Process mapping approaches for high-value safety-critical aircraft modification design and development: A case study

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Abstract

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Andréa Cartile

The aircraft modification sector of the aerospace industry involves the design, build, test, and certification of complex, safety-critical systems for existing aircraft. The high product diversity and low-volume high-value production of this sector results in many unique process challenges. Small-to-medium sized aircraft modification enterprises have adopted product lifecycle management (PLM) methodologies to manage these complex product development processes.

This thesis studies the current-state processes of a typical aircraft modification case study company in Canada, using the research methodology of process mapping. The current-state processes are captured in process maps, which are then assessed to find areas of opportunity for process improvement. The current-state processes are mapped at three different levels of detail: a Tier 1 Phase level, a Tier 2 Milestone level, and a Tier 3 Activity level.

Results of the Tier 1 Phase level analysis illustrate some of the challenges related to simultaneously using multiple PLM methodologies across the product development lifecycle. This finding also affects process communication at the Tier 2 Milestone and Tier 3 Activity levels. Tier 2 Milestone level findings also demonstrate the impact of product diversity on milestone traceability. Tier 3 Activity level findings include the level of detail for effective Tier 3 process mapping, the importance of workflow traceability through documentation, and the challenges of change management.

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Table of Contents

Table of Figures

Table of Tables

Table of Acronyms

ARP4754A: Aerospace Recommended Practice 4754A

CAD: Computer Aided Design

CAR521: Canadian Certification Regulations 521

CM: Configuration Management

DAO: Design Approved Organization

MRO: Maintenance, Repair and Overhaul

OEM: Original Equipment Manufacturers

PLM: Product Lifecycle Management

PMBoK®: Project Management Body of Knowledge®

ROI: Return on Investment

SME: Small-to-medium Enterprise

STC: Supplemental Type Certificate

TC: Type Certificate

TCCA: Transport Canada Civil Aviation

Chapter 1: Introduction

The Canadian aerospace industry ranks among the 5 largest aerospace hubs in the world [1]. According to the joint Innovation, Science and Economic Development (ISED), and Aerospace Industries Association of Canada (AIAC) State of Canada's Aerospace Industry 2017 Report [2], the Canadian aerospace industry generated almost $28 billion in revenues and employed over 87,000 Canadians in 2016, which accounted for 1.83% of Canada's Gross Domestic Product (GDP) [3], and 1% of the employed Canadian labour force [4].

ISED and AIAC divide Canada's civil and defense aerospace sectors into two categories. The first category is manufacturing, accounting for 70% of aerospace GDP, and the second is maintenance, repair and overhaul (MRO), accounting for the remaining 30%. ISED and AIAC reported that aerospace manufacturing was the number one contributor to Canadian manufacturing R&D in 2016, and led all manufacturing sectors in the four divisions of innovation practices: product, process, organizational, and marketing innovation. The aerospace manufacturing sector also collaborated significantly more with industry, academia, and government than other Canadian manufacturing sectors.

Despite the secondary role played by MRO in terms of revenues, employment, and R&D participation, the aerospace MRO sector increased its contribution to Canada's GDP by 21.4% and its employment by 16.3% between 2011 and 2016, compared to the manufacturing sector with only 3.3% and 3.1%, respectively [2]. However, despite the rapid growth of MRO, research and innovation in this sector is still less than 2.5% of all R&D performed by the aerospace industry. This is one of the areas of opportunity identified in the AIAC's 2016 Aerospace Innovation White Paper [1], which presents 10 recommendations for increasing innovation opportunities within the Canadian aerospace sector. The recommendations include the creation of research and training opportunities in aerospace, and the pursuit of research collaborations across multiple sectors in response to the aerospace industry's challenges.

The research project presented in this thesis responds to these recommendations through an industry-academia collaborative case study focused on research in process innovation in the Canadian aerospace Maintenance, Repair and Overhaul (MRO) business. The research targets innovation in process management for the MRO aircraft modification and missionizing business sector, and specifically uses process mapping techniques to examine the processes and ontologies associated with Product Lifecycle Management methodologies. The impact of these methods is examined within the context of requirements management and process efficiency across the product development cycle for this important Canadian business model.

1.1 Background

1.1.1 Aerospace Maintenance, Repair and Overhaul

The aerospace MRO industry provides after-market support for continued airworthiness of aircraft designed, manufactured, and certified by Original Equipment Manufacturers (OEMs) such as Bombardier, Boeing, Airbus, and Gulfstream [5]. A less documented but rapidly expanding portion of the MRO business model is the aircraft major modification, or mission integration, sector [6]. Companies operating in this niche area provide engineering and manufacturing services to update existing aircraft with more modern technology, or modify them as repurposed aircraft to perform missions for which they were not originally designed.

Aircraft are composed of safety critical systems, defined as "systems whose failure could result in loss of life, significant property damage, or damage to the environment" [7]. Civil aviation in Canada is strictly regulated by law in order to mitigate risks of failure. Transport Canada Civil Aviation (TCCA) [8], the Canadian regulatory body governing aircraft safety, must certify that aircraft conform to development documentation such as CAD drawings and test reports, and must certify that the aircraft is safe for flight. This process is known as aircraft certification [9], an approval process that must be completed and passed for all newly designed or clean sheet aircraft, and for any changes made to existing aircraft. The approved certification document for a new aircraft is a Type Certificate [10], and the approved certification document for a modified aircraft is a Supplemental Type Certificate (STC) [11]. TCCA makes a distinction between minor and major aircraft modification, whereby a modification is considered major if "an alteration to the type design of an aeronautical product in respect of which a type certificate has been issued that has other than a negligible effect on the weight and centre-of-gravity limits, structural strength, performance, power plant operation, flight characteristics or other qualities affecting its airworthiness or environmental characteristics" [8]. An STC is issued to document the major change to the aircraft's conformity to its original basis of certification [12]. The process of categorizing a modification as minor or major; identifying changes in regulations between the aircraft's original basis of certification and the regulations at the time of the modification; and assessing the systems affected by the modification and corresponding safety-relevant regulatory amendment levels is known as the Changed Product Rule (CPR) [11] [13]. CPR is one of the certification processes that differentiates aircraft modification from OEM clean sheet aircraft design.

Another distinction between the MRO and aircraft modification business models is licensing. Businesses performing maintenance, repair and overhaul are required to obtain an Approved Maintenance Organization (AMO) designation from Transport Canada [14], whereas major modifications may only be undertaken by a company designated as a Design Approved Organization (DAO) [15]. Both original equipment manufacturers such as Bombardier and Airbus and aircraft modification companies require a DAO designation for their design and certification activities.

Civilian and military aircraft operators are under increasing economic pressure, and are therefore revising procurement strategies [16]. There is a growing investment interest in the major refurbishment and life-extension of aging aircraft fleets as an alternative to the purchase of new aircraft. There is also a market for re-purposed or "missionized" aircraft, where OEM certified designs are modified in the after-market in response to the needs of specific market segments and mission profiles. The missionization approach to filling niches in the aircraft market is significantly less expensive than designing an entirely new aircraft. Examples of comparative costs associated with clean sheet and derivative OEM aircraft, versus modified aircraft, are presented in Table 1 and Table 2, respectively.

Table 1: OEM Aircraft Development Costs

OEM Aircraft Development Costs

Aircraft	Company	Reported Development Cost	Scale
787 Dreamliner	Boeing	$32 billion [17]	Clean-Sheet
C-Series (CS-100 and CS-300)	Bombardier	$5.4 billion [18]	Clean-Sheet
E-Jet E2	Embraer	$1.7 billion [19]	Derivative
A320NEO	Airbus	$1.3 billion [20]	Derivative

Table 2: Aircraft Modification Costs

Aircraft Modification Costs

Modification	Cost
Average US Airforce Modification Program Cost	$52.95 million [16]
Average Freighter Conversion Cost	$6.12 million [21]

1.1.2 Aircraft Major Modification in Canada

Occupying a significant niche in the after-market modification business, aircraft missionization is characterized by a high-value, low-volume product resulting from a complex design. The design, development, and certification process of aircraft modification has a significant current and historical presence in Canada. The first documented Supplementary Type Certificate for an aircraft modification issued to a Canadian applicant by Transport Canada authorized the installation of Pee-Kay 1500 Floats on a Luscombe 8F in 1959 [22]. Also in 1959 was the very Canadian canoe-carrying installation for the Cessna 180 and 180A-F [23]. This STC was revised in 1963, the product of which is shown in Figure 1, 51 years later.

Figure 1: "Cessna 180 in the bush pilot canoe race", demonstration of 1959-1963 Canoe-carrying capability STC for Cessna 180 [24]

Another example of a Canadian aircraft modification is the Martin JRM-3 "Martin Mars Waterbomber", shown in Figure 2. Originally manufactured in 1945 in Baltimore, USA, as a sea plane used to transport cargo and personnel [25] [26], the conversion to a waterbomber was performed under a Canadian STC by the British Columbia company Flying Tankers Inc. [27]. The modification was categorized under Aircraft Type Approval, Restricted Category [28]. Water dropping capabilities are seen in Figure 2 which shows the Mars Waterbomber in action.

Figure 2: Martin Mars Water bomber, example of a Canadian modification to an aircraft [29]

The Luscombe 8F Floats, Cessna canoe attachment, and Martin Mars Waterbomber are just a few examples of what has become a substantial Canadian aircraft modification industry. Figure 3 illustrates the increasing trend in the number of STCs issued by Transport Canada for a period of 37 years from 1980 to 2017 [30].

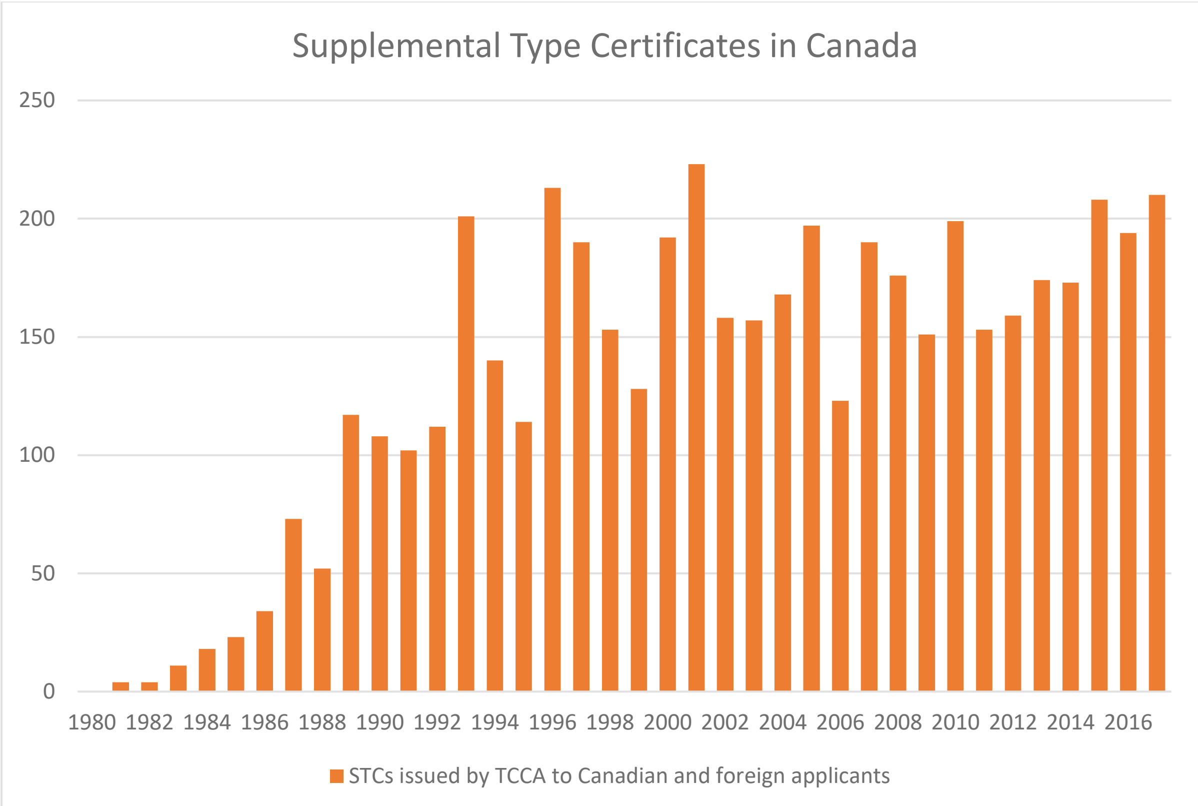

Figure 3: Supplemental Type Certificates in Canada [30]

Between 1993 and 2017, Canada has issued an average of 175 STCs annually. The Design Approved Organization (DAO) must present all of the relevant modification data in a coherent, logical and traceable manner to Transport Canada Civil Aviation (TCCA) to obtain the Supplementary Type Certificate (STC). As each aircraft modification is a unique, highly integrated, multi-disciplinary, complex system-of-systems and the design and development process is bound not only by customer and performance requirements but also by laws regarding compliance to design certification and ongoing airworthiness regulations [31], the design, development and certification of an aircraft modification requires significant resources from both the DAO and TCCA. Combined with high product variability, process efficiency remains a significant challenge in the industry. Research in improving process efficiency is a significant area of opportunity for adding value to cost and resource management for both the aircraft modification industry and TCCA.

1.2 Problem statement

The aerospace product is a complex system-of-systems, and the associated design and development process and product lifecycle are challenging to manage. The aerospace product is a highly integrated, multi-disciplinary, complex system-of-systems and the design and development process is bound not only by customer and performance requirements but also by laws regarding compliance to design certification and ongoing airworthiness regulations [31].

Managing these challenges in aerospace product development and certification programs motivates businesses to develop standards and adopt methodologies that can help them demonstrate compliance to customer, certification and business-related requirements and constraints. Product Lifecycle Management (PLM) is a term commonly used to describe a variety of institutionalized methodologies and software tools developed for the purpose of integrating people, processes, business systems and information from product concept to end-of-life. Over the last 30 years, PLM solutions have been developed across a large variety of industries and business sectors. The philosophy is that processes management solutions can be developed independently of the product and therefore can be applied regardless of industrial differences. However, individual methodologies describe the problem and structure the solution from the perspective, and in the vocabulary, of specific functional groups associated with corporate disciplines such as project management, design, manufacturing, quality and supply chain. Functional group-specific PLM solutions often do not address processes and information management requirements associated with other functional groups that are equally critical to the product development process. As a result, different functional groups within the same enterprise, will adopt the PLM solution that responds to their perception of the needs of their group, although without realizing that the perspectives and vocabulary is not always responding to the needs and understanding of other functional groups.

