities of products. The huge investment costs (such as molds or set ups) are absorbed over a very large number of products, allowing them to have a lower average cost per unit. A large minimum efficient scale also poses an entry barriers for smaller producers which could not produce as efficiently as big factories. The advent of AM may eventually break this tendency because the technology does not require any molds, fixtures or long set ups. By reducing the minimum efficient scale, AM could help smaller suppliers to take part in the market with low-to-medium-sized production runs (Cotteleer and Joyce, 2014). The figure below illustrates that conventional manufacturing offers an advantageous price per unit for larger productions (passed the breaking point), while AM offers a unit price that is barely affected by the size of the production run and is shown to be more advantageous for smaller production runs.

Figure 1: Breakeven analysis comparing traditional and additive manufacturing processes



Source: Recreated from Cotteleer, Mark and Jim Joyce (2014). « 3D Opportunity - Additive Manufacturing paths to performance, innovation and growth », *Deloitte Review*, no 14.

2.4.2. *Cheaper tooling and jigs*

An underestimated time and money consuming step of production is tooling. AM offers the possibility to print complex custom jigs directly from a Computer Aided Design (CAD) file in a few hours at a relatively low cost. The same situation occurs when making patterns for dies and molds. AM can deliver complex patterns at low cost within a short delay. AM equipment providers claim that their machines can reduce the lead time associated with tooling fabrication by 40-90 percent (Hiemenz, 2011). Even for parts which are manufactured with traditional methods, AM is beneficial when it is time to make custom jigs to fix the parts on the welding machine or the milling machine. With parts that need to be molded, AM is useful in creating a quick and cheap prototype over which the mold can be created. Moreover, AM can produce molds with unique features such as free-form cooling channels yielding faster and more homogeneous heat removal, allowing for shorter cycle time and higher-quality parts (Cotteleer, Neier and Crane, 2014).

Not only the production of the molds themselves is expensive, but the cost of maintenance, storage and tracking has to be considered. AM becomes interesting by significantly reducing the costs related to traditional tooling. The effect of tooling cost change should be taken into account in any full business case comparing AM and traditional manufacturing. Although expensive traditional tooling costs are usually justified for large production runs, the flexibility and responsiveness of tooling made by AM might be justified in the phase of product introduction and product support. When mechanically equivalent to tooling made by traditional methods, tooling made by AM could allow for significant reduction in production cost even for long runs. Its lower cost allows it to be recycled or discarded rather than tracked and stored (Cotteleer, Neier and Crane, 2014).

2.4.3. *Reduction of logistics and transportation cost*

The fact that the labor cost becomes less significant will result in the advent of distributed manufacturing. While the design can be centralized, the manufacturing can be done simultaneously in locations closer to every customer. This decentralization of manufacturing is an opportunity to reduce lead time, packaging, logistics and transportation costs (Aliakbari, 2012).

2.4.4. Lower labor cost

Part simplification and functional assembly printing, made possible through AM, may allow for economies on labor cost. Going from many components (looking to be assembled together) to one product or one functional assembly leads to a faster and cheaper supply chain by lowering the need for labor to assemble it. On the other hand, if a part requires extensive post processing, the labor cost might increase (Aliakbari, 2012). The cases of high post processing cost only happen when a part is not suitable for AM or when its design is not well adapted to the AM process.

2.4.5. Expensive AM equipment

Machine costs are the most important part of direct costs. New complete production-capable AM systems represent an investment of hundreds of thousands of dollars. Added to that, depending on the material used, the room in which the machines are situated may have to be adapted to them. Build volume (i.e. product size), machine utilization, depreciation and tax-incentives have to be taken into account when doing a business case comparison between AM and traditional manufacturing (Cotteleer, Neier and Crane, 2014). The fact that the evolution of the technology and the machines is very fast makes the investment riskier. Machines can become outdated after only a few years.

2.4.6. Materials cost

Materials produced for metal AM use are still relatively expensive. This is mostly due to the fact that they require complex and expensive transformations before being AM-ready. Even though AM offers a fraction of the waste obtained through traditional methods, the price per kilogram is so high that it is often cheaper to produce with traditional methods and to scrap big amounts of material.

Another consideration that plays a role on costs is the recyclability of the materials. Even though AM allows for less waste, it does not reach zero waste. Some parts need to be built on a support structure that will be removed during post-processing and some technologies will affect the quality of the unused powder near the fusion zone. Because of the diversity of materials and technologies, material recycle rate varies from one case to the other and should be taken into consideration while building a business case (Aliakbari, 2012).

2.5. Quality

2.5.1. Weight reduction

Since the process is additive, it only puts material where it is needed. By previously performing a topological optimization, the designer can calculate which sections of a part require more material and which sections do not need as much. That analysis being done, a part can contain hollow sections, lattice structures or even variation of density in order to save weight without compromising its physical resistance. Since the cost of an AM part is directly correlated with the quantity of material used, the lighter it is, the cheaper it gets (Coykendall *& al.* , 2014). However, as mentioned in section 2.4.6, one needs to take into account that the price per kilogram of raw material is higher with AM than with traditional manufacturing. Additionally, in the aerospace industry, lighter parts will translate into fuel cost savings for the airline that will operate the plane. Northwest Airlines estimated that a weight reduction of 25 pounds on a plane flying international routes could lead to annual fuel savings of around $440,000 (Churchill, 2008). With these considerations, the opportunity of weight reduction can be translated into cost savings for airlines and into higher quality products for manufacturers.

2.5.2. Quality consistency

Repeatability from one print to the next still is a problem. As the technology evolves, improvements in repeatability of parts should come up with more performant machines, softwares and in-process automated *in-situ* dimensional accuracy inspections. The quality of the products would be positively affected if AM machines could detect imperfections and correct them as a part is being manufactured (Coykendall *& al.* , 2014). Well aware of this issue, the industry is currently working on the integration of in-process inspection to improve print's quality.

2.5.3. Talent and expertise shortage

To be sustainable, the rise of a new technology has to be followed by a rise of experts. As the use of AM rises, there will be a growing need for people with AM-specific skills in many areas such as CAD, quality inspection, machine making, operations and maintenance, raw material preparation, supply chain management, etc. (Giffi, Gangula and Illinda, 2014). As AM activities will gain ground, there will be a growing need for training and skill development programs in the industries using it. Since it is still immature, the training happens more often by experimenting on the job floor rather than through formal education (IBISWorld, 2013). In order to create a stable and capable workforce, academic institutions, AM service providers and end-user industries will have to work together to create those programs and ensure a sufficient talent supply in the future (Feloy and *al.*, 2013).

2.5.4. Certifications and material characterization

In the aerospace industry, when a new part needs to be commercialized, there is an obligation from Transport Canada to certify the raw material, the part itself and sometimes even the manufacturing process (Transport Canada, 2014). While waiting for a common standard to exist, manufacturers need to invest in characterizing every material, part and process internally. In order to be able to certify more parts, manufacturers will need more product orders from their clients, which is not about to happen soon since the actual parts made with conventional manufacturing already meet the needs of the clients. This vicious circle will keep the market in a *status quo* until it will be ready to try something different. The situation might change when an enterprise will come up with a business case which will radically reduce cost or improve performance.

2.6. Lead time

2.6.1. Lower inventory

By reducing transportation, assemblies, and disruptions in the supply chain or by customizing production, it is easier to lower the level of inventory and the related operations. This way, implementing just-in-time production is simplified (Koff and Gustafson, 2012).

2.6.2. Faster product development

By being able to produce prototypes faster, cheaper and more easily, the R&D centers will be able to have small rapid manufacturing labs closer to their work environment. If the cost to manufacture prototypes is lower, less work and verification will have to be done prior to building and testing. According to Ford, the development and creation of the prototype of a component such as an engine manifold usually costs around $500,000 and takes about 4 months. When Ford used AM to do the same component, they developed multiple iterations of the components and got them manufactured in 4 days at a cost of $3,000 (Ford Motor Company, 2013).

By having R&D, engineering and production closer to one another, the communication between departments will be increased (compared to companies where it is split worldwide). This will reduce significantly the product development time and accelerate innovation.

2.6.3. Simplification of the supply chain network and logistics

Through the simplification of the production network configuration, AM could help in the simplification of logistics by reducing the intermediary steps and the distances over which raw materials, components and products will be transported (Bureau, 2014).

Thanks to the digitalization of manufacturing, it is now possible to electronically send CAD file of parts instead of physically sending parts. Besides savings in transportation, it also helps to avoid customs fees, insurances and to reduce delays in shipping. It makes even more sense to do so now that AM machines allow enterprises to print some parts closer to the assembly site (Campbell, Williams and al., 2011). 3D printing some parts on site reduces the friction in the supply chain, eliminates shipping delays and costs and reduces levels of inventory (Koff and Gustafson, 2012).

2.6.4. Slow build time

The time required to build one component through AM (one layer at a time) is usually longer than the time required to do the same part through another process like injection molding (injecting liquid metal/plastic into a mold and cool it down). But the advantage of AM is that it does not require the use of a mold. In such context, AM may come faster for smaller production (because of the quick set up time), but injection molding may come faster for mass production. In their white paper, Stratasys insists on the fact that, when comparing AM to traditional methods, a manufacturer should not only look at the build time, but at the entire process before judging which technology is more attractive. In some cases, AM may require more build time, but less manufacturing steps, resulting in a shorter total process (Stratasys Ltd., 2014).

2.7. Variety

2.7.1. Design flexibility

AM gives rise to unprecedented design flexibility. While the cost of traditionally manufactured parts is strongly dependent on the parts complexity, AM allows the creation of previously unfeasible designs at no additional cost. With such a process it makes sense to lighten the part as much as possible. But the real innovation resides in the possibility of creating completely reinvented designs and new products with breakthrough features (LaMonica, 2013). To achieve that goal, enterprises need to provide a creative and innovation-friendly working environment. A new teaching approach in design and engineering schools will also be necessary. If the tools available on the market evolve, the education and training should follow this evolution.

2.7.2. Printing functional assemblies

AM processes have the capacity to print fully-functional assemblies in one single print. This implies that AM opens the door to a new variety of product manufacturing that could significantly reduce the lead time, production cost and production resources. Not only the labor that assembles the parts is not required anymore, but the whole logistics of collecting all the parts from various suppliers with different lead times and different batch sizes represents a significant reduction in transportation, coordination, cycle time and inventory costs. Added to that, since the components don't need to be assembled anymore, they don't need to be designed the same way. The design-to-assemble constraint disappears, leading to simpler and lighter parts. This possibility eases the way for manufacturers to consolidate parts and create robust design more easily. The best example to support this type of opportunity is probably the case of LEAP engine 3D-printed fuel nozzles of GE. The original fuel nozzle, an assembly of 19 components, has switched into a single piece printed in one go. GE claims that the new 3D printed design is lighter, more durable, more fuel efficient and simpler to manufacture (Kellner, 2014).

2.7.3. More accessible Mass-Customization

Because of the low set up cost and set up time achieved with AM, it is very easy to customize products for each client. The digitalization of production allows the CAD to be modified at almost no cost (the only cost is the salary of the designer) and sent to the machine that will manufacture it without a need for long set ups (unlike traditional machines). It can allow manufacturers to increase their level of service without significantly increasing their cost (DeAngelis, 2013).

2.7.4. Allows economies of scope

AM allows for better economies of scope by allowing the production of multiple products with the same capital. It allows to make a very efficient use of the AM machines and to reduce costs associated with customization and changeovers. Because of its flexibility, AM allows for the production of additional products in the same printing run, without significant increase in capital (Cotteleer and Joyce, 2014).

2.7.5. Limited size of product

For most AM machines, the physical size of the manufactured product is limited to relatively small printing volumes since it is limited to the size of the printer. This constraint makes AM inappropriate for the fabrication of large parts. Larger prints also come with problems such as more residual stress, more distortion and longer cycle time. In order to overcome these limitations, researchers and machine manufacturers are actually working on commercializing new machines with bigger printing volumes. For example, Lockheed Martin is working with Oak Ridge National Laboratory on a new system which will print larger parts through multiple coordinated printing heads in an open environment (Coykendall *& al.* , 2014). The new dilemma that comes with AM machines with bigger build chambers is that they are not as profitable when only a fraction of their printing capacity is utilized.

2.7.6. Limited range of materials

AM works only with a limited range of materials. Only some selected metals and plastics can be used to additively manufacture parts and those materials are generally much more expensive than their equivalent in traditional manufacturing. Over the next years, advances and improvements in material science will expand the portfolio of materials and bring their cost down (Coykendall *& al.* , 2014). Even if today's range of AM-ready materials may seem restricted, one needs to remember that during the emergence of molding processes, the range of materials was restricted and greatly enlarged over the years of its development. AM has the potential to follow the same path.

2.8. Other

2.8.1. Improved process sustainability

Additive manufacturing is generally more sustainable than traditional manufacturing. As said previously, the transportation needs can be significantly reduced. It is also beneficial with respect to waste flows, resource consumption and emissions generated during production. Contrary to subtractive manufacturing, additive manufacturing only uses a bit more than the amount of material required for the part it builds. In the aerospace industry, buy-to-fly ratio (ratio of raw material input to final product mass) generally rank from 12:1 to 25:1, while AM processes ranks around 1.5:1 (McGrath *& al.* , 2015).

2.8.1. Contribution in Lean Manufacturing

The main goal for a lean system is to produce efficiently through the reduction of any form of waste. With AM, waste of material is reduced since the process puts material only where it is needed and where support structures are needed. Some AM techniques require less energy input than traditional methods to produce the same final part. The simplified building process of AM allows for the removal of many intermediate steps of manufacturing, leading to a reduction in the number of machines required, necessary floor space, set up time and some assembly stages (through part consolidation). Previously, some products needed distinct suppliers to manufacture the many components and to assemble them together. When these distinct manufacturing stages can be reduced to a single one, JIT becomes easier to implement within a given supply chain (Aliakbari, 2012).

In their case study published in 2014, Morel Industries showed how they successfully implemented AM to become leaner (reduction of scrap rate and lead time) by replacing their traditional 3-cores wood and sand patterns by a single core 3D printed sand mold. The scrap rate decreased from 9% to 1%, lead times went from 5 weeks to 2 weeks (60% reduction) and cost per batch went from $8,000 to $1,200 (85% reduction) (ExOne, 2014).

2.8.2. Contributions in Agile Manufacturing

The focus in agile systems is more on responsiveness to changing demand. It requires processes that are reconfigurable and adaptive to ever new situations. Since the input of AM machines is always a CAD file and the additive process doesn't require any jigs or fixture, changing a product only requires a designer to modify the CAD file and to send it to the AM machine. A newly designed product can be ready within a few hours. This works very well with small and medium batches of highly customized products, but is not yet adapted to large batches because of cost and production time issues (Aliakbari, 2012).

2.8.3. Reshoring manufacturing jobs

Additive manufacturing could have the effect of bringing manufacturing back in the developed countries, but not exactly as we think. It is not a matter of bringing back the production that has been outsourced to countries with lower labor cost. It is more in a way that the designs of products will evolve and those new designs will only be "manufacturable" in countries with a high expertize in additive manufacturing. There will be a clear incentive for manufacturing countries to develop this know-how in order to stay competitive on the market (Giffi *& al.* , 2015).

2.8.4. General understanding of the technology

Additive manufacturing is an umbrella-name covering multiple different technologies that are too often generalized as one. This misconception of AM can have as consequence that many people underestimate or overestimate its true potential; leading to failures or missed opportunities.

Even though the design freedom allowed by AM alleviates some of the traditional manufacturing restrictions, designers still have to take into consideration the achievable tolerances of every machine, the laser speed, the laser power, the build orientation, and the wall thickness of the parts they design. The Design for Manufacturing and Assembly (DFMA) doesn't disappear. It only becomes different; with new machines come new design considerations (Hietikko, 2014).

2.8.5. Intellectual Property Protection (IPP)

To be patented, AM products need to show obvious differentiation compared to existing products. By being too vague, this leads to a lack of clarity on what can be patented or not and therefore, leaves place for counterfeit components on the market. Laws around IPP are adapting to the reality of the industry and are yet to be clarified. It will be necessary for the implicated industries to keep an eye on how the legal environment around AM is evolving during the upcoming years (Giffi, Gangula and Illinda, 2014). Aerospace is a highly competitive industry. The protection of IP is a necessary element of each enterprise's survival. Therefore, R&D department are highly hermetic and partnerships with other enterprises are necessary, but highly controlled.

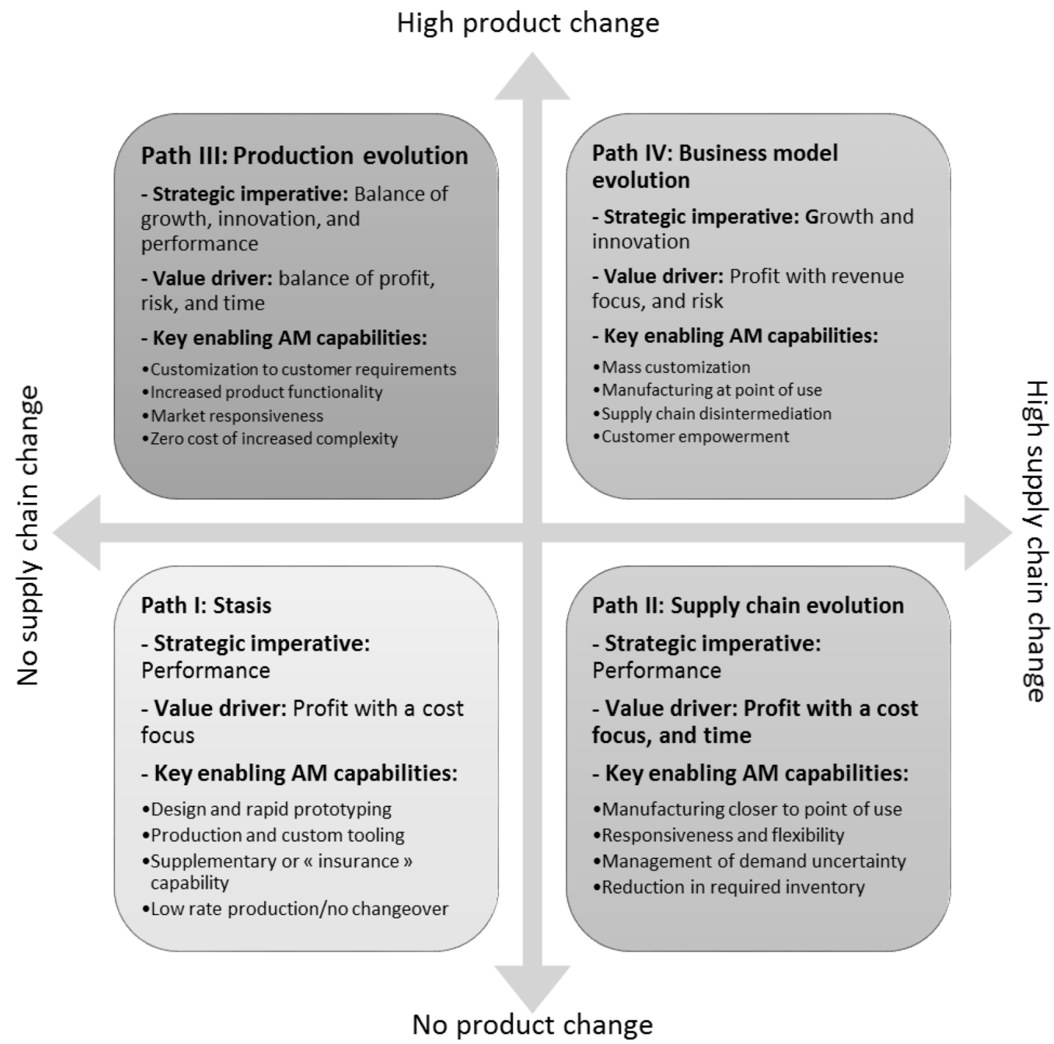
2.9. Technological integration

As explained in the Deloitte review on AM opportunities, enterprises could follow diverse tactical paths towards the integration of AM in their processes depending on their strategic imperatives and drivers of value. The drivers of value are: profit, risk and time. The imperatives are usually: performance (the accomplishment of an objective relative to identified standards and relevant trade-offs), innovation (a combination of activities or technologies that breaks existing performance trade-offs in a way that makes new outcomes possible), or growth (an increase in revenues that results from a set of management choices) (Cotteleer and Joyce, 2014).

