CRANFIELD UNIVERSITY

YAFANG YANG

A LEAN FRAMEWORK FOR TOOLING DESIGN PROCESS IN CHINESE AEROSPACE

SCHOOL OF APPLIED SCIENCES

MSc by Research Thesis
Academic Year: 2011 - 2012

Supervisors: Dr. Patrick McLaughlin and Dr. Jörn Mehnen
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ABSTRACT

Lean Manufacturing (LM) has been used in production processes to help manufacturing companies maintain competitive advantages for decades. However, with the increasingly fierce competition and pressure to sustain survival and long-term growth, enterprises cannot be satisfied with just improving the performance of a single process. Therefore, adoption of lean to the whole product development processes has become a necessity.

There is evidence that lean thinking and some lean manufacturing tools are able to improve Product Development (PD) processes. Thus, terms of Lean Product Development (Lean PD) and Lean Product and Process Development (Lean PPD) are becoming popular in engineering fields.

In this project, the research aimed to improve the tooling design situation in Chinese aerospace by implementing lean techniques to the design process. Tooling is an indispensible part of aircraft manufacturing and assembly. The quality and development time can influence aircraft quality and delivery time. However, there is little research about the lean techniques implementation based on aircraft tooling design characteristics and there are few lean frameworks for aircraft tooling design process. Therefore, this research will be conducted to fill this gap.

The research comprised four phases. In the first phase, a comprehensive literature review about lean (lean thinking and lean manufacturing), Lean PD and Lean PPD, tooling design, lean models/frameworks and the relationship between lean and organisational culture was conducted. In the second phase, data and information from three Chinese aircraft manufacturing companies (Company A, B and C) and literature were collected and analysed, aiming to discover the current lean implementation status in tooling design process and find improvement opportunities. In the third stage, a lean framework for tooling design process was synthesised. Finally, the proposed framework was validated by academic and industry experts.

Finally, the research can contribute to companies which need a lean transformation. Moreover, the lean framework also could be used as a reference for research in lean and tooling design field.

Keywords*: Lean manufacturing, Lean thinking, Product development, Lean PD, Lean PPD, Tooling design, Aerospace*

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LIST OF ABBREVIATIONS

Acronyms	Description
CE	Concurrent Engineering
DFMA	Design for Manufacturing and Assembly
DFSS	Design for Six Sigma
DOE	Design of Experiment
FEA	Finite Element Analysis
FMEA	Failure Mode and Effects Analysis
IDEF0	Integration Definition for Function Modelling
IPT	Integrated Project Team
JIT	Just In Time
KB	Knowledge-Based
KBE	Knowledge-Based Environment
KLC	knowledge Life Cycle
Lean PPD	Lean Product and Process Development
LM	Lean Manufacturing
LPD	Lean Product Development
LPDS	Lean Product Development Systems
MBD	Model Based Definition
NC	Numerical Control
PBCE	Point-Based Concurrent Engineering
PD	Product Development
QFD	Quality Function Deployment
RSM	Response Surface Methodology

Acronyms	Description
SBCE	Set-Based Concurrent Engineering
SMED	Single Minute Exchange of Die
SS	Six Sigma
TPDS	Toyota Product Development System
TPM	Total Productive Management
TPS	Toyota Production System
TRIZ	Theory of Inventive Problem Solving
UML	Unified Modelling Language
VOC	Voice of Customer
VSM	Value Stream Mapping

1 Introduction

1.1 Research Background

The development of globalisation and technology brings much pressure and competition to aviation manufacturing companies. To maintain a competitive advantage, companies have been investigating how to produce high quality products in a shorter time with less cost. Lean manufacturing in the production process is notable among the approaches developed to achieve this aim. There are many published reports and journals with successful lean manufacturing implementation practices in various fields.

The great success of applying lean to manufacturing processes has led experts and researchers to reconsider the role of lean and whether it can be extended to other product development processes. Aerospace companies also participate in this extension activity. It is in this context that the current research to investigate how to apply lean concepts and approaches to tooling design process is carried out.

1.2 Research Motivation

In aerospace, tooling can directly influence aircraft manufacture and assembly, quality and launch time. Therefore, it has become pertinent to conduct research on how to produce high-quality tooling efficiently and economically.

The cost for correcting defects during manufacturing and testing stages is far more than rectifying defects at the design stage. Therefore, it is wise to avoid the defects by focusing on the tooling design stage. To help achieve this goal, it is also necessary to extend lean to tooling design process.

However, in Chinese aerospace, manufacturing companies pay more attention to lean manufacturing. There are relatively few studies about lean tooling design.

This research aims to investigate this field and develop a lean framework for tooling design process with a special focus on the requirements of Chinese aerospace.

1.3 The Sponsor Company and Case Companies

The sponsor company is a state-owned company established in China in 2008. It adopts a "Main manufacturers - Suppliers" model, which means that it cooperates with aircraft manufacturers and suppliers globally. The sponsor company focuses on civil aircraft design, manufacture and final assembly, marketing, customer service and acquisition of certification.

The company manufactures Chinese regional aircrafts and large models which are safe, economical and environmentally friendly. The long-term goal of the sponsor company is to open up the world markets and build a world-class reputation in the aviation industry to rival Boeing and Airbus. Facing such fierce competition in aerospace, the sponsor company has attached great importance to technologies and research which can reduce related cost and improve aircraft performance. Lean as a tool to enhance competition of business has thus attracted the sponsor company's attention.

Company A is one of the branch companies of the sponsor company and it is responsible for the manufacture and assembly of civil aircrafts. It began focusing on lean manufacturing in 2003 and regards this as one of the key elements influencing development. It has also invested a great deal of training and funding in lean manufacturing and has witnessed improvement. However, concerning tooling, the question of how to extend lean to other processes such as planning, designing and testing to gain the same benefit is neglected by Company A.

Company B is an industrial corporation of Chinese aerospace. It is a main manufacturer for some Chinese military airplanes and it is also responsible for civil airplanes components manufacturing. In international fields, Company B is a strategic partner of Boeing and Airbus and produces the vertical trails for the B737 and wings for the A320.

Company C is the main manufacturer of Chinese fighter airplanes. It is also a component supplier for Chinese civil airplane manufacturing.

1.4 Project Scope

Tooling is an extremely broad topic and it has specific characteristics for different products in different fields. This MSc research was conducted based on the tooling design situation in Chinese aerospace. However, the scope of literature review in this research goes beyond tooling in the aerospace industry to include the practices in automotive and other domains. Moreover, the lean framework should be implemented from the company's perspective with the involvement of all people related to tooling design process.

1.5 Aim and Objectives

The aim of this research is to develop a framework based on lean techniques for the tooling design process in Chinese aerospace. This is achieved by the following objectives.

1. Identify elements influencing lean implementation from lean manufacturing, lean product development and lean product process development;

2. Investigate the tooling design process situation (especially lean implementation status) in Chinese aerospace;

3. Apply the identified enablers and lean approaches to synthesise a lean framework;

4. Validate the proposed framework through academic and industry experts' judgement.

1.6 Thesis Structure

Figure 1-1 illustrates the thesis structure consisting of seven chapters. Chapter 1 introduces the research background, motivation, the sponsor company and case companies, and research aim and objectives. In chapter 2, a literature review related to this research topic is presented. Chapter 3 shows the methodology for this project. In chapter 4, a survey to investigate the lean implementation status in the tooling design process is described with an analysis of the data. Chapter 5 describes the synthesis of the lean framework. Chapter 6 explains the validation of the lean framework. Chapter 7 includes a discussion about the research, research contribution and research limitations. Chapter 8 concludes the whole research project and Chapter 9 shows the future work.

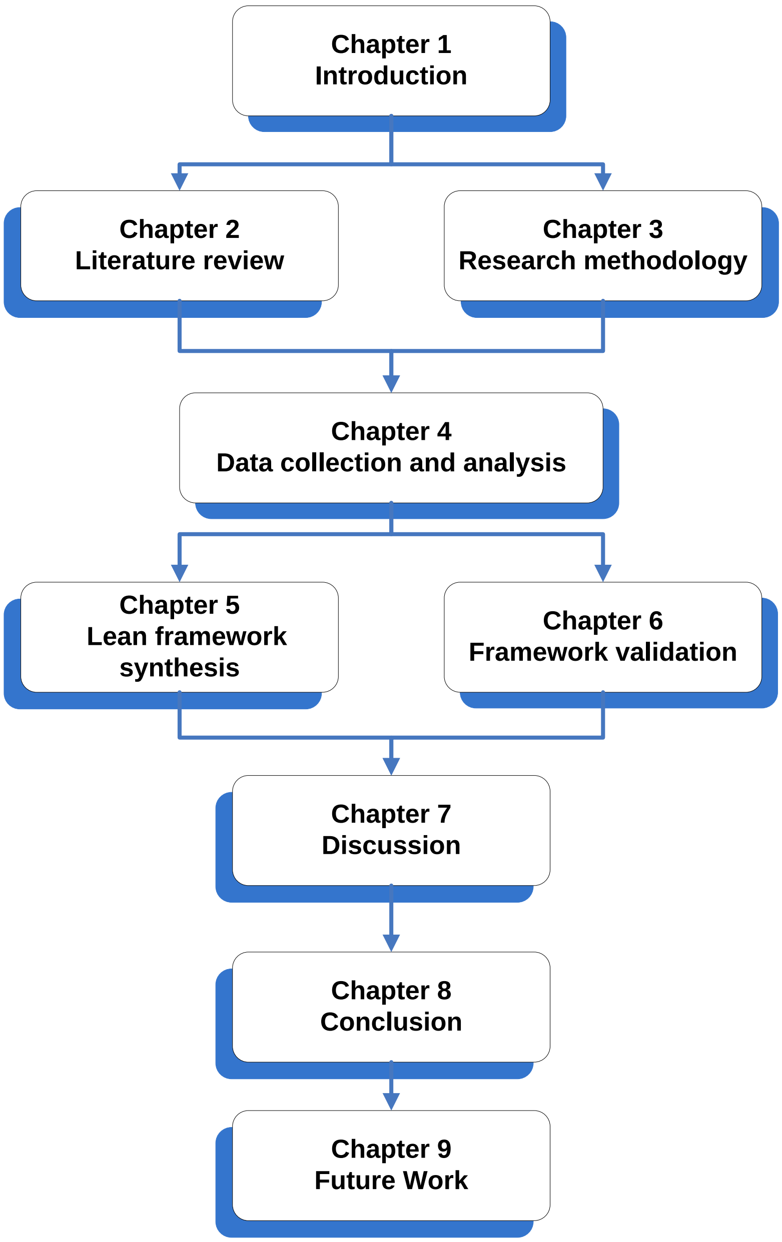


Figure 1-1 Thesis structure

1.7 Summary

This chapter has provided a general introduction about this research. Firstly, the research background about lean, research motivation and information about the sponsor company and case companies were introduced. Secondly, research aim and objectives were mentioned. Finally, the thesis structure was illustrated.

2 Literature Review

2.1 Introduction

The chapter comprises eight sections. Figure 2-1 illustrates the literature review structure.