In this study, the problem of competing organizational methodologies is investigated by means of a case study performed on-site at a typical medium-sized aircraft modification enterprise. Process mapping is used to compare a number of PLM solutions adopted by different functional groups to manage similar or identical processes across the product life cycle, including the Project

Management Body of Knowledge® (PMBoK®), Configuration Management, Lean, CAR521, and ARP4754A. The process maps are used to identify communication barriers and associated process inefficiencies.

1.3 Thesis Organization

The first Chapter of this thesis serves as an introduction and provides the motivation and background for the research and presents the problem statement. Chapter 2 is a review of the literature on PLM relevant to the problem statement. The evolution of PLM methodologies is discussed, and some of the widely used PLM methodologies relevant to the case study are described. Chapter 3 outlines the research methodology used for data collection and interpretation and Chapter 4 presents the results, discusses them and makes associated recommendations based on the research. Chapter 5 concludes the thesis with a summary and recommendations for future work.

Chapter 2: Literature Review

CIMData [32], an international Product lifecycle management (PLM) research and consulting firm, defines PLM as "A strategic business approach that applies a consistent set of business solutions that support the collaborative creation, management, dissemination, and use of product definition information, supporting the extended enterprise (customers, design and supply partners, etc.), spanning from concept to end of life of a product or plant, [and] integrating people, processes, business systems, and information." Similarly, the PLM International Conference (PLM IC) [33], structured as a platform for international collaboration under the International Federation for Information Processing (IFIP), defines Product Lifecycle Management (PLM) as "an integrated business approach to the collaborative creation, management, and dissemination of engineering data throughout the extended enterprises that create, manufacture, and operate engineered products and systems."

There is consensus in the literature that PLM, as it is referred to by PLM IC [33], arose as a consequence of the introduction of computer aided design (CAD) [34], [35], [36], [37]. The data generated through the use of CAD systems for engineering product design drove the need for product data management (PDM), and the desire for improved inter-departmental data communication lead to the eventual inclusion of systems such as enterprise-resource planning (ERP), and material resource planning (MRP) software tools. Originally, none of these tools attempted to address the management requirements across the entire product life cycle, and were not PLM solutions as we know them today.

2.1 PLM and large-scale product development

Terzi & al. address a driving need for PLM as challenges in scalability [37]. The authors draw upon a "cobbler model" presented by Ameri and Dutta [38] to present the differences in small and large scale product development lifecycles. The cobbler, or shoe-maker, single-handedly executes every aspect of the shoe's product lifecycle, from tailored customer requirements, to fabrication, sales, and maintenance. In this model, a single person holds the requirements, data, information, and knowledge from start to finish of customized footwear product development, and manages all changes. Trade knowledge is communicated directly to an apprentice through training, preserving the product development processes through knowledge transfer. A problem arises, however, when the number of people involved in this process increases. The human brain does not come with an open-access function for others to read through its contents, and it does not function as a suitable primary information storage location when information must be shared regularly amongst many people. The cobbler model therefore illustrate a lack of linear scalability when the product development process becomes decentralized, which is further exacerbated by the level of complexity associated with the product development. PLM has been developing to meet the needs of international, quickly expanding and large-scale businesses, where small company processes no longer support the scale of product development.

The scalability issue was resolved historically through automation and the use of software tools, and PLM today has evolved to respond to the scaled nature of international businesses. The aircraft modification industry is much greater in scale, complexity, and safety criticality than the cobbler, and is adopting PLM strategies to manage aircraft product development programs. The complexity of the aerospace design and product development problem has lead the world's major OEMs to adopt product lifecycle management strategies in an attempt to meet the workflow, communication and data management needs of their large-scale decentralized product development business model.

2.2 PLM and communication

The cobbler model also provides a perspective on communication in the context of product development. The jargon, or lingo, associated with a discipline can be referred to as an ontology. Roy et al. [39] define ontology within the product development context as allowing "different stakeholders to have a shared conceptualisation of the product requirements in terms of mutually accepted and understood abstractions and associated language. The result is the consensual convergence in the vocabulary, definitions and attributes that describe the product requirements." Lee and Suh [40] discuss ontology with respect to knowledge management and interpret a definition of ontology from Heijst, Schreiber, and Wielinga [41]; "Ontologies describe the structure and vocabulary of the domain knowledge, and the domain knowledge refers to a collection of statements about the domain." Ontologies and associated challenges of communication are well understood by software developers, where multiple coding languages are often integrated to interface with one another [42] [43] [44] [45]. As the cobbler's work does not involve other disciplines, or having to interact with professionals having received different training, the cobbler does not have to navigate through ontologies other than his or her own. This, however, is not the case for the large-scale systems associated with the aerospace industry. Aerospace design and development projects involve multiple participants from many different disciplines and functional groups, often dispersed geographically at multiple locations. Communication between stakeholders is critical to success in this industry and it is important to maintain a common understanding of the vocabulary used to describe processes and procedures.

2.3 PLM and the aerospace product

Systems complexity

Hirschi and Frey [46] describe complexity within a parametrized design task as a function of variable coupling. The authors define a process as complex when an input variable can impact multiple output variables in multiple capacities, as opposed to a linear one-to-one input-output relationship between variables. The authors found that design solution of increasingly complex systems involved more iteration and more time than linear systems in experiments conducted with individual designers. Hobday [47] presents complexity within the context of product development as the creation and development of customized, high cost, and engineering-intensive complex products and systems (CoPS). The author argues that CoPS differ from other goods in several ways, including having a low-volume production and a stronger emphasis on "design, project management, systems engineering and systems integration" than their common goods counterparts. PLM has also been evolving to meet the managerial needs of complex processes for both large and small-scale businesses. Aerospace design and development is one such business and whether on a small or large scale, the aircraft design problem is one of world's most complex and multi-disciplinary tasks.

Safety Critical Systems

Safety-critical systems further increase complexity [48] and present challenges for process management. John Knight [7] defines safety-critical systems as "systems whose failure might endanger human life, lead to substantial economic loss, or cause extensive environmental damage." While safety in aerospace is regulated by the constraints of certification, the safety-critical systems increase process complexity in product development [49], furthering the need for product development management throughout the lifecycle. PLM is readily adopted by companies developing safety-critical systems as a tool to manage the resulting complex processes.

Product diversity

A variety of PLM solutions have been developed to serve a number of different types of products. Traditionally, a product is categorized as a physical entity, an intangible good (such as a software), a service [35] [50], or as being "engineered, discrete, and physical" [51]. These definitions are based on an imposed mutual exclusivity that does not reflect the multi-disciplinary nature of aircraft development. Defining an aircraft as a discrete engineered physical entity excludes the substantial avionics software integration within increasingly electric aircraft [52] [53], as well as the in-service support and continued airworthiness from the product development process [51, p. 9] [37]. Terzi et al. offer a more inclusive product classification, as "complex long-life manufacturing object (e.g. a car, a plane or a turbine), a complex short-life manufacturing object (e.g. a PC, a CD player or a camera), a pharmaceutical specialty (e.g. a vaccine or an antibiotic, a building (a house or a flat), a fashion garment, etc." [37].

The large-scale, decentralized, complex, safety-critical, and diverse product definition of the aerospace design problem has lead the world's major OEMs to adopt product lifecycle management strategies in an attempt to meet the workflow communication needs of the product development business model.

2.4 PLM methodologies

Terzi & al. [37] developed a generic model of the product lifecycle today, and their model is shown in Figure 4. The authors present the highest level of product lifecycle phases as containing a first phase, Beginning of Life (BOL), a middle phase, Middle of Life (MOL), and a final phase, End of Life (EOL). Lower level phases describe more levels of detail, such as Design and Manufacturing phases in BOL, Distribution, Use and Support in MOL, and Retirement for EOL. The product development lifecycle, at its most detailed phase description, starts at Requirements Analysis and ends with Dismissal.

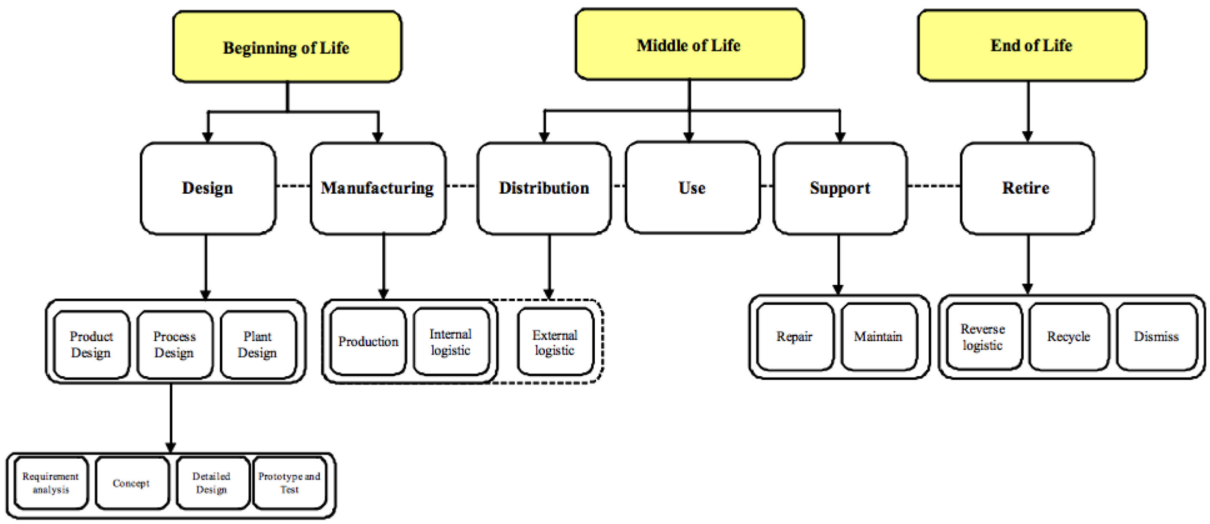

Figure 4: Terzi et al. adapted product lifecycle phases [37]

The PLM product has transitioned from its origins as a CAD data management tool to a software solution for the management of product lifecycle development processes. Hewett [54] explains the need for multiple management solutions across the product lifecycle: "While the PLM functional footprint is improving, it is still fairly common to need two to three different vendor solutions to effectively address the company's needs, especially if those needs span the entire product development life cycle. As a result, the PLM solution is typically a complex collection of tools, originally developed separately and then loosely connected – sometimes by a vendor as a tool suite, but more often by the PLM implementation team." The software itself, supporting hardware, customized back-end software integration to integrate with company-specific software, amount of training required for company-wide implementation (including time for the cultural shift incurred when adopting major new process), and upgrade requirements can add significant costs for businesses adopting a PLM software solution [54]. In this thesis, PLM is discussed in the context of a methodology, and not a software tool.

Although some PLM methodologies claim to represent the entire product lifecycle, several authors suggest that PLM methodologies can be categorized by lifecycle phase or by functional interaction with the product [37] [55]. PLM methodologies are presented in two broad categories in this thesis: PLM methodologies, and PLM certification guidelines. These categories are distinct from one another, as while PLM certification guidelines support aircraft certification required by law, the PLM methodologies presented in this thesis do not include any mention of certification.

Three PLM methodologies and two PLM aircraft certification guidelines typically responding to the needs of one functional group are summarized in Table 3, and are described briefly in the rest of this chapter. Each methodology is structured around a fixed set of pillars, principles, phases, or techniques. These signature pillars are often used as identifiable hallmarks of the methodology and are the basis of the brand. Each methodology employs a unique approach, uses a different ontology, and is designed to meet the needs of a specific functional group within the product development lifecycle. A summary of the vocabulary used to describe the phases of product development for each of the PLM approaches is presented in Table 4. The selected PLM methodologies and certification guidelines are introduced in this chapter to reflect the results presented in Section 4.1.

Table 3: Functional Group and corresponding PLM methodology

PLM Category	Functional Group	PLM Method used
PLM Methodology	Project Management Function	PMBoK®
PLM Methodology	Engineering Design	Configuration Management
PLM Methodology	Production Function	Lean
PLM Certification Guideline	Aircraft Certification Function	CAR 521
PLM Certification Guideline	Engineering Function	ARP4754 A

Table 4: PLM Methodology phase summary

PMBoK®	Configuration Management	Lean	CAR 521	ARP4754A
Initiate	Configuration Management Planning and Management	Identify Value	Pre-application Phase	Aircraft Requirements Identification
Plan	Configuration Identification	Map the Value Stream	Phase 1: Application and Establishing Certification Basis	System Requirements Identification
Execute	Configuration Change Management	Create the Flow	Phase 2: Establishing Means of Compliance and Transport Canada Civil Aviation Level of Involvement	Item Requirements Identification
Monitor	Configuration Status Accounting	Establish Pull	Phase 3: Demonstrate and Record Compliance	Item Design
Close	Configuration Verification and Audit	Seek Perfection	Phase 4: Approval of A Change to the Type Design	Item Verification
			Phase 5: Post-certification Activities	System Verification
				Aircraft Verification

2.4.1 PMBoK® for Project Management

The Project Management Institute (PMI®) [56], founded in 1969, is an American-based not-for-profit organization that aims to "advance careers, improve organizational success and further mature the profession of project management through globally recognized standards, certifications, resources, tools, academic research, publications, professional development courses and networking opportunities." PMI® offers 8 certification programs including Project Management Professional (PMP®). The certification exam preparation guide, Project Management Body of Knowledge (PMBOK®) [57], provides the following language to describe the 10 project management knowledge areas: Project Integration, Scope, Time, Cost, Quality, Human Resources, Communications, Risk, Procurement, and Stakeholder Management [58].