The chosen business imperatives and drivers of value will lead an enterprise into one of the four different tactical paths described below. They either induce change in the products themselves, the associated supply chain, both of them or none of them (Cotteleer and Joyce, 2014).

- Path #1 : Stasis (no changes)
- Path #2 : Supply chain evolution (change in the supply chain)
- Path #3 : Product evolution (change in the products)
- Path #4 : Business model evolution (change in the product and the supply chain)

Figure 2 : Framework for understanding AM paths and value



Source: Adapted from Cotteleer, Mark and Jim Joyce (2014). « 3D Opportunity - Additive Manufacturing paths to performance, innovation and growth », *Deloitte Review*, no 14.

The figure 2 shows the 4 paths that a business who integrates AM could take and the possible related outcomes. According to Deloitte's analysis, as the maturity of AM technologies and the enterprises goals will evolve, they will probably move from one path to the other.

On the short term, enterprises started by adopting AM following the stasis path in the unique goal of creating added-value without changing their product nor processes. In this case, AM is used to create mock-up, functional models, tooling and prototypes.

On a medium term, enterprises might go from the stasis path to the product evolution path by developing more complex products or sub-assemblies with improved functionalities. Other enterprises might go from the stasis path to the supply chain evolution path by shortening it or by reducing their inventory level. Some companies working in maintenance, repair and overhaul could benefit from the responsiveness of AM and turn the spare parts logistics into a more demand-driven system (Coykendall *& al.* , 2014).

On the long term, it might be possible to see new companies that will come in with a totally new business model where they have innovative processes and new products. This path will require an innovative mindset that might come with the next generation of designers (Cotteleer and Joyce, 2014).

2.10. Conclusion

Being aware of all the advantages and limitations of today's additive manufacturing technologies, it is easier to have a more thoughtful opinion on the matter. So far, AM is more applicable to produce low volumes of highly complex parts. It is also very efficient with customized product and with products that are of relatively small size. The additional barriers reside in materials, cost, post-processing and repeatability. These constraints will be reduced as the machines evolve. AM does not and will not entirely replace the traditional methods and it only complements them. For some types of product, traditional manufacturing will remain the best option. The next chapter will discuss some particularities of the Canadian aerospace industry and how AM might influence it.

Chapter 3
The Aerospace industry

3.1. Why focusing on the aerospace industry?

Given the geometric complexity of its products, the high cost of materials and some of the other characteristics of AM described in the previous section, the aerospace industry has been looking at AM since its commercialization during the 1980s with the idea of improving its processes. In fact, aerospace applications constitute 12.3% of the general AM revenues (Wohlers, 2014). The aerospace parts usually have long product life cycles (PLC), high cost and medium demand. They are often lightweight and feature-rich, both internal and external; which makes them complex to manufacture and assemble with traditional methods. Long time-to-market and continuous improvement can lead to multiple changes in the design of a part, which increase lead time and total cost (Aliakbari, 2012). All put together, these characteristics make the aerospace industry a great candidate for additive manufacturing.

The possibility to create more complex parts at no additional cost changes importantly the role of designers. They can now design to get the features they need at no additional cost, in contrast with designing a part only to make it possible to manufacture (Aliakbari, 2012). AM will eventually allow to switch the design thinking from "design-for-manufacturing" to "design-for-function". A great example of that are freeform internal cooling channels for molds (described in the previous section). Traditionally, feature rich assemblies need to follow a long set of steps in order to manufacture all the components (sometimes manufactured at various plants), get them all on the assembly line and assemble them. Meanwhile, AM could allow to reduce the number of steps and the related logistics by manufacturing near net shape part in one go. Even if post-processing operations will be required afterwards, the total amount of time and related cost has a great potential of reduction (Aliakbari, 2012).

In the aerospace sector, materials are often selected for their temperature resistance and strength to weight ratio. Light weight helps to save on fuel consumption and to be more environment friendly. The most popular materials are composite, stainless steel, inconel, cobalt-chrome and titanium alloys (Aliakbari, 2012). Given the high price of these specialized alloys, material waste can be a significant concern. As explained in the previous section, the aerospace industry traditionally has "buy-to-fly" ratios (ratio of raw material input to final product mass) that are between 12:1 and 25:1, and AM processes could lower it to around 1.5:1 (McGrath *& al.* , 2015). This would be an opportunity for considerable material savings. As shown in the previous section, AM processes such as DMLS, LMD, SLS and EBM support these aerospace materials. Depending on the trade-offs between accuracy, roughness, speed and cost, one process or another may be selected as more suitable for a given application (Coykendall *& al.* , 2014).

3.2. Portrait of the Canadian Aerospace Industry

With some 700 companies[1] involved, 76,000 direct jobs and revenues of $27.7B, the Canadian aerospace industry is ranked third globally in terms of global civil aircraft production. With partners in the United States, Europe, Asia and South America, the aerospace sector plays a major role in Canada's export intensity and trade diversity. With over 20% of its activities being dedicated to R&D, it is considered as a fast growing and innovative sector. It also makes it a great candidate to integrate new and promising technologies, such as additive manufacturing (Industry Canada and AIAC, 2015).

Geographically speaking, the majority of aerospace manufacturing activities are led in central Canada (56% in Quebec and 23% in Ontario), while maintenance, repair and overhaul (MRO) is mainly done in Western Canada (44% in Western provinces, 24% in Ontario and 18% in Quebec). 73% of the industry's activities is dedicated to manufacturing and the other 27% is dedicated to MRO. Both, manufacturing and MRO, have been expanding rapidly over the last 10 years, at a growing rate of respectively 29% and 37% (Industry Canada and AIAC, 2015).

The sector mostly consists of a majority of SMEs and a few larger enterprises such as OEMs. 93% of the firms have less than 250 employees and employ 19% of the

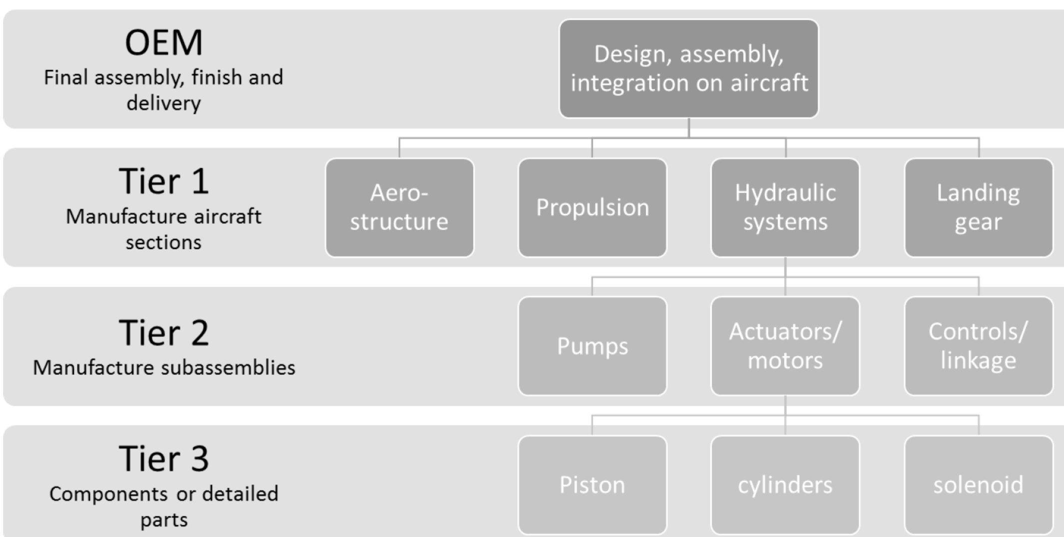
[1] All data is from 2014 unless otherwise stated

workforce. On the other hand, bigger firms (250 or more employees) employ 81% of the workforce and are responsible for over 90% of the sales, R&D spending and exports (Industry Canada and AIAC, 2015).

3.3. The Structure of the Aerospace Supply Chain

The aerospace industry works with a tier structure. As shown in the figure below, enterprises from Tier 3 provide higher tiers with basic components. Enterprises from tier 2 assemble those components to provide tier 1 and OEM with small systems such as pumps, actuators, servo control, etc. Tier 1 are responsible to provide the OEM with major systems such as aircraft engines, aerostructure, landing gear, etc. Finally, the OEM act as the client of sub-tiers, the designer and the final system integrator of all the systems and major structures of the aircraft.

Figure 3 : Tier structure of the Canadian aerospace industry for the production of an aircraft



Source: Adapted from PricewaterhouseCoopers, Globalisation in Aerospace and Defense

3.4. Current Applications of AM in the Aerospace Industry

Due to complex aerospace certification processes and a high level of risk, the first applications of AM in the aerospace industry couldn't be within structural or key on-plane components. The first applications were prototypes since the risk is low and the associated AM machines represent a lower investment. As the expertise was being developed, enterprises started to build non-structural parts (internal door hinges for examples) just to test and prove the resistance of those parts over long periods of service. For example, Airbus redesigned a nacelle hinge bracket for their A320 aircraft. The original part was a simple-shape steel casting and the alternative version has an organic shape and is 3D printed in titanium alloy. The redesigned titanium bracket is lighter, and could lead to a weight saving of 10-kg per aircraft. (Wohlers, 2014). With time and experience, enterprises will go towards the manufacturing of parts with higher criticality. Additionally, having the CAD catalog on-hand, some maintenance centers started to print non-structural replacement parts instead of ordering them to benefit from shorter lead time and cheaper cost (Coykendall *& al.* , 2014).

OEMs are now working hard to get flight-certification for more crucial and complex parts (see section 2). Within those parts figure structural components and complex engine parts. A good example of it is the fuel nozzle of GE which was originally a 19-pieces assembly that can now be printed as a single part in a lighter, cheaper and more durable version thanks to AM. The main obstacles for GE to mass produce it are: 1) obtaining flight certifications, 2) the skilled capital required, and 3) the big amount of AM machines required to meet its delivery schedule for full production (Wohlers, 2014).

Chapter 4
Methodology

Following the literature review on AM and all the related key elements of this exploratory research, this chapter presents and justifies the methodology that is used to shape our recommendations according to the research question: *How to successfully integrate metal additive manufacturing in the Canadian aerospace supply chain?*

4.1. Complete methodology overview

The chosen methodology consists of four main steps:

1. The first step consists of meeting and interviewing multiple actors of the industry in order to have their insights on the different facets of AM integration. These actors consist of suppliers, equipment manufacturers, consultants and clients. The qualitative information they provide will help to better understand the opportunities, challenges and cost drivers faced by these different actors. The interviews will also help to create a list of initiatives and programs with a potential to accelerate the deployment of AM among the aerospace industry.

2. A survey will be built based on the results and interrogations raised from the previously conducted interviews and will contain some solutions that could be profitable for the industry. This survey will be sent across the Canadian aerospace manufacturing industry in order to measure quantitatively the importance given to the suggested programs and initiatives. It will also link the challenges, opportunities of the industry to the concerned organizations depending on their position in the supply chain.

3. The results of the survey will be analyzed and illustrated in order to get a better understanding of the state of the industry. This analysis will bring conclusions based on facts and numbers instead of conclusions based on the perception of a few.

4. From the previously made conclusions, some recommendations will be made in order to guide the different players of the market (suppliers, OEMs, governmental organizations, research centers, universities, etc.) towards the most effective strategies to accelerate the integration of additive manufacturing into the aerospace supply chain.

4.2. Qualitative and Quantitative research

By combining 15 interviews and a national survey, this research is both qualitative and quantitative. Its objective is to gain preliminary insight on the state of AM in the aerospace industry and to provide the basis for more in-depth research. It is therefore an exploratory research (Karlsson, 2009) that answers to the following question:

How to successfully integrate metal additive manufacturing in the Canadian aerospace supply chain?

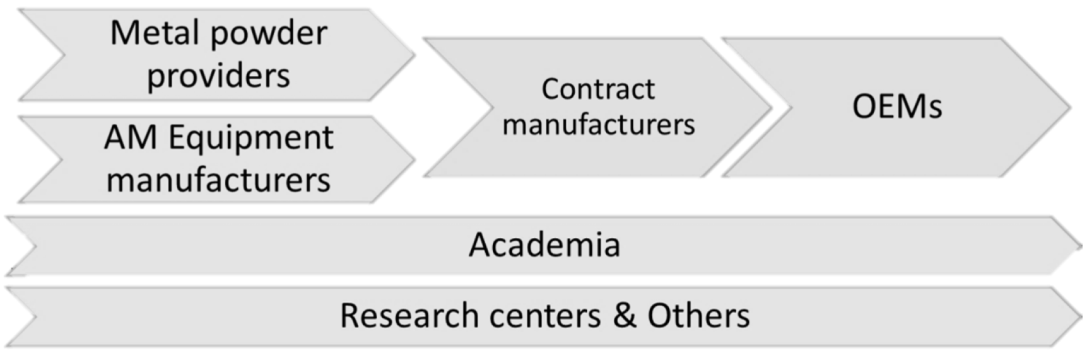
The multiple organizations concerned by this question are facing different challenges due to their position in the value chain and the benefits their organization could take out of AM. Hence, 15 semi-structured interviews have been done with representatives from every segment of the industry in order to grasp their personal point of view of the situation.

These 15 interviews brought to light the different challenges and opportunities that organizations are facing and showed some contradictions between different segments of the value chain. Depending on the position in the value chain, the goals with respect to AM are different, and therefore, the means to reach them are different. Even though interviews, in the context of an exploratory study, are a great tool to get a deeper understanding of a subject with relatively little information, they only give a glimpse of the state of the market. The main drawback of interviews is that the obtained results are usually hard to generalise to a larger population (Myers, 2013). Therefore, we decided to conduct a survey across the national industry to measure the actual trends in the industry, and to verify if the interviews reflect accurately the state of the industry. From the 307 participants that have been targeted, 107 responded to the survey. With a participation rate of over 34% it has been possible to draw accurate trends of the Canadian additive manufacturing aerospace industry.

4.3. Segmentation of the aerospace AM supply chain

In the context of this study, the aerospace additive manufacturing supply chain has been segmented into 6 distinct groups:

Figure 4: Segmentation of the aerospace AM supply chain



1. Metal powder producers: This group contains only a handful of enterprises who provide the AM industry with raw material: metal powder. The powder is sold to AM equipment users either directly or via an intermediate entity.

2. AM equipment manufacturers: This group manufactures and sells AM equipment (3D printers) to any of the later 4 groups.

3. Traditional contract manufacturers (potential AM machine users) & AM contract manufacturers (AM machine users): This group is defined as manufacturers of components and small assemblies for their clients (mostly OEMs). Later in this research, a distinction will be made between manufacturers who use traditional equipment and AM equipment.

4. OEMs (AM parts designers and buyers): For the purpose of this research, Original Equipment Manufacturer (OEM) is defined as an organization who is owner of its design, with or without internal manufacturing capabilities. It will

include many tier 1, since they have similar challenges and interests towards AM.

5. Academia: This group includes teachers and researchers from colleges and universities.

6. Research centers & Other: This group includes AM-focused research centres, specialized consulting firms, para-governmental organizations and the likes.

By regrouping all the organizations with a similar behavior and interest into these groups, the analysis of the whole industry can be simplified.

4.4. Data collection – Interviews

4.4.1. Semi-structured interviews

Even though qualitative data can be collected via multiple tools like observation, interviews, recordings and questionnaires, we chose to use semi-structured interviews because of the direct contact it allows us to have with the participants (Fortin, 1996). It allows the interviewer to have more flexibility on the progress of the interview. The interviewer only gives a direction to the interview and has the opportunity to choose the right questions to ask depending on the previous answers given by the participant (Gravel, 1986). Prior to these interviews, an interview guide (see appendix 7) has been built.

Semi-structured interviews can be biased since they represent a conversation between two individuals (Yin, 2003). The way the interviewer asks a question can induce an answer or another from the participant. We reduce this effect by asking very general questions that only bring in a given subject, by asking every participant the same exact question and by handing the questionnaire to the participant prior to the interview. On the other side, biases can be induced by the participant if an answer is based on his expectations instead of facts (Fortin, Côté and Filion, 2006). We took care to differentiate facts from expectations in the analysis of the interviews.

To avoid losing information we received from the majority of the participant's permission to record the interview. The recordings themselves have been kept confidential and used only to write down the important information obtained during the interviews.

The interviews have two purposes: 1) Building the survey questionnaire. Even if the information gathered in the literature review greatly helped in the construction of the questionnaire, the interviews provided a more practical point of view on certain topics, which was complementary to the previously collected information (e.g. additional challenges and cost drivers). Some interviews also greatly helped to build and discuss the viability of many initiatives that could accelerate the deployment of the technology (which is the last question of the survey). 2) By interviewing the participants on the same topics that are measured with the survey, it is possible to use their insights to explain the trends that are observed thereafter from the survey results.