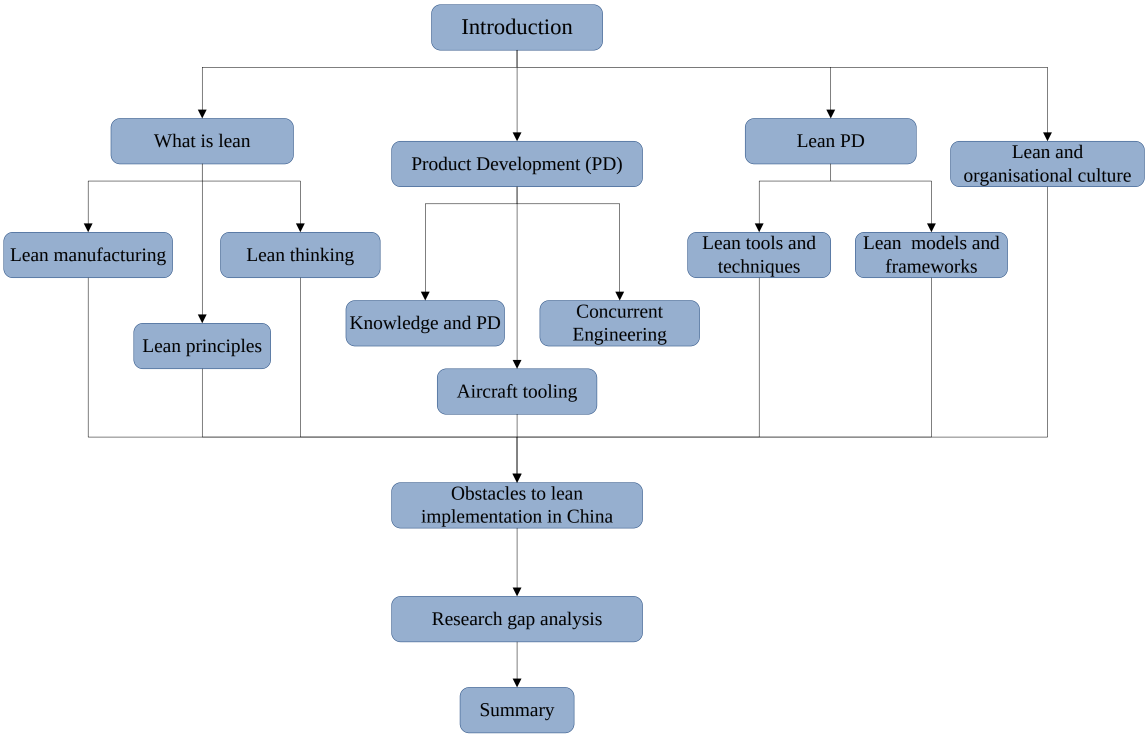


Figure 2-1: Structure of the literature review

2.2 Lean

2.2.1 What is Lean?

The term "lean", which is regarded as the combination of principles and ideas, was first developed by Toyota (Womack et al., 1990). The lean philosophies evolved from the Toyota Production System (TPS) can be defined as: "producing what is needed, when it is needed, in the time that is needed, with the minimum amount of resource and space" (Al-Ashaab et al., 2010, p. 3).

With the development of lean, some terminologies are becoming popular in engineering fields, such as lean manufacturing, lean principles and lean thinking.

2.2.2 Lean Manufacturing

In the early 1990s, lean was first applied to production and manufacturing. It was only thought to be a method of maximising production efficiency and output. A concept known as Lean Manufacturing (LM) was developed.

Lean manufacturing is also known as lean production. LM is regarded as a management philosophy mostly coming from TPS, which can guide people to reduce seven wastes (Womack et al., 1990) and thus add customer value. LM's target is waste elimination. LM tools include: VSM, JIT, Single Minute Exchange of Dies (SMED), Continuous Improvement (Kaizen), 5S, TPM and Pull Systems.

2.2.3 Lean Principles

Womack and Jones (2003) proposed five lean principles: 'specify value', 'identify the value stream and eliminate waste', 'make the value flow', 'let the customer pull the (value) process', and 'pursue perfection'. In fact, the five core lean principles are also regarded as steps which help implement lean thinking.

2.2.4 Lean Thinking

Womack and Jones (2003, p.15) stated that "lean thinking is lean because it provides a way to do more and more with less and less - less human effort, less equipment, less time, and less space-while coming closer and closer to providing customers with exactly what they want". Lean thinking is a concept comprising continuous waste reduction and value addition.

Shetty et al. (2010) stated that lean thinking is a philosophy which has been adopted by many organisations to obtain flexibility to help meet challenges of reducing waste, increasing productivity and boosting innovation. The lean thinking concepts allow organisations to generate more with fewer resources.

Khan et al. (2011) claimed that lean thinking, as an improvement philosophy focusing on waste elimination and value creation, can help organisations to gain improvement and competitiveness. They also agreed that the focus of lean thinking has been on improving production processes, as well as administration, management and the supply chain.

Therefore, it can be seen that there is a different focus between earlier and present lean work. The earlier focus was on waste reduction, especially in manufacturing operations; whereas the latter focus attempted to add value and apply the same principles to different sectors. Jobo (2003) stated that lean is not restricted to value creation and waste elimination; when and where value is delivered is also of concern.

Moreover, researchers and practitioners also believed that lean is not confined to production improvement and it can also make a difference to the whole product development processes. Therefore, application of lean to product development is underway across the engineering industries.

2.3 Product Development

2.3.1 PD Background

Kennedy (2003) suggested that product development can be regarded as activities of company technology and concepts being converted to products. These products can meet both customers' requirements and companies' goals.

Morgan and Liker (2006) stated several unique characteristics of product development by comparing with production. First and foremost, the concern of PD is data flow. Second, tasks of product development need days, months or years to finish. Moreover, product development concerns diverse and unpredictable knowledge accumulation and is associated with a nonlinear data flow. Lastly, product development requires the contribution of different groups of participants, not just a single department.

The product quality and team members' coordination can be assured by a well-defined product development process. Ulrich and Eppinger (2008) illustrated a generic product development process including six stages: Phase0: Planning; Phase 1: Concept Development; Phase 2: System-level Design; Phase 3: Detail Design; Phase 4: Testing and Refinement; Phase 5: Production Ramp-up (see Figure 2-2).

Figure 2-2: New PD process (Ulrich and Eppinger, 2008)

2.3.2 Knowledge and PD

PD is a knowledge-intensive activity which requires gathering and managing knowledge from various sources (Schilling and Hill, 1998). Due to the complexity of PD activities, increasingly deeper and broader knowledge will be required, and engineering decisions need to be taken based on the knowledge and experience coming from best practices or previous projects. Reinertsen (2005) stated that from the modelling perspective, the primary output of most PD processes is information. Furthermore, Yang (2010, p. 8) stated that PD is such a process of "information mining, transformation and creation".

Studies have shown that developing a knowledge management system in a lean PD process is crucial and indispensable (Khan et al., 2011). Applying proven knowledge to product development can prevent non-value added activities such as the redesign of a product and a process. Therefore, managing knowledge and information becomes increasingly urgent.

2.3.3 Concurrent Engineering in PD

Concurrent Engineering (CE) is no longer a novelty and it has been widely shifted from automotive fields to aerospace industries. For many companies, CE has been a standard approach during the conceptual stage of product design in product development (Hihn et al., 2011).

In 1989, Pennell and Winner (p. 648) gave an interpretation of CE below:

"*Concurrent engineering is characterized by a focus on the customer's requirements and a conviction that quality is the result of improving a process, and a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise".*

Walker (1996, p. 7) defined concurrent engineering as *"a systematic approach to the integrated, concurrent design of products and their related processes, including, manufacturing and support. This approach is intended to cause the developers from the very outset to consider all elements of the product life cycle, from conception to disposal, including cost, schedule, quality and user requirements."*

Abdalla (1999) suggested that CE is a strategy which can improve organisations' competitiveness, efficiency and productivity. Operating cross-functional teams efficiently is a key step for CE implementation.

Kennedy (2003) stated that there are two kinds of CE: Point-Based Concurrent Engineering (PBCE) and Set-Based Concurrent Engineering (SBCE). These two CEs are introduced in the following sections.

2.3.3.1 Point-Based Concurrent Engineering (PBCE)

In PBCE, after initially evaluating several product concepts, the final one will be refined and developed until the production stage. PBCE tends to converge quickly to a design solution and then analyse and eventually modify the final design option according to the customer's requirements (Sobek et al., 1999).

2.3.3.2 Set-Based Concurrent Engineering (SBCE)

SBCE is a part of Toyota's PD systems, which is characterised by demanding a wide range of design solutions for the product at the beginning and along with the design processing, the sets gradually narrow down. Based on the design requirements, experience and knowledge of designers or trade-offs, the weaker solutions are eliminated (Sobek et al., 1999). Sobek et al. (1999) argued that SBCE may need more time to decide the design solutions during the early design stage, but it moves fast to converge and to ultimate production.

Kennedy (2003) claimed that SBCE causes much information generation and discarding, but this information can be recorded as knowledge for re-use.

More recently, Williams (2008b) stated that CE tends to change from PBCE to SBCE, because PBCE can lead to subsequent and time-consuming iterations of a design concept refinement and end with a suboptimal design. SBCE can help avoid these problems. Figure 2-3 illustrates the characteristics of the two CEs.

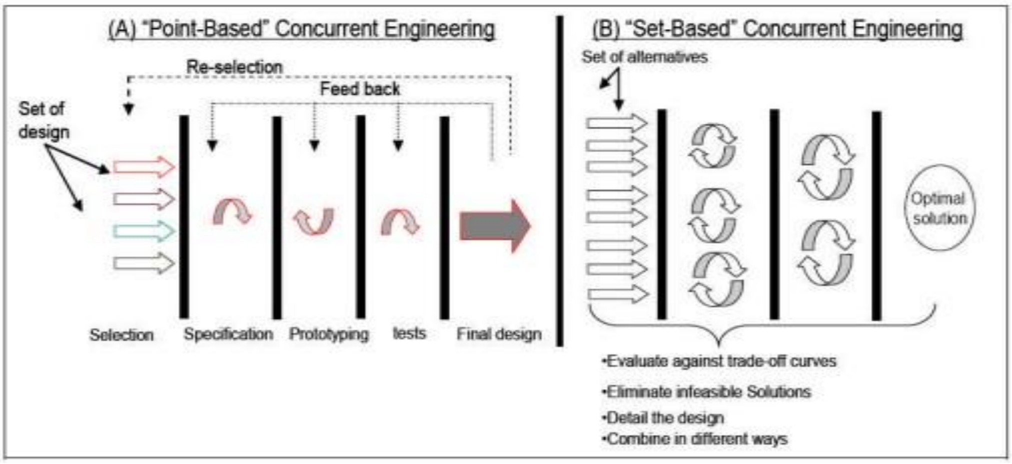


Figure 2-3: PBCE and SBCE (Williams, 2008b)

2.3.4 CE in the Aircraft Industries

In aerospace, CE has been applied widely in the product development process. It focuses on the improvement of integration, collaboration and process compression through developing organisational mechanisms (Hihn et al., 2011). Sun (2011) also stated that some benefits can be gained by the application of CE, such as reducing design and manufacturing time, cost, and making product quality better.

2.3.5 Aircraft Tooling

2.3.5.1 Definition and Role of Tooling

Tooling is the general name for the tools used in manufacturing, including cutting tools, fixtures, mould, measuring tools and checking fixtures. Fixtures and jigs are usually named as tooling (Kakish et al., 2000). Generally speaking, fixtures and jigs can provide the right position, support and orientation for workpieces when workpieces are manufactured, assembled, inspected or in other operations (Zhou et al., 2011). Fixtures also can influence accuracy of a product and determine a manufacturing system's flexibility (Mervyn et al., 2005).

According to the sponsor company's internal documents, aircraft tooling is defined as equipments with functions of locating, inspection, coordination and test, which are used in aircraft parts' and components' manufacturing, assembly and test (including flight test).The main components of a tooling are supporting elements, locating elements, clamping elements and guiding elements. In aircraft research and development, tooling plays an important role. In the sponsor company, tooling designers considered that the tooling design and manufacturing ability are key indicators of aircraft manufacturing proficiency.

For a manufacturing system, according to Bi and Zhang (2001), the cost related to fixtures such as fixture design, manufacture, assembly and operation accounts for 10% to 20% of the total cost. Therefore, much research has been conducted to optimise fixture development, especially fixture design, because 80% of product's lifecycle cost is determined by design stage (McManus et al., 2005).

2.3.5.2 Tooling Design Process

Boyes (1989) suggested a systematic and orderly procedure for a tooling design which consists of five major phases or steps, namely: (1) first phase: product analysis; (2) second phase: operation analysis; (3) third phase: machine analysis; (4) fourth phase: operator analysis; (5) fifth phase: cost analysis. The five steps show that tooling designers should analyse product requirements and also consider operation type and sequences, machine capacity, the easiness for operators to use of tooling, and tooling design and fabrication cost.

In aerospace, Pan (2008) stated that aircraft tooling design is restricted both by aircraft design in upstream and some processes in downstream such as tooling process planning, tooling fabrication and usage. First, tooling design is required to be in parallel with aircraft design. The frequent changes of aircraft design directly lead to tooling redesign which causes much waste. Second, tooling design should be concurrent with tooling fabrication. For some assembly tooling in the design stage, in order to reduce the whole tooling fabrication cycle, some tooling components need to be manufactured before the tooling design is finalised. Soltanmohammad and Malaek (2008) stated that the existence of some design iterations in the product design process is the primary reason of the product development cycle time extension and associated cost generation.

Tooling design knowledge reuse and automated application is another key factor influencing design process efficiency. The wide use of knowledge during fixtures design process has been recognised (Ríos et al., 2005). Besides design knowledge, there is extensive information required during the design process which is mainly aircraft, material and fabrication knowledge.