2.4.2 Configuration Management for Engineering Design

Configuration Management (CM) is defined by the SAE International Standard EIA-649-B as a "process for establishing and maintaining consistency of a product's performance, functional and physical attributes with its requirements, design and operational information." [59]. This method is supported by the Institute for Configuration Management, CMII, established in 1988 [60] [61]. The CMII states that "configuration information serves as the basis for all product lifecycle phases" [60], and their mission statement is to "help clients plan and achieve their transformation strategy, improve their core business operating model, embrace the digital wave, maximize efficiency, and implement sustainable growth initiatives." [62].

2.4.3 Lean for Production

The main objective of Lean Manufacturing, or Lean Thinking, is to "maximize customer value while minimizing waste. Simply, lean means creating more value for customers with fewer resources", and is accomplished through process flow optimization [63]. Lean attributes its roots to Henry Ford's assembly line and Kiichiro Toyoda's process flow in the early and mid-20th century [64]. Its international popularization was catalyzed by James P. Womack, Daniel T. Jones, and Daniel Roos in "The Machine That Changed the World" in 1990, and has since permeated far beyond the manufacturing sector [65] [66]. Lean, structured on a motto of "people, process and purpose", adopted and created several techniques that have become synonymous with the brand such as just-in-time (JIT) manufacturing, Kanban, and Kaizan [63].

2.4.4 CAR521 for Aircraft Certification

Civil aviation authorities have adopted the concept of product lifecycle and incorporated it in their recommendations for managing certification requirements. Transport Canada Civil Aviation

(TCCA) Canadian Certification Regulations (CARs) regulate aircraft design safety, and AC521-004 [11] is an Advisory Circular regarding Changes to the Type Design of an Aeronautical Product.

2.4.5 ARP4754A for Aircraft Certification

In the United States, the FAA has funded the development of certification practices through SAE International. The Aerospace Recommended Practice ARP4754A: Guidelines for Development of Civil Aircraft and Systems [67] is an SAE International standard developed to support the certification safety process throughout aircraft design and modification. Their process diagram has a similar V-shape and design level breakdown to that used by Systems Engineering, but uses aircraft safety-specific language, as shown in Figure 5.

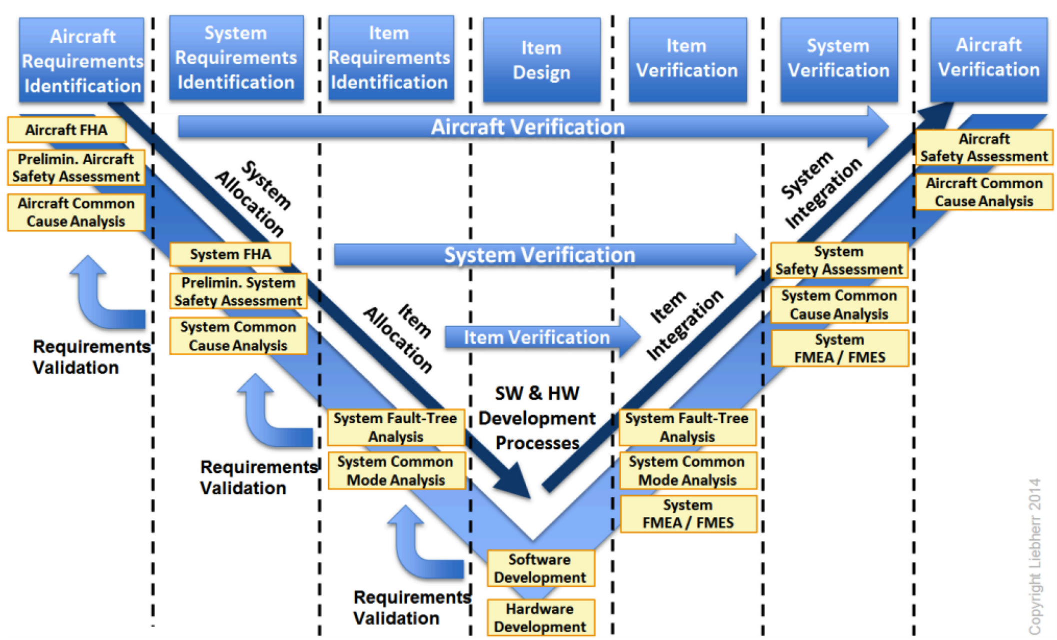

Figure 5: Adaptation of ARP4745A V-Diagram by Taibi et al. [68]

2.5 PLM conflicts across functional groups

PLM methodologies offer a variety of approaches for improving efficiencies across the product lifecycle. The methodologies often reflect the needs of a specific functional group, and add value to process efficiencies in the product lifecycle for the respective discipline. Rachuri et al. state that "PLM is akin to supporting a composition of information exchanges across time, space and multiple disciplines." [43]. A product during its development will be interpreted differently depending on how a functional group interacts with the product. Krishnan and Ulrich present this notion of perspective within product development [55]. While the Marketing function may view a product as "a bundle of attributes", the Engineering function may view the product as "a complex assembly of interacting components." This difference in perspective is reflected by the PLM methodologies, which strive to meet the process and communication needs within a specific company function or department.

Dave Nave [69] summarizes the issue of conflicting PLM solutions: "Within the American business community a multitude of process improvement champions are vying for leadership attention. Each champion advocates the adoption of his or her improvement methodology in your organization. Almost all plead that if you adopt their specific tools or follow a specific way of thinking, all your business problems will be solved." In the aerospace industry, and in particular the small-to-medium enterprise (SME) sector, there are a number of variables that need to be considered before adopting a PLM solution [70] [71] [72]. The assessment of company policies and procedures, the motivation for adopting PLM solutions, the choice of PLM strategy, and the metrics selected for measuring the success of implementation through return-on-investment (ROI) are only some of the elements requiring a thorough analysis. The ROI of a PLM software solution implementation, while important for SMEs with lower financial resource margins, is a difficult figure to estimate before implementation, and even more difficult to calculate explicitly post-implementation [73] [74].

The research project that is the subject of this thesis uses a process mapping approach to examine the current state processes of a typical aircraft modification SME. Existing processes are mapped and identified with respect to their inputs and outputs, sub-processes, procedures, practices, documentary artefacts and related PLM methodologies. Areas for opportunity related to process improvements, such as gaps and duplicated procedures and artefacts, are identified and analyzed for improvement recommendations.

Chapter 3: Research Methodology

Product life cycle processes in the aircraft modification industry must be able to support the development of complex and safety-critical systems. The research approach for the thesis described here uses a process-mapping technique to provide a visual representation of a complex and inter-related flow of work and information. Process maps of the company's current-state product lifecycle were developed using data collected through interviews with company personnel and from internal documents outlining company processes and procedures. Maps were constructed at three levels, or tiers; each representative of a different group of stakeholders and level of detail. This section presents the process mapping technique as adapted and applied for the purposes of the current study.

The process mapping methodology was selected as the research method approach to address the research question within the aircraft modification case study. The approach was selected because of its usefulness in understanding current-state aircraft modification processes, while providing an easily accessible and understandable visual representation of the process across functional groups within the company. The reasoning for adopting the process mapping approach is discussed in Section 3.1. Section 3.2 describes the specific mapping strategies and levels of detail adopted from the literature and adapted to the needs of the current research. Data collection methodologies are outlined in Section 3.3.

3.1 Background and motivation

3.1.1 Emergence of Process Mapping

Rummler and Brache [75] identify the area of process as being the greatest opportunity for improvement within an organization, and Hammer [76] explains the importance of process understanding for strategic selection of processes to be automated. Process mapping tools are used to reveal process-related inefficiencies, and can also identify those most likely to benefit from automation or digitalization. Mapping techniques, implementation methods, and benefits are well documented [77] [78] [79] [80] [81] [82] [83] [84].

3.1.2 Motivation

Process improvement

Sharp and McDermott [83] explain how mapping can help in the assessment and improvement of business-related processes. Their mapping technique, illustrated in Figure 6, is first used to understand the current-state processes and then to assess areas most suitable for process improvement as part of the development and implementation of an ideal future-state system. In this case study, process mapping is used to provide an assessment of the current state processes, and the findings of this process mapping assessment are presented as recommendations for process improvement to move toward ideal-state processes.

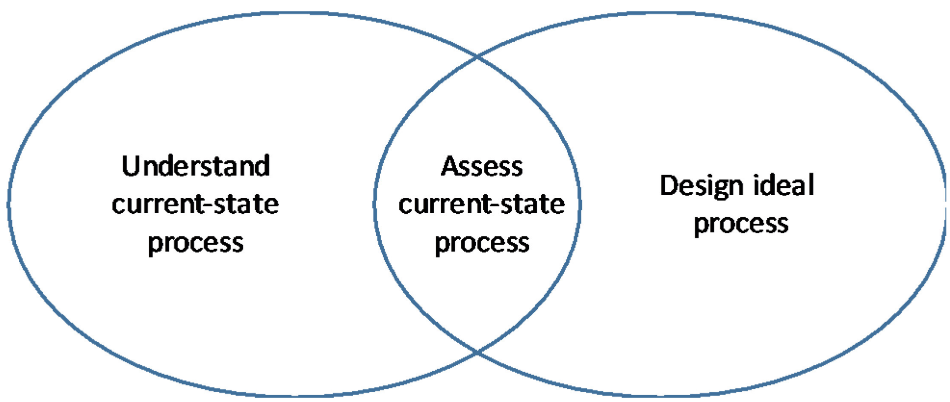

Figure 6: Assessment as a product of process improvement, adapted from Sharp and McDermott [83, p. 221]

Knowledge management

One of the distinguishing features of "flow" in knowledge work is that the knowledge is not always apparent or visible [85]. Particularly in aerospace-related product development, much of the work takes place as a combination of worker's knowledge, discussion and data-intensive computerized modeling activity. "Knowledge workers frequently don't know what occurs before, or after their "part" of each workflow, or what activities the computer is actually performing" [85, p. 124]. In this case study, mapping techniques are used to visually identify knowledge contributions and how they fit into overall product development processes.

Overcoming organizational silos

Process maps can be used as a tool for overcoming barriers to understanding process [75]. The "Silo Phenomenon" from [75] is shown in Figure 7, and demonstrates how departments or functional groups can work in a hierarchal structure with limited inter-departmental visibility of process flow.

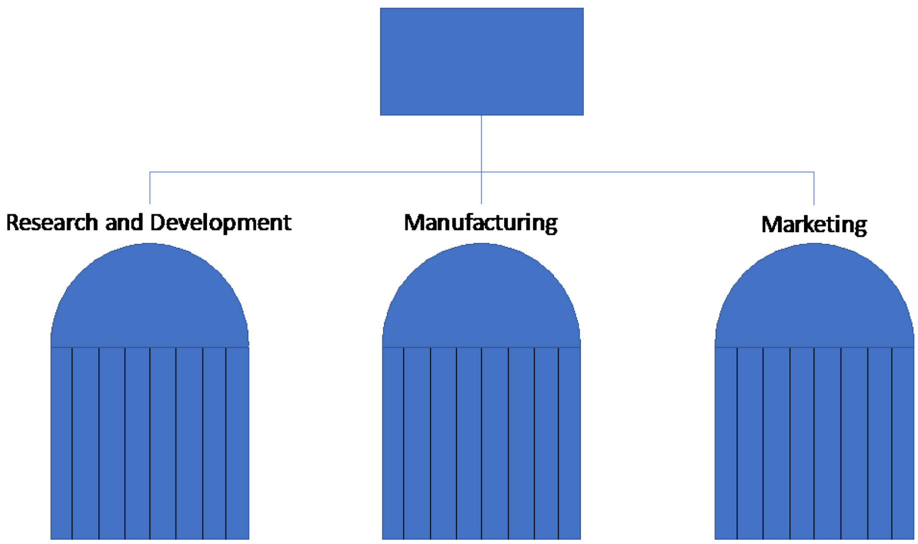

Figure 7: Silo Phenomenon, image adapted from Rummler and Brache [75, p. 6]

A silo structure is created when information can only be transferred up and down the organizational hierarchy, and lower-level employees are discouraged from exchanging information directly with other functional groups. This "windowless" structure creates an isolated, function-specific view of company processes for employees, and a barrier to communication between sub-managerial groups. Process mapping can be used to create windows whereby a visual map of the processes is used to communicate current-state process understanding to employees at all levels.

The complex, inter-dependent, and safety-critical systems that are the product of the aircraft modification process require a work flow characterized by transparency and clear communication, and the silo phenomenon can pose a potentially significant barrier to process understanding and process efficiency. The method of process mapping was selected as a means to both identify areas of opportunity within the context of the silo phenomenon, and as a method for overcoming this barrier. Process mapping was used to identify instances of the Silo Phenomenon within the company, and to reveal process gaps and communication barriers both within and across the silos.

3.1.3 Level of Detail for Effective Process Mapping

Effective process mapping is bound by cost, and there is a trade-off between the cost of detail and the benefits of process mapping. A high-level overview process map costs the least to generate but is the most expensive level at which to execute change, whereas a detailed-level map costs the most to generate but the least to execute changes [80]. Too much detail can also be detrimental [83] with the risk of "paralysis by analysis" when getting stuck in the details, and it is necessary to critically assess the value added per level of detail. Rummler and Brache [75] identify the importance of structuring process maps in direct relation to the needs of primary end-users, where each category of end-user requires a different level of detail for the map to be useful. A well-structured process map should allow the user to choose the level of detail needed when assessing a specific process, and provide sufficient detail for process improvement within appropriate mapping cost boundaries.

The process maps in this study were structured at a level of detail aimed at creating a platform for multi-stakeholder involvement in assessing current-state processes at the Analyst, Manager, and Executive levels. The intent was to provide well-understood current-state process maps for company personnel at all levels to be able to identify process gaps and inefficiencies, and work collectively to create ideal-state processes aimed at strengthening company-wide workflow efficiency. In addition, the process level of detail was designed to support product traceability, a critical component for aircraft certification and continued airworthiness.

3.2 Stakeholder analysis and mapping strategy

3.2.1 Mapping structure by level of detail and stakeholder category

Process maps were structured at three levels of detail, with each level defined specifically to be useful to an identified group of stakeholders within the company. Stakeholder categories of "Executive", "Manager" and "Analyst" from [75, pp. 28, 63] were modified to more accurately reflect the aircraft modification business sector. Typical company roles from the aerospace design and development business sector corresponding to the stakeholder categories from [75] are presented in Table 5.