4.4.2. Participants

The objective was to interview at least two participants in every segment of the value chain (defined earlier in section 4.3). Given the fact that metal additive manufacturing still is an emerging technology, experts are rare and thus hard to find. A good way to find them is to attend advanced manufacturing shows and networking events. Therefore, the main researcher built a personal network of experts by going to the AM conferences and AM shows in Boston, Brampton, Hamilton, Toronto and Montreal (see appendix 6 for the details on conferences). Given the relevance of the research project, many organization representatives showed interest in participating in the study. From this network, the 15 representatives listed below, have been selected for an interview. The selection of the participants has been done as follows: For each segment of the supply chain mentioned in the section 4.3, between 4 and 6 organizations have been identified. A representative with a broad knowledge in AM has been identified for each of these organizations. The identified representatives have been contacted by email or phone to discuss the possibility of giving an interview about AM. The 15 representatives listed in table 4 are the ones who accepted the invitation.

Table 4: List of acronyms for interview participants

Metal Powder Providers	
1	MPP1
2	MPP2
Equipment Manufacturers	
3	EM1
4	EM2
Contract manufacturer with AM in-house	
5	CMAM1
Contract manufacturer	
6	CM1
7	CM2
Original Equipment Manufacturers	
8	OEM1
9	OEM2
10	OEM3
Academia	
11	ACAD1
12	ACAD2
Others (research centres, para governmental organizations, consulting firms, etc.)	
13	CRD1
14	CRD2
15	CRD3

4.5. Data collection – National survey

4.5.1. Canada-wide survey

Further to the 15 semi-structured interviews, a short questionnaire has been sent across the Canadian aerospace industry in order to draw the trends of the market with up to date quantitative data.

The questionnaire contains 7 questions covering the following subjects:

- The nature of the participants manufacturing operations (traditional or AM)
- Perceived opportunities for utilizing AM
- Perceived challenges for utilizing AM
- Perceived most influential cost drivers in AM
- Type of AM-related initiative that could accelerate AM deployment

The integral version of the questionnaire can be found in the appendix section at the end of this thesis (see appendix 3 and 4).

The multiple choices questionnaire has been built based on the concerns raised during the semi-structured interviews. Every suggested opportunity, challenge and cost driver has been taken from the interviews with industry representatives and the literature review. Following these interviews, AM-related initiatives that could accelerate AM deployment have been defined. Each of them has been suggested at the end of the questionnaire in order to let the participants choose the one they consider the most adapted to their situation.

4.5.2. *Participants*

The population of the survey is composed of additive manufacturing specialists, CEOs, engineering directors, engineers responsible of AM projects, R&D managers, researchers, teachers responsible of AM-related projects, etc. The list of 307 industry/academia representatives has been built from a combination of the main researcher's personal network, Aéro Montréal's aerospace cluster directory, CRIAQ and CARIC (consortiums for research and innovation in aerospace in Quebec and Canada) list of researchers who participated in collaborative AM-related research projects. Prior to the official launch, a pilot version of the survey has been sent to 7 well-known participants from the industry and academia in order to test it. Then an electronic version of the survey has been sent to the full list of targeted participants by email and has been shared on the weekly newsletter of Canada Makes (Canada's biggest AM network). Added to that, a third party has been hired to do a follow-up among the survey population to increase the participation rate. Since the participants are spread across Canada, the questionnaire was available in both English and French. Given the relevance of the research project for the industry, the survey list is composed of well-targeted and well-informed people. The distribution of the survey via credible platforms and the close follow-up ensured a very high participation rate.

Over 34% of the 307 targeted industry representatives participated in the Canada-wide survey. For an exploratory research, this participation rate is considered more than acceptable in order to represent the population. Section 4.6 provides the details on the composition of the surveyed sample.

4.5.3. Validity and analysis of the collected data

The neutrality of the researcher, which is not accessible for neither the government nor industrial players, helps to reduce biased results, and therefore, increase their validity. If this data collection was made directly by a given OEM, equipment provider or contract manufacturer, the collected results would be influenced by the relation between the both parties (e.g. if an OEM asks its supplier if they are thinking in investing in newer technologies, they might say “yes” only to make a good impression and keep their contracts with their client). Similar biases would happen if a government-related entity would lead this study. The neutral position of a M.Sc. student (without any conflict of interest) combined with the provided confidentiality of the study make it possible to collect more unbiased answers through the survey questionnaire and even during live interviews.

In order to consider a survey as being suitable and feasible, the researcher should minimize the following four types of errors: sampling error, measurement error, statistical conclusion error and internal validity error (Karlsson, 2009). In this research, the sampling error has been minimized by sending the survey to a very well selected group of people. Each of the participants had to be related to the Canadian aerospace industry and most of them had knowledge of AM through the projects they work in. This preselection helps to avoid missing relevant information that could have been blurred by answers from irrelevant participants. No data is considered as missing since a representative number of participants from every segment of the supply chain participated in the survey, allowing to cover all the categories that needed to be looked at. Measurement error was minimized by offering multiple choices questions from which the participants had to choose their favorite option. The provided choices were well studied and covered the most popular answers that were possible. The concept of statistical conclusion error is irrelevant for this research because no statistical test has been performed. Finally, internal validity has been confirmed because the conclusions of the survey reflect the opinion of the people who participated in the survey. Very few participants used the "other" box to suggest an additional answer. Additionally, the external validity is also confirmed because the conclusions of the survey can be generalized to the Canadian aerospace industry since the participation rate was very high and the information collected during the interviews confirm the results of the survey. However, the results of this survey cannot be generalized to any other Canadian industry, nor to the aerospace industry of any other country.

4.6. Composition of the survey sample

As presented in the section 4.3, the participants have been classified into different groups according to their role in the supply chain. The main groups are: Metal powder providers, AM equipment manufacturers, contract manufacturers, OEMs and Academia. A sixth group, called "others", regroup every participant who did not fit into the main categories. "Others" regroup organizations such as research centres, para-governmental organizations, consulting firms, funding institutions, etc. Table 5 shows the number of individuals and organizations who participated in the survey in each category.

Table 5: Participation per supply chain segment

Segment	Nb. of organizations	Nb. Of participants
Metal Powder provider	2 to 4	4
AM Equipment manufacturer	4 to 5	6
Contract manufacturer	30 to 34	35
OEMs	10 to12	19
Academia (universities and colleges)	11 to 15	25
Others	12 to 16	18
Total	71 to 86	107

*N.B. the number of organizations is a range because some participants decided to anonymously answer the survey

It is to be noted that some organizations have been represented by more than one individual. This is mostly true for OEMs who provided experts from different departments and Academia which has many parallel research projects on AM going on. Every organization is represented by 1 to 4 individuals. The goal of this survey is to understand the trends of the industry through the opinion of experts from various horizons; not to quantify with precision the corporate position of every participating organization. The range of participating organization is due to the fact that some individuals decided to participate anonymously to the survey.

The figure below illustrates the repartition of the participants among the different segments of the AM supply chain. The sample is considered well distributed given the fact that all the segments of the supply chain are represented by at least 4 participants and the more numerous groups are represented by a larger number of participants.

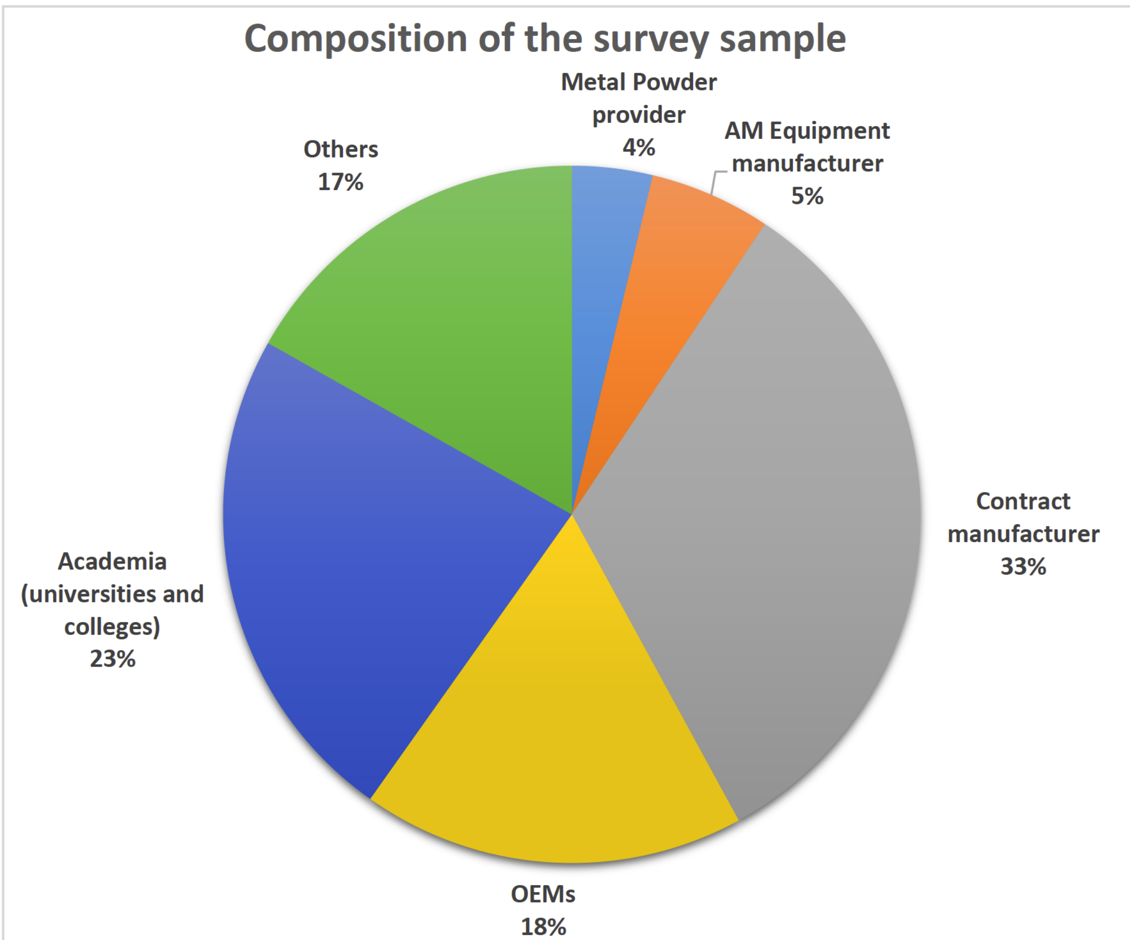


Figure 5: Composition of the survey sample

Table 6 shows the geographical presence of the participants. Most of the participants are from Québec and Ontario, which is where most of the aerospace and manufacturing industry of Canada is active. The answers from participants outside of Canada come from enterprises who did AM projects in Canada.

Province	Nb. of participants
Québec	92
Ontario	17
Prince Edward Island	1
Manitoba	1
Alberta	1
British Columbia	1
Outside of Canada	5

Table 6: Geographical distribution of the participants

4.7. Analysis methodology

The advantage of the chosen methodology is that we can build trends from the results of the survey (quantitative data), identify the areas of concerns and then explain the reason behind them with the information obtained through the interviews (qualitative data).

The next section will provide the reader with an overview of the results obtained through the survey by explaining the main questions of the survey and showing the distribution of the answers on a few charts. At the end of each sub section, the survey results will be analysed and explained using the information obtained during the interviews.

Chapter 5
Results and discussion

This section will provide the reader with an overview of the actual trends with respect to metal AM in the Canadian aerospace industry. With the distinction made between the different segments of the supply chain, it is possible to distinguish the perceived challenges, cost drivers, opportunities and preferred initiatives from one group to another. Each sub set of results will be followed by a discussion aiming at the identification of the gaps, needs and areas of concern. These are made by isolating different group of results one by one and look at the areas that are the most popular and unpopular. The identified trends are then explained with the support of citations from some of the specialists that have been interviewed. The four areas of concern that will be discussed in this section are:

- The lack of interest from the manufacturers to invest in AM equipment
- The underestimation of post-processing operations costs
- The divergence of opinion from the stakeholders towards the initiatives that should be undertaken to accelerate AM deployment
- The absence of AM equipment in the OEM's plants

The table below associates the different supply chain segments with the acronyms corresponding to the multiple anonymous specialists that were interviewed in the context of this project.

Table 7: Acronyms corresponding to the supply chain segments

Supply chain segment	Acronym
Metal Provider	MPP1, MPP2
AM Equipment Manufacturer	EM1, EM2
Traditional Contract manufacturer	CM1, CM2
Contract Manufacturer with in-house AM equipment	CMAM1
Original Equipment Manufacturer and Tier 1	OEM1, OEM2, OEM3
Academia	ACAD1, ACAD2
Others	CRD1, CRD2, CRD3

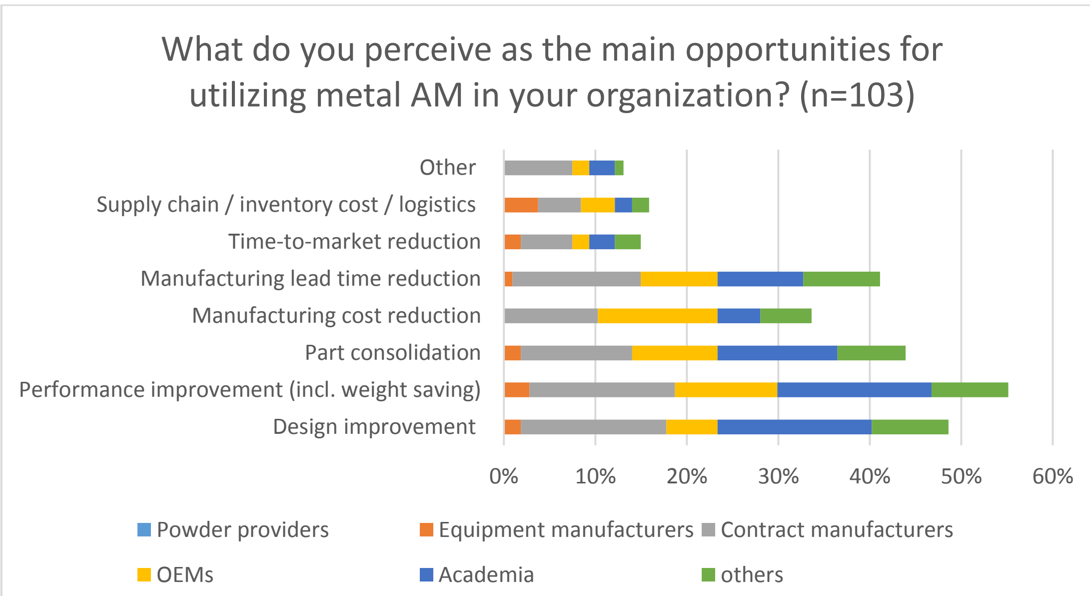
5.1. Aerospace main opportunities

In the survey questionnaire, after drawing the profile of the respondent, the first question that was asked is:

What do you perceive as the 3 main opportunities for utilizing metal additive manufacturing (AM) in your organization?

The graph below regroups the point of view from all segments of the industry towards this survey topic.

Figure 6: Main opportunities for utilizing metal AM



The most popular perceived opportunities are performance improvement, design improvement and part consolidation, which are all related to product design. Therefore, organizations primarily perceive AM as an opportunity to design differently. The two other type of opportunities which scored high in the survey are manufacturing lead time reduction and manufacturing cost reduction. The high score of those two opportunities shows that the aerospace industry has confidence that AM can lead to faster and cheaper manufacturing, even though design-related opportunities constitute the main interest. On the other hand, even if equipment manufacturers claim that their AM machines can reduce the time-to-market and the logistics-related cost, these two categories scored lower than the other options and do not seem to be the main focus of the aerospace industry.

5.1.1. Low interest from the contract manufacturers to invest in AM

When performing a deeper analysis of the data, an interesting detail came up with the question: What do you perceive as the 3 main opportunities for utilizing metal additive manufacturing (AM) in your organization? A considerable amount of participants from the segment of contract manufacturers (which is the group that would most likely buy AM equipment) purposely checked the "Other" box and left a comment to mention that, "they don't see any opportunity in AM for their business" or that "AM technologies are not profitable".

This disinterest from the contract manufacturers can have many origins. According to AM equipment manufacturers (EM), it could come from a lack of education. EM keep realizing through their clients which are manufacturers that they often present a lack of education about AM opportunities and limitations (interview with CRD2, EM1 and EM2). Even some people who consider themselves "experts" have no machine and an inaccurate vision of the technical reality of AM (interview with EM2).

The point of view of the manufacturers is quite different. They would consider the actual state of the aerospace market as "unfriendly and unprofitable". The aerospace industry is a very conservative environment. Even if contract manufacturers would invest in AM and start to offer products made out of AM, their clients (OEMs) would not necessarily buy them (interview with CM2). The supply does not automatically create a demand. According to CM2, with the usual learning curve, it is fair to estimate that a manufacturer will not be profitable with its new equipment for the first 2 years because of the mistakes and learning process of the operators (interview with CM2).

The interview with CRD3 gives us some insights about the financial struggle that comes with the viability of integrating AM into an enterprise's manufacturing processes. First, we need to consider that AM still is an emerging technology and it evolves fast. An AM machine bought today may be outdated within the next ~5 years. Therefore, contract manufacturers would like to amortize the cost of acquisition over only ~3 years.

Considering the basic assumptions that the cost of acquisition and installation of the equipment costs over $1M, that printing a metal part will take on average 24-36 hours and that many parts and material will be discarded through the learning process, a significant portion of the cost of each printed component goes to pay for the acquisition of equipment and the technical mistakes. For now, this business case works for research centers and academia, but not for the aerospace industry (interview with CRD3). Additionally, most contract manufacturers are SMEs which might be reluctant to invest such amount of money in new equipment due to their limited revenue.

However, even if profitable business cases are not there yet, AM technologies present great potential opportunities and manufacturers should start to develop AM-related knowledge and stay up to date about the state of the technology and the market to be able to take the leap and integrate AM technologies as soon as it will become profitable (interview with CRD3 and CM2).

In the upcoming years, we hope to see a strategic positioning of Canada in terms of advanced manufacturing that would be beneficial to the AM industry. For the moment, there is no clear roadmap for advanced manufacturing at the federal level. With a roadmap that aligns and unites the efforts that are already being made at the regional levels, we could eliminate the duplication of efforts and have a coherent national strategy (interview with CRD1).