Hunter et al. (2006) suggested that for a fixture design process, Integration Definition for Function Modelling (IDEF0) can help identify the information existing in every task which composes the design process. By mapping an IDEF0, the inputs, outputs, controls and mechanisms of each stage of a design process can be illustrated clearly (Sun, 2011). Figure 2-4 shows the form of a basic IDEF0 map.

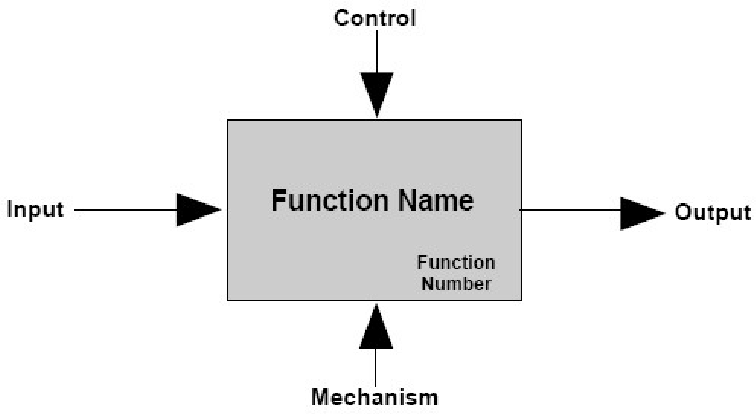


Figure 2-4 A schematic diagram of basic IDEF0 map (Defense Acquisition University, 2001)

2.3.5.3 Systems and Models for Tooling Design

Murman et al. (2000) concluded that the life cycle cost of a product is mainly influenced by the earlier stage and approaches. Tools should be developed to incorporate as many elements influencing product development as possible into the design phase. The design stage accounts for 80% of the total life cycle costs and has a high ability to influence product development, as illustrated in Figure 2-5.

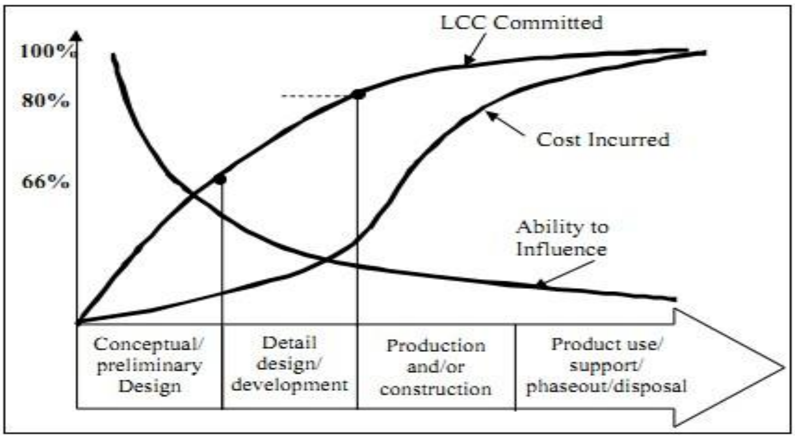


Figure 2-5: How design influences the life cycle of product development (Murman et al., 2000)

Fixture design is regarded as a difficult procedure which can be accomplished by designers with extensive knowledge and experience (Sanchez et al., 2009). Zhou et al. (2011) concurred that fixtures design usually relies on the knowledge and experience of fixture designers, which can cause deviation of fixture design quality. Boyle et al. (2011) stated that expert and knowledge systems can influence automated fixture design enormously. However, it is hard to capture and retain the design knowledge and experience for future reuse due to the complicated and experience-based fixture design process.

Hunter et al. (2005) maintained that fixture design process cannot be regarded as independent with respect to the fabrication process. Therefore, information related to the fixture fabrication is also needed to be represented in the design process. Hunter et al. (2005) defined some basic knowledge and information related to the design process (see Table 2-1).

Table 2-1: Knowledge group for machining fixture

(Reproduced from Hunter et al., 2005)

Knowledge group	Characteristics
Part geometry	Geometry: holes, slots, etc.
	Dimensions
	Tolerances
Machining process	Type of machining process
	Machining phase and sub phase
	Machining operations
Functional and detailed fixture design processes	Methodology of design
	Design rules
	Interpretation rules
	Design constraints
Fixture resources (functional elements and commercial elements)	Type of fixture (modular, general or dedicated)
	Type of fixture elements (support, locate, clamp)
	Type of machine tool (vertical milling machine, horizontal milling machine etc.)

Due to the complicated nature of fixture design, much significant research has been carried out and associated models or systems have also been developed for this process (see Table 2-2). However, most focused on the design knowledge capture, transfer, representation, reuse and how to automate fixture design. Some systems such as Boyle's computer-aided fixture design system (Boyle et al., 2011) and Zhou's methodology (Zhou et al., 2011) can support and simplify the entire design process and eventually reduce the fixture design cost.

Table 2-2: Systems and models for fixture design

Year	Researcher	Models or systems
1990	Darvishi and Gill	Expert system rules for fixture design
1990	Nnaji and Lyu	A framework for a rule-based expert fixturing system.
1992	Nee et al	A feature-based classification for fixtures
1995	Lin and Yang	An expert system modular fixtures
1999	Ma and Rong	An automated fixture design system
2000	Anumolu and Shewchuk	Tool management systems
2003	Mervyn et al	An internet-enabled interactive system for fixture design
2006	Mervyn et al	Information models for fixture design knowledge description
2005	Hunter et al	Knowledge template model for inspection fixture design
2011	Vukelic et al	A rule-based system for fixture design
2011	Zhou et al	A feature-based fixture design methodology
2011	Boyle et al	A computer-aided fixture design system

2.4 Lean Product Development (Lean PD)

2.4.1 An Overview of Lean PD

Karlsson and Ahlstrom (1996) suggested that lean PD is part of a whole production strategy. Lean PD is more than tools and techniques. Thus applying tools is not sufficient to achieve lean PD. Researchers should pay more attention to the coherent whole. In their research, three techniques which have specific roles were mentioned: (1) supplier involvement, (2) simultaneous engineering (or concurrent engineering) and (3) cross-functional teams. Supplier involvement means suppliers participate in the PD activities at the start. Concurrent engineering enables the performing of different activities in parallel to reduce the development time. Cross-functional teams aim to integrate all the functional aspects from the beginning. Direct contacts and meetings are the main communication methods instead of product planning or liaison functions.

The Aberdeen Group (2007, p. 8) suggested that "Lean Product Development is not a technology. It is a product development philosophy that encompasses a number of core disciplines". Yang and Cai (2009) suggested that the Lean PD process has a characteristic of developing products by maximising customer value with minimum resource waste.

Martinez Leon and Farris (2011, p. 29) proposed another broad Lean Product Development (LPD) definition:

"LPD is viewed as the cross-functional design practices (techniques and tools) that are governed by the philosophical underpinnings of lean thinking- value, value stream flow, pull, and perfection - and can be used (but are not limited) to maximize value and eliminate waste in PD".

However, Khan et al. (2011) argued that Lean PD should refer to PD theory based on the critical elements of Toyota PD rather on lean manufacturing. They also stated that if Lean PD is established based on Toyota PD, it may evolve into a discipline in its own right. Therefore, another Lean PD definition was proposed by Khan et al. (2011, p. 6):

"Lean PD is value-focused PD. Value is a broad term used to define stake-holder needs and desires. SBCE is a strategic and convergent PD process guided by consistent technical leadership throughout. SBCE enables the focus on value and in particular knowledge and learning. Continuous improvement is the culture and an outcome of the SBCE learning process".

2.4.2 Lean Tools and Techniques in Lean PD

Many methods and approaches can help achieve lean PD. The following section presents some identified approaches.

2.4.2.1 Lean Manufacturing (LM) Tools

LM has successfully helped reduce waste, costs and enhance product quality for decades. Its focus is waste and cost reduction, which can be achieved by avoiding the creation of non-value added activities in the manufacturing process.

Before introducing the LM tools, a comparison of waste in lean PD and lean manufacturing according to Al-Ghamdi (2008) is illustrated (see Table 2-3).

Table 2-3: Waste comparison between lean manufacturing and lean PD (Reproduced from Al-Ghamdi, 2008)

Waste type	Lean manufacturing	Lean PD
Over processing	Non-value added activities to the service, incorrect processing	Unnecessary tasks, excessive paperwork and reviews
Motion	Unnecessary operators' movement	Excess activities through tasks and more efforts to find needed information
Overproduction	Producing more than customer needs	Unnecessary information and many details
Conveyance	Unnecessary products/parts movement	Unnecessary handoffs from one activity to another
Correction	Repair of product, inspection and scrap	Wasting time on inspecting the new components, rework/redesign, incomplete information
Waiting	Operators are idle waiting for material and auto-processing	Unnecessary continuous meetings and delays
Inventory	Having more than customers required and more than stock needed	Excess non-useful information

The goal of lean PD is to reduce waste and increase product value simultaneously. Therefore, some LM tools can be modified to achieve this aim. Commonly used ones include Value Stream Mapping (VSM), Just-In-Time (JIT) and Kaizen.

1) VSM

Rother and Shook (1999) suggested that VSM is a key tool to understand the material and information flow and see the manufacturing processes. Morgan and Liker (2006) explained that by mapping the current state and identifying the waste that interrupts flow, value steam mapping can move to a leaner future state vision which is translated to an action plan.

Although it is difficult to apply VSM to product development, researchers have successfully modified this tool and adopted it into the complex PD environment. A framework using VSM in PD was presented by McManus (2005). Therefore, with modification, VSM can become an influential tool for product development value streams improvement.

2) JIT

The concept of JIT is producing the needed product in the required numbers, to the required quality at the required time. It is widely used in manufacturing. The application of JIT in the new product process (NPD) was identified by Smith and Reinertsen (1991). The pull concept of JIT used in manufacturing can be applied to the product development process for the information flow improvement.

3) Kaizen (Continuous improvement)

In manufacturing, Kaizen is defined as continuous improvement which means achieving more value from manufacturing process through constant improvements. Huthwaite (2007) stated that Kaizen is an intensive team effort to solve a manufacturing problem. Khan et al. (2011) suggested that a culture of Kaizen should be considered in lean PD.

2.4.2.2 Design for Six Sigma (DFSS)

Before introducing DFSS, Six Sigma (SS) will be considered first. Banuelas and Antony (2004) stated that SS initially aims to improve an existing process by following five sequences: Define, Measure, Analyse, Improve and Control (DMAIC). SS also can be applied to achieve high quality by designing and redesigning processes, which is known as DFSS. DFSS follows an IDOV (Indentify, Design, Optimise and Validate) methodology to identify and solve quality problems prior to product fabrication. However, the decisive factors influencing the application of SS or DFSS still need additional research.

DFSS is a tool to enhance the product value and quality by preventing defects and minimising variation and it is mainly adopted in the early stages of product development (Yang and Cai, 2009; Fiore, 2005).

Fiore (2005) suggested that DFSS includes three elements: Design for Performance, Design for Manufacturing and Design for Reliability. These match the design considerations for customer requirements, manufacturing capabilities and operating environment respectively. DFSS can enable product and process design to meet customer requirements and eventually help produce products to meet Six Sigma requirements.

Yang (2010) argued that DFSS is focused on strengthening the early stages of the product development processes by applying some tools. Table 2-4 illustrates the different DFSS tools mentioned by Yang.

Table 2-4: DFSS tools for product development processes

(Adapted from Yang, 2010)

Design Stages	DFSS Tools
1.Customer requirements study	Voice of Customer data collection Ethnographic / Observation VOC (Voice of Customer) Data Analysis QFD (Quality Function Deployment)
2. Concept design	TRIZ (Theory of Inventive Problem Solving) Axiomatic Design / DOE (Design of Experiment) Simulation / Optimisation
3. Product parameter design and prototyping	Taguchi Methods / Robust Design DOE, RSM (Response Surface Methodology), Design for X Simulation/ Optimisation Reliability based design / testing and elimination
4. Process design	DOE Taguchi Method / Robust Design Trouble shooting and diagnosis

In the following sections, some lean design tools which support DFSS, such as Quality Function Deployment (QFD), Design for Manufacturing and Assembly (DFMA), Failure Mode and Effects Analysis (FMEA), are introduced.

2.4.2.3 Lean Design Tools

In terms of lean design, Al-Ashaab et al. (2008) suggested an explanation about lean design principle. This principle consists of three main considerations: maximising customer value representation; ensuring the elimination of harm to end user and operation environment; and ensuring that waste and resource are minimised during manufacture.