Table 5: Typical company roles corresponding to Executive, Manager and Analyst stakeholder categories

Stakeholder Category	Corresponding company role
Executive	Chief Operating Officer (COO)
	Vice President Engineering
	Vice President Production
	Vice President Projects
Manager	Airworthiness Manager
	Business Development Manager
	Planning Manager
	Senior Projects Manager
	Senior Quality Manager
	Supply Chain Manager
Analyst	Airworthiness Analyst
	Configuration Management Analyst
	Document Management Analyst
	Materials Analyst
	Planning Analyst
	Project Engineering Analyst
	Quality Assurance Analyst
	Supply Chain Analyst

At the top of the corporate structure, the Executives include the Chief Operating Officer and the Vice Presidents of Engineering, Production, and Projects. They have a requirement to be informed of company-wide processes at the highest level in order to develop organizational goals, establish and maintain competitive advantage, and configure the organizational structure to best suit company needs. The Airworthiness Manager and the Senior Quality Manager are Manager-level stakeholders and use process maps as “perspective and tools to identify and close quality, cost, and cycle time gaps; manage the interfaces with other departments and the interfaces within their own departments; implement change, and effectively allocate resources" [75]. At the third level are the Analysts, who "design the systems and procedures that enable managers to implement change" [75]. In the current study, the Analysts category corresponds to company personnel working for the Managers and includes the Project Engineering Analyst and Supply Chain Analyst. Individuals in these company functional roles should be able to use process maps to understand how daily activities flow within the bigger organizational picture, and to critically assess and "recommend improvements that will have a significant impact on organizational performance" [75].

3.2.2 Tier 1 Phase Map

The Tier 1 Phase map is the highest-level map, and provides a high-level overview of the product lifecycle, broken down into phases. An example of a Tier 1 Phase Map is shown in Figure 8. The Phase map corresponds to the needs of Executives, and provides a useful summary of the major stages and milestones of the product lifecycle. Phase titles, definitions and start-finish boundaries vary significantly according to the product lifecycle methodologies employed, but, in general, this is the broadest categorization of product lifecycle activity.

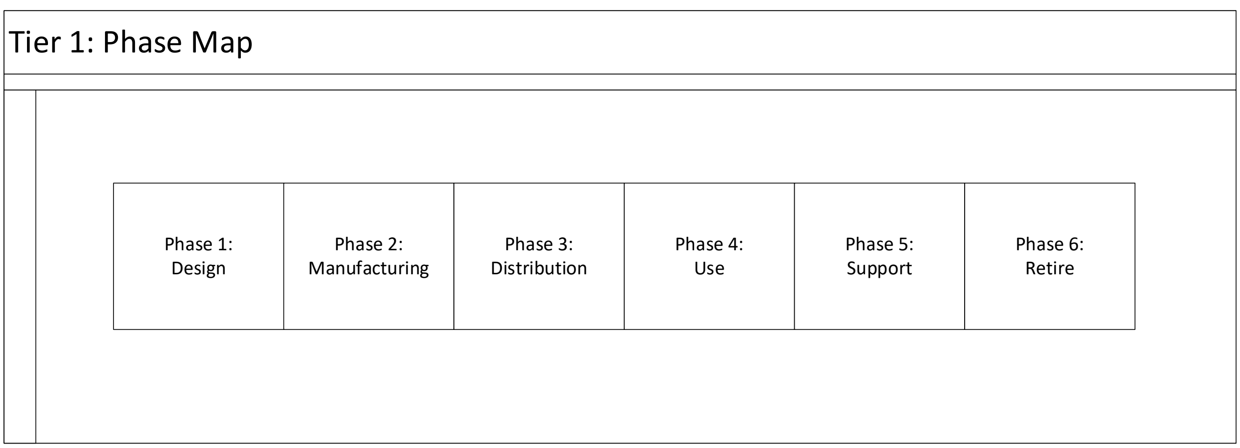

Figure 8: Example of a Tier 1 Phase Map, adapted from the Terzi et al. generic product lifecycle phases [37]

3.2.3 Tier 2 Milestone Map

The Tier 2 Milestone maps are the second level of product lifecycle detail, and correspond to the needs of the Managers. Milestone maps display the major deliverables, milestones and decision gates grouped under each Tier 1 Phase. This second level of detail of the product lifecycle map is practical for managing project cost and scheduling and identifying the milestone workflow and critical paths, and it presents a first opportunity to examine workflow efficiency. The example shown in Figure 9 extracts some typical major deliverables from the Tier 1 Phase map of Figure 8. The Tier 1 phase is identified at the top left-hand corner, and the Tier 2 Deliverable Map denotes the level of detail of the process that is represented in the map.

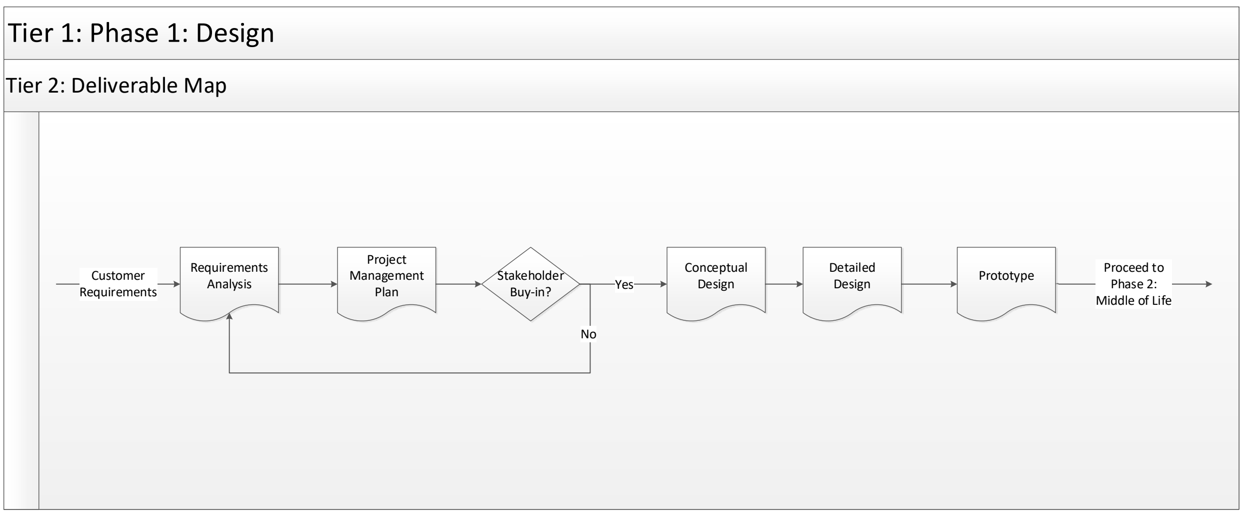

Figure 9: Example of a Tier 2: Deliverable map, adapted from the Terzi et al. generic product lifecycle [37]

3.2.4 Tier 3 Activity Map

The Tier 3 Activity map is the most labour-intensive mapping level. It is intended to map out the details of activities associated with processes from a Tier 2 Milestone map, which are in turn associated with one or more product lifecycle phases identified as part of the Tier 1 Phase map. This level of detail responds to the needs of the Analysts performing daily activities, who should be able to use the map to understand activity workflow both across functions or departments, and within the bigger company-wide process context. The method used in this research for the Tier 3 Activity level of detail is adapted from the techniques presented by Robert Damelio in his book, *The Basics of Process Mapping* [85]. Workflow of complex product development involves activities across company functions which can be particularly difficult to visualise. The question of "who does what, and when" is difficult to capture in process documentation, but is necessary for process understanding. It is therefore important to incorporate a visual workflow representation with the functions responsible for the activities in that workflow in a single map.

Two process mapping techniques introduced by Damelio were selected and adapted for this research project: a swimlane-based Cross-Functional process map, and a Flow Chart map. These techniques were selected for the Tier 3 Activity map level because they are relatively easy to follow, implement, and present, and lend themselves well to the mapping of complex processes at the activity level of detail.

3.2.4.1 Cross-Functional Process Maps and Flow Charts

An example of a Cross-Functional map is shown in Figure 10, where the project phase is identified at the top of the map. The Cross-Functional process map provides a "swimlane" or horizontal space for each of the functional groups or departments involved in the project phase. Activities are mapped out from left to right, and placed in the swimlane of the functional group responsible for the activity, with arrows connecting activities to represent workflow.

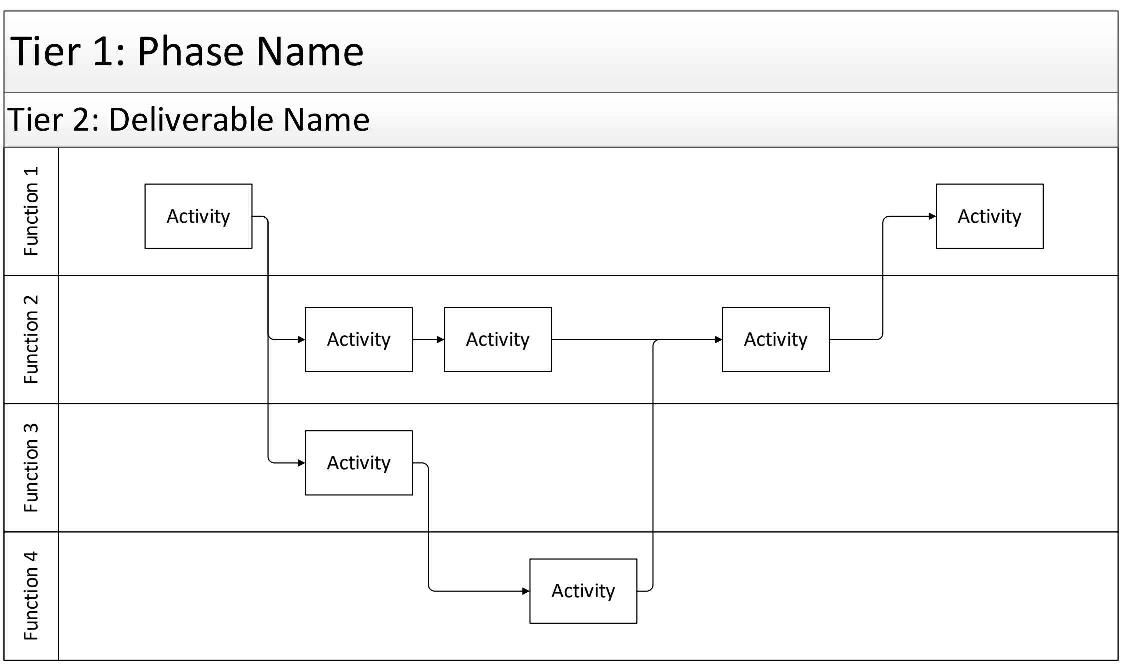

Figure 10: Building blocks of Cross-Functional process map, adapted from Damelio [85, p. 74]

An example of the Flow Chart approach to work representation is shown in Figure 11. The Flow Chart is an appealing workflow visualisation tool because it uses a number of unique symbols to denote the varied nature of activities in the workflow. The Flow Chart in Figure 11 shows work in the form of an Activity depicted as a square in the chart, whereas work comprising of a Decision is depicted as a rhombus.

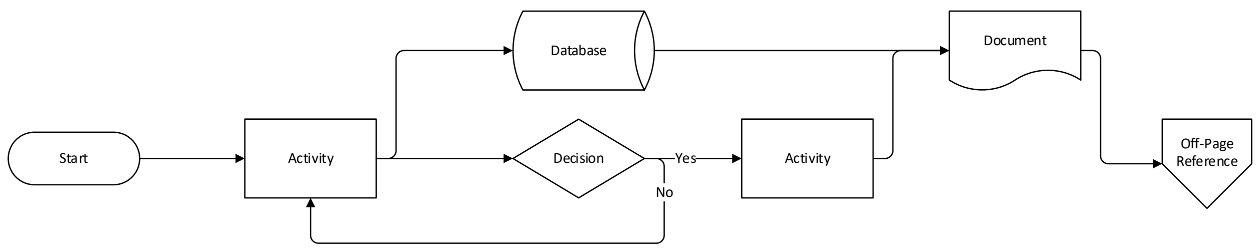

Figure 11: Flow Chart Map, adapted from Damelio, using a series of symbols to denote the varied nature of work [85, p. 94]

The cross-functional mapping and flow chart techniques can be merged and used together in the same diagram. A combination of the two approaches has been used in the context of aerospace best practice development by Doumit, Huet and Fortin [86] as shown in Figure 12. Although their work was limited to the development of engineering work packages for the engineering design phase rather across the product development lifecycle, a similar approach was adopted to represent the aircraft modification workflow that is the subject of this case study. Workflow charts from the current study will be presented and discussed in Chapter 4.