Mohawk College, situated in Hamilton, Ontario, decided to overcome this issue by partnering up with surrounding manufacturing enterprises to exchange AM knowledge and resources. The multiple partners have different AM machines which are shared within the cluster, students get hands-on experience with AM and with the industry needs (interview with CRD1). This kind of partnership helps the participating enterprises to get in touch with the many AM technologies before investing significant amount of money in it, to understand the technical challenges, to better define their needs in terms of AM and to have access to local qualified labor.

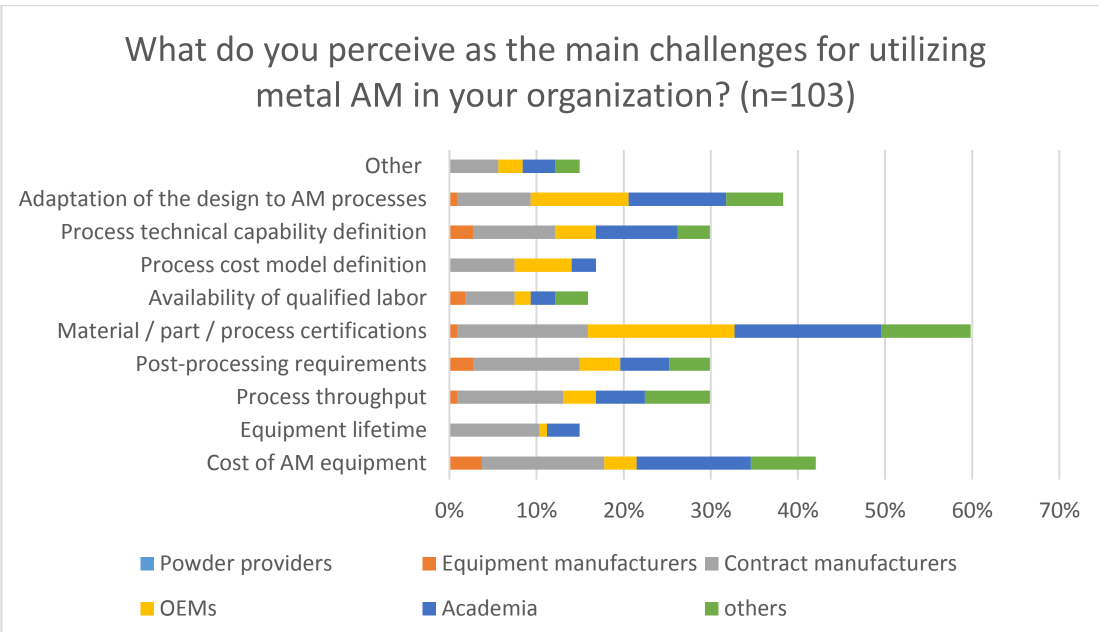
5.2. Aerospace main challenges

The second question that was asked in the survey questionnaire is:

What do you perceive as the 3 main challenges for utilizing metal additive manufacturing (AM) in your organization?

The graphs below regroup the point of view from all segments of the industry towards this survey topic.

Figure 7: Main challenges for utilizing metal AM



The most popular challenge is the certification of materials, parts and processes. As explained in section 2.5.4, there is actually no certification for products made through AM and manufacturers need to invest in characterizing every material, part and process internally. In order to be able to certify more parts, manufacturers will need more product orders from their clients, which is not about to happen soon since the actual parts made with conventional manufacturing already meet the needs of the clients. This vicious circle creates an aura of risk around AM and will keep the market in a *status quo* until someone decides to take the risk.

The adaptation of conventional design to AM process also represents a considerable challenge because the whole industry is used to "design for manufacturing and assembly" (DFMA) with conventional equipment. For AM to be part of the manufacturing process, designers will have to considerably modify the way they design products. As explained in section 2.5.3, there will be a growing need for people with AM-specific skills in many areas such as CAD, quality inspection, machine making, operations and maintenance, raw material preparation, etc. According to OEM2, the actual design softwares are not adapted to AM (topological optimisation, G-code, etc.) and even experimented designers will require more time to design, leading the non-recurring cost (design cost) to increase significantly. It might be acceptable to do such an exercise for a one-off job, but it is not profitable with normal production (interview with OEM2).

The cost of equipment ranks as the second biggest challenge. This cost includes not only the AM machine, but also the construction of a room, outside of the production floor, adapted to metal AM[2]. Added to that, the two previously mentioned challenges (certification and adaptation of design) represent an additional risk. The initial investment can appear to be enormous for some manufacturers, but in fact, if the business case was profitable, investing in this technology would not be a hard decision. The problem is that the investment is still too risky due to the lack of profitable business cases (interview with CM2).

5.2.1. *Are post-processing operations underestimated?*

When performing a deeper analysis of the data, an interesting detail came up with the question: What do you perceive as the 3 main challenges for utilizing metal additive manufacturing (AM) in your organization? There was a contrast between the responses of the manufacturers with practical experience in metal additive manufacturing and those who have no in-house metal AM capabilities.

[2] The need for an independent room is only necessary for metal AM technologies

As it can be observed in Figure 9 and Figure 8, manufacturers with no in-house metal AM equipment ranked post-processing operations as the 6th biggest challenge out of 9 options, while manufacturers with experience in metal AM rated post-processing as being their biggest challenge.

Figure 8: Main challenges for manufacturers with in-house AM capabilities

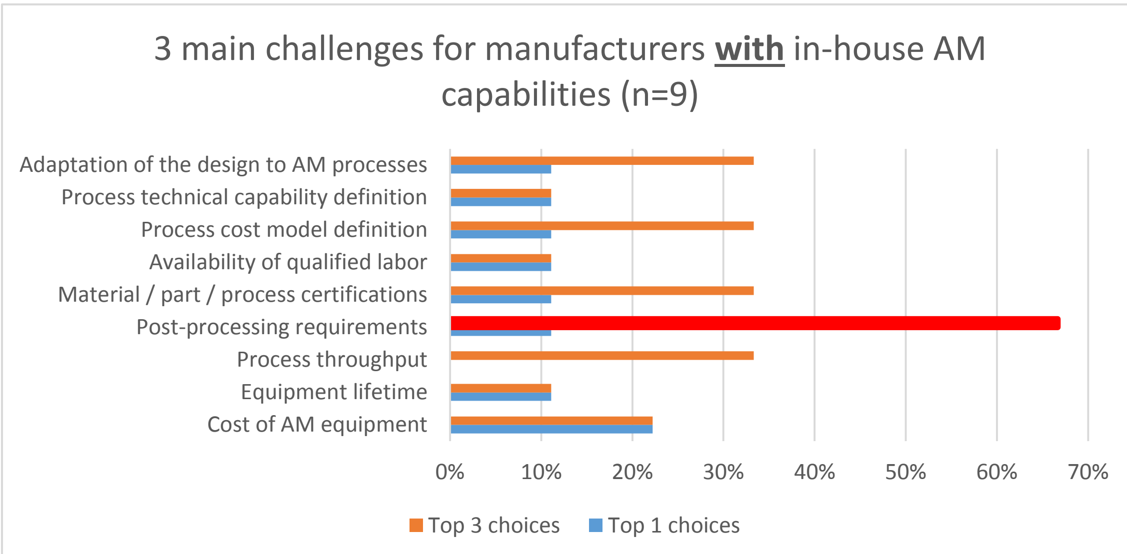
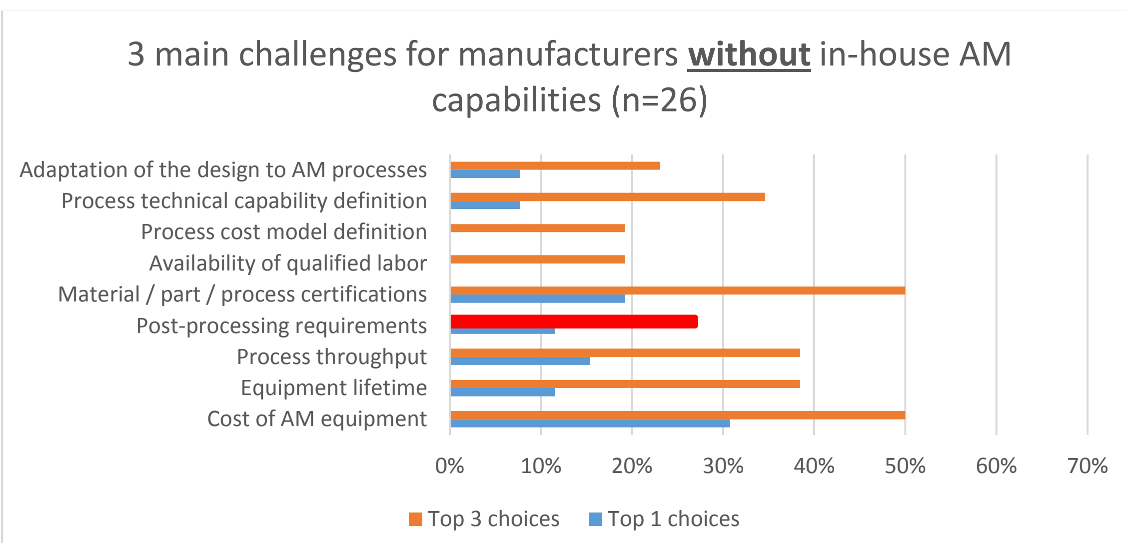


Figure 9: Main challenges for manufacturers without in-house AM capabilities



This observation highlights the fact that the challenge of post-processing operations is probably underestimated by manufacturers without AM capabilities, but becomes a real struggle for those who have extensive experience with AM. Below are a few reasons why post processing can be a considerable challenge.

Firstly, the chosen material has a considerable influence on the post-processing cost. Just like in traditional manufacturing, machining a soft metal (e.g. aluminum) is faster and cheaper than machining a harder one (e.g. titanium). Designers need to re-think not just their designs but also the materials they want to print a part in (interview with OEM2).

Secondly, designers need to consider not only the design of their part according to its functionality, but also for its "manufacturability". Too often, AM manufacturers receive parts that are designed and optimized for traditional manufacturing from their clients. Besides missing the full potential of AM technologies, the amount of required post-processing will uselessly increase the cost of the manufactured part (interview with CMAM1). An easy solution to reduce the cost of post-processing is to reduce the required post-processing operations as much as possible. Considering the post-printing operations in the design will reduce the overall cost. Added to that, according to EM2, there is a lack of knowledge in this area, but we have the necessary tools to do all the required post-processing operations (interview with EM2). A recent experiment of OEM1 revealed that post-processing can represent over 50% of the price of a part that has been outsourced to a specialized supplier. It has also revealed that the post-processing cost could be significantly lowered if all the heat treatments and other related operations were done by the OEM itself (interview with OEM1). This might open the door for collaborative manufacturing between OEM and contract manufacturers for certain AM products.

Finally, another point that has been discussed with OEM1 is the consequence of having an incomplete AM supply chain in Canada. The need to outsource some services outside of Canada increases the lead time and the cost of a manufactured product. For example, most of the products manufactured through metal AM will require Hot Isostatic Pressing (HIP) to increase their density (reduce the amount of air in the metal), but there are no commercial providers of HIP in Canada. In fact, there is only one commercially available provider of large HIP in Northeast America and it is situated in Boston. Every printed metal that requires this specific treatment will cross the Canada-U.S. border twice and pay customs twice. In the future, if the volume of metal parts done through AM increases significantly, HIP could become a bottleneck.

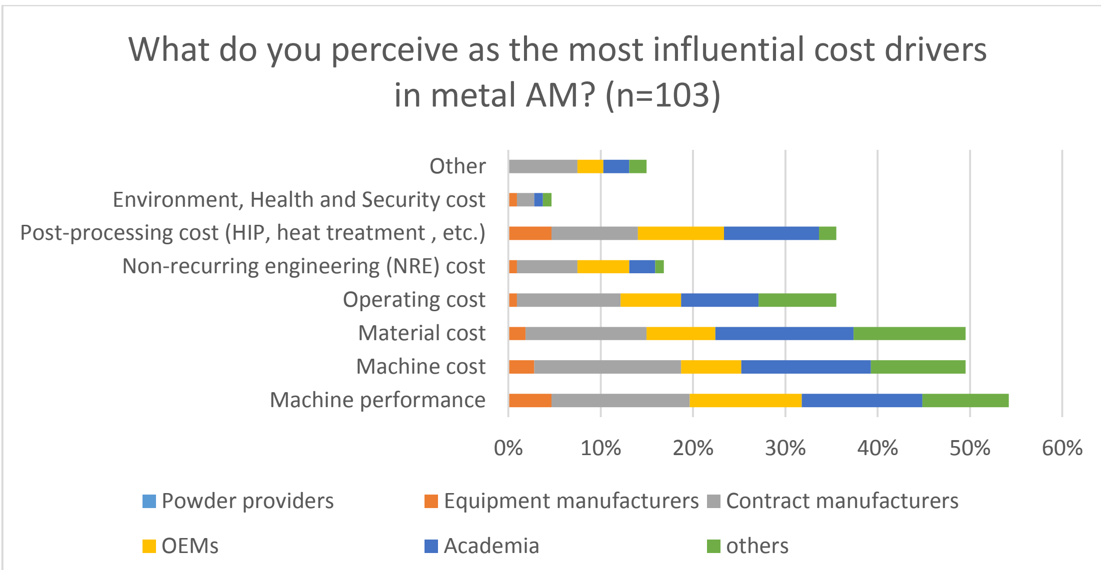
5.3. AM most influential cost drivers

The third question that was asked in the survey questionnaire is:

What do you perceive as the 3 most influential cost drivers in metal additive manufacturing (AM)?

The graphs below regroup the point of view from all segments of the industry towards this survey topic.

Figure 10: Most influential cost drivers in metal AM



Results show that the three main perceived cost driver for AM are machine performance, the equipment acquisition cost and the material cost. Luckily, these costs tend to decline over time. The performance of the machine (accuracy, repeatability, speed, etc.) is constantly evolving to provide the manufacturers with equipment of higher quality (interview with EM1). The acquisition cost of the machine will go down as the process will gain stability and as the EM will sell larger volumes of machines (interview with CRD1). The cost of material will go down as more metal powder providers will enter the market and as the demand for material will increase (interview with CRD3). Another variable responsible for the higher price of metal powders is the presence of many middlemen on the market, re-selling the material at a higher price to their clients (interview with MPP1).

The participants who chose the "other" option mostly left comments about the fact that the cost structure of AM is unclear and the behavior of its many variables is hard to understand. When looking at the entire product life cycle (PLC), the cost considerations for AM and traditional manufacturing are so different that it is not obvious were AM is generating savings or additional costs.

5.4. Preferred initiative for the deployment of AM

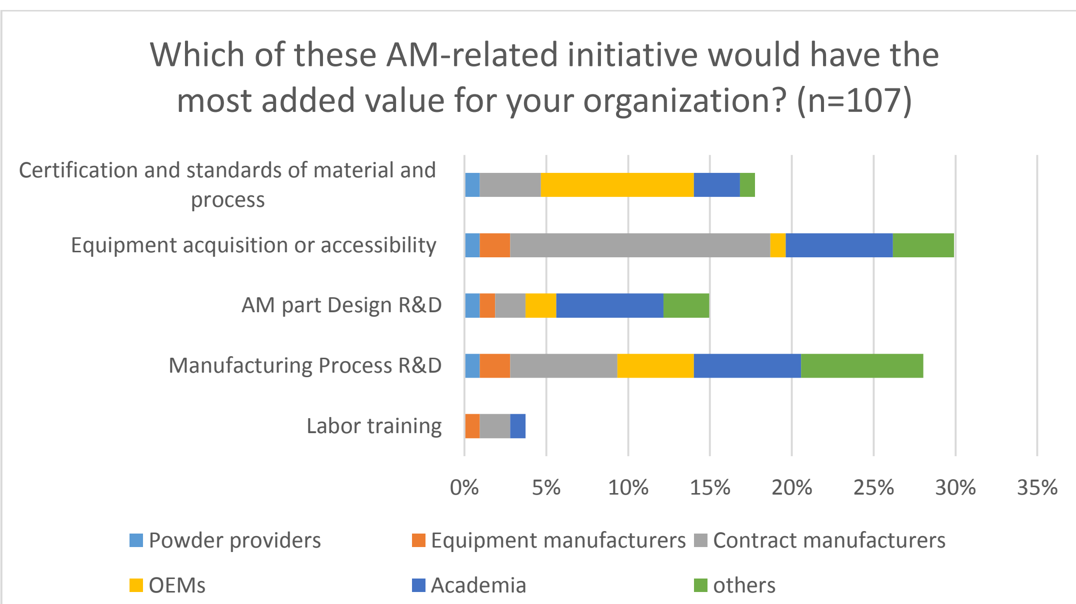
The fourth question of the survey was formulated as follows:

The following fields have been brought up as challenges over which governmental support could accelerate metal AM deployment.

Please select the type of AM-related initiative that would have the most added value for your business.

The graph below regroups the point of view from all segments of the industry towards this survey topic. Participants were only allowed to choose one initiative.

Figure 11: High added value AM-related initiative

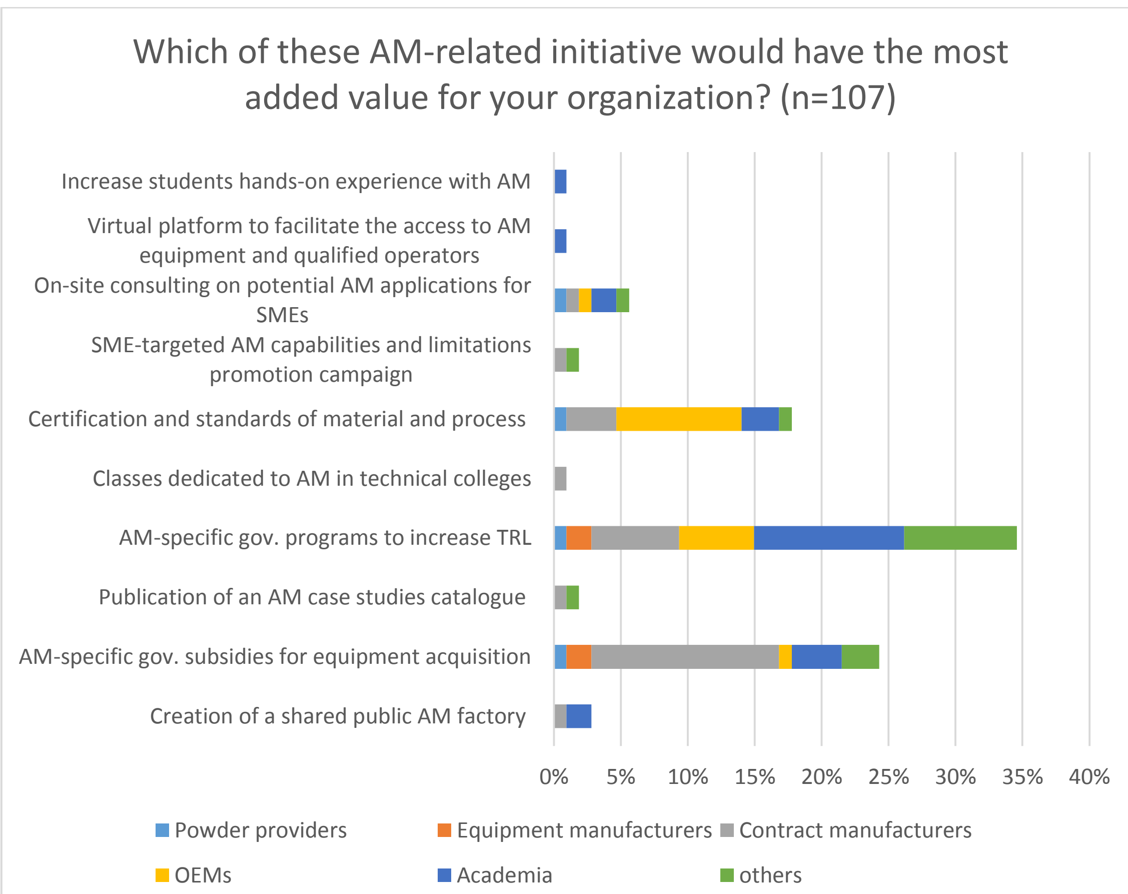


Depending on the chosen answer at the previous question, a set of more detailed initiatives was given to the respondent to choose from. The question was exposed to the participants as follows:

From the previously selected type of initiative, please select the action, from the list below that will have the most added value for your organization.