Dvorak (2005, p. 47) also suggested that “a lean-design department relies on a range of tools and techniques that traditional department do not”. QFD, DFMA and VSM tools are proposed. QFD, DFMA are introduced as follows.

1. QFD (Quality Function Deployment)

QFD has been regarded as a key factor in transforming the Japanese automotive industry (Williams, 2008a). It is a powerful but inexpensive tool used in gathering and analysing requirements. It can help avoid product failure by discovering existing opportunities which can help develop a product to meet customer demands.

2. DFMA (Design for Manufacturing and Assembly)

Boothroyd et al. (2002) stated that DFMA can assist design and emphasise potential problems in the different life stages of a product. This technique aims to deliver products with a lower manufacturing cost without influencing the product quality. By optimising product design, DFMA can help increase the manufacturability and assemblability of the parts.

The target of DFMA is to enable each part of a product to be multi-functioning and thereby minimise the parts number of a product. Therefore, cost caused by manufacturing, storage, tools and other processes can be reduced. DFMA includes: “understanding the organization's process capabilities, obtaining early manufacturing involvement, using formalised DFM/A guidelines, using DFM/A analysis tools, and addressing DFM/A as part of formal design reviews” (DRM Associates, 2007).

3. FMEA (Failure Mode and Effects Analysis)

According to Mascitelli (2004) and Fiore (2005), FMEA aims to discover and minimise the potential risks in the product development. It includes four levels:

system, design, process and service level respectively. At the system level, in general, FMEA is used to identify the failure risk in the product. At the design level, sub-assemblies and components of the product will be considered. FMEA at the process level is applied to discover the weakness in the following aspects, such as the defect risks, potential safety and the manufacturing plan. At the last level of service, human factors and maintenance or repairs related to the product will be considered.

2.4.2.4 Lean PD Tools Summary

Würtemberg et al. (2011) offered a summary of lean PD tools after researching multiple sources and categorised them into six types: 1) customer focused; 2) knowledge sharing; 3) visual management; 4) efficiency tools; 5) problem solving; 6) quality assurance, which were illustrated in Table 2-5.

Table 2-5: Lean PD tools in literature mapped into tool categories (Adapted from Würtemberg et al., 2011)

Tool category	Tools
Customer focused tools	Customer representation
	Front loading
	Quality function deployment
	Set-based concurrent engineering
	Set-based design
	Trade-off curve
Knowledge sharing tools	A3 documentation
	Cross functional teams
	Go see
	Obeya room
Visual management tools	5S
	A3 documentation
	Andon
	Obeya room
	Value Stream Mapping
	Visual management
	5S
	Cross functional teams

Efficiency tools	Front loading
	Just in time
	Kaizen
	Kanban
	Set-based concurrent engineering
	Staged freezing
	Standardization
	Takt
	Trade-off curve
	Value Stream Mapping
Tool category	**Tools**
Problem solving tools	Ask why
	Brainstorming
	Plan-Do-Check-Act (PDCA)
	Value Stream Mapping
Quality assurance tools	Checklists
	Failure Mode and Effect Analysis
	Kaizen
	Standardization

2.4.3 Lean Models and Frameworks

In this section, the Toyota Product Development System (TPDS) model is introduced initially as most lean models and frameworks are an extension of it. Following this, lean manufacturing models, lean PD and lean PPD frameworks are discussed.

2.4.3.1 TPDS Model

In terms of resources utilisation, knowledge management and efficiency, TPDS has been regarded as the most efficient (Kennedy, 2003). In order to describe TPDS, a sociotechnical system (STS) model was developed by Morgan and Liker (2006). The model consists of three main subsystems: process, skilled people and, tools and technology. Figure 2-6 shows that 13 principles comprising the Lean Product Development Systems (LPDS) model are brought forward to further define the subsystems of the STS.

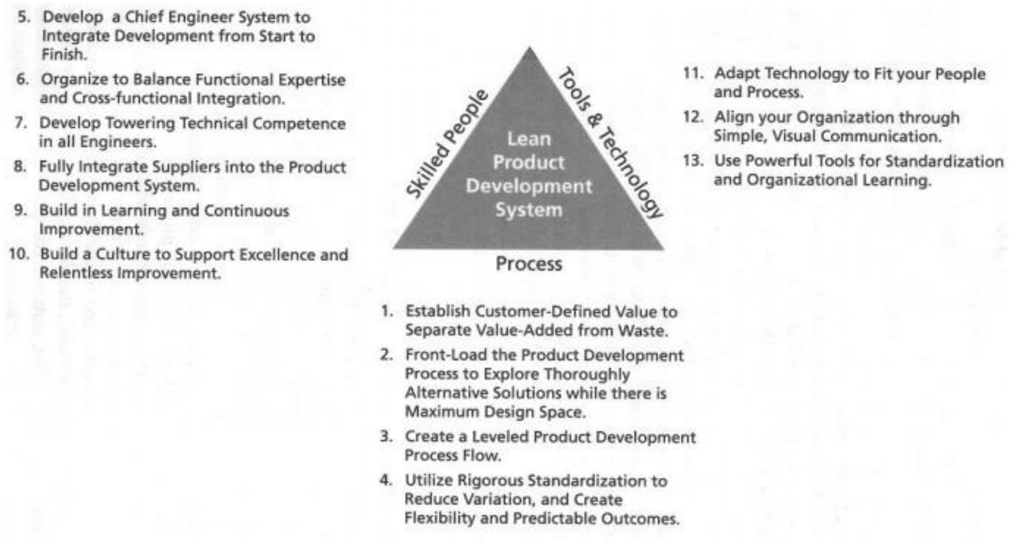


Figure 2-6: Lean PD model and 13 principles (Morgan and Liker, 2006)

2.4.3.2 Lean Manufacturing and Lean Implementation Models

Based on Toyota's LM system, Dennis (2002) created a model called the house of lean production in Figure 2-7. It emphasised the customer focus as the goal, standardisation and stability as the top and foundation of the house respectively. Two important LM tools, JIT and Jidoka, support the house. In the house, people involvement and continuous improvement are essential.

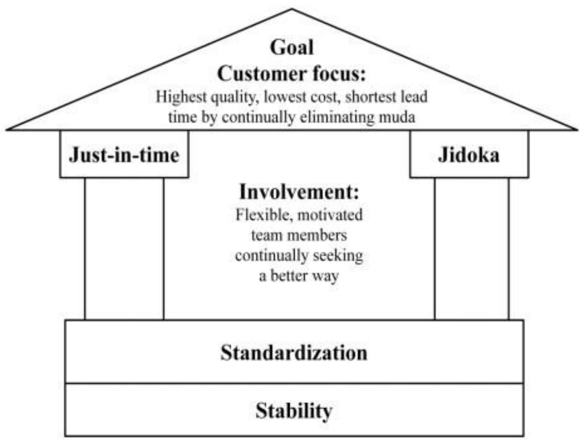


Figure 2-7: House of lean production (Dennis, 2002)

Convis (2001) shared his experience of the Toyota Production System (TPS) by using the triangle with philosophy, management, and tools and techniques on three sides respectively as illustrated in Figure 2-8. He regarded the core element of TPS to be people development, which is more important than other factors.

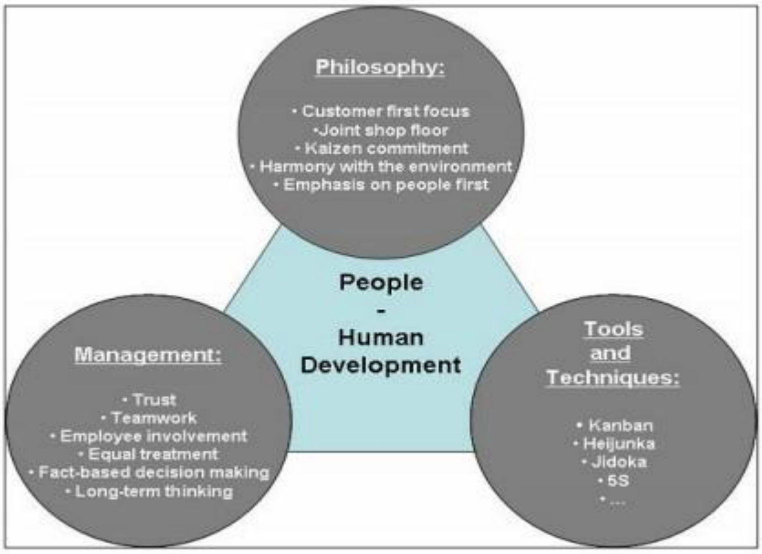


Figure 2-8: Lean triangle model (Convis, 2001)

Hines et al. (2004, p. 14) concluded that "lean exists at two levels: strategic and operational", suggesting a lean framework based on these two aspects in Figure 2-9. They stated that understanding the difference of lean thinking at two levels is crucial for applying the right tools and strategies to add customer value.

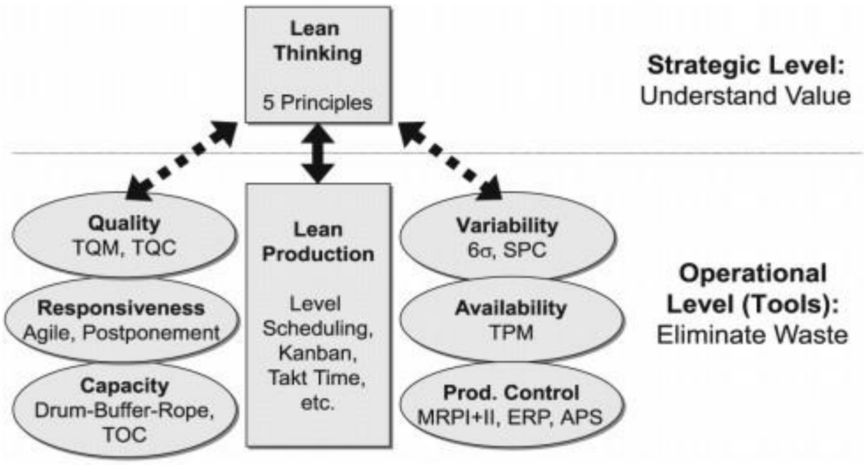


Figure 2-9: Lean framework (Hines et al., 2004)

Li (2010) presented a customised lean model including four distinct stages as illustrated in Figure 2-10. In the first stage, support, company strategy and goals should be confirmed. The second stage is to make preparations and the third is characterised by lean tools implementation. The final stage concerns continual improvement. This model can be used as a roadmap for companies which have just started their lean journey.

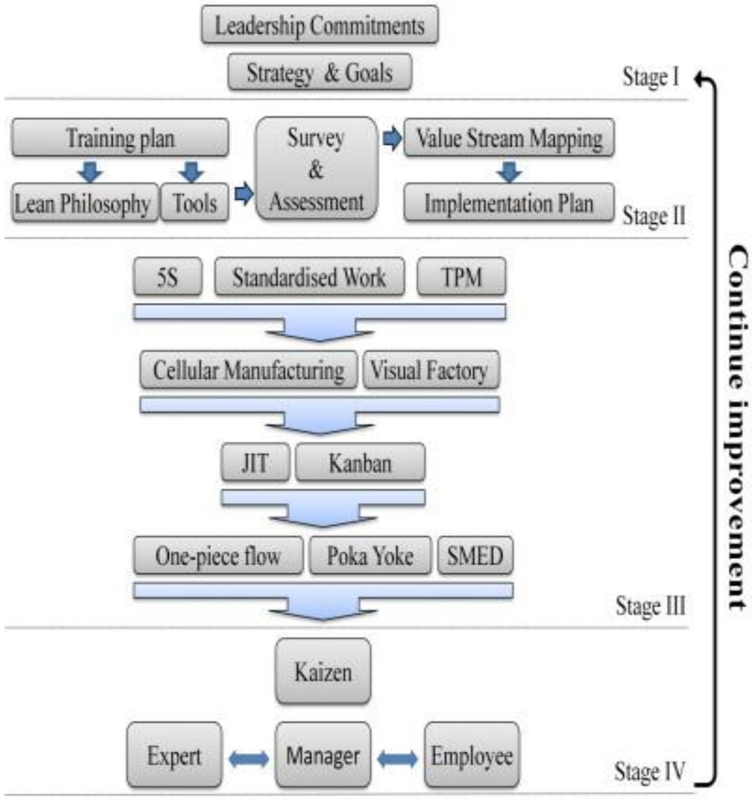


Figure 2-10: A customised lean model (Li, 2010)

Hines et al. (2008) suggested a model called the “Lean Sustainability Iceberg” which consists of two parts: items above the water line (visible) and elements underwater (enabling) as shown in Figure 2-11. The key areas underwater are all people-related; strategy and alignment, leadership, behaviour and engagement. The items above water are technology tools and techniques, and processes.