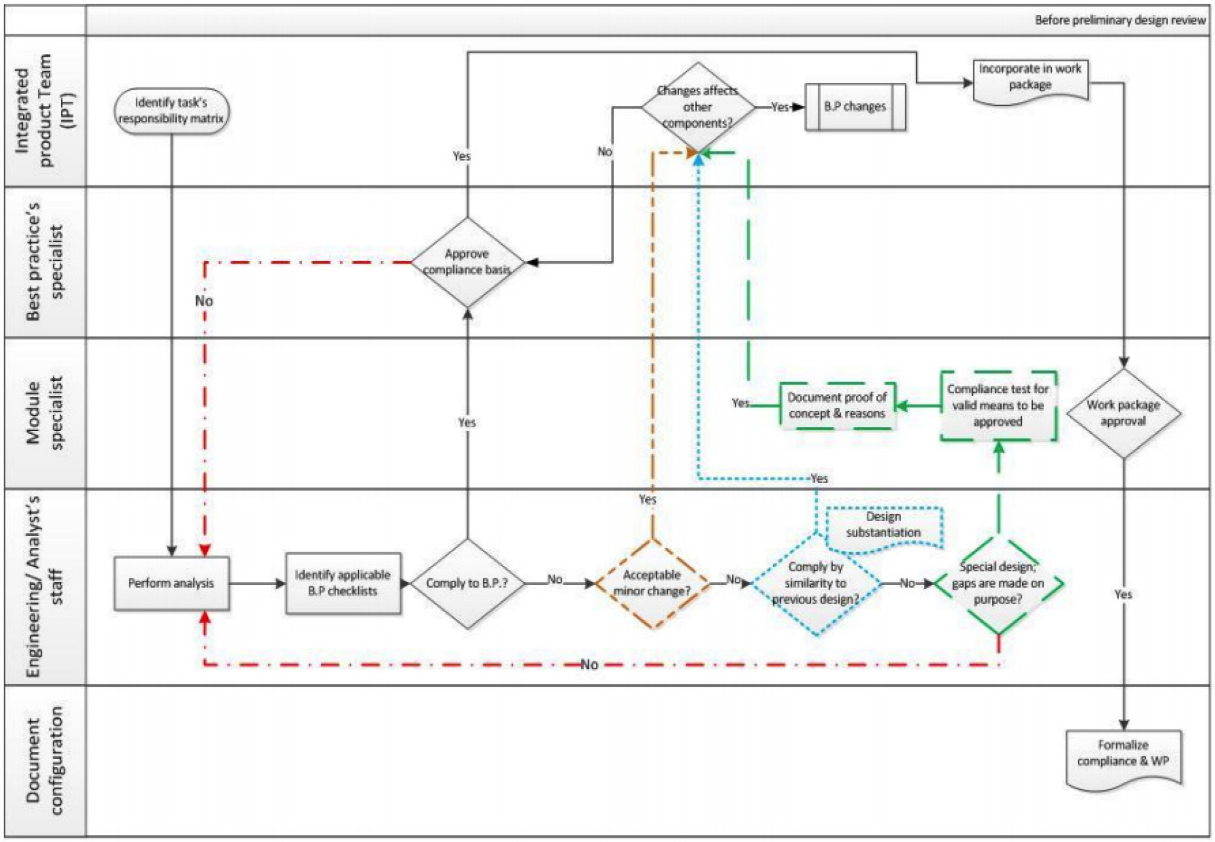

Figure 12: Doumit, Huet, and Fortin illustrate a Cross-Functional map and Flow Chart combination in an aerospace design application [86]

3.3 Process mapping procedure

This section presents the research procedures involved in collecting the data that was used to construct the process maps.

3.3.1 Product lifecycle familiarization

Before beginning the process mapping activity, it was necessary for the researcher to become as familiar as possible with the corporate culture, business model, product diversity, product lifecycle development scope, organizational structure, and functional group structure of the industrial partner where the case study was to be conducted. The complex nature of the industry required significant time invested toward gaining a sufficient grasp of the many associated variables. This familiarization process was accomplished through an industrial internship where the researcher worked for four months, immersed in the engineering department, focusing on project management, design engineering, configuration management, certification, manufacturing planning, and supply chain traceability. Once a general understanding of the business was obtained, the process mapping method was implemented.

3.3.2 Data collection

The primary source of process data for map generation was company personnel, and the data was obtained through interviews. Three techniques for obtaining process map data were selected and adapted for this research: one-on-one interviews, content (document) review, and group facilitation [85].

One-on-one and small group interviews

One-on-one and small group interviews were conducted with company personnel at all organizational levels and functional groups. The purpose was to capture the current-state flow of information as perceived by individuals from each functional group; to identify communication systems and perceived barriers and process inefficiencies between functional groups; and to identify formal and informal methodologies employed in the interest of "getting things done". Interviews were conducted with Analysts, Managers, and Executives, one-on-one and in small groups typically made up of a Manager and one or two Analysts. A total of 82 interviews were conducted, and Table 6 summarizes the interview formats and associated stakeholders.

Table 6: Interview summary for process map data collection

Interview Type	Number of Interviews
Interviews with Analysts	30
Interviews with Managers	27
Interviews with Executives	4
Small group interviews (Manager and Analyst)	13
Large group facilitation	1
Meetings with external parties	7
Total number of interviews conducted	82

Interview questions and discussion fell into two broad categories based on the role of the company personnel. Discussions with Executives and Managers centered around current-state company-wide process challenges such as managing resources and workflow across company functions, and as well as from external factors such as aircraft regulatory bodies and shifts in technology. Analysts, or employee-level interviews focused on questions such as “What do you do and how do you do it?”, “Who are your inputs and outputs?”, and “How do you manage change?”

Interview structure

In the initial stages of data collection, interviews were structured informally to collect the stakeholder’s perception of the case study’s current state processes, including perceived roadblocks and day-to-day frustrations experienced within the context of workflow. After having acquired sufficient background knowledge to start process mapping, interview questions and discussion were structured around the three stakeholder categories.

Executives

Interviews with Executives focused on big-picture, company-wide current-state processes and challenges. Executives were also more familiar with the role of the researchers within the partnership and required less prompting to convey information. Questions asked during a one-on-one Executive interview are as follows:

1. What are the primary roles of the company?
2. What are the major process challenges for the company as a whole?
    a. Internal company-wide process challenges?
    b. Challenges with external interfaces?
3. What are the major challenges of workflow between functional groups?
4. What process areas have the most opportunity for improvement?

Managers

Interviews with Managers focused on workflow and workflow interfaces at the functional group level. Topics included product diversity, scope of work, and current-state process challenges such as managing resources and workflow. Questions were structured to solicit information for the purpose of understanding current-state processes, to discover relevant documentation and to identify relevant stakeholders for consultation at the Analyst level. Questions asked during Manager interviews are as follows:

1. What is your position in the company?
2. What is the role of the functional group that you manage?
    a. What types of projects do you work on?
    b. What are some of the deliverables your group is responsible for?
    c. Do the types of deliverables change with respect to different projects?
    d. How does workflow occur across your group?
    e. How are resources managed in your functional group?
3. What functional groups do you interface with?
4. What are the major process challenges faced by your functional group?
5. What work has already been done on process improvement?

Analysts

The first group of Analysts to be interviewed were chosen based on Manager recommendations. As the process maps were developed, additional Analysts were consulted in order to fill gaps in the maps. The Analysts interviews focused on workflow at the activity level, with questions centered around "What do you do and how do you do it?", "Who are your inputs and outputs?", and "How do you manage change?" Questions for an Analyst interviews are listed below.

1. What is your position in the company?
2. What does your functional group do?
    a. What is the general process?
    b. What documents is the department responsible for?
    c. What software is used, and what is it used for?
    d. What are some of the challenges faced by your department?
3. What are the inputs and outputs to your department?
    a. Input: you are assigned a task. What happens next?
4. What do your daily tasks look like?

a. Who gives you work?
b. Who do you give your work to?
c. Who do you report to?
d. How do you communicate within your department?
e. If you communicate with people outside your department, how do you communicate, and are the results of that communication recorded? If so, where?
f. How do you track or report your work?
g. What are some of the challenges or frustrations you face in your daily work?

5. What happens when there is a change?
    a. How do you get notified of changes?
    b. What people or departments do you receive changes from?
    c. Who do you have to notify of changes?
    d. If multiple people need to be involved in a change process, how do you know who to involve, and where is the communication recorded?
6. How do you perceive work is done in interfacing departments?

3.3.3 Process map development

The information gathered was captured by the researcher with written notes, and transformed into a generic Tier 1 Phase map and several first iterations of process maps at the Tier 2 Milestone and Tier 3 Activity levels of detail. When necessary, second and third interviews were conducted with the same individuals to obtain iterative feedback and ensure the maps accurately reflected the stakeholders' perceptions and comments. Also recorded were the employees' perceived areas of inefficiency or frustration with day to day work. Suggestions for activity-level process improvement were recorded for later analysis.

Document review

The interview process revealed a loosely linked structure of internal and external documents supporting the reported daily activities. Internal documentation included policies, process procedures and work instructions used for day-to-day operations. External documentation included international standards such as the ISO quality standards AS9100 and AS9110, and certification regulations from both Transport Canada on (TC) and the United States Federal Aviation

Administration (FAA). These agencies were found to heavily influence internal documentation, and required both a thorough review and that they be incorporated into process maps. Incorporating documentary artefacts into the process map required an iterative process where the researcher would compile sources into a proposed map, then consult in additional interviews with subject matter experts, knowledge owners, and stakeholders involved in the processes as to how the map reflected current-state.

Group facilitation

Group facilitation was implemented for the purpose of multi-stakeholder map buy-in. Cross-functional proof-of-concept meetings were held with departmental representatives, managers, and other stakeholders likely to use the process map being developed. These meetings helped to correct details in the maps themselves and, more importantly, to obtain stakeholder buy-in for the process mapping technique.

3.3.4 Process Map of research methodology

The adapted process mapping method used for the current study was iterative and is illustrated in Figure 13. Following the identification of the company organizational structure, functional groups and stakeholders, the procedure of generating processes maps included data gathering, map development, multi-departmental review and commentary and map modification. Group buy-in was a continuous process performed throughout the current-state, assessment, and ideal-state process map generation. Communication and seeking input from company personnel were found to be critical to success and resulted in frequent consultation and map updates.

The process mapping research was performed using Microsoft Visio Process Modelling tool. Visio has hyperlinking functions that can be exported to a PDF format. The hyperlinks act as “buttons” that allow the user to jump from one map Tier to another in a visual and logical interface, and maintaining these hyperlinks in a PDF format allows the files to be opened and viewed interactively on any device.

The techniques described in this chapter were used to generate process maps at the Tier 1, Tier 2 and Tier 3 levels. Throughout the map generation, processes were continuously assessed for underlying causes of process inefficiency and areas of process improvement. The results of the process mapping research and identified major areas for process improvement are presented in Chapter 4.

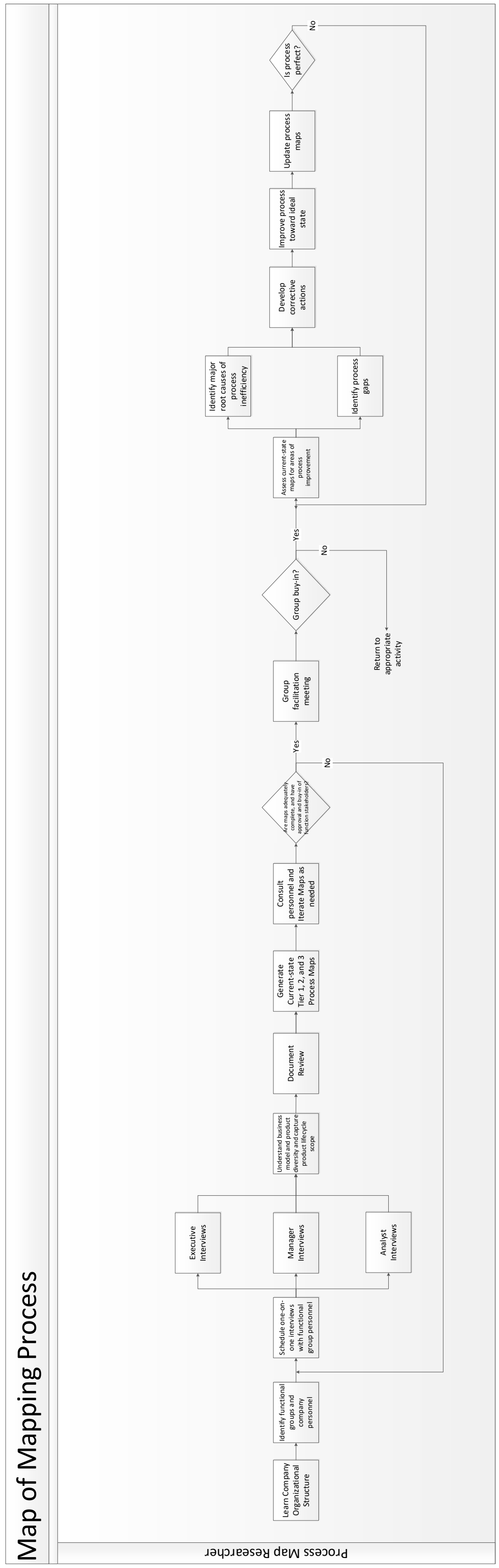

Figure 13: Illustrative figure of process Map of Activities involved in mapping the company processes has been blurred to protect confidential information

Chapter 4: Case Study Results and Discussion

The results of the process mapping research are presented in this section, illustrating the current-state processes of the aircraft modification case study and identifying areas for process improvement. Section 4.1 presents the Tier 1 Phase Map and includes a discussion of the process-related improvement opportunities identified as a result of the mapping process. Section 4.2 presents the Tier 2 Milestone Map and outlines some of the risks and opportunities associated with using this level of detail to map the complex processes associated with the aircraft modification business model. Tier 3 Activity Level mapping results are presented in Section 4.3 and includes a discussion of the usefulness of Tier 3 maps for identifying gaps in process artifact development and traceability. The Chapter concludes with Section 4.4, where more general results are presented, some advantages and disadvantages of the process mapping approach are discussed and recommendations are made.

4.1 Tier 1 Phase Map

Tier 1 Phase Map – first iteration

The scope of the case study encompassed product development lifecycle stages including contract acquisition, project planning, design engineering, implementation, testing, certification, and product delivery. Information obtained through interviews at Executive, Manager and Analyst levels, as described in Chapter 3.2, was combined with data from internal documents and used to build a Tier 1 Phase map. During the interviews it was found that each functional group described the phases of the product development process using a different terminology and, as a result, the Tier 1 Phase Map was developed to accommodate the terminology used by each functional group. The Project Management Body of Knowledge (PMBoK®), Configuration Management defined by the Military Handbook 61A, and the Canadian Aviation Regulations CAR 521 phases were identified as being used concurrently by different functions. The first iteration of the Tier 1 Phase Map is presented in Figure 14 and the functional groups providing data for the map are listed in Table 7 with the corresponding source of the terminology used in the map.