The graphs below regroup the point of view from all segments of the industry towards this survey topic. Once again, participants were only allowed to choose one initiative. For more details about the logic structure that links the questions of figure 11 and figure 12, see appendix 5.

Figure 12: High added value AM-related initiative



The distribution of the results, shown in Figure 12, clearly illustrates 3 initiatives that stand out of the list. It also shows a clear divergence of preference between OEMs, contract manufacturers, Academia and other organizations. The following section will discuss the different points of view based on the interviews with some of the participants.

The three initiatives which stand out are:

- AM-specific governmental programs to increase the technology readiness level (TRL)[3]
- AM-specific governmental subsidies for equipment acquisition
- Material and process certification and standards

Results also show that the priority of the industry is not towards qualified labor training, receiving specialized consulting services or shared AM factories.

However, even if qualified labor training did not stand out as a priority, it doesn't mean that it is not important. It only means that it is not the top priority for the vast majority of the survey participants. Based on the interviews with CRD1, CRD2, EM2, OEM1 and OEM2, design expertise is considered as the starting point of AM. There will be a growing need for better optimization and simulation software. Even if it is possible to train traditional technicians, engineers and operators in designing for AM, it is the next generation of designers that will come up with more innovative business cases based on a different design mindset (interview with CRD1, CRD2, EM2, OEM1 and OEM2). Engineering-related programs should be adapted to the new technological trends (interview with CRD1).

[3] The TRL scale is a metric for describing the maturity of a technology. The acronym stands for Technology Readiness Level. The scale consists of 9 levels. Each level characterizes the progress in the development of a technology, from basic research (TRL 1) to the market introduction (TRL 9). See appendix for the details on the complete TRL scale

5.3.1. *Divergence of preferences for support initiatives*

In order to have a better overview of the opinion of the different segments, the figure 13 and figure 14 show the answers to the same question separately for the segments of Academia-others and OEM-contract manufacturers.

Figure 13: High added value AM-related initiative for Academia and others

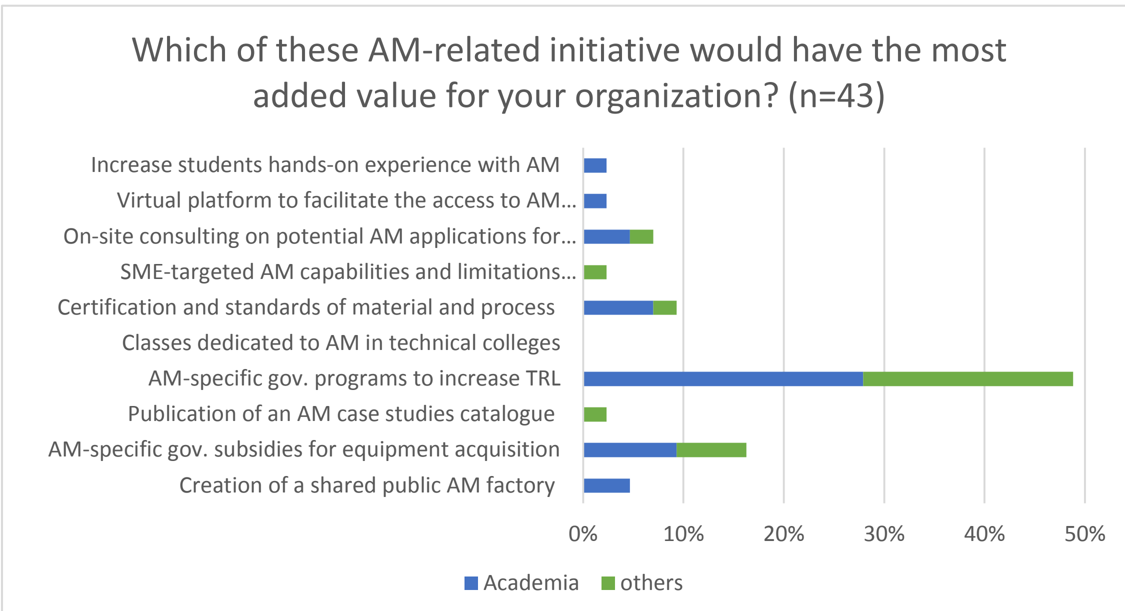


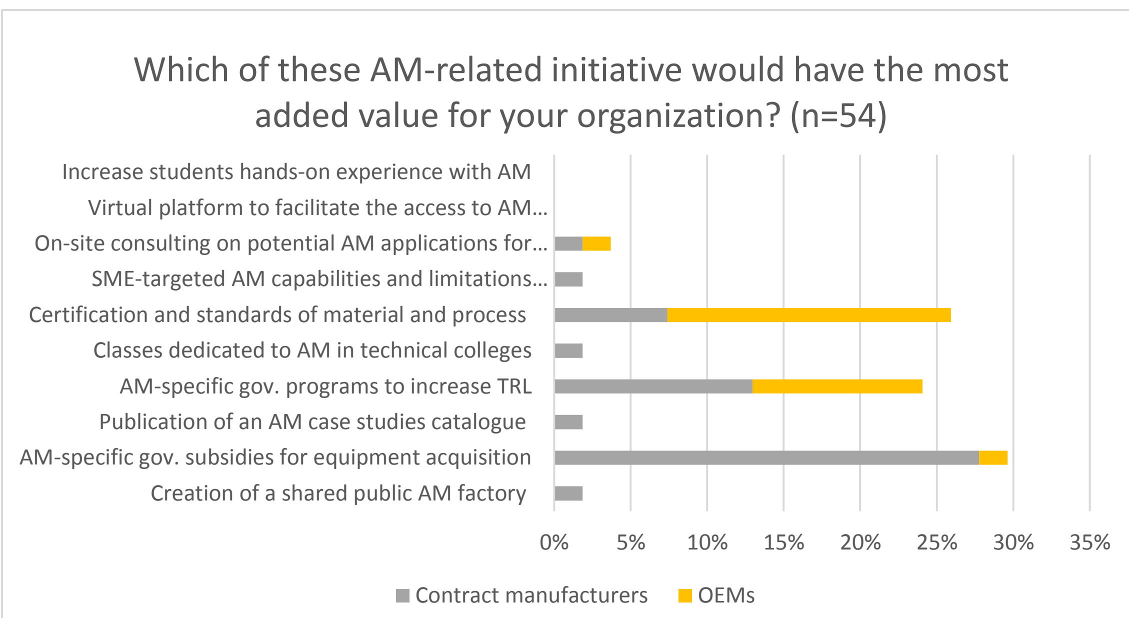
Figure 13, isolates Academia, research centers and para-governmental organizations to show their preference to invest in programs to increase the TRL of AM technologies.

The limited performance of the available AM equipment and the quality of the prints are obstacles for AM deployment (interview with CRD2). The increase of AM machines performance and quality of prints is one of the factors that will be responsible for the rise in demand from the market for additively manufactured products.

Collaborative research is a good mean to share the knowledge and the risk of AM-related R&D projects. Research centers and Academia can provide high-tech equipment and knowledge to industrial players while working on increasing the TRL of a project in line with the industry needs (interview with CRD1). However, collaborative research is not flawless, it could be improved if the funding mechanism and governmental support programs were simplified. This would help to reduce the administrative burden that sometimes slows down some projects (interview with CRD1). Another characteristic of collaborative research made with universities and industrial partners in Canada, is the pressure for academic researchers to publish their research. It does not represent a treat for enterprises working on low TRL projects (fundamental research and lab experiments), but when it comes to high TRL projects, confidentiality is a priority for industrials (interview with OEM1). The lack of confidentiality in collaborative research with universities discourages industrial partners to join in, by fear of losing a competitive edge.

The choice of initiative from Academia and R&D centers can be biased by the two following factors: 1) given the fact that these groups work mostly on low TRL projects, their perception of the whole AM industry is biased. 2) AM-specific programs to increase the TRL will lead to more R&D projects, therefore, more work and budget for the research centers, colleges and universities.

Figure 14: High added value AM-related initiative for OEM and contract manufacturers



When isolating only the preferences of OEMs and contract manufacturers (see Figure 14), aside from their common interest in increasing AM technologies' TRL, contract manufacturers show a clear preference for receiving AM-specific subsidies for equipment acquisition, while the majority of OEMs would rather put their efforts in the creation of certifications and standards for AM materials and processes.

The acquisition and installation of metal AM equipment cost over a $1M and the ROI is uncertain. It is very risky to invest in such a technology with no certification, no clients and no expertise. Unless a solid business case is built, investors are usually reluctant to lend money for this kind of investments (interview with CRD2). This explains why contract manufacturers have a need for AM-specific subsidies or incentives. There are fewer funding programs available in Canada than in the United States or in some European countries, however, Canadian enterprises benefit from collaborative research projects through sectoral clusters and consortiums in order to get interesting funding leverage and tax credits. However, this type of program is usually not meant to cover a significant part of the cost of acquisition of AM equipment (interview with CRD1).

Even if the funding of AM equipment is a hurdle, it is not the only cause of demotivation for manufacturers. The other causes behind the low interest of contract manufacturers to invest in AM technologies are discussed previously in section 5.1.1.

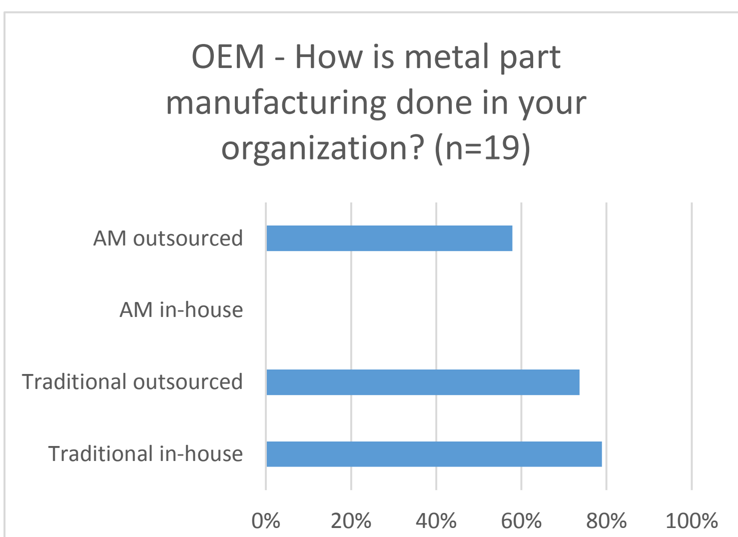
From the OEMs' point of view, as discussed in section 3.4 there is a will to put efforts in the standards and certification process. To have approved and reliable international standards and certifications would clearly improve the industry's confidence and understanding of the process and subsequently remove a considerable obstacle to the increase in the demand for additively manufactured products. Should we inject more money to accelerate the process then? The interview with CRD2 taught us that it is worth to wait for it. There is a minimum amount of time required for the creation of standards. By-passing some steps would not help the deployment of the technology and it can even worsen it if mistakes are made. ISO, ASTM and BNQ are already working on this case and results will arrive when ready. Back in the days, molding suffered some problems at the level of its normalization because it was not properly done. As of today, the industry still lives with these problems and molding requires big safety factors because the process is considered "less reliable" (interview with CRD2).

However, even though this process cannot take less than a given minimal amount of time, what the industry can do is to make sure it goes as fast as possible by sharing internal data. It is possible to see it arrive within the next 5 years if considerable investments and a lot of collaboration between organizations end enterprises is being done. If enough entities contribute to the creation of standards by sharing the data they acquired through their R&D projects, everyone would benefit from this situation. At the opposite, if only a few enterprises contribute while the others stand by and wait for results to come, the idea would not be viable (interview with OEM2).

5.5. Manufacturing methods

At the beginning of the survey, in order to draw the profile of the participants, OEMs and contract manufacturers were asked if their metal manufacturing operations were done through additive or traditional manufacturing and if these operations were done in-house or outsourced. As shown in the Figure 15, when OEMs have been asked how their metal parts were manufactured, none of them claim to be doing in-house metal AM. The reason is: none of them has metal AM equipment in-house (in Canada).

Figure 15: Metal parts manufacturing methods for OEM



In Canada, the AM equipment of the industry is scattered among a handful of universities, research centers and contract manufacturers. At the moment, AM equipment is rare and mostly used for R&D purposes. As the technology will gain in maturity, more AM equipment will enter the industry. It becomes interesting to ask ourselves:

In order to accelerate the deployment of AM, which segment of the supply chain should acquire AM equipment in the short term?

If support has to be given in order to stimulate technological development in the aerospace industry, it could be either towards OEMs, manufacturers or both. In other words, should we boost the supply (manufacturers) and expect the demand (from the OEMs) to increase? Should we boost the demand (from the OEMs) and expect the supply (manufacturers) to follow? Or should we link them and boost both the supply and the demand?

According to OEM2, there is a lack of maturity from the manufacturer’s side. As it says: No manufacturer with AM capabilities actually meets the aerospace quality requirements with AM parts. A few enterprises like Fusia[4] and Burloak are on their way to get there, but the step between prototyping and production is huge. Given the low number of manufacturers with metal AM capabilities on the market right now and the prices that are hard to negotiate, AM is not necessarily an attractive option for manufacturing. Production of metal parts through AM will become conceivable when more certified contract manufacturers offering high quality services will be available on the market (interview with OEM2).

The opposite thinking goes towards getting OEMs to better design their parts for AM, get comfortable with this new manufacturing process and then increase their demand in additively manufactured parts. EM2 shares this thinking by affirming that it is the new generation of engineers that will change the way OEMs think and design their parts. Funding should go towards educating OEMs in re-thinking their design for AM. Contract manufacturers cannot go forward if their clients do not order any products

[4] Fusia claims they are active on production in France, but not in Canada

(interview with EM2). The contract manufacturer CMAM1, which has plans to invest more in AM agrees to this point by saying that for him, one of the biggest challenge is to evaluate the risk of investing in the acquisition of AM equipment, but that if his clients (OEMs) would guarantee a significant volume of parts done through AM, he would be ready to invest (interview with CMAM1).

Finally, a third option might be to meet somewhere in the middle. A basic notion of supply chain says that a given supply chain cannot go faster than its slowest link. Giving support to the various segments of the aerospace supply chain according to the specific needs of each link may be an effective solution. If we vulgarize the situation we get to these two conclusions:

- OEMs need to:
  - Accept AM as a viable manufacturing option
  - Identify personal current designs which suit AM best
  - Improve their understanding of AM
  - Increase their demand in AM parts
  - Re-think their future designs

- Contract manufacturers need to:
  - Improve their understanding of AM
  - Understand how AM fits in as a manufacturing option
  - Invest in the acquisition of AM equipment and operators training
  - Meet aerospace quality requirements

In the AM industry, design and manufacturing are so intertwined that the most efficient way to improve both is to have a collaboration between OEMs and manufacturers that allows many iterations of design through a retroactive process. Therefore, the actual state of the industry could be improved through a partnership between OEMs and contract manufacturers in which each stakeholder agrees to work on their weaknesses. While the manufacturer would guarantee an investment in AM equipment and a given quality target, the OEM would provide new designs adapted to AM and guarantee a significant amount of parts done through AM.

5.6. Synthesis of the results

The previous graphs provided a general overview of the actual trends in the Canadian aerospace industry. The details of the data that has been used to build these graphs is available in a more extensive form in the appendix section (see appendix 1). It has been anonymized and made publicly available in order to allow the industry and academy to re-manipulate the data and get extra conclusions from it. Results have been shared on the newsletters of Canada Makes and *Réseau Québec 3D* in June 2016.

The next chapter will build recommendations based on the previously discussed areas of concerns. These recommendations suggest actions to undertake in order to accelerate the deployment of additive manufacturing into the aerospace supply chain.

Chapter 6
Recommendations

This section provides recommendations that have been built from the analysis of the previous chapter. The main objective behind these recommendations is to point out different ideas of solutions and initiate discussions among the industry, the academia and the governmental entities in order to raise more energy towards working on the resolution of the concerns mentioned in the analysis of this study.

6.1. Recommendations

Recommendation #1: Improve general understanding of AM and design expertise, through education, research and consulting

This recommendation is the logical first step of a successful technology deployment: Getting the stakeholders to understand the true potential and limitations of the technology. AM experts are clear on this point: it is evolving very fast and the upcoming technological breakthrough will change the manufacturing landscape. Manufacturers and OEMs should stay aware of the new developments and business case opportunities that will appear if they want to keep their competitive edge or position themselves into a new niche. This education can be done through research, attending advanced manufacturing shows and specialized consulting.

The next step is about improving design expertise. In the short term, it is more about training the current employees to take into consideration the particularity of a given AM process in the design of a product. Most of these products will probably be already existing parts that will require some topological optimization. In the medium term, a new generation of designers will graduate from schools that will bring in a new approach to design. It will be the mandate of academia to shape these designers to fulfill the needs of the industry through new and innovative products and assemblies.