Hines et al. (2008) stated that organisations which need a lean change should focus not only on the lean visible elements such as process management and technology, but more importantly, on the invisible elements including strategy, leadership and employee engagement.

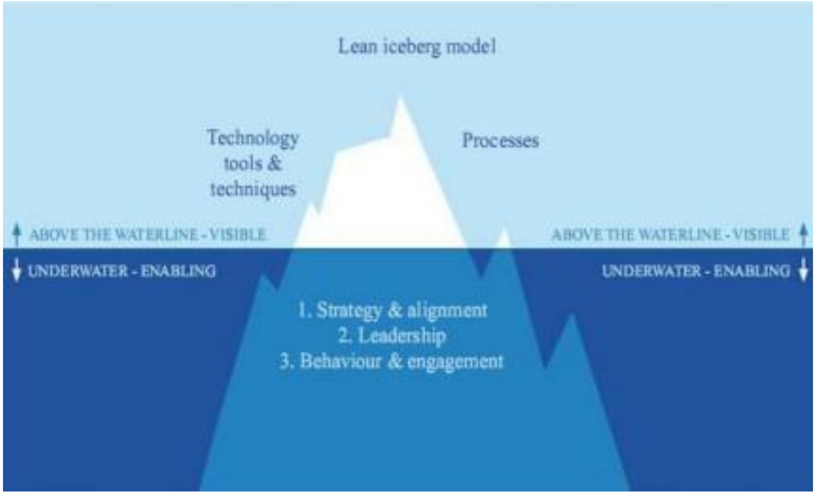


Figure 2-11: Lean sustainability (Hines et al., 2008)

Wan and Chen (2009) claimed that considering all the lean tools and approaches at once will result in chaos. Therefore, practitioners should select feasible ones according to the actual situation. Wan and Chen focused on three aspects: lean training, VSM and lean assessment as illustrated in Figure 2-12.

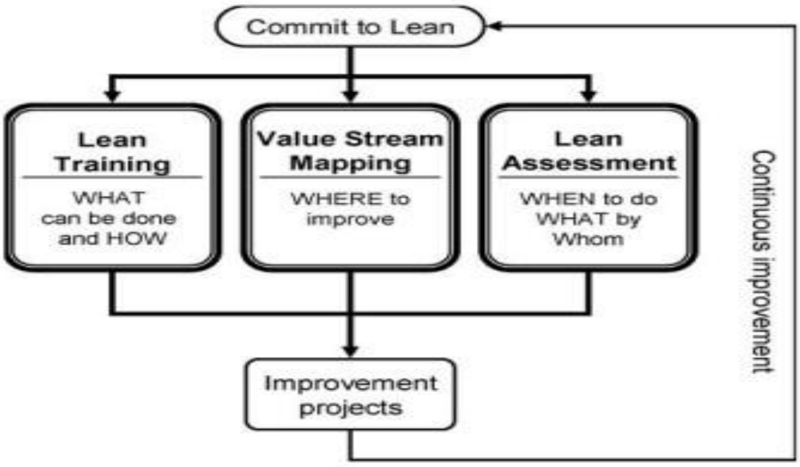


Figure 2-12: Lean implementation framework (Wan and Chen, 2009)

Ronald (2003) proposed a lean implementation methodology in Figure 2-13, which includes three phases: set-up, planning, and execution and follow-though. In each phase, there are steps to guarantee the success of lean initiatives. Leadership support is a critical factor for commencing lean implementation.

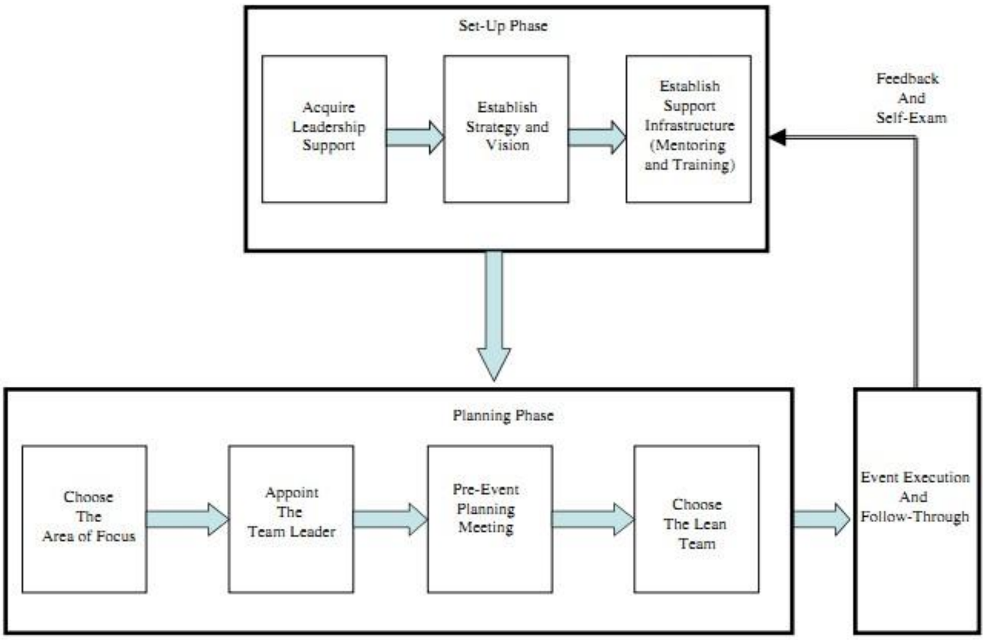


Figure 2-13: Lean implementation framework (Ronald, 2003)

2.4.3.3 Lean PD Models and Frameworks

Martinez Leon and Farris (2011) carried out a literature review on lean PD frameworks from 1987 to 2009. These frameworks are summarised in Table 2-5.

Table 2-5: Lean Product Development (LPD) frameworks (Adapted from Martinez Leon and Farris, 2011)

Framework name	Framework elements
Lean design techniques (Womack, Jones and Roos, 1990)	Leadership
	Team work
	Communication
	Simultaneous development
LPD techniques (Karlsson and Ahlstrom, 1996)	Cross-functional teams
	Strategy
	Supplier involvement
	Simultaneous (concurrent) engineering
LPD subsystems (Liker and Morgan, 2006)	People
	Process

	Tools & techniques
Framework name	**Framework elements**
LPD principles (Ward, 2007)	Value-focus
	Entrepreneurial System Designer (ESD)
	Teams of responsible experts
	Set-based Concurrent Engineering (SBCE)
	Cadence, pull, and flow

Mague (2009) developed a lean PD framework including four main elements: 1) Knowledge Management; 2) Value Mapping Tool; 3) Process Management; and 4) Measurement System as shown in Figure 2-14.

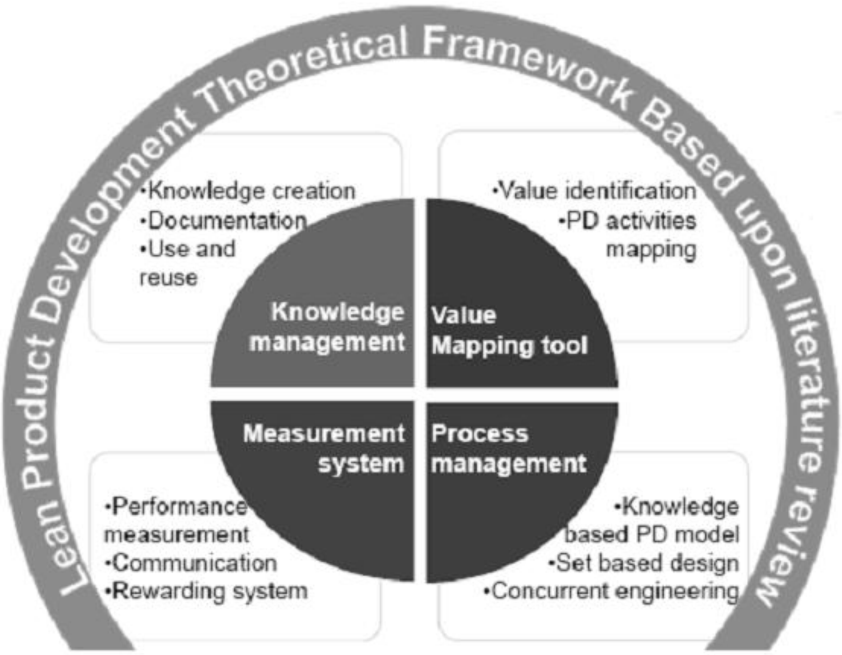


Figure 2-14: Lean PD theoretical framework (Mague, 2009)

Würtemberg et al. (2011) proposed an abstract LPD model comprising five concepts, which are Goal, Role, Tool, Process and Product as illustrated in Figure 2-15. There are three types of relationships between these concepts namely Connection, Process flow and Contributes positively/ negatively to. This abstract model is explained in detail in Figure 2-16.

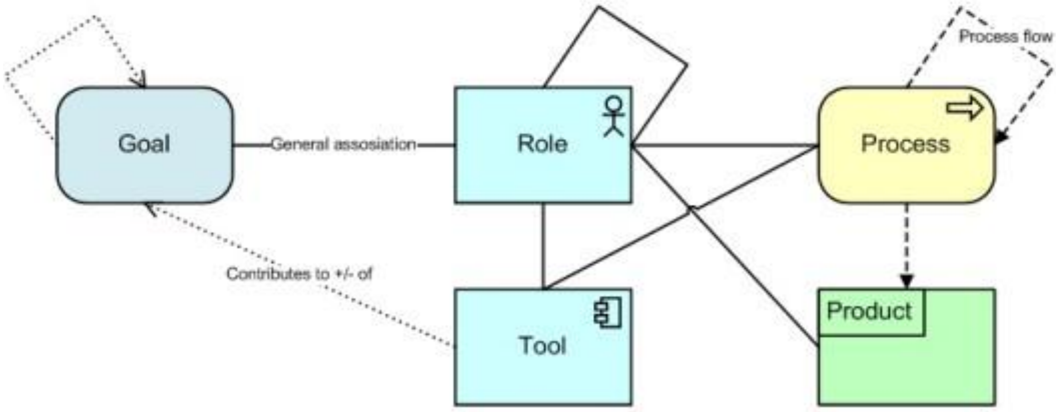


Figure 2-15: Definition of notations used in the abstract model of LPD (Würtemberg et al., 2011)

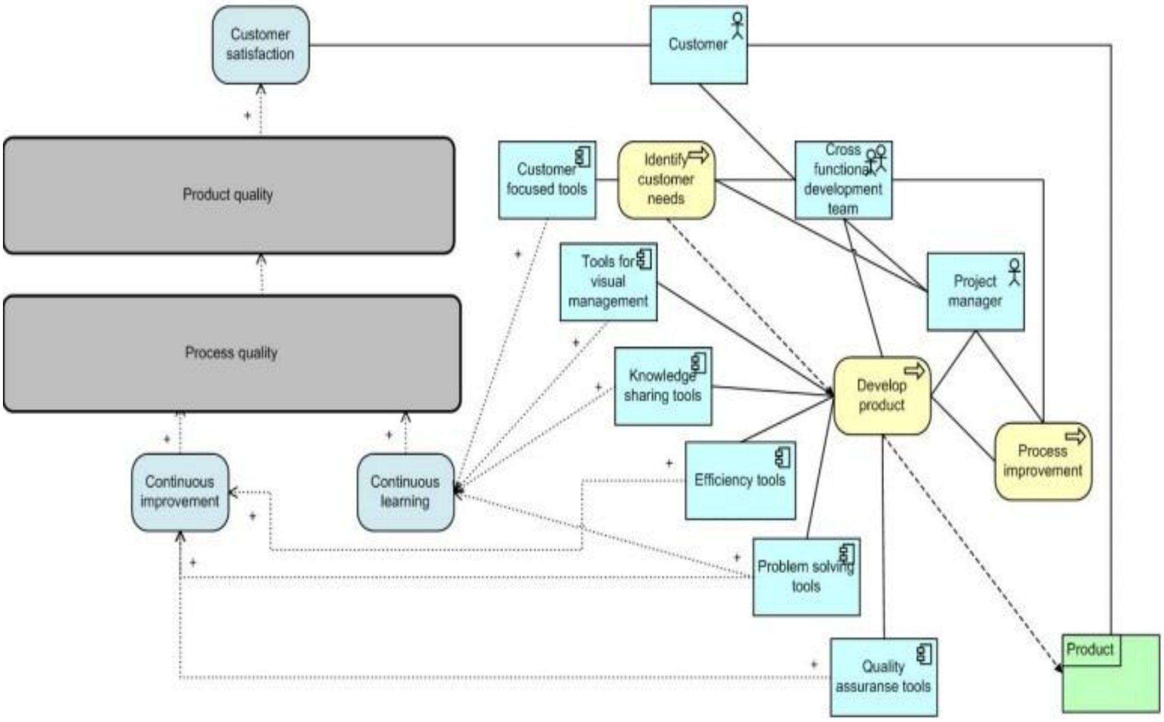


Figure 2-16: An abstract model of LPD (Würtemberg et al., 2011)

2.4.3.4 Lean PPD Models and Frameworks

Before discussion of models or frameworks in lean PD and lean PPD, the Lean PPD project will be introduced. Lean PPD is a four-year European project with a consortium comprising partners from universities, industrial companies and research centres, such as Cranfield University, Rolls-Royce and SISTEPLANT. The goal of the project is to develop a novel model based on the knowledge environment by utilising lean thinking principles to cover the whole product life cycle instead of just focusing on the production area. The Lean PPD project also aims to develop an assessment tool to measure the readiness and level of lean thinking principles adoption in product design and development processes (Lean PPD, eu, 2009).