Table 7: PLM Methods used by different company functional groups in the first iteration of the Tier 1 Phase Map

Functional Group	**Sub-Function**	**PLM Method Used**
Project Management Function		PMBoK®
Engineering Function	Engineering Design	Configuration Management
Engineering Function	Airworthiness	CAR 521

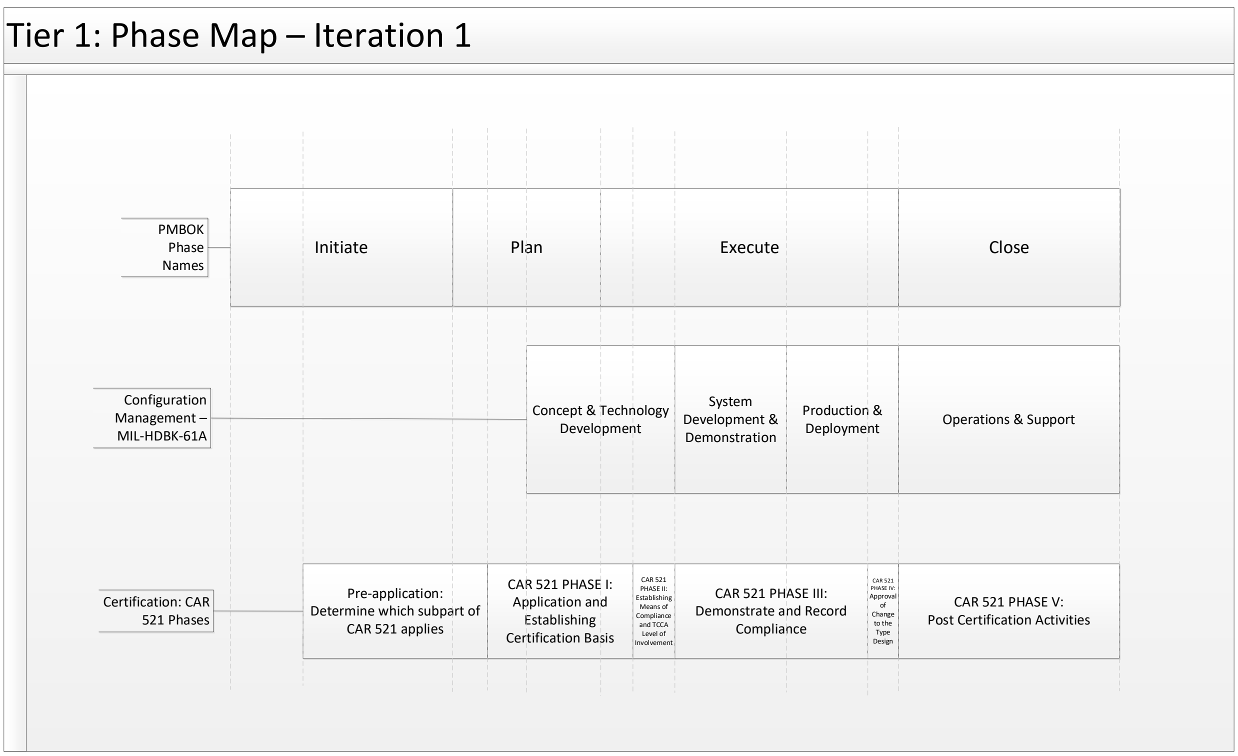

Figure 14: Tier 1 Process Map - Phase Equivalencies

The Tier 1 Phase Map reveals a potential barrier to communication between functional groups as a result of competing PLM methodologies and their associated terminologies. The vertical dashed lines in Figure 14 identify the phase definitions and a suggested alignment with respect to one another across the product lifecycle. For example, the PMBoK®, used by project management, identified the first two phases of a program with the terminology "*Initiate*" and "*Plan*"; while

CAR521, used by airworthiness, uses the terminology "*Pre-application*" and "*Phase 1: Application and Establishing Certification Basis*" to describe the two first phases.

In addition to the use of parallel terminologies, the Tier 1 Phase Map illustrates the gaps and overlaps associated with each functional group's product lifecycle phase definitions. For example, the first PMBoK® phase begins before the first CAR521 phase, and the Configuration Management, used by design engineers, started its first phase of "*Concept and Technology Development*" well into the second phases of both PMBoK® and CAR521.

Tier 1 Phase Map – second iteration

Iterative feedback was obtained during second and third interviews as described in Section 3.3.3. The second iteration of the Tier 1 Phase map shown in Figure 15 includes terminology from other PLM methods discussed during these validation interviews. The second iteration includes the ARP4745A, used by the engineering and airworthiness functional groups to assess safety-critical systems, and also the Lean methodologies used by Production functional groups in the aerospace sector. The functional groups and corresponding PLM methodologies displayed in the second iteration Tier 1 Phase map are listed in Table 8.

Table 8: PLM Methods identified by company functional groups in the second iteration of the Tier 1 Phase Map

Functional Group	**Sub-Function**	**PLM Method used**
Project Management Function		PMBoK®
Engineering Function		ARP4754 A
Engineering Function	Engineering Design	Configuration Management
Engineering Function	Airworthiness	CAR 521
Production Function		Lean

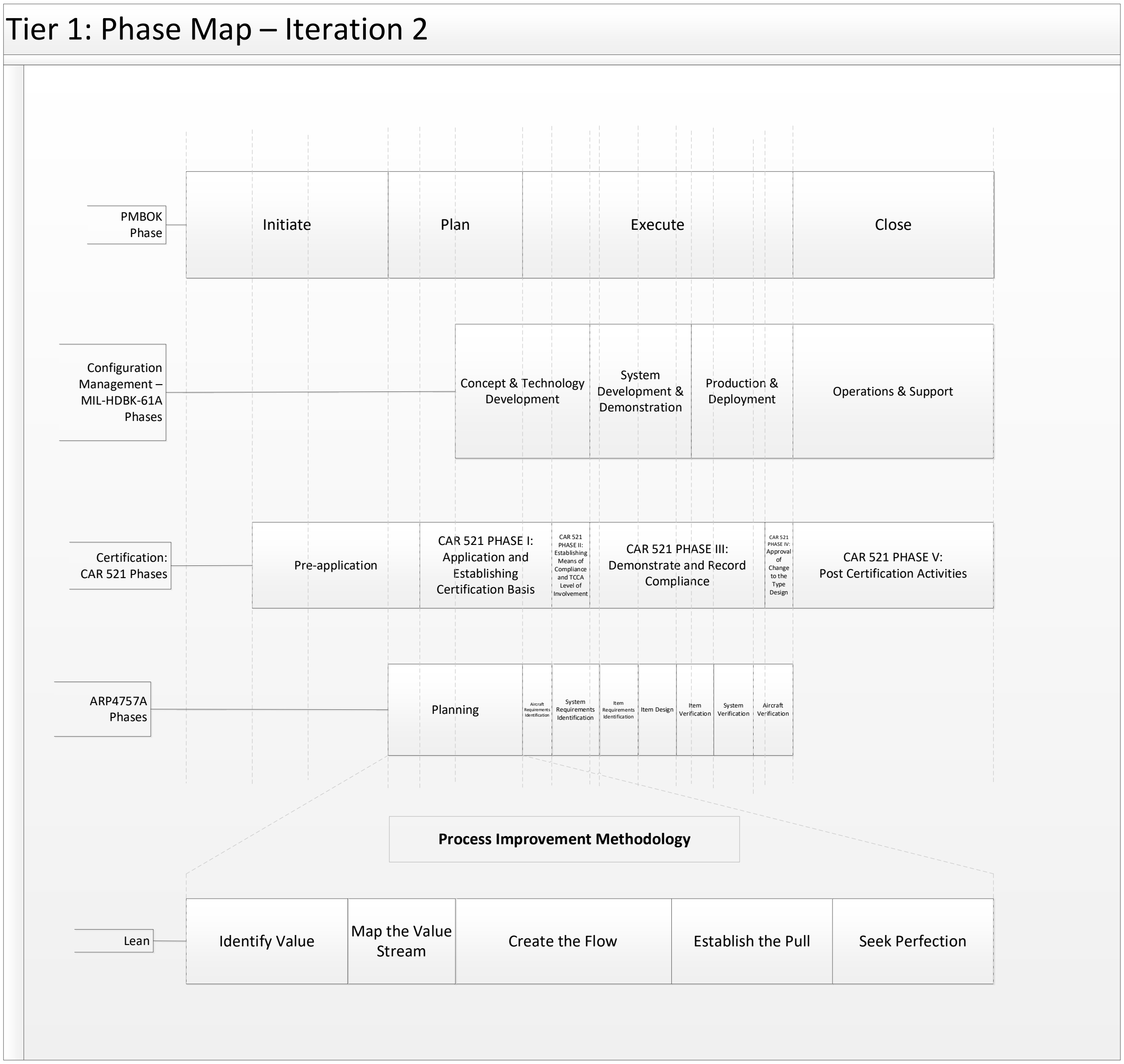

Figure 15: Second iteration of Tier 1 Phase Map

In addition to the findings associated with the Tier 1 Phase map in Figure 14, the second iteration Tier 1 Phase map in Figure 15 identifies an additional feature associated with terminology, where a word can mean different things in the context of competing methodologies. The words *Plan* and *Planning* are used in the PMBoK® and the ARP4754A, but do not refer to the same phases within the product lifecycle. Figure 15 illustrates that the work for a project is composed of activities that start at different times and last for different durations according to each functional group. Table 9 provides an example of the competing terminologies across functional groups for the first project phase. The Tier 1 Phase Map provides a means to correlate between the phases associated with each functional group and to plan and align milestones and decision gates when multiple functions are involved.

Table 9: First Phase names of each PLM methodology

Functional Group	Sub-function	PLM Method	First PLM Phase Name
Project Management Function		PMBoK®	Initiate
Engineering Function	Engineering Design	Configuration Management	Concept & Technology Development
Engineering Function	Airworthiness	CAR 521	Pre-Application
Engineering Function		ARP4754A	Planning
Production Function		Lean	Identify Value

4.1.1 Tier 1 Phase Map Discussion

The following discussion of the Tier 1 mapping results is intended to describe three principle findings from this part of the study. The first is how the ontologies associated with PLM methodologies described in Section 2.4 contribute to the silo phenomenon described in Section 3.1.2, where barriers to communication between silos lead to process inefficiencies. Secondly, the challenges of process transparency across functional groups due to the ontology barriers is discussed in terms of the consequences for efficient workflow throughout the product development process. The third finding is that the different methodologies, although intended to represent the entire product lifecycle across functional groups, are usually focused on the needs of a specific functional group and can be maladapted to the needs of other groups.

Ontology as a contributor to the Silo Phenomenon

The Tier 1 study found that different methodologies implemented in individual functional groups interfacing with a common product also used different ontologies to describe the product lifecycle. This practice of simultaneously using these different PLM methodologies can contribute to the silo phenomenon described in Section 3.1.2, which in turn can amplify barriers to communication between the silos and contribute to a reduction in workflow efficiency. Within functional groups, written policies and procedures used ontologies that reflected the PLM method best suited to that functional group. While ontologies associated with specific PLM methods were meant to be efficient in supporting the respective functional groups, it was found that their use inhibited the development of unified company-wide processes and led to disagreements on the methods that should be used as a foundation for company-wide process development. For example, as a result of the different ontologies used by each functional group, it was difficult to translate phase equivalencies between methods during the Tier 1 process map generation. This was identified as a possible barrier to the development of company-wide processes that should reflect the requirements of the product development lifecycle, instead of the needs of the individual functional groups.

Process transparency

The simultaneous use of multiple PLM methods and their corresponding ontologies was found to be a barrier to workflow visibility. The resulting barriers to process transparency increases the possibility of consequences such as overlooking internal stakeholder involvement at key decision making stages and obscuring critical workflow paths that might influence stakeholder involvement throughout the product development process. For example, the use of methods from PMBoK® and CAR521 by the Program Management and Engineering functions, respectively, was identified as a potential barrier to understanding and communication that could contribute to challenges for project managers and airworthiness engineering managers when one functional group interfaced with the other during the product development lifecycle. While it is certainly the case that the complexity and product variability associated with the aircraft modification product makes it difficult for a single person to have a detailed understanding of all functional group interfaces, the differing ontologies were found to further impede this understanding of functional roles and interfaces.

The noted misalignment between the methodologies was found to contribute to discrepancies in the placement of milestones and decision gates common to multiple functional groups throughout the product development lifecycle. Aircraft design activities include many complex and highly interrelated variables, and optimizing decisions taken at milestone gates requires multi-functional and multi-stakeholder involvement. A well-planned milestone process is therefore within the best interest of company for time and cost effectiveness, and will be discussed further in Section 4.3.

Competing PLM Methodologies

The Tier 1 mapping process revealed areas for process improvement associated with competing PLM methodologies. Individual functional groups expressed a strong preference for, and loyalty to, their preferred methodology and associated ontology. It was found that the competing, externally-developed PLM methods either did not fully address the needs of functional groups other than the one(s) it was designed for, or were not readily adopted by other functional groups as a result of the ontological barrier discussed above. For example, while Configuration Management was useful to both engineering and production, it was less relevant to project management. The Lean methodology, while an effective approach to process improvement, was distinct from other methods in that it did not provide an approach to product development but was rather a tool for improving existing processes.

4.1.2 Advantages of Tier 1 Phase Mapping

The Tier 1 Phase map exposed opportunities for process improvement and provided a visual infrastructure to help overcome barriers between functional groups. When the same map is used across functional groups, it can serve as a useful introduction to processes less widely understood by certain disciplines. For example, in the case of the CAR 521 Aircraft Certification Phases, the map provides insight into airworthiness practices surrounding certification requirements for employees or stakeholders less familiar with certification processes. Because aircraft certification accounts for a significant percentage of the product development costs and must be addressed during each phase of the product development process, a widespread understanding of the complex requirements associated with aircraft certification can help employees at all levels and in all functional groups reduce design and development costs.

4.2 Tier 2 Milestone Level

The Tier 1 Phase map does not explicitly illustrate workflow, but rather highlights the scope of product development across the company to meet the needs of the Executive stakeholders. The Tier 2 Milestone level map shows the flow of work between major milestones in terms of deliverables and decisions that take place during each of the product development lifecycle phases. An accurate Tier 2 map is important to the aircraft modification business model where forward and backward traceability of artefacts documenting the aircraft modification history is required by the certification regulatory body.