Recommendation #2: Make innovation more attractive and reachable

Given the actual conservatism of OEMs and the actual level of performance of AM equipment, most manufacturers are not interested to integrate this technology in their processes. The investment is too high and too risky given the rapidly evolving technology and the low demand from the OEMs. For AM deployment to happen, manufacturers must find interest in the technology. This objective could be reached by:

- Stimulating the demand from OEMs for additively manufactured products through incentives such as R&D tax credits
- Adapting industrial R&D financing programs to allow more funding for equipment acquisition in order to de-risk this considerable investment in AM
- Encouraging collaborative R&D and partnerships like the case of Mohawk college cluster or OEM-supplier contracts that share the investments and the risks (see recommendation #5)

Recommendation #3: Increase efforts for material and process characterization

Material and process characterization will have to be developed as soon as possible for the deployment of AM to happen. In order to keep this development as short as possible a collaboration of the whole industry to contribute with their data on processes and materials characterization would be beneficial for the whole industry, as long as everyone participates. The reason why enterprises usually avoid participating in projects of higher TRL is the high risk of IP leakage and the conservation of the company's competitive advantage (see section 2.8.5). However, some effects of this characterization will be an improvement of the understanding of the AM process capabilities followed by a growth of demand for AM products from OEMs.

Recommendation #4: Provide each industry segment support that is adapted to its situation

As seen earlier, the different segments of the industry show different needs according to the challenges they face. Academia and research centers would like efforts being made to increase the technology's TRL, contract manufacturers want the investment in equipment to be less risky and OEMs would like efforts to be focused on material and process certification and standards. None of these is necessarily more important than the others. Actually, since they are all linked together, they need to evolve in parallel. A supply chain can never work faster than its slowest link (bottleneck), therefore, multiple efforts should be made in research, design techniques & tools, certification & standards and the creation of profitable business cases.

Recommendation #5: Improve collaboration incentives between the industry segments

Collaboration and partnership between the supply chain segments will not only increase the general understanding of AM technologies, but also the mutual relationship enterprises have with each other. Linking enterprises together to have them share the risk and benefits of AM can increase the commercial activities they have together. Consortiums such as CRIAQ and CARIC are already leading the aerospace industry in this direction by providing an attractive financial leverage for every R&D project regrouping academic and industrial organizations. This collaboration model works very well for low TRL projects, but becomes impractical for high TRL projects due to intellectual property protection (IPP) concerns.

Another idea could be to encourage partnerships where OEMs and contract manufacturers co-develop a product manufactured through AM, the IP is shared and the OEM commits to order a given quantity of the co-developed product. This kind of collaboration would ease the process of characterisation of the supplier and would allow for a better mutual understanding between the designers and the manufacturers.

Finally, a concept that could help in reducing the price of an AM product and the investment for the contract manufacturer would be to have a dynamic where the OEM is the owner of the raw material (metal powder) and lends it to its supplier to manufacture the ordered parts. This way, the OEM has a better control on the price and the investment of the contract manufacturer is reduced.

Chapter 7
Conclusion

7.1. General conclusion

This study describes the actual state of the Canadian aerospace industry towards the integration of metal AM into manufacturing processes by measuring the differences of perception of the stakeholders about AM-related opportunities, challenges, cost drivers and advancement initiatives. By interviewing 15 professionals involved in the topic and surveying 107 participants from over 70 organizations related to AM in aerospace, this study gathered enough information to draw some trends and to make recommendations to the stakeholders.

Results showed a lack of interest from the manufacturers to invest in AM, an absence of AM equipment in the OEM's plants, an underestimation of post-processing operations costs and a divergence of opinion from the stakeholders towards the initiatives that should be undertaken to accelerate AM deployment. Following these observations, the following recommendations have been presented:

- Improve general understanding of AM and design expertise, through education, research and consulting

- Make innovation more attractive and reachable (for every segment of the market)

- Help demand from OEMs to grow (by improving trust, understanding of the process, certifications and research projects) and supply will follow

- Provide each industry segment support that is adapted to its situation

- Improve collaboration incentives between the industry segments

There is a gap between the needs and challenges of every segment. They have to work together even if their interests are different. The end goal is the same for everyone: improving manufacturing capabilities and profitability. But at the local scale, the challenges and short term objectives diverge. In order to have a more fluid relationship, the industrial environment in which they need to collaborate will have to change.

In short, this innovative research project is a response to a current problem which will open the way to other researchers who wish to participate in the next manufacturing revolution.

7.2. Limits of the research

Considering it is an exploratory study, this M.Sc. thesis provides a broad overview of the actual state of the Canadian aerospace industry and shows a reliable image of the particular reality of every segment of the supply chain. However, it does not provide any detailed implementation strategies, nor a complete roadmap for AM integration. Taking this study as a starting point, this kind of work could be undertaken in a near future by another researcher or stakeholder.

The data provided in the context of this study provides an accurate overview of the targeted market in 2016. However, given the speed at which AM technologies and the market evolve, this data will become obsolete within the next 2-3 years. Given the cost and time involved in such an extensive study, stakeholders should take advantage of this information in the near future.

Finally, the topics and concerns brought up in this study are the ones that have been measured in the context of the national survey. Many other interesting AM-related topics, such as reachable mechanical properties, business cases profitability, cost structure breakdown, cost comparison models and international benchmarking, are not covered in this study and should be addressed by the parties involved.

7.3. Contribution of the research

The quality of the data collected during this study and the fact that it is both, quantitative and qualitative has a high value for the industry. The state of AM in Canada evolves quickly and is often based only on the subjective point of view of experts in the domain. The trends that have been measured in this study are based on the answers from 107 participants with AM knowledge from over 70 organizations situated everywhere in the Canadian aerospace supplier chain (from material providers and academia to OEMs and manufacturers). Given the relevance of the collected data, decision makers at the industrial and governmental levels will be able to use it to justify investments or build roadmaps based on facts instead of intuition.

The data collected in the context of this study has been requested by Industry Canada and Canada Makes in order to help in the production of an overarching report on the additive manufacturing activities in Canada.

This same data will also be integrated in an advanced manufacturing project of the Consortium for research and innovation in aerospace in Quebec (CRIAQ) as a work package on the integration of AM in the local supply chain.

The results have been given to *Réseau Québec 3D* in order to help its committee of value chain creation in understanding and filling the gaps of the AM industry in the province.

Finally, the results and recommendations of this thesis have been presented by the main researcher during a conference at the 84th congress of ACFAS.

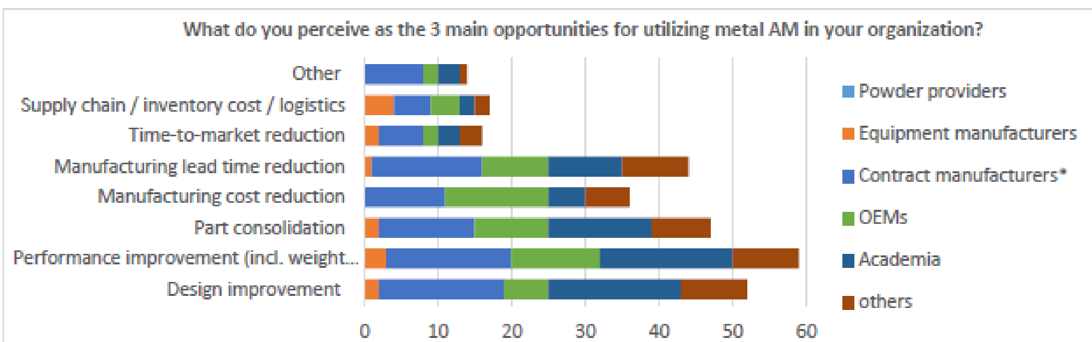
Funding acknowledgement

This M.Sc. thesis was financially supported by HEC Montréal, the Natural Sciences and Engineering Research Council of Canada [EGP 490485-15] and the Consortium for Research and Innovation in Aerospace in Quebec [2015-AConnect-02Q].

Appendix 1: Survey results

What do you perceive as the 3 main opportunities for utilizing metal AM in your organization?								
Suggested Opportunities	Powder providers	Equipment manufacturers	Contract manufacturers without AM	Contract manufacturers with AM cap.	Contract manufacturers*	OEMs	Academia	others
Design improvement	0	2	13	4	17	6	18	9
Performance improvement (incl. weight saving)	0	3	12	5	17	12	18	9
Part consolidation	0	2	11	2	13	10	14	8
Manufacturing cost reduction	0	0	10	1	11	14	5	6
Manufacturing lead time reduction	0	1	11	4	15	9	10	9
Time-to-market reduction	0	2	5	1	6	2	3	3
Supply chain / inventory cost / logistics	0	4	4	1	5	4	2	2
Other	0	0	6	2	8	2	3	1

*The data associated with "Contract Manufacturers" is the sum of the 2 previous columns. Only data from "Contract Manufacturers" is shown in the chart below

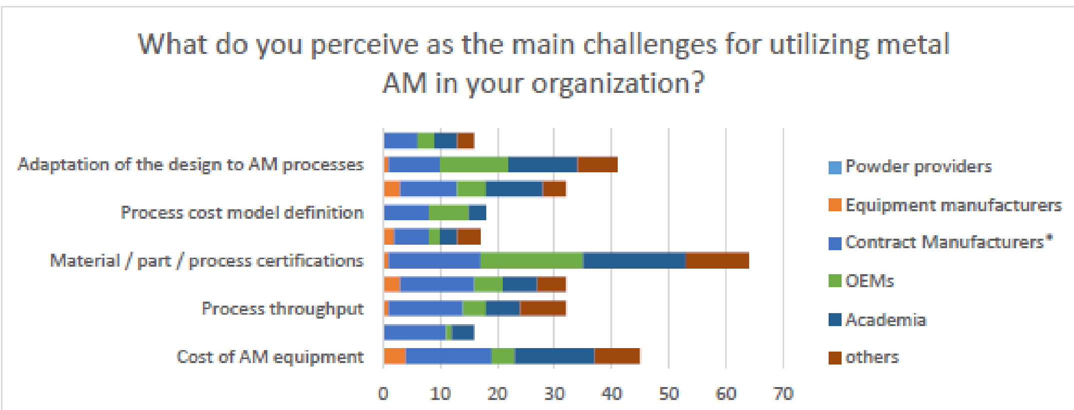


**The horizontal axis represents the absolute number of participants which voted for a given category

What do you perceive as the <u>top 1</u> opportunity for utilizing metal AM in your organization?								
Suggested Opportunities	PP	EM	CM w/o AM	CM W/ AM	CM*	OEM	ACAD	others
Design improvement	0	1	8	2	10	4	11	8
Performance improvement (incl. weight saving)	0	1	4	3	7	6	6	3
Part consolidation	0	0	1	0	1	2	4	0
Manufacturing cost reduction	0	0	2	1	3	2	2	2
Manufacturing lead time reduction	0	0	5	1	6	4	0	1
Time-to-market reduction	0	1	1	0	1	0	0	0
Supply chain / inventory cost / logistics	0	2	2	0	2	1	1	2

What do you perceive as the main challenges for utilizing metal AM in your organization?								
Suggested Challenges	Powder providers	Equipment manufacturers	Contract manufacturers without AM	Contract manufacturers with AM cap.	Contract Manufacturers*	OEMs	Academia	others
Cost of AM equipment	0	4	13	2	15	4	14	8
Equipment lifetime	0	0	10	1	11	1	4	0
Process throughput	0	1	10	3	13	4	6	8
Post-processing requirements	0	3	7	6	13	5	6	5
Material / part / process certifications	0	1	13	3	16	18	18	11
Availability of qualified labor	0	2	5	1	6	2	3	4
Process cost model definition	0	0	5	3	8	7	3	0
Process technical capability definition	0	3	9	1	10	5	10	4
Adaptation of the design to AM processes	0	1	6	3	9	12	12	7
Other	0	0	5	1	6	3	4	3

*The data associated with "Contract Manufacturers" is the sum of the 2 previous columns. Only data from "Contract Manufacturers" is shown in the chart below

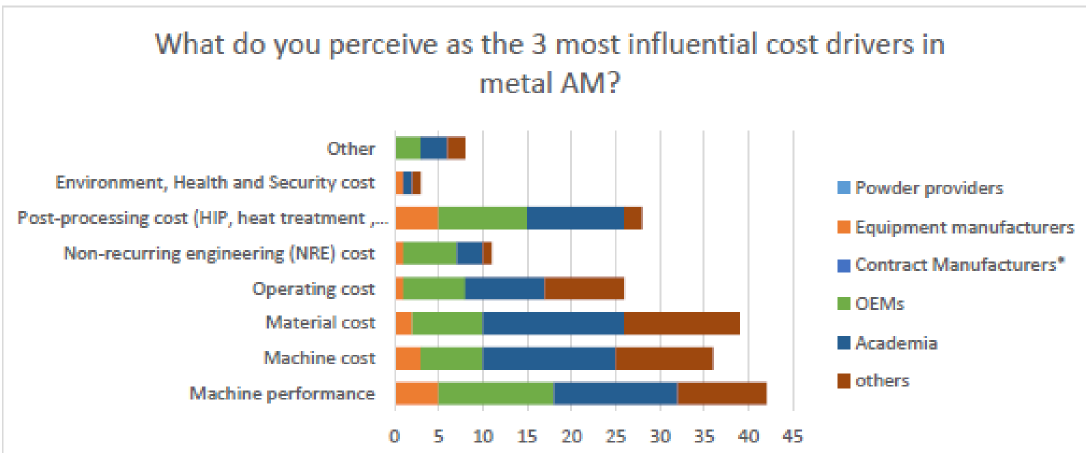


**The horizontal axis represents the absolute number of participants which voted for a given category

What do you perceive as the top 1 challenge for utilizing metal AM in your organization?								
Suggested Challenges	PP	EM	CM w/o AM	CM W/ AM	CM*	OEM	ACAD	others
Cost of AM equipment	0	2	8	2	10	2	13	3
Equipment lifetime	0	0	3	1	4	1	0	0
Process throughput	0	0	4	0	4	1	1	4
Post-processing requirements	0	1	3	1	4	1	2	2
Material / part / process certifications	0	0	5	1	6	14	4	5
Availability of qualified labor	0	0	0	1	1	0	1	2
Process cost model definition	0	0	0	1	1	1	0	0
Process technical capability definition	0	1	2	1	3	1	2	1
Adaptation of the design to AM processes	0	1	2	1	3	1	3	2
Other	0	0	0	0	0	0	0	0

What do you perceive as the 3 most influential cost drivers in metal AM?								
Suggested cost drivers	Powder providers	Equipment manufacturers	Contract manufacturers without AM	Contract manufacturers with AM cap.	Contract Manufacturers*	OEMs	Academia	others
Machine performance	0	5	14	2		13	14	10
Machine cost	0	3	15	2		7	15	11
Material cost	0	2	12	2		8	16	13
Operating cost	0	1	9	3		7	9	9
Non-recurring engineering (NRE) cost	0	1	6	1		6	3	1
Post-processing cost (HIP, heat treatment , etc.)	0	5	5	5		10	11	2
Environment, Health and Security cost	0	1	2	0		0	1	1
Other	0	0	5	3		3	3	2

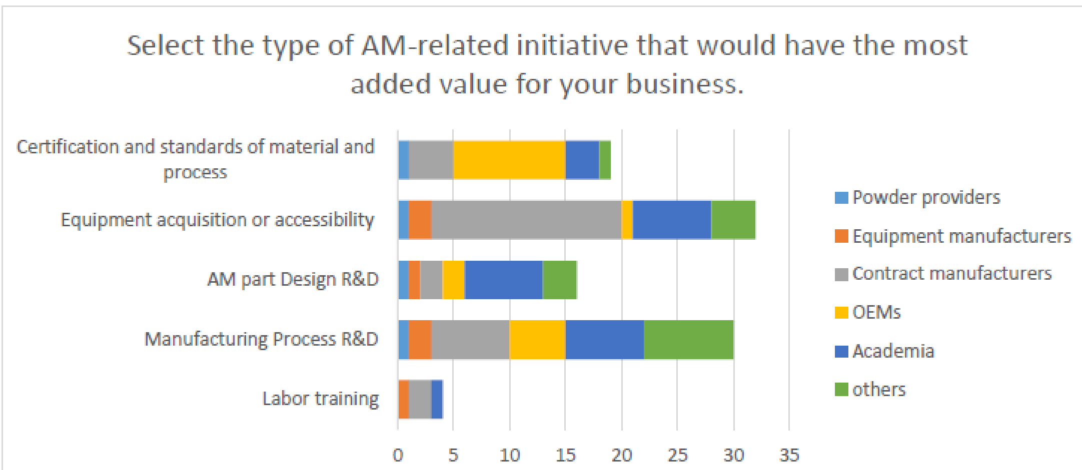
*The data associated with "Contract Manufacturers" is the sum of the 2 previous columns. Only data from "Contract Manufacturers" is shown in the chart below



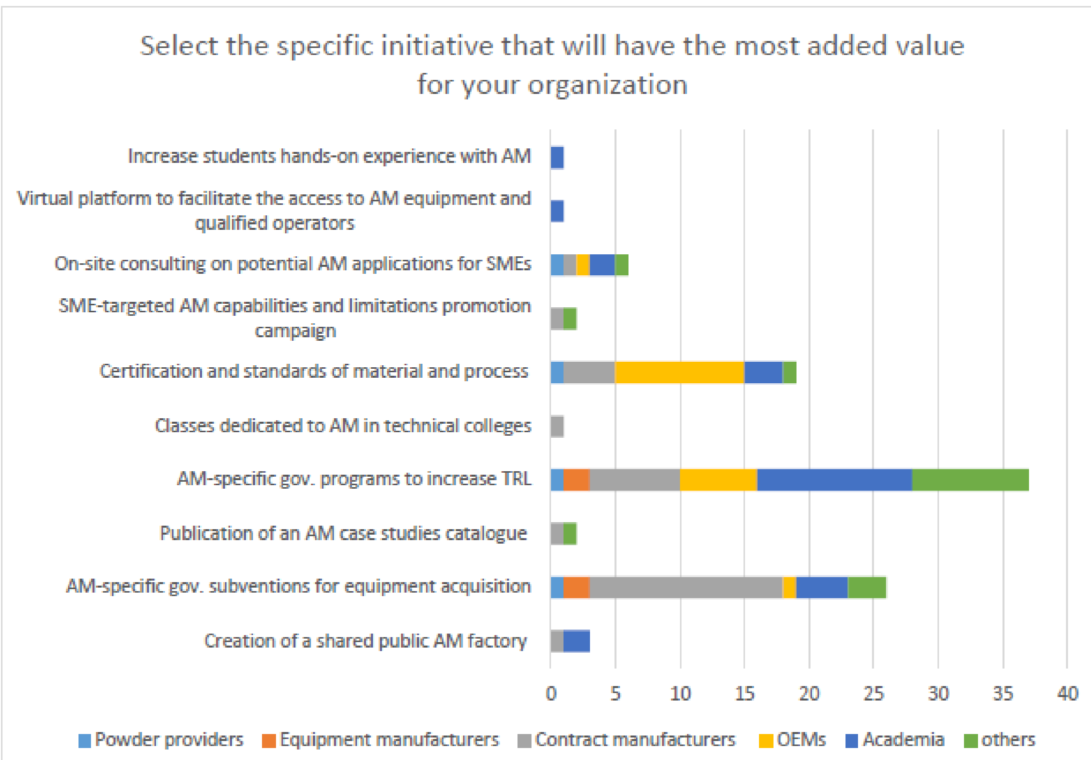
**The horizontal axis represents the absolute number of participants which voted for a given category