Al-Ashaab et al. (2010) proposed a conceptual lean PPD model based on three main features: value creation; KB (Knowledge-Based) environment and SBCE, which is illustrated in Figure 2-17. One key objective of lean is to identify value and remove non-value added activities. Therefore, Al-Ashaab et al. (2010) regarded the developing of tools to discover value creation opportunities to be the first focus of the conceptual lean model. Regarding KB environment, Al-Ashaab et al. (2010, p. 8) stated that "lean product development is product development in a knowledge-based environment". In this environment, knowledge and experience which can influence engineering decisions will be captured from previous projects. SBCE can help finalise the suitable lean design concept between different tradeoffs.

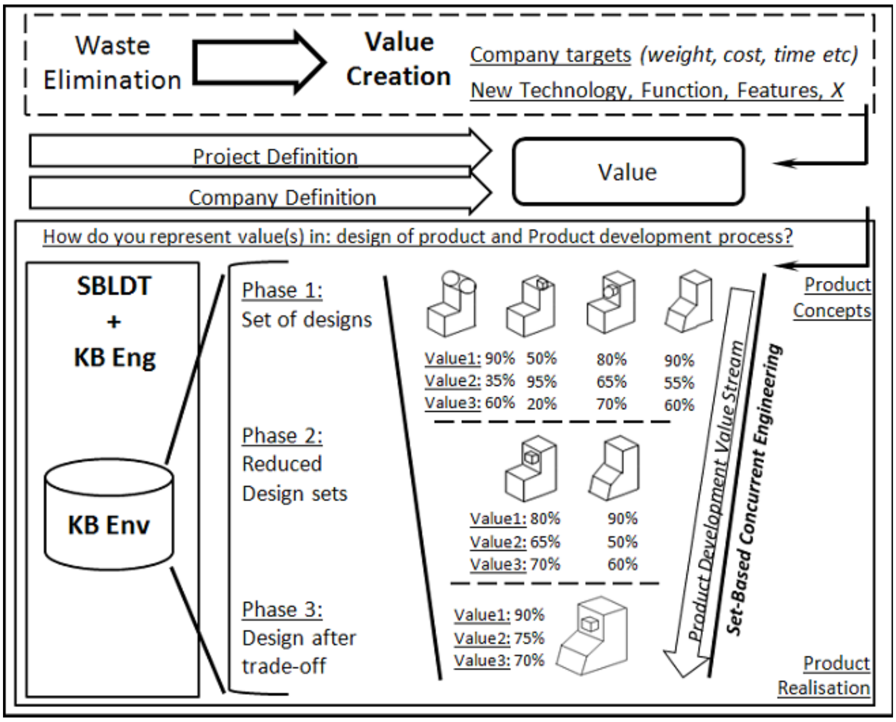


Figure 2-17: The conceptual lean PPD Model (Al-Ashaab et al., 2010)

Khan et al. (2011) also introduced a conceptual lean PPD model as shown in Figure 2-18. It consists of five core enablers: 1) SBCE process; 2) Chief engineer technical leadership; 3) Value-focus; 4) Knowledge-focus; 5) Continuous improvement (Kaizen) culture.

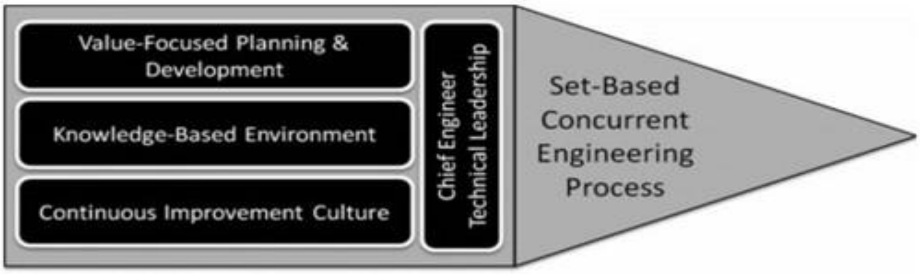


Figure 2-18: The conceptual lean PPD model (Khan et al., 2011)

2.5 Lean and Organisational Culture

2.5.1 Organisational Culture Definition

Plakhotnik and Rocco (2011) suggested versions of definitions of organisational culture. Among them, Schein's (2010) definition of culture consisting of three levels is noteworthy (Wong and Cheah, 2011).

Schein (2004, p. 17) suggested organisational culture to be "a pattern of shared basic assumptions that was learned by a group as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems". He lists three levels of culture: "artifacts (surface level), espoused beliefs and values, underlying assumptions". The "artifacts" level mainly includes some "visible organisational structures and processes". The organisational "strategies, goals and philosophies" composes the "espoused beliefs and values" level. The "underlying assumption" level consists of "unconscious and take-for-granted beliefs, perception, thoughts and feelings" (Schein, 2004, p. 26).

2.5.2 Culture Role in Lean

Wong and Cheah (2011) claimed that culture determining the success of lean transformation for a company has been identified by many researchers. Thelen (2010) stated that culture, mainly referring to culture change, will be the most difficult roadblock to the success of lean implementation. Companies focusing on lean tools rather than committing to long-term development of lean will obtain limited success and remain unsustainable.

Hines (2010) noted that lean change in an organisation requires the right culture creation. Profitability, productivity and performance of a company cannot just be driven by exterior tools or methods. The employees' emotional engagement also has an influence.

Atkinson (2010) suggested that "lean is a cultural issue", whereas current attention is mostly focused on lean tools and methodologies. Atkinson also stated that lean culture creation is equally important compared with lean implementation. Therefore, before implementing lean, a culture change should be first conducted.

2.5.3 Drivers of Culture Development

Due to the significance of culture in lean achievement, it is crucial to initially build such lean culture for a company. The following part will present the drivers of culture change cited by researchers. Somerville and Dyke (2008) reported seven possible factors driving culture change (based on an examined sample including 51 organisations) which are vision, leaders' action, leadership personnel changes, personnel turnover, human resources practices changes, communication, and structure and processes enabling changes.

Schein (2004, p. 225) suggested that culture is rooted in three areas which are: "(1) the beliefs, values, and assumptions of founders of organizations; (2) the learning experiences of group members as their organization evolves; and (3) new beliefs, values, and assumptions brought in by new members and leaders". The first area is emphasised by the founders acting as strong leaders who are crucial for the beginning of culture creation. Besides this, leaders also dominate the management and change of a culture.

Atkinson (2010) concluded from Schein (2004) that leaders' focus and response to crucial events are critical factors influencing culture building. Strong leaders can impose verified assumptions and ways of solving problems on a group. In terms of lean culture creation, Atkinson (2010) also emphasised that "process design is a key driver of the culture".

To conclude, leadership is key factor influencing culture change. Therefore, in order to achieve a successful culture creation or change, leaders' support and commitment should be established first.

2.6 Obstacles to Lean Implementation in China

This section listed four obstacles for lean implementation and lean sustainment in Chinese enterprises, which are:

1) Insufficient lean knowledge

   Employees in some enterprises lack basic lean knowledge and practical experience of implementing lean. It is hard to implement lean in a company without any lean background (Li, 2010; Ballbach, 2010).

2) Over reliance on lean tools

   Many Chinese companies begin lean implementation with applying lean tools. However, understanding lean philosophy first is more important than pursuing tools (Chen and Meng, 2010; Li, 2010).

3) Poor implementation of lean practices

   People think that by imitating successful lean practices such as some lean tools, a desirable outcome will be achieved. If one lean tool fails, they will pursue other tools. People do not understand that lean implementation should be combined with their own conditions and culture (Chen and Meng, 2010; Li, 2010).

4) Unrealistic expectations of lean

   Many enterprises want to achieve instant results after introducing lean. Such attitudes - of being eager for instant success and caring for the results rather than the process - will lead to lean implementation failure. Lean implementation is a long-term task. Toyota, for example, spent nearly 40 years developing TPS (Chen and Meng, 2010; Li, 2010).

2.7 Research Gap Analysis

The role of design in product development has been emphasised. Tooling's role in aircraft manufacturing and assembly was also investigated. After analysing research in the tooling design field, it can be found that there are many tooling design systems and models (such as information and knowledge-based). However, there is little research about how to improve tooling design process by using lean techniques in aerospace. Therefore, the following research gaps are identified after analysing the literature findings, which are:

- Many Chinese companies conduct lean at tool level (Showing that lean sustainment is hard to achieve).
- These identified lean tools are too general and there is little research about use of these tools according to tooling design characteristics.
- There are few lean frameworks specially for tooling design process.

2.8 Summary

The literature review introduced lean, lean manufacturing and lean thinking. It then presented knowledge about PD, the relationship between knowledge and PD, and CE in PD. The importance of tooling design in aircraft manufacturing, the elements influencing tooling design process and some systems and models applied to improve tooling design were also included in this chapter. Moreover, the review covered lean PD knowledge including lean tools and techniques used in PD and lean models and frameworks. The relationship between lean and organisational culture was also identified. Finally, the difficulties of implementing lean in China and a research gap were presented.

From the literature review, it can be concluded that lean has not just been restricted to production; it can be applied to other processes such as design, service and product development. In product development, the design stage occupies the most important position. After analysing lean implementation models, it was found that most of them emphasised leadership, strategy, culture and people involvement first and then considered lean tools and approaches. In terms of lean PD and lean PPD models and frameworks, it was found that lean PD and lean PPD are implemented under a concurrent engineering and knowledge-based environment and also with a range of lean tools and techniques.

In the aircraft industry, tooling design quality can influence airplane quality and launch date. However, research into the relationship between lean and tooling design process is limited. This identified research gap verifies the research motivation.

3 Research Methodology

3.1 Introduction

Methodologies vary due to the difference of research programs. Therefore, for a particular research, an appropriate methodology becomes crucial and it can help exploit the required data and information.

Whiteside (2008) suggested two main kinds of research methods, which are quantitative and qualitative methods. The former involves objective statistics and follows deductive methods to verify theories or ideas. However, the qualitative method works with subjective data and must follow an inductive method to develop a conclusion.

The research aim related to developing a lean framework for tooling design process, which means that it does not involve much statistics and verification of some theories. Moreover, lean is a philosophy and cultural issue. Therefore, a qualitative methodology with an inductive approach was chosen during this research. Sun (2011) used a qualitative methodology with the following methods: literature review, questionnaire, interviews and IDEF0 to help build a knowledge model. Therefore, in this research methodology, literature review, questionnaire, interviews, IDEF0 and fish bone diagram are also be used to help build the lean framework. Figure 3-1 introduces the methodology applied in this project and it also describes how each phase assists the building and validation of the proposed framework.

3.2 Research Methodology Adopted

The research methodology consists of four major phases, as illustrated in Figure 3-1. The main tasks and deliverables for each phase are also presented.