Information obtained through interviews at Executive, Manager and Analyst levels, as described in Chapter 3.2, was combined with data from review documents and used to build the Tier 2 Milestone maps. An example of a Tier 2 Milestone Map is shown in Figure 16, where the milestones are grouped by corresponding Tier 1 Phase, and, in the electronic version, are hyperlinked to the Tier 1 Map (the electronic version is proprietary and is not included as part of the thesis document). The Tier 2 map shown in Figure 16 represents the milestones corresponding to the "*Plan*" phase of the PMBoK® methodology. The Tier 1 Phase name is identified at the top left-hand corner, and the current Tier 2 level is listed below. A "Back to Tier 1" button allows the user to navigate back and forth between the Tier 1 and Tier 2 levels.

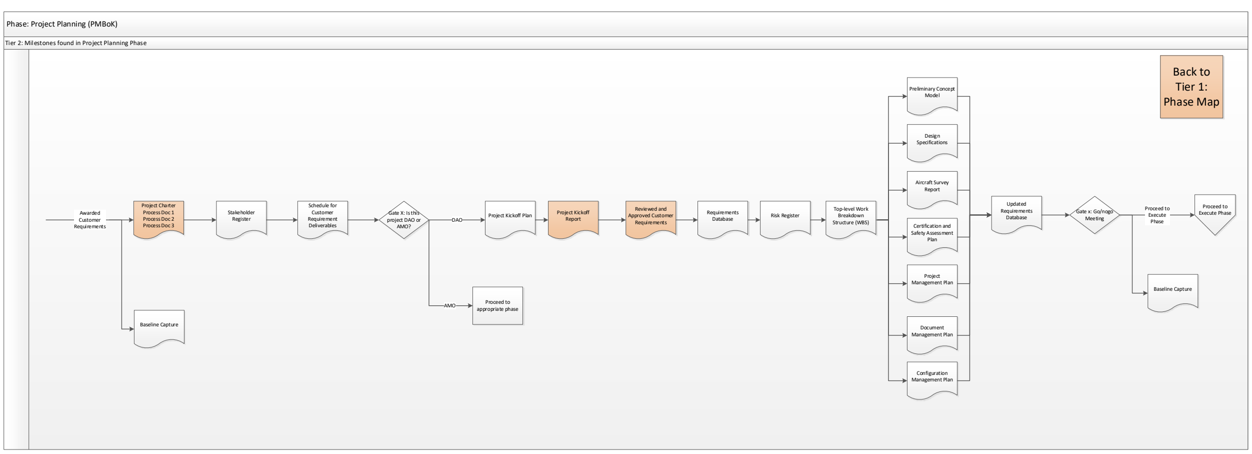

Figure 16: Illustrative figure of case study result example of a Tier 2 Milestone level map has been blurred to protect confidential information

In addition to the flow of milestones, deliverables, and decisions, the structure of the Tier 2 Milestone map can be used to identify the current state of related Tier 3 maps and supporting documentation. In the generic example presented in Figure 16, the orange-coloured milestones indicate that a Tier 3 Activity level map exists for that deliverable, and colourless milestones indicate that a Tier 3 Activity level map has not yet been generated. Documents listed inside the milestone shape denote documented policies, processes, or procedures corresponding to that milestone. In the example shown in Figure 16 the Project Charter is supported by three different process documents, whereas the Requirements Database does not yet have any approved or released documentation.

4.2.1 Tier 2 Milestone Map Discussion

The following discussion of the Tier 2 mapping results outlines the two principle findings from this part of the study. The first is how the multiple methodologies and corresponding functional group "swimlanes" in the Tier 1 map leads to difficulties establishing common milestones at the Tier 2 process mapping level. The second finding was that the aerospace industry-specific variations in size, scope and technical content from one project to another make it difficult to create generic milestones applicable to all projects.

The effect of multiple Tier 1 swimlanes

One of the challenges to generating cross-functional Tier 2 Milestone maps stemmed from the variation in PLM methodologies and phase definitions across functional groups whereby the milestones were defined and grouped differently depending on the PLM method employed. The different phase names and definitions creates a barrier to understanding the critical path of milestone placement. A consensus on when milestones happen within the project schedule, what order they happen in, and the placement of appropriate checkpoints to verify that the product development is on track to meet customer, business, and certification requirements, is a process that is inhibited by a lack of consensus on a Tier 1 phase approach.

Two types of milestones were identified. The first type of milestone is a deliverable or a decision reflecting artefacts related directly to product development and imposed by external and internal stakeholders including the customer, suppliers, and internal functional groups. The project plan, stakeholder register, work breakdown structure, and certification plan are all examples of generic deliverables driven by internal and external stakeholder needs. These milestones can be placed directly within one of the phases in the Tier 1 map. A second type of internal milestones flows directly from the Tier 1 Phase definitions as checkpoints, such as meetings to plan a new phase, or go/no-go decision gates for concluding one phase and proceeding to the next. This type of milestone differs in naming convention and corresponding project phase depending on the PLM methodology being followed. For this reason, establishing milestones involving multiple internal functional groups and external stakeholders at the Tier 2 level is strongly dependant on the selected Tier 1 mapping strategy. The Tier 2 mapping reveals that major milestones such as critical design reviews require full process transparency, strong communication and a mature workflow understanding that is difficult to facilitate with multiple swimlanes in the Tier 1 Phase map.

The possible solution of circumventing the Tier 1 Phase map altogether could temporarily facilitate the development of a cross-functional Tier 2 Milestone map development. However, a single map showing every milestone, deliverable and decision throughout the entire product lifecycle would quickly become unreadable, and therefore defeat the purpose of being a tool for process understanding. Additionally, eliminating a Tier 1 Phase map would fail to address the underlying area of improvement, as the multiple PLM methodology approach as barriers to communication within existing processes, which would continue to present challenges to policy, process, and procedural documentation.

Project scope and technical content

The variability of aircraft modification projects in terms of scope and technical content resulted in the necessity to create non-generic Tier 2 process maps composed of different milestones and deliverables for each individual project studied. The two main project categories were identified as projects with a small enough scope to be executed by a group of four or five engineers, and large projects requiring teams composed of members from multiple functional groups. Smaller project milestones were fairly consistent from one to the next, with a distinct set of deliverables occasionally using the same terminology as large projects. Smaller projects also had less of a perceived need for supporting policy, process, or procedural documentation, as approaches to product development were easily communicated verbally within the smaller team. For larger projects, the milestones, deliverables, and decisions varied between projects, with few generic deliverables, documents or templates across projects. An absence of generic, standardized milestones and deliverables was identified as a root cause of re-documentation at the start of each project. Addressing this area of opportunity would result in the re-use of processes and documentation from previous projects, increasing planning and document management efficiency. The variation also had an impact on document management, with file location, title, and revision structure being organized differently depending on the type and subject of individual projects. Variability across project milestones also created barriers to identifying relevant lessons learned from previous programs.

4.3 Tier 3: Activity Level

A shortcoming of the process mapping methodology at the Tier 2 Milestone map level was that the variation between projects at the milestone level, combined with the complexity of the aircraft modification process, resulted in most Tier 2 maps containing a combination of Tier 2 Milestone and Tier 3 Activity levels of detail in order to obtain the necessary understanding of current-state process within the case study. This section presents the findings at this final level of process map detail.

The purpose of the Tier 3 Activity level process map is to show workflow at the activity level across functional groups. Each Tier 3 activity maps correspond to a Tier 2 Milestone, and the electronic version includes a hyperlink allowing the user to click on any milestone and access a map of the activities involved in reaching that milestone (the electronic version is proprietary and is not included as part of the thesis document). Examples of Tier 3 Activity maps are show in Figure 17 and Figure 18. The top left-hand corner indicates the corresponding Tier 1 Phase and the Tier 2 Milestone maps, and a hyperlinked button in the right-hand corner allows the user to navigate back to the Tier 2 Milestone level. Additional hyperlink functionality at the Tier 3 Activity level includes forward and backward navigation buttons to the input and output milestones, allowing the user to navigate within the Activity level. Activity workflow is presented left-to-right. This level of map also features the company functional groups in swimlanes, with the horizontal divisions labeled on the left-hand side of the map with the functional group name. Table 10 lists the functional groups represented as distinct swimlanes in the Tier 3 maps.

Table 10: Functional group swimlane divisions for Tier 3 Activity level process map

Swimlane	Functional Group	Sub-function
1	External Stakeholder	Customer, Vendor
2	Business Development Function	
3	Project Management Function	
4	Financial Management Function	
5	Engineering Function	Engineering Design, Airworthiness
6	Production Function	Production, Manufacturing
7	Supply Chain Function	Purchasing, Inventory

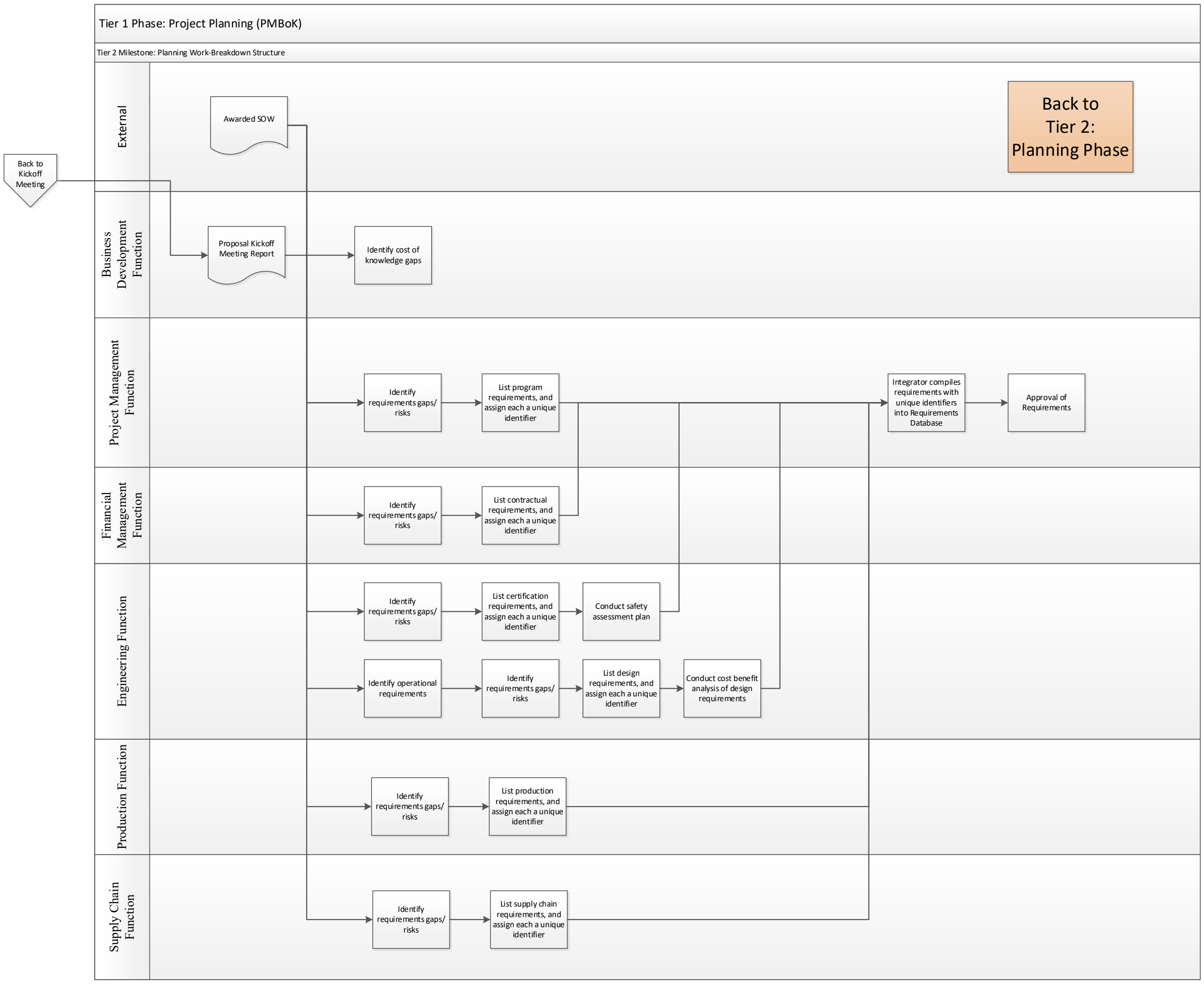

Figure 17: Illustrative figure of Tier 3 Activity level map result for Work-breakdown Milestone in planning phase has been blurred to protect confidential information