What do you perceive as <u>the most</u> influential cost drivers in metal AM?								
Suggested cost drivers	PP	EM	CM w/o AM	CM W/ AM	CM*	OEM	ACAD	others
Machine performance	0	2	9	1		6	9	7
Machine cost	0	2	5	2		3	10	4
Material cost	0	0	1	1		3	3	3
Operating cost	0	0	1	0		2	0	0
Non-recurring engineering (NRE) cost	0	1	2	0		2	0	1
Post-processing cost (HIP, heat treatment , etc.)	0	1	3	1		1	1	0
Environment, Health and Security cost	0	0	0	0		0	0	0
Other	0	0	0	0		0	0	0

The following fields have been brought up as challenges over which governmental support could accelerate metal AM deployment. Please select the type of AM-related initiative that would have the most added value for your business.						
Suggested type of initiative	Powder providers	Equipment manufacturers	Contract manufacturers	OEMs	Academia	others
Labor training	0	1	2	0	1	0
Manufacturing Process R&D	1	2	7	5	7	8
AM part Design R&D	1	1	2	2	7	3
Equipment acquisition or accessibility	1	2	17	1	7	4
Certification and standards of material and process	1	0	4	10	3	1



Please select the specific initiative that will have the most added value for your organization.						
Suggested specific initiative	Powder providers	Equipment manufacturers	Contract manufacturers	OEMs	Academia	others
Creation of a shared public AM factory	0	0	1	0	2	0
AM-specific gov. subventions for equipment acquisiti	1	2	15	1	4	3
Publication of an AM case studies catalogue	0	0	1	0	0	1
AM-specific gov. programs to increase TRL	1	2	7	6	12	9
Classes dedicated to AM in technical colleges	0	0	1	0	0	0
Certification and standards of material and process	1	0	4	10	3	1
SME-targeted AM capabilities and limitations promot	0	0	1	0	0	1
On-site consulting on potential AM applications for S	1	0	1	1	2	1
Virtual platform to facilitate the access to AM equipm	0	0	0	0	1	0
Increase students hands-on experience with AM	0	0	0	0	1	0



Contract manufacturers - manufacturing methods per activity sector							
manufacturing method	**Prototyping**	**Metal part manufacturing**	**Plastic and composite part manufacturing**	**Post-processing operations**	**Jigs & fixtures**	**Tooling & die**	**Maintenance and repair**
Traditional in-house	24	25	15	18	26	17	13
Traditional outsourced	5	10	8	10	9	6	3
AM in-house	19	9	7	9	12	8	5
AM outsourced	10	6	7	7	5	3	2
AM in-house & outsourced	0	1	0	0	0	0	0

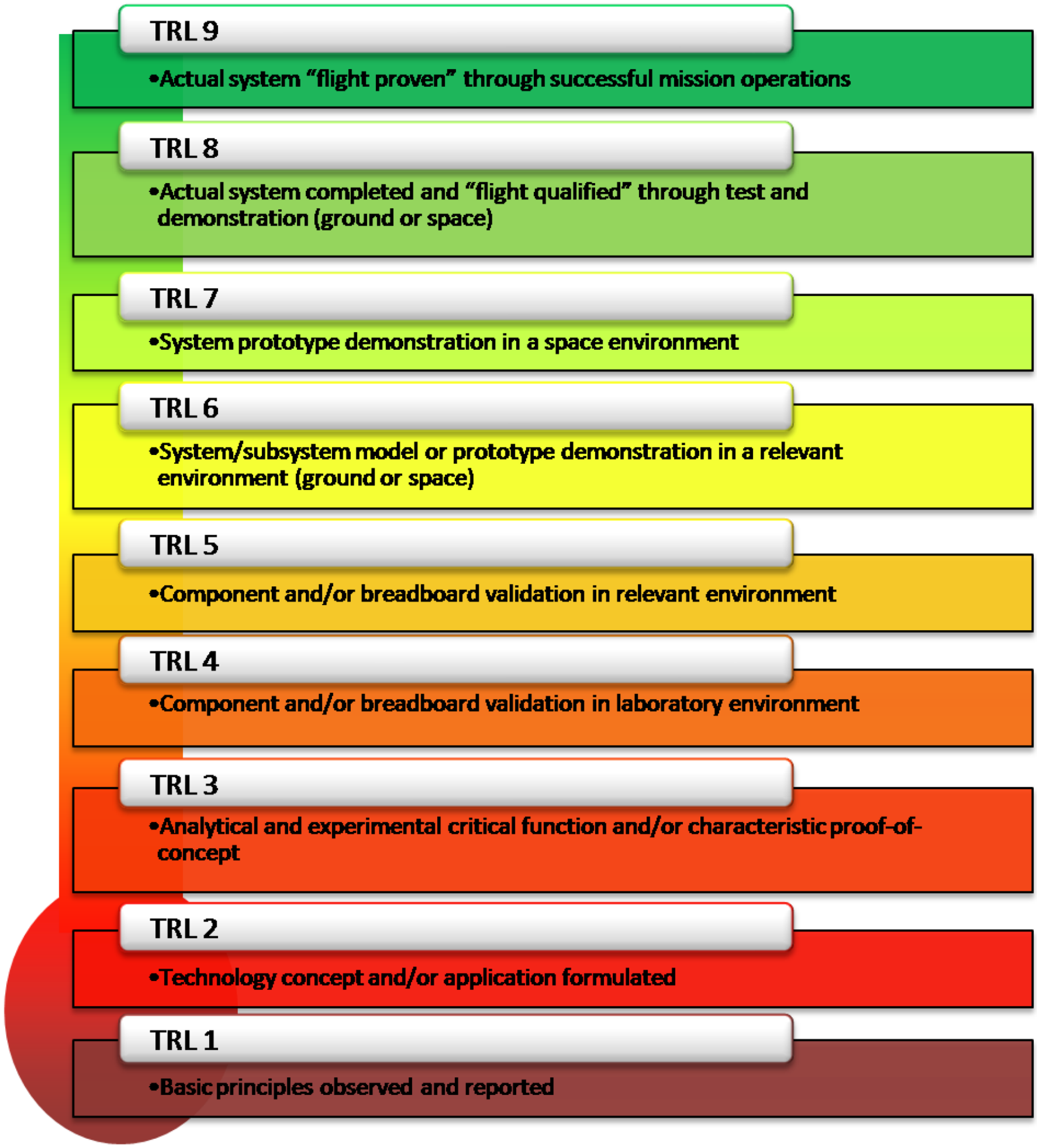
OEMs - manufacturing methods per activity sector							
manufacturing method	**Prototyping**	**Metal part manufacturing**	**Plastic and composite part manufacturing**	**Post-processing operations**	**Jigs & fixtures**	**Tooling & die**	**Maintenance and repair**
Traditional in-house	14	15	9	12	13	11	9
Traditional outsourced	14	14	14	14	16	14	15
AM in-house	13	0	4	0	5	3	1
AM outsourced	12	11	9	9	7	6	5

Participation of individuals		
Participation of individuals	Nb. of participants	
Total population contacted	307	individuals
Complete Answers	107	individuals
participation rate	35%	

Participation of organizations		
Participation of organizations	Nb. Of organizations	
Total number of enterprises contacted	185	org
Minimal quantity of org. who participated	71	org
Maximal quantity of org. who participated	86	org
Minimal participation rate	38%	
Maximal participation rate	46%	

Participation per SC segment		
Segment	Nb. of organizations	Nb. Of participants
Metal Powder provider	2 to 4	4
AM Equipment manufacturer	4 to 5	6
Contract manufacturer	30 to 34	35
OEMs	10 to12	19
Academia (universities and colleges)	11 to 15	25
Others	12 to 16	18
Total	71 to 86	107

Appendix 2: Technology Readiness Level (TRL) scale



Source: (NASA, 2012)

Retrait d’une ou des pages pouvant contenir des renseignements personnels

HEC Montréal - 514-340-6282 - raf.jans@hec.ca

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The following pages contain a confidential questionnaire, which we invite you to complete. This questionnaire was developed as part of a collaborative research project between CRIAQ and HEC Montréal.

The estimated time for completing the questionnaire is between 5 to 10 minutes.

The information collected will remain strictly confidential. It will be used solely for the advancement of knowledge and the dissemination of the overall results in academic or professional forums.

The online data collection provider agrees to refrain from disclosing any personal information (or any other information concerning participants in this study) to any other users or to any third party, unless the respondent expressly agrees to such disclosure or unless such disclosure is required by law.

You are free to refuse to participate in this project and you may decide to stop answering the questions at any time. By completing this questionnaire, you will be considered as having given your consent to participate in our research project and to the potential use of data collected from this questionnaire in future research.

If you have any questions about this research, please contact the principal investigator, Gabriel Doré, at the telephone number or email address indicated below.

HEC Montréal's Research Ethics Board has determined that the data collection related to this study meets the ethics standards for research involving humans. If you have any questions related to ethics, please contact the REB secretariat at (514) 340-6051 or by email at cer@hec.ca.

Thank you for your valuable cooperation!

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INTEGRATION OF ADDITIVE MANUFACTURING (3D PRINTING) IN THE AEROSPACE INDUSTRY

1. In which province(s) of Canada is your organization located?
(You may choose more than one answer.)

- [ ] Newfoundland and Labrador
- [ ] Prince Edward Island
- [ ] Nova Scotia
- [ ] New Brunswick
- [ ] Quebec
- [ ] Ontario
- [ ] Manitoba
- [ ] Saskatchewan
- [ ] Alberta
- [ ] British Columbia
- [ ] Outside of Canada (please specify)

* 2. In which sector do you work?

- ○ Industry, including research centres
- ○ Academia / Association / Non- Governmental Organization
- ○ Other (please specify)

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* 3. Please check the box that best corresponds to the position of your organization in the Additive Manufacturing (AM) supply chain:
(You may choose more than one answer.)

- [ ] Metal Powder supplier
- [ ] AM equipment manufacturer
- [ ] Raw material / semi-finish supplier (wrought, forging, casting, etc.)
- [ ] Contract manufacturer ("build-to-print" machine shop and the likes)
- [ ] Original equipment manufacturer (owner of their design, with or without internal manufacturing capabilities)
- [ ] Post-processing operations (heat treat, anodizing, painting, coating, etc.)
- [ ] Other (please specify)

4. What percentage (approximately) of your revenues are made in these sectors:
(total must equal 100%)

Aerospace

Medical

Automotive

Other

5. How many employees work for your organization in Canada?

6.

Please, check all manufacturing activities that relate to your organization:
(AM: Done with additive manufacturing equipement)
(Traditional: Done with traditional manufacturing equipment)

	AM in-house	AM outsourced	Traditional in-house	Traditional outsourced
Prototyping	☐	☐	☐	☐
Metal parts manufacturing	☐	☐	☐	☐
Plastic and composites parts manufacturing	☐	☐	☐	☐
Post-processing operations	☐	☐	☐	☐
Jigs & fixtures	☐	☐	☐	☐
Tooling & die	☐	☐	☐	☐
Maintenance & repair	☐	☐	☐	☐

Other (please specify)

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7. What do you perceive as the 3 main opportunities for utilizing metal additive manufacturing (AM) in your organization?

	Top 1	Top 2	Top 3
Design improvement (free complexity)	○	○	○
Performance improvement (including weight saving)	○	○	○
Part consolidation (i.e. multiple discrete parts are fabricated together into a single part)	○	○	○
Manufacturing cost reduction	○	○	○
Manufacturing lead time reduction	○	○	○
Time-to-market reduction	○	○	○
Supply chain / inventory cost / logistics improvement	○	○	○

Other important oppotunity (please specify)

8. What do you perceive as the 3 main challenges for utilizing metal additive manufacturing (AM) in your organization?

	Top 1	Top 2	Top 3
Cost of equipment (AM machines)	○	○	○
Equipment lifetime	○	○	○
Machine printing speed	○	○	○
Post-processing requirements	○	○	○
Material / part / process certifications	○	○	○
Availability of qualified labor	○	○	○
Process cost model definition	○	○	○
Process technical capability definition	○	○	○
Adaptation of the parts design to the AM process	○	○	○

Other important challenge (please specify)

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9. What do you perceive as the 3 most influential cost drivers in metal additive manufacturing (AM)?

	Top 1	Top 2	Top 3
Machine performance (speed, accuracy, reliability, etc.)	◯	◯	◯
Machine cost	◯	◯	◯
Material cost	◯	◯	◯
Operating cost	◯	◯	◯
Non-recurring engineering (NRE) cost	◯	◯	◯
Post-processing cost (HIP, heat treatment & surface treatment)	◯	◯	◯
Environment, Health and Security (EHS) related cost	◯	◯	◯

Other influential cost driver (please specify)

10. The following fields have been brought up as challenges over which governmental support could accelerate metal AM deployment.
Please select the type of AM-related initiative that would have the most added value for your business:

- ◯ Equipment acquisition - accessibility to machines
- ◯ Labour training
- ◯ Manufacturing Process R&D
- ◯ AM part Design R&D
- ◯ Material and process certification and standards

11. From the previously selected type of initiative, please select the action, from the list below, that will have the most added value for your organization.

- ◯ AM-specific governmental subventions for equipment acquisition
- ◯ The creation of a public factory where academia and industry can have access to AM equipment (e.g. makerspace)
- ◯ Set up a virtual platform to facilitate the access to AM equipment and qualified operators for enterprises who only need it part-time (i.e. sharing AM capital within the industry)
- ◯ To offer manufacturers on-site consulting on potential AM applications for their business

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12. From the previously selected type of initiative, please select the action, from the list below, that will have the most added value for your organization.

- [ ] The integration of classes dedicated to AM in engineering universities programs
- [ ] The integration of classes dedicated to AM in technical colleges (or CEGEP) programs
- [ ] To increase students hands-on experience with AM
- [ ] The creation of a public factory where academia and industry can have access to AM equipment (e.g. makerspace)
- [ ] SME-targeted Additive Manufacturing capabilities and limitations promotion campaign

13. From the previously selected type of initiative, please select the action, from the list below, that will have the most added value for your organization.

- ○ AM-specific governmental programs to increase the technical readiness level (TRL).
- ○ The publication of a catalogue containing multiple well-detailed technical and commercial case studies in order to give enterprises the means to support their decisions of integrating or not AM in their processes.

14. From the previously selected type of initiative, please select the action, from the list below, that will have the most added value for your organization.

- [ ] AM-specific governmental programs to increase the technical readiness level (TRL)
- [ ] The publication of a catalogue containing multiple well-detailed technical and commercial case studies in order to give enterprises the means to support their decisions of integrating or not AM in their processes
- [ ] SME-targeted Additive Manufacturing capabilities and limitations promotion campaign
- [ ] To offer manufacturers on-site consulting on potential AM applications for their business

15. Do you have any additional recommendations in order to accelerate the integration of metal additive manufacturing in the aerospace industry?

16. If you are interested in receiving the analysis of the results of this research project, please leave your email address below. It will be sent to you during the summer of 2016.

Name

Company

Email Address

HEC MONTRĒAL

Retrait d'une ou des pages pouvant contenir des renseignements personnels

Vous trouverez dans les prochaines pages un questionnaire confidentiel auquel nous vous invitons à répondre. Ce questionnaire a été développé dans le cadre d'un projet de collaboration entre le CRIAQ et HEC Montréal.

Le temps estimé pour compléter ce questionnaire est de 5 et 10 minutes.

Les renseignements recueillis resteront strictement confidentiels; ils ne seront utilisés que pour l'avancement des connaissances et la diffusion des résultats globaux dans des forums savants ou professionnels.

Le fournisseur de collecte de données en ligne s'engage à ne révéler aucune information personnelle (ou toute autre information relative aux participants de cette étude) à d'autres utilisateurs ou à tout autre tiers, à moins que le répondant consente expressément à une telle divulgation ou que celle-ci soit exigée par la loi.

Vous êtes complètement libre de refuser de participer à ce projet et vous pouvez décider en tout temps d'arrêter de répondre aux questions. Le fait de remplir ce questionnaire sera considéré comme votre consentement à participer à notre recherche et à l'utilisation des données recueillies dans ce questionnaire pour d'éventuelles recherches. Puisque le questionnaire et anonyme, une fois votre participation complétée, il vous sera impossible de vous retirer du projet de recherche, car il sera impossible de déterminer quelles réponses sont les vôtres.

Si vous avez des questions concernant cette recherche, vous pouvez contacter le chercheur principal, Gabriel Doré, au numéro de téléphone ou à l'adresse de courriel indiqués ci-dessus.

Le comité d'éthique de la recherche de HEC Montréal a statué que la collecte de données liée à la présente étude satisfait aux normes éthiques en recherche auprès des êtres humains. Pour toute question en matière d'éthique, vous pouvez communiquer avec le secrétariat de ce comité au (514) 340-6051 ou par courriel à cer@hec.ca.

Merci de votre précieuse collaboration!

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2.

1. Dans quelle province est située votre organisation ?
(vous pouvez sélectionner plus d'une province)

- ☐ Terre-Neuve
- ☐ Île-du-Prince-Édouard
- ☐ Nouvelle-Écosse
- ☐ Nouveau-Brunswick
- ☐ Québec
- ☐ Ontario
- ☐ Manitoba
- ☐ Saskatchewan
- ☐ Alberta
- ☐ Colombie-britannique
- ☐ Étranger (veuillez préciser)

* 2. Dans quel secteur se situe votre organisation ?

- ○ Industrie (y compris les centres de recherche)
- ○ Université et collège
- ○ Autre (veuillez préciser)

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3.