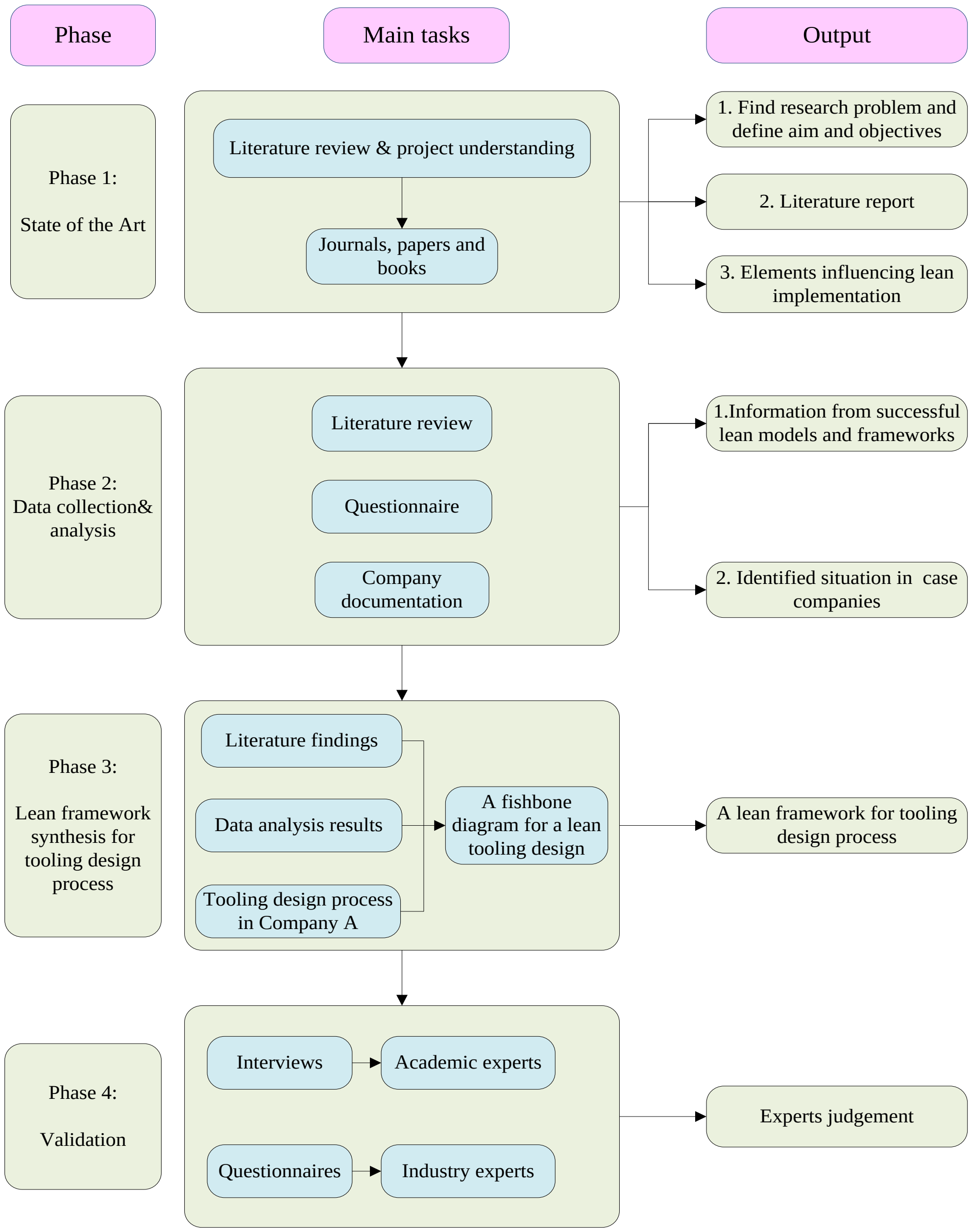


Figure 3-1: Research methodology

● **Phase 1: State of the art**

In this phase, a literature review based on books, journal papers and related research was conducted. Many findings and practices related to lean, LM, lean PD, lean PPD and tooling design were covered. The purpose of this phase is to gain a clear understanding of the project by reviewing the previous work in this area. Moreover, the researcher can also develop the required knowledge and theory about this domain which are beneficial to the research progress.

● **Phase 2: Data collection and analysis**

Data and information quality will greatly influence the development of the framework. Therefore, the data collection for this project is based on a combination of literature review, document study and questionnaire.

In the literature review, the key task is to select some practices and models or frameworks related to this research for analysis. This includes investigation of engineering enterprises which have successful implementations of lean in their product design.

Documentation related to lean practices in Company A was investigated. The documents consisted of reference materials about lean manufacturing, good examples of lean implementation in different departments and assessment reports.

The lean implementation status in tooling design process in Chinese aircraft manufacturers is gauged by using a questionnaire. Company A, which is an aircraft manufacturing company in China, was chosen as the main research object. Two respondents from two other Chinese aircraft companies (Company B and Company C) also participated in this questionnaire.

The data analysis includes literature review findings analysis, documents results analysis and questionnaire findings analysis. After the data analysis, the lean implementation status in tooling design process in Chinese aerospace was identified. With the key factors found in the domain of PD, lean PD and lean PPD, the synthesis of a lean framework can commence.

● **Phase 3: Lean framework synthesis for tooling design process**

The lean framework is developed in this phase. The synthesis of this framework was based on the key findings in the literature review, tooling design process in Company A, and lean implementation status in tooling design process in all three companies.

In this stage, an IDEF0 map was used to illustrate the tooling design process. Doggett (2005) suggested that fishbone diagram also can be called Cause-and-Effect Diagram which is developed by Kaoru Ishikawa. Fishbone diagram can help analyse possible causes to a problem visually and eventually help solve problems. Therefore, by using a fishbone diagram for a lean tooling design, lean gaps in case companies can be identified clearly.

Literature informed the synthesis of the framework. Data gathered from Chinese aerospace companies through the questionnaire were used to refine the framework and then provide a lean framework that has applicability in Chinese aircraft manufacturing companies.

- **Phase 4: Validation**

The final phase of the methodology is the validation of the proposed lean framework. It includes two stages: an initial validation and a final validation.

In the initial stage, an academic expert who has experience in lean was interviewed. The interview aimed to collect more knowledge about elements contributing to lean design and how to develop a concurrent work environment and a knowledge-based environment. This academic expert was also invited to comment on the initial lean framework. After that, the framework was modified and refined according to the suggestions of the academic expert.

In the final stage, the revised lean framework was assessed by academic experts and industry experts by doing interviews and questionnaires. The feedback and judgement of these experts was gathered during this period, based on whether the framework can be implemented and whether it requires improvement.

4 Data Collection and Analysis

4.1 Introduction

In order to find improvement opportunities for tooling design process, the internal documents about lean implementation in Company A were studied and a questionnaire was designed and sent to Company A. This section introduces the documents findings, questionnaire design and questionnaire results analysis.

4.2 Internal Documents Findings

The internal documents illustrated that lean implementation in Company A is on shop floor level. Company A concentrated on the application of lean manufacturing tools such as JIT and one piece flow to the production process. Concerning lean techniques for tooling design process, only standardisation of tooling parts and components was mentioned. The internal documents are Chinese versions which are not included in Appendix.

4.3 Data Collection (Questionnaire)

Based on lean models and frameworks in the literature review, a questionnaire was developed to investigate lean implementation status in the tooling design process in Chinese aerospace.

In this research, three main aircraft manufacturing companies in China were chosen to be investigated. Company A was the main case object. Although it was harder to investigate situations in Companies B and C, the researcher invited a process engineer from each company to answer the questionnaire. In this investigation, 60 questionnaires were sent to Company A by email and 50 were returned. The target respondents of the questionnaire were the employees in different departments involved with tooling, such as tooling design departments, tooling manufacturing workshops and the user workshops.

The questionnaire comprised four parts and contains 24 questions. There were four types of questions: Likert scale questions (Allen and Seaman, 2007), yes/no questions, multiple-choice questions and one open question. These questions were timed to be completed in 20 minutes.

Firstly, there were three general questions aiming to verify the respondents' quality and discover whether it is necessary to develop this lean framework. In the second and third sections, three questions on CE and seven questions on Knowledge-Based Environment (KBE) were designed to collect information. In the last section, eleven questions about lean tools were designed to discover whether they had been applied and how efficient these tools were. Figure 4-1 illustrates the questionnaire structure.

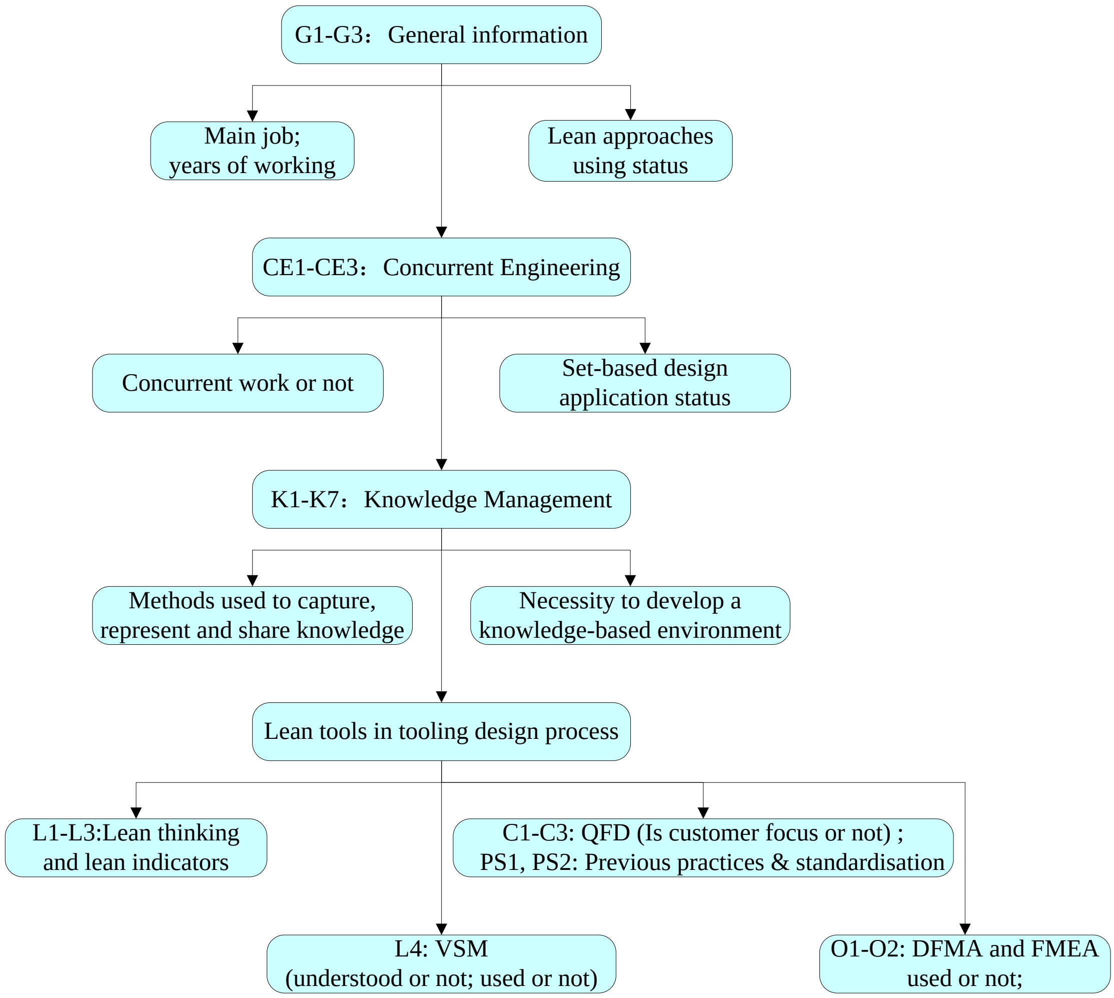


Figure 4-1: Questionnaire structure

The respondents are all Chinese. Therefore, the questionnaire was designed in two versions: Chinese and English. The English version is attached in Appendix A, but the Chinese version is not included in this thesis. Two examples of the questions posed in this questionnaire are illustrated in Figure 4-2.

G3. Your company has used lean approaches in tooling design.

Yes	Not sure	No

If yes, please enumerate and comment on these lean approaches:

K7. It is important to have a knowledge-based environment to support tooling design process.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

Figure 4-2: Questionnaire examples

4.4 Data Analysis (Questionnaire)

The questionnaire answers and comments are presented in Appendix B. The results of each question are shown in a bar/pie chart.

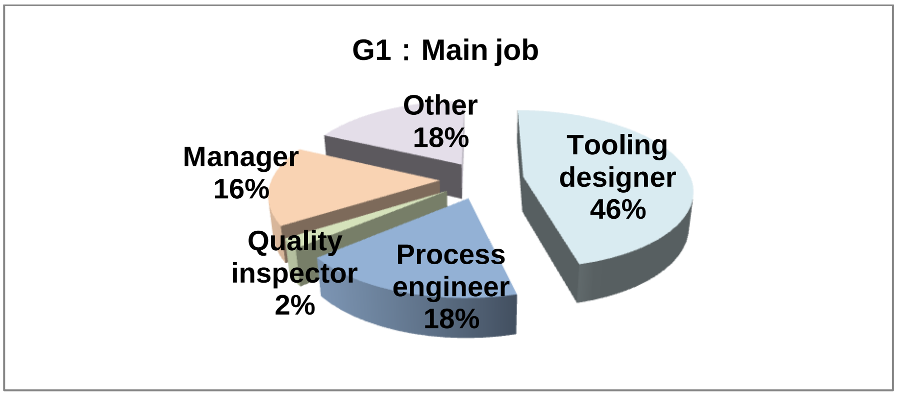
4.4.1 General Information

This investigation covers different departments involved with tooling design. Answers to questions G1, G2 indicated the level of respondents and how familiar they were with the tooling design process. G3 question was used to find what lean approaches had been applied in Company A.

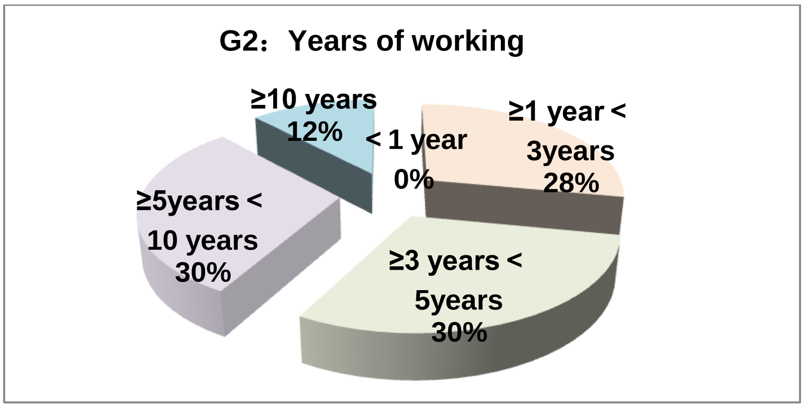
As illustrated in Figure 4-3-(a), there are 50 respondents from Company A who participated in this investigation, including tooling designers, process engineers (coming from fabrication workshop and customer workshop), managers from different departments, quality inspector and respondents who were particularly responsible for lean implementation in workshops.

Respondents who have long periods of working experience are more familiar with Company A's situation and problems. In this research, 72% of respondents have more than 3 years experience (see Figure 4-3-(b)), which means the collected questionnaire results can help show the real situation of tooling design in Company A and be used for the following analysis.

It can be seen from Figure 4-3-(c) that 36% (18) of respondents regarded that Company A had taken some lean measures in the tooling design stage. Those who answered "yes" to this question mentioned the lean approaches illustrated in Figure 4-4. It can be seen from Figure 4-4 that only 3 respondents mentioned standardisation, modularisation and FEA respectively. The methods of rapid design, DFMA and FMEA, and Six Sigma were just mentioned once respectively. Although these respondents believed that methods outlined in Figure 4-4 can help achieve a lean tooling design in Company A, G3 comments showed that these methods were not applied well and should be reinforced. The detailed G3 comments can be seen in Appendix B.



(a)



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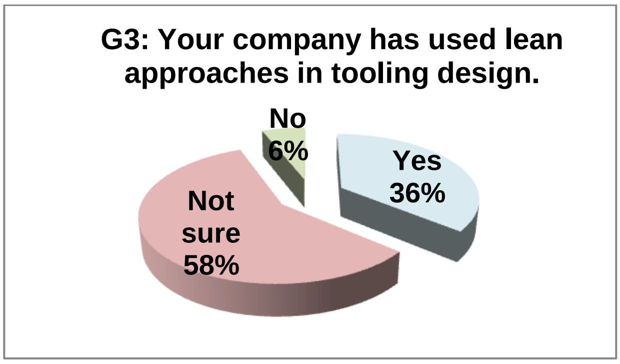


(c)

Figure 4-3: General information results

Lean approaches	Standardisation	Modularisation	FEA	Rapid design	DFMA & FMEA	6σ
Respondence	3	3	3	1	1	1

Figure 4-4: Lean approaches found in Company A

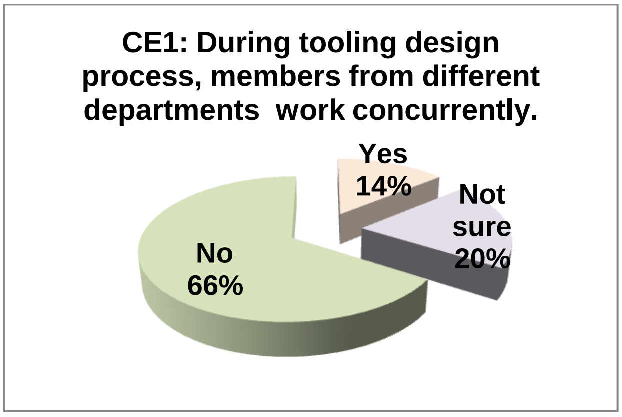
Conclusion: In terms of tooling design, Company A still lacked lean support. Few people were familiar with the commonly used lean design methods found in literature (such as QFD, DFMA and FMEA) and this company did not apply lean approaches in tooling design process broadly. Therefore, it is necessary to conduct this research to develop a lean framework.

4.4.2 CE in Company A

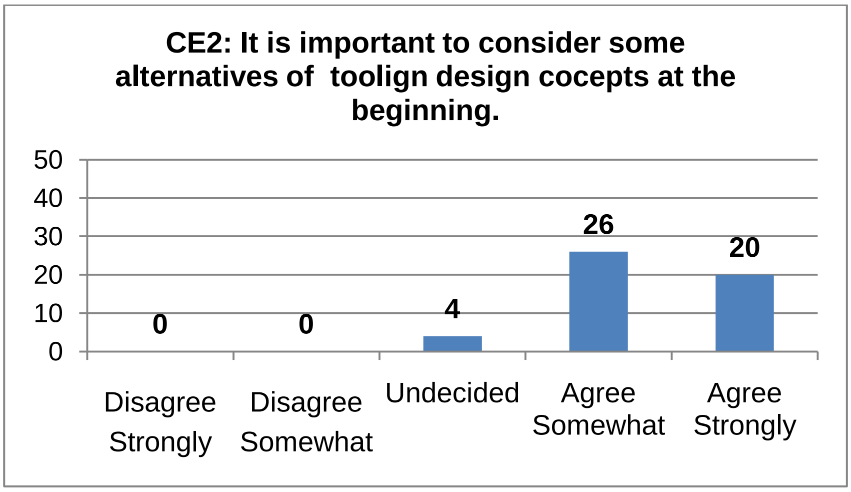
Questions CE1-CE3 aimed to discover how concurrent work operates in Company A and whether a set-based design method had been implemented.

Figure 4-5-(a) shows that there were only 14% (7) of respondents who selected “yes” to question CE1. Among the respondents who chose “no” and “not sure” to question CE1, 12 affirmed the importance of this collaborative working style and had a willingness to apply it in Company A (see A.2 CE1 in Appendix B). From their comments, it is found that members from different departments worked together when there were problems.

Figure 4-5-(b) shows that 92% (46) of respondents regarded set-based design as important, but only 24% (12) of respondents used this method during a tooling design process (Figure 4-5-(c)).



(a)



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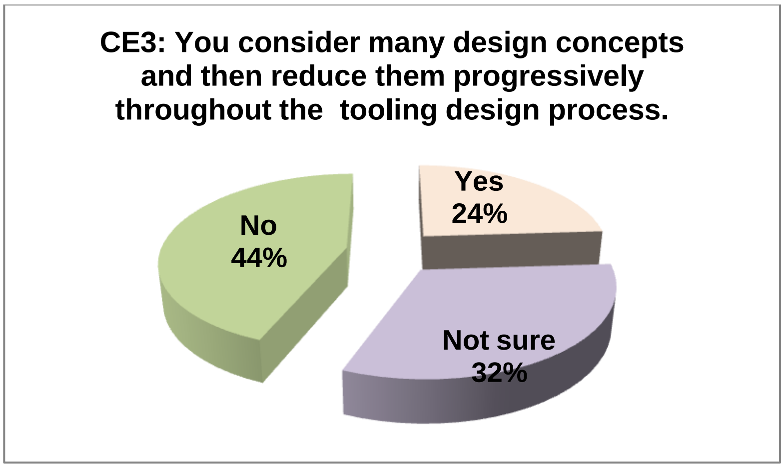


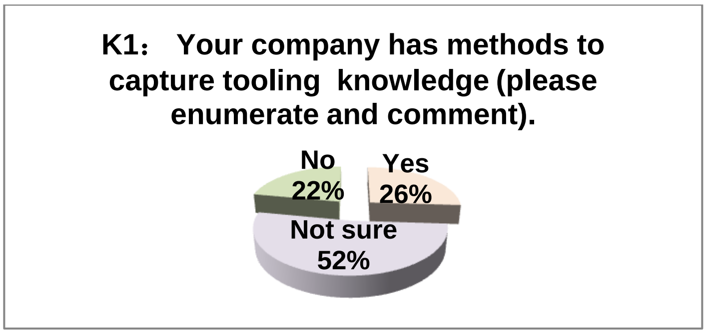
(c)

Figure 4-5: Concurrent Engineering (CE) questions results

Conclusion: In the tooling design process, concurrent design which can help shorten tooling development cycle time and improve communication efficiency did not work well in Company A. Set-based design was not widely used.

4.4.3 Tooling Knowledge Management in Company A

Due to the importance of knowledge in the tooling design process, questions in this part were designed to investigate how Company A deals with tooling knowledge. Answers to questions K1, K2 and K5 show the capturing, representing and sharing methods of tooling knowledge operating in Company A (see Table 4-1). From Table 4-1, it can be seen that Company A did not employ formal methods to manage tooling knowledge.



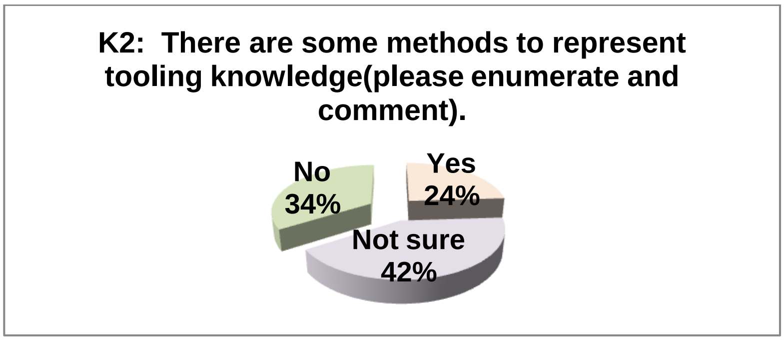
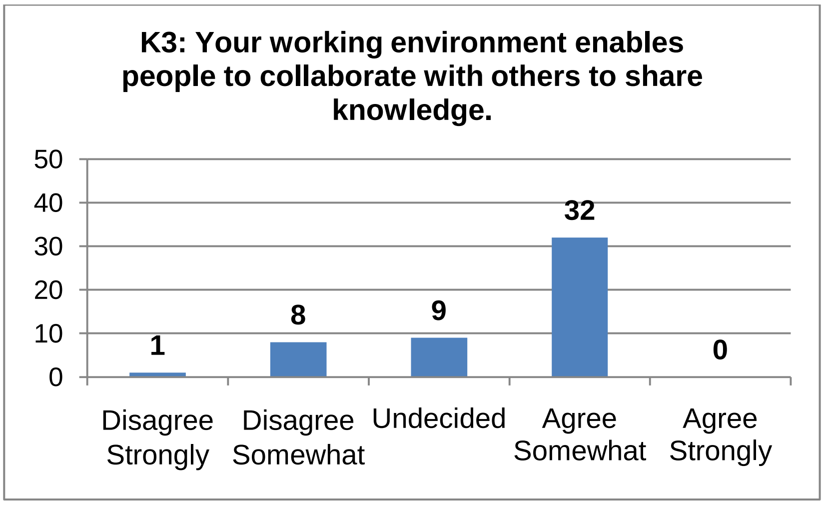