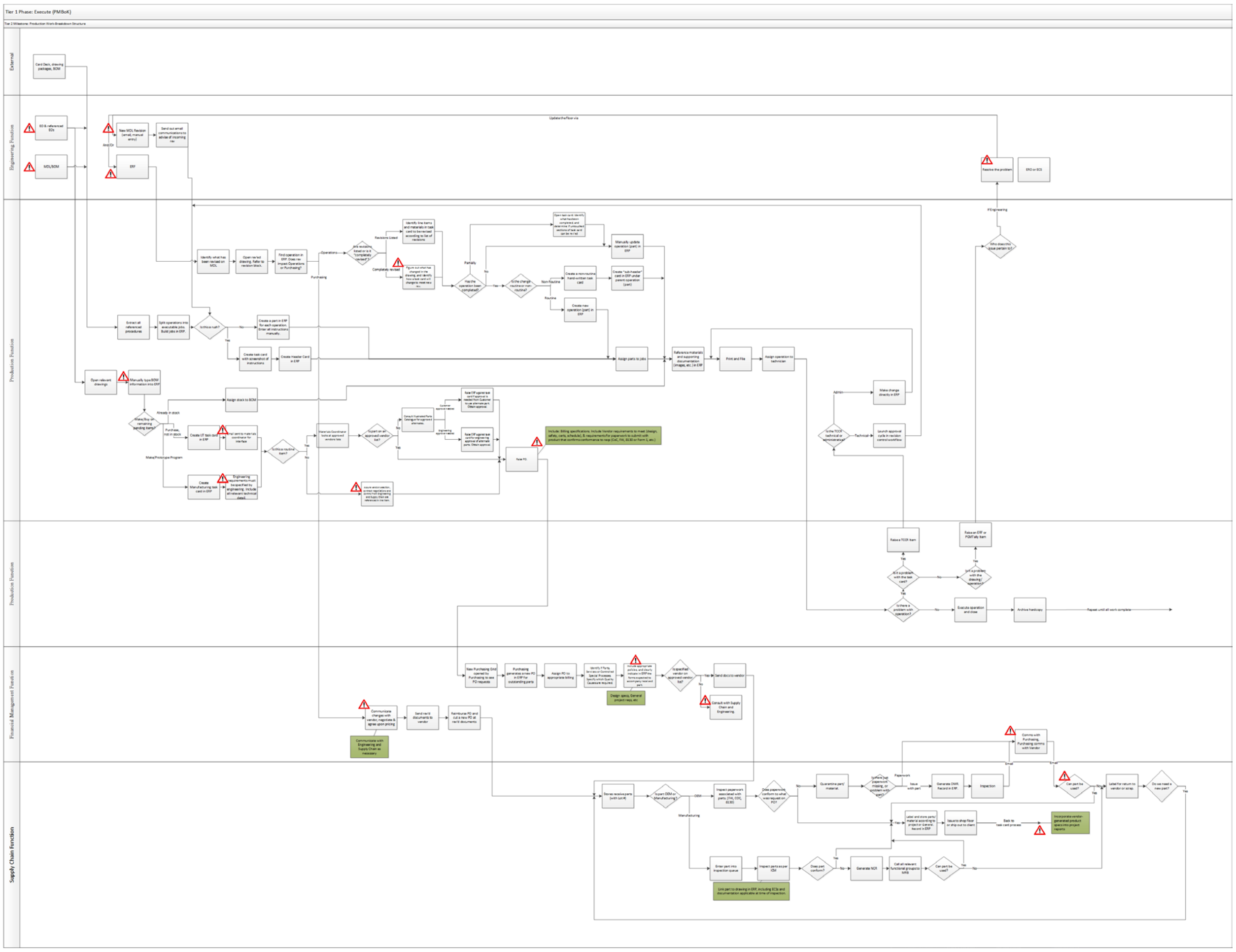

Figure 18: Illustrative figure of Tier 3 Activity level map result for Work-breakdown Milestone in production phase has been blurred to protect confidential information

The activity map example shown in Figure 17 illustrates the activity-level work involved in the Work-Breakdown milestone in an early upstream planning phase, while Figure 18 represents the activity-level work involved in the Work-Breakdown milestone during a downstream production phase. Work-breakdown activities refer to the steps undertaken for a work package to be broken down into executable tasks. The upstream planning phase work-breakdown involves converting customer requirements into a project plan, whereas the downstream production phase work-breakdown activities take engineering designs and convert them into executable steps for production. The findings associated with multiple PLM methodologies revealed during the Tier 1 Phase mapping cascade down to the Tier 2 Milestone and Tier 3 Activity levels, where the actual placement of these maps is interpreted differently by each functional group. As an example, the associated Tier 1 Phase names for the Tier 3 maps of Figure 17 and Figure 18 are presented in Table 11 as a function of the PLM method employed to generate the Tier 1 phase map.

The Tier 3 Activity maps are structured in a left-to-right flow, with loop-backs to indicate opportunities for iteration. A major drawback of this methodology is that it does not always accurately reflect the true iterative nature of the aircraft modification product development process across all the Tiers. The complexity depicted in Figure 18 attempts to capture the process complexity for changes occurring during the production phase without compromising map readability. However, the complexity exists regardless as to whether it is captured on paper, and therefore an appropriately detailed activity-level map is worthwhile generating to illustrate these processes.

The red hazard signs in Figure 18 indicate identified areas of risk within the activity-level workflow due to undocumented processes or the transmittal of outdated information. Green boxes are comments documenting some of these issues, or questions arising as the map was developed for validation with subject matter experts.

Table 11: Tier 1 Phases corresponding to the Tier 3 Activity Maps of Figure 17 and Figure 18.

Functional Group	**Sub-function**	**PLM Method**	**PLM Phase name for location of Figure 17 Map**	**PLM Phase name for location of Figure 18 Map**
Project Management Function		PMBoK®	Initiate	Execute
Engineering Function	Engineering Design	Configuration Management	N/A	Production and Deployment
Engineering Function	Airworthiness	CAR 521	Pre-Application	CAR 521 Phase III: Demonstrate and Record Compliance
Engineering Function		ARP4754A	Planning	Item or System Verification
Production Function		Lean	N/A	N/A

4.3.1 Tier 3 Activity Level Discussion

The following discussion of the Tier 3 mapping results focuses on four main findings from this part of the study. The first concerns the level of detail required for a useful Tier 3 map that is still understandable by the user. The second finding relates to opportunities for improving communication and workflow traceability identified as a result of the Tier 3 mapping exercise. A third finding concerns the differences in supporting documentation practices between functional groups, and the last is related to configuration management.

Tier 3 level of detail

The level of detail to include at the Tier 3 Activity level map was an important consideration. A map without enough detail was not useful for both illustrating process and conveying complexity, but a map with too much detail quickly became unreadable for the intended Analyst end-user. Tier 3 maps are simplified by including an additional Tier 4 level of detail that includes the procedures, work-instructions and templates that support the Tier 3 Activities. This allows a Tier 3 map user to understand the workflow at the Activity level, and access supporting documentation at the Tier 4 level in order to execute the work and meet quality standards.

Communication and workflow traceability

The primary findings for areas of process improvement at the Tier 3 Activity level were related to communication and workflow traceability. Questions in both interviews and document review focused on inputs and outputs, work approvals and work traceability as a means of understanding the daily activities of the Analysts. The Analysts were often assigned work either verbally or through email, and unlogged communications and individualized data storage were potential barriers to work traceability. Tier 3 maps also revealed that activity-level work could be tracked differently depending on the nature of the work, and that naming and numbering schemes for artifacts such as drawings and test reports were difficult to link to requirements and deliverables. A generic artefact traceability architecture with a mechanism for capturing important verbally or electronically communicated data would increase efficiency across the product development processes.

Documentation practices and internal vs. external stakeholders

The number of work instructions, procedures, and templates supporting the Tier 3 Activity level varies between functional groups. Groups with more repeatable, consistent activities were more likely to have documentation describing the best practices for these activities. Groups with less predictable activities had less documentation describing the Tier 3 Activity level of work and were more likely to operate on an individual project basis, using the knowledge of subject matter experts and as-needed verbal or emailed communications.

The Tier 3 Activity level map displays the flow of internal stakeholder activities and identifies process gaps, but also highlights areas of opportunity for creating supporting work instructions, procedures and templates to improve quality and traceability. Supporting documentation was found to be more robust for communication with external stakeholders such as customers or vendors, than it was for communication with internal stakeholders such as other functional groups. While the documentation for the external stakeholders was not found to entirely prevent instances of iterations, it was found to support an expectation of record keeping, impose quality and compliance checkpoints, and improve overall work traceability. This approach to documentation was recommended as an area of opportunity to improve traceability within internal stakeholder communication.

Change management – cost and certification

Challenges associated with change management can be identified from the Tier 3 Activity level maps. Policy, process, procedure, work-instructions and template documentation related to change were the most difficult to identify and trace across all functional groups. Change assessment, communication, and documentation is critical to both project cost and traceability related to certification requirements. Including change management procedures addressing change incorporation requirements were identified as beneficial for reducing the amount of work at the end-of-project consolidation for certification, and the risk of missing changes if they are incorporated as they occur.

4.4 Summary and recommendations

4.4.1 Summary

The aircraft modification business model and associated processes are challenging to map accurately due to the high-value, low-volume product diversity and the complex nature of aerospace certification requirements for safety-critical systems. The process mapping research findings presented in this thesis are the result of a year-long research collaboration between the researchers and the industrial collaborator, where understanding current-state processes and developing process maps was found to be intensive and time-consuming work. As such, the approach should be considered a medium- rather than a short-term investment. Recommendations for the application of the process maps produced as part of this project include the creation of generic program documentation, the implementation of a continual assessment and improvement process, and the opportunity to address requirements management on a company-wide scale.

4.4.2 Recommendations

Standardization and traceability across programs and functional groups

One key advantage of a well-constructed process map is that it permits the development of generic documents for procedures, best practices and process checklists across varying product development programs and functional groups. It was found in the case study that product variability between projects resulted in different milestones, deliverables, and decisions from one project to another. The process maps developed as part of this study can be used to improve the consistency and repeatability of process that play a critical role in the forward and backward traceability of artifacts for the certification process. Capturing the link between milestones, the order in which they should be addressed, and clearly presenting the upstream and downstream flow of work is key to reducing the cost of safety-critical system development and certification. This traceability communicates an understanding of all elements of the product development process, presents a clear platform for communication with the certification body during the process and at the time of certification, and makes it less costly to meet the requirements of continuing airworthiness whereby artifacts supporting the safety of the aircraft modification are accessible until the aircraft's retirement. Traceability also contributes to an increase in process efficiency considering the highly iterative nature of aircraft modification product development.

Continual assessment

A balance is required between improving workflow efficiency by filling process gaps identified through process mapping, and stifling workflow with unnecessarily heavy processes. Continual and critical assessment of process relevance is important for determining the processes that enhance quality by imposing thorough up-front work, and which processes create barriers to efficiency with no value added. This continual assessment is one of the primary roles of the Lean methodology presented in the Section 2.4.3 and Section 4.1 Tier 1 Phase map, and was found to be used actively within the case study.

Requirements management

A larger area of opportunity associated with the findings of the current work is that of requirements management. The need for requirements management is often overlooked by PLM methodologies, researchers, and experts. The results of this study indicate that a requirements management approach could have prevented some of the process inefficiencies revealed in the study. The gaps in traceability that appear at both the Tier 2 Milestone and Tier 3 Activity levels are only discussed in terms of the links between one artefact to another. For coherent program management across functional groups, all artefacts should in fact be derived from, and be traceable to, a specific requirement generated by a stakeholder, business process, operational constraint, or certification body.

The challenge of requirements management is not new. In the 1980's the United States Navy launched the A7 Aircraft Operational Flight Program, intended to improve the operational availability of the fleet through a software upgrade project. The challenges faced in requirements, process and product management were well summarized by Kathryn Heninger [87]:

> "Writing down the requirements turned out to be surprisingly difficult in spite of the availability of a working program and experienced maintenance personnel. None of the available documents were entirely accurate; no single person knew the answers to all our questions; some questions were answered differently by different people; and some questions could not be answered without experimentation with the existing system."

The importance of requirements management, however, is a topic that has only begun to emerge in the larger PLM context [88] [89] [90]. Nuseibeh and Easterbrook state that "The primary measure of success of a software system is the degree to which it meets the purpose for which it was intended" [91], an approach which involves the active management of requirements throughout the entire product lifecycle. It is recommended that requirements be at the forefront of product development planning and that and all milestones, deliverables, decisions, and activities should link directly to a requirement. This provides direct access to top-level information that can be continually assessed for in- and out-of-scope work, and the fulfilment of requirements functions as justification for the work. Requirement-driven work plans can be used to transcend the PLM methodology and ontological barriers at the Tier 1 Phase level, and set the foundation to create a robust milestone and activity documentation architecture. Requirements traceability can reduce rework, improve process transparency and traceability for certification, and increase workflow efficiency.

5. Conclusion and Recommendations for Future Work

5.1 Conclusion

Aircraft modification is a high-value business model with complex product development processes, high product diversity, and unique challenges. Certification of major aircraft modifications requires reverse-engineering of the original aircraft's basis of certification in addition to the design, validation, and safe integration of the new modification development, and demands significant financial and resource investment from the Design Approval Organization and the regulatory body Transport Canada Civil Aviation. The aircraft modification industry has tackled this challenge in part through programs aimed at increasing process efficiency, and has adopted multiple Product Lifecycle Management (PLM) approaches in search of a holistic solution. The multiple PLM process adoptions, particularly in small-to-medium enterprises, has led to the simultaneous application of competing methodologies and associated ontologies, often resulting in process misalignment and obstacles to communication within the company. This, in turn, has re-enforced the functional silo walls that the PLM systems were intended to help overcome.

In this research project a process mapping tool was used to expose PLM-driven communication and process-control gaps and overlaps. The process map was also used to propose approaches for overcoming these obstacles and improving company-wide process efficiency. Through the collection and visual presentation of current-state processes across the Tier 1 Phase level, Tier 2 Milestone level, Tier 3 Activity level maps, the approach has proven to be a useful tool in both generating constructive discussion between company personnel and incorporating existing documentation in a more accessible format. The process mapping tool can be used to identify root causes to process workflow hindrance, overcome ontological barriers between functions, and identify gaps and areas for process improvement as the basis for an ideal-state process map.

5.2 Future Work

While process mapping is a useful tool for analysis and can be used to unify product lifecycle process, it does not address the underlying issue of having different approaches to the product lifecycle across PLM products. Addressing this directly would require the development of a unified, company and product development cycle-specific PLM methodology. While the PLM methodologies in use at the case study company of this thesis reflect the fundamental needs of a functional group, the challenge in developing a unified PLM methodology tailored to the company's product development needs is to do so while not compromising the needs of the individual functional groups. A PLM methodology would therefore require an in-depth assessment of the functional group needs through consultation with subject matter experts to integrate the processes that support these needs, and a well-structured roll-out plan for implementing the unified approach to product development.

The approach of developing a unified PLM methodology, however, does not necessarily respond to the driving factors of product development: the requirements. The author recommends that future research focus on requirement management as the critical product lifecycle process across all functional groups. Requirements, as they evolve from that of the customer, the business and the certification authority, into detailed specifications across company functions, are the driving justification for all product activity. If the process architecture in place is designed to support, manage, and track these requirements as they iterate and evolve into a finished product, the resulting milestones and activities should be directly linked to these requirements, and therefore inherently exist in a forward and backward traceable structure that is critical for aircraft certification and ongoing airworthiness. The product lifecycle processes would then be developed to support the needs of the product with respect to its requirements, which would in turn transcend the functional group silo phenomenon, and improve workflow and communication efficiency.

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