* 3. Cochez la case qui correspond le mieux à la place occupée par votre organisation dans la chaîne d'approvisionnement de la fabrication additive (FA)

- ☐ Fournisseur de poudre métallique
- ☐ Fournisseur d'équipement de FA
- ☐ Fournisseur de matière première ou semi-finie (brut, pièces forgées, pièces coulées)
- ☐ Manufacturier / sous-contractant
- ☐ Donneur d'ordre (*OEM*) (propriétaire de son design, avec ou sans équipement manufacturier à l'interne)
- ☐ Opérations de post-traitement (traitement thermique, anodisation, peinture, revêtement, etc.)
- ☐ Autre (veuillez préciser)

4. Quel pourcentage (approximativement) de vos revenus proviennent de ces secteurs :
(Le total doit être de 100%)

Aérospatiale	
Médical	
Automobile	
Autre	

5. Combien d'employés compte votre organisation au Canada :

- ○ 1-4 employés
- ○ 5-19 employés
- ○ 20-99 employés
- ○ 100-499 employés
- ○ Plus de 500 employés

6. Cochez toutes les activités de votre organisation et veuillez indiquer si elles sont faites à l'interne ou sous-traitée, par fabrication additive (FA) ou traditionnelle :

	FA à l'interne	FA sous-traitée	Fabrication traditionnelle à l'interne	Fabrication traditionnelle sous-traitée
Prototypage	☐	☐	☐	☐
Fabrication de pièces métalliques	☐	☐	☐	☐
Fabrication de pièces de plastique et composites	☐	☐	☐	☐
Opérations de post-traitement	☐	☐	☐	☐
Gabarits et adaptateurs de montage (*jigs & fixtures)*	☐	☐	☐	☐
Moule et matrice (*Tooling and die)*	☐	☐	☐	☐
Maintenance et réparation	☐	☐	☐	☐

Autre (veuillez préciser)

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4.

7. Selon vous, quelles sont/seraient les trois principales opportunités à utiliser la fabrication additive (FA) métallique dans votre organisation ?

	Top 1	Top 2	Top 3
Amélioration du design (simplification)	○	○	○
Amélioration de la performance (incluant la réduction de poids)	○	○	○
Consolidation des pièces (plusieurs pièces discrètes sont fabriquées en une seule impression)	○	○	○
Réduction des coûts de fabrication	○	○	○
Réduction des délais de mise en œuvre (lead time)	○	○	○
Réduction du temps de mise en marché	○	○	○
Amélioration de la logistique / Chaîne d'approvisionnement / Coûts d'inventaire	○	○	○

Autre opportunité (veuillez préciser)

8. Selon vous, quels sont/seraient les trois principaux défis à utiliser la fabrication additive (FA) métallique dans votre organisation ?

	Top 1	Top 2	Top 3
Coût de l'équipement (machine de FA)	○	○	○
Espérance de vie de l'équipement	○	○	○
Vitesse d'impression des machines de FA	○	○	○
Exigence de post-traitement	○	○	○
Certification des procédés / des matériaux / des pièces	○	○	○
Disponibilité de main d'œuvre qualifiée	○	○	○
Définition d'un modèle de coût des procédés (process cost model)	○	○	○
Définition des capacités techniques du procédé	○	○	○
Adaptation du design des pièces au procédé de fabrication additive (FA)	○	○	○

Autre défi (veuillez préciser)

9. Selon vous, quels sont/seraient les trois inducteurs de coûts reliés à l'utilisation de la fabrication additive (FA) métallique dans votre organisation ?

	Top 1	Top 2	Top 3
Performance de la machine (vitesse, précision, fiabilité, etc.)	◯	◯	◯
Coût de la machine	◯	◯	◯
Coût des matériaux	◯	◯	◯
Coûts d'opération	◯	◯	◯
Coûts d'ingénierie non-récurrents (NRE)	◯	◯	◯
Coûts de post-traitement (HIP, traitement thermique, traitement de surface)	◯	◯	◯
Coûts reliés à l'environnement, la santé et sécurité (ESS)	◯	◯	◯

Autre (veuillez préciser)

10. Les domaines suivants ont été identifiés comme des thèmes à travers lesquels le gouvernement pourrait agir en vue d'accélérer le déploiement de la fabrication additive (FA) métallique.

Veuillez sélectionner l'initiative qui aurait le plus de valeur ajoutée pour votre organisation.

◯ Acquisition d'équipement et/ou accessibilité à l'équipement

◯ Formation de la main d'œuvre

◯ R&D des procédés reliés à la fabrication additive (*process R&D*)

◯ R&D en conception de pièces pour la fabrication additive (*Design R&D*)

◯ Certification et normalisation de matériaux et procédés

11. Acquisition d'équipement et/ou accès à de l'équipement. Veuillez sélectionner l'initiative de la liste ci-dessous qui aurait le plus de valeur ajoutée pour votre organisation

◯ Subventions gouvernementales ciblées à l'achat d'équipement de FA

◯ Création d'une usine publique où l'industrie et les universités auraient accès à de l'équipement de FA (markerspace)

◯ Création d'une plate-forme virtuelle pour faciliter l'accès à de l'équipement de FA de façon temporaire (ainsi qu'à des opérateurs qualifiés

◯ Offrir des services de consultation spécialisée sur les applications de FA à l'intention des entreprises manufacturières.

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7.

12. Formation de la main d'œuvre. Veuillez sélectionner l'initiative de la liste ci-dessous qui aurait le plus de valeur ajoutée pour votre organisation

- ◯ Intégration de cours spécialisés en FA dans les programmes de génie des universités.
- ◯ Intégration de cours spécialisés en FA dans les programmes techniques des CEGEP.
- ◯ Augmentation de l'expérience pratique en FA des étudiants.
- ◯ Création d'une usine publique où l'industrie et les universités ont accès à de l'équipement de FA (markerspace)
- ◯ Campagne de promotion destinée à éduquer les PME sur les capacités et les limites réelles de la FA.

13. R&D des procédés de fabrication additive. Veuillez sélectionner l'initiative de la liste ci-dessous qui aurait le plus de valeur ajoutée pour votre organisation

- ◯ Programmes gouvernementaux spécifiques à la FA destinés à accroître le niveau de maturité technologique (TRL).
- ◯ Publication d'un catalogue contenant de nombreuses études de cas détaillées destinées à aider les entreprises à décider ou non d'adopter la FA.

14. R&D en conception de pièces pour la fabrication additive. Veuillez sélectionner l'initiative de la liste ci-dessous qui aurait le plus de valeur ajoutée pour votre organisation

- ◯ Programmes gouvernementaux spécifiques à la FA destinés à accroître le niveau de maturité technologique (TRL).
- ◯ Publication d'un catalogue contenant de nombreuses études de cas détaillées destinées à aider les entreprises à décider ou non d'adopter la FA.
- ◯ Campagne de promotion destinée à éduquer les PME sur les capacités et les limites réelles de la FA.
- ◯ Offrir des services de consultation spécialisée sur les applications de FA à l'intention des entreprises manufacturières.

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10.

15. Avez-vous des recommandations supplémentaires pour accélérer l'adoption de la fabrication additive (FA) métallique dans l'industrie aérospatiale ?

16. Si vous souhaitez recevoir l'analyse des résultats de ce projet de recherche, veuillez laisser votre courriel ci-dessous. L'étude vous sera envoyée dans le courant de l'été 2016.

Nom

Organisation / compagnie

Courriel

Appendix 5: Survey logic structure for question 10

Type of AM-related initiative	*Suggested specific initiatives*
Equipment Acquisition – Accessibility to Machines	AM-specific governmental subventions for equipment acquisition
	The creation of a public factory where academia and industry can have access to AM equipment (e.g. makerspace)
	Set up a virtual platform to facilitate the access to AM equipment and qualified operators for enterprises who only need it part-time (i.e. sharing AM capital within the industry)
	To offer manufacturers on-site consulting on potential AM applications for their business
Labour Training	The integration of classes dedicated to AM in engineering universities programs
	The integration of classes dedicated to AM in technical colleges (or CEGEP) programs
	To increase students hands-on experience with AM
	The creation of a public factory where academia and industry can have access to AM equipment (e.g. makerspace)
	SME-targeted Additive Manufacturing capabilities and limitations promotion campaign
Manufacturing Process R&D	AM-specific governmental programs to increase the technical readiness level (TRL).
	The publication of a catalogue containing multiple well-detailed technical and commercial case studies in order to give enterprises the means to support their decisions of integrating or not AM in their processes.
AM Part Design R&D	AM-specific governmental programs to increase the technical readiness level (TRL)
	The publication of a catalogue containing multiple well-detailed technical and commercial case studies in order to give enterprises the means to support their decisions of integrating or not AM in their processes
	SME-targeted Additive Manufacturing capabilities and limitations promotion campaign
	To offer manufacturers on-site consulting on potential AM applications for their business
Material and Process Certification and Standards	Increase the resources and effort for material and process certification and standards

Appendix 6: List of attended conferences, shows and forums

- **Visit of the Centre for Advanced Manufacturing and Design Technologies (CAMDT)**
  Brampton, ON, Canada. April 29th 2015

- **Canada Makes forum**
  Hamilton, ON, Canada. April 30th 2015

- **Additive Manufacturing + 3D Printing Conference & Expo (AM3D)**
  Boston, MA, United States. August 2nd-5th 2015

- **Canadian Aeronautics and Space Institute (CASI) conference**
  Montreal, QC, Canada. September 23rd 2015

- **Canadian Manufacturing and Technology Show (CMTS)**
  Mississauga, ON, Canada. September 28th-30th 2015

- **Consortium for research and innovation in aerospace in Quebec (CRIAQ) research forum**
  Montreal, QC, Canada. April 27th 2016

- ***Réseau Québec 3D* annual conference**
  Boucherville, QC, Canada. May 5th 2016

- ***Colloque - Impression 3D* – Acfas**
  Montreal, QC, Canada. May 9th-10th 2016

Appendix 7: interview questionnaire

Interview Guide

1. **Enterprise's profile**
    1.1. Name of the organization:

    1.2. Check the box that corresponds to the position of your organization in the AM supply chain.

    __Metal powder production
    __Part manufacturer (offering AM parts)
    __Part manufacturer (not offering AM parts)
    __Post-processing operations organization
    __Other: ____________________
    __Machine manufacturer
    __Academia
    __OEM or Tier 1
    __Para-governmental

    1.3. What percentage of your activities are done in:

    __% in Aerospace
    __% in Medical
    __% in Automotive
    __% in Other: ___________

    1.4. Which family of materials you are using?

    __Metal
    __Plastics
    __Composites

    1.5. To which of these applications is your organization related?

    __R&D
    __Low volume part production
    __Post-processing operations
    __Tooling & die
    __Net & near-net shape forming
    __Prototyping
    __High volume part production
    __Jigs & fixtures
    __Maintenance & repair

    1.6. Is additive manufacturing integrated into your processes?

    __Yes
    __No

    1.7. If, integrated, is additive manufacturing done in-house or is it outsourced?

    __In-house
    __Outsourced

2. **General**

   2.1. What are the three main obstacles preventing your business to improve its use of AM?
   2.2. What are the three biggest opportunities with which AM could improve your business?

3. **Supply Chain**

   3.1. Which part of the value chain is a bottleneck for the development of AM?
   3.2. What is your point of view on how the growth of AM might change the relationships within your actual supply chain? (OEM, suppliers, OSP, post-processing)

4. **Financial aspects, Support and incentives**

   4.1. Knowing that the main cost drivers in metal AM are the following:

- Volume to be melted
- Material cost
- Height of build
- Required post-processing (HIP, heat treatment & surface treatment)
- Machine costs
- Amount of support structure
- Number of parts on the build plate
- Layer thickness

What do you see as improvements to mitigate those cost drivers?

   4.2. What is your point of view on the support offered to Canadian organizations through governmental programs and initiatives at the moment?
   4.3. What could be done to improve the support offered to Canadian organizations?
   4.4. What is your point of view on the available data to take a rational business case-based decision on entering the AM market

5. **Education, Training & Expertise**
   5.1. What skill sets will enterprises working with AM be interested in, in the near future?
   5.2. Would you find any benefits in a shared academic/private research center

6. **Technology**

   6.1. What is your point of view on the burden associated with post-processing operations?
   6.2. What is your point of view on the materials available on the market right now for AM?
   6.3. What is your point of view on characterization of AM materials?
   6.4. What is your point of view on first pass yield of additive manufacturing?
   6.5. What is your point of view on the life cycle and development cycle of the machines?
   6.6. What is your point of view on the place of hybrid machines in the market?

6.7. What is your point of view on the metal powder production market?
6.8. What is your point of view on the quality of the parts offered by AM? (surface finish, material integrity, dimensional)

7. Recommendations

7.1. Any recommendations in order to accelerate the integration of additive manufacturing in the aerospace industry? Any solutions you would like to see appear in the future?

Appendix 8: CER forms

INSTRUCTIONS INCLUDED WITH A QUESTIONNAIRE

Integration of Additive Manufacturing (AM) in the Aerospace Value Chain

The following pages contain a questionnaire, which we invite you to complete. This questionnaire was developed as part of a Master's thesis at HEC Montréal.

Since your first impressions best reflect your true opinions, we would ask that you please answer the questions included in this questionnaire without any hesitation. There is no time limit for completing the questionnaire, although we have estimated that it should take about 15 minutes.

The information collected will be used solely for the advancement of knowledge and the dissemination of the overall results in academic or professional forums.

The online data collection provider agrees to refrain from disclosing any personal information (or any other information concerning participants in this study) to any other users or to any third party, unless the respondent expressly agrees to such disclosure or unless such disclosure is required by law.

You are free to refuse to participate in this project and you may decide to stop answering the questions at any time. By completing this questionnaire, you will be considered as having given your consent to participate in our research project and to the potential use of data collected from this questionnaire in future research.

The objective of this study is to help organizations situated at every level of the aerospace value chain to better understand the potential and limits of AM, to inform them about the actual trends on the national market and to improve the flow of material along the supply chain related to AM. Once public, this study should influence organizations in the aerospace industry when making strategic partnerships and investments related to AM.

If you have any questions about this research, please contact the principal investigator, Gabriel Doré, at the telephone number or email address indicated below.

HEC Montréal's Research Ethics Board (REB) has determined that the data collection related to this study meets the ethics standards for research involving humans. If you have any questions related to ethics, please contact the REB secretariat at (514) 340-6051 or by email at cer@hec.ca.

Thank you for your valuable cooperation!

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CONSENT FORM FOR AN INTERVIEW IN AN ORGANIZATION

1. Information on the research project

You have been invited to participate in the following research project:
Integration of Additive Manufacturing in the Aerospace Value Chain

This project is being conducted by:

Gabriel Doré B.Eng.	Jacques Roy	Raf Jans
Master's student in Supply Chain Management	Professor in Logistics and Operations Management	Professor in Logistics and Operations Management
HEC Montréal	HEC Montréal	HEC Montréal
gabriel.dore@hec.ca	514-340-6282	514-340-6282
	jacques.roy@hec.ca	Raf.jans@hec.ca

Summary: The project has the objective to improve the maturity of the Canadian aerospace supply chain in terms of Additive Manufacturing (AM). The research project aims at increasing our current knowledge about integration methods of AM into the supplier's processes and the perception of the many players at different level of the value chain concerning challenges, ambitions, risks, problems, actual status, labor qualification, product's quality, etc.

2. Research ethics considerations

Your organization provided us with your name as a potential respondent for this research project. Your participation in this research project is strictly voluntary. You have the right to refuse to answer any of the questions. In addition, you may ask to end the interview at any time, in which case the researcher would be prohibited from using the information gathered. HEC Montréal's Research Ethics Board (REB) has determined that the data collection related to this project meets the ethics standards for research involving humans. If you have any questions related to ethics, please contact the REB secretariat at (514) 340-6051 or by email at cer@hec.ca. Do not hesitate to ask the researcher any questions you might have.

3. Confidentiality of personal information gathered

You should feel free to answer the questions frankly. The researcher, as well as all other members of the research team, if applicable, undertake to protect the personal information obtained by ensuring the protection and security of the data gathered from participants, by keeping all recordings in a secure location, by discussing the confidential information obtained from participants only with the members of the research team and by refraining from using in any manner data or information that a participant has explicitly requested be excluded from the research.

Furthermore, the researchers undertake not to use the data gathered during this project for any purpose other than that intended, unless approved by HEC Montréal's Research Ethics Board. **Please note that by consenting to participate in this research project, you also consent that the data gathered may be used for future research projects, subject to approval of any such projects by HEC Montréal's Research Ethics Board.**

All persons who may have access to the content of your interview, as well as the person in charge of transcribing the interview, have signed a confidentiality agreement.

4. Protection of personal information in the publication of research results
The information that you provide will be used to produce a document that will be made public. Although the raw information will remain confidential, the researcher will use this information in the work submitted for publication. It is up to you to indicate the level of protection of your personal information that you would like with regard to the publication of the research results.

- <u>**Level of confidentiality of the company/organization**</u>

  Option 1:

  - ☐ **I give my consent for the name of my company/organization to be disclosed in the dissemination of the research results.**

  Option 2:

  - ☐ **I do not give my consent for the name of my company/organization to be disclosed in the dissemination of the research results.**

- <u>**Level of confidentiality**</u>

  Option 1:

  - ☐ **I give my consent for my name and title to be disclosed in the dissemination of the research results.**

If you check this box, the researchers can quote you from your interview and mention your name and title in any documents or research articles produced following this study. Even if the name of your company is not mentioned, you should not expect your anonymity to be protected in this case.

Option 2:

- ☐ **I give my consent for my title only to be disclosed in the dissemination of the research results.**

If you check this box, no information concerning your name will be disclosed in the dissemination of the research results. Even if the name of your company is not mentioned, it is possible that someone could obtain your name by cross-referencing. Consequently, you should not expect your anonymity to be protected.

Option 3:

- ☐ **I do not want either my name or my title to appear in the dissemination of the research results.**

If you check this box, neither your name nor your title will be disclosed in the dissemination of the research results. Even if the name of your company is not mentioned, it is possible that someone could obtain your name by cross-referencing. Consequently, complete protection of your anonymity cannot be assured.

- <u>**Consent for audio recording of the interview:**</u>

  ☐ **I give my consent for the researcher to make an audio recording of this interview.**

  ☐ **I do not give my consent for the researcher to make an audio recording of this interview.**

You can signify your consent either with your signature, by email or verbally at the beginning of the interview.

PARTICIPANT'S SIGNATURE:

First and last name: ____

Signature: ______________________ Date (dd/mm/yyyy): ________________

RESEARCHER'S SIGNATURE:

First and last name: Gabriel Doré_______________________________________

Signature: ______________________ Date (dd/mm/yyyy): ______________

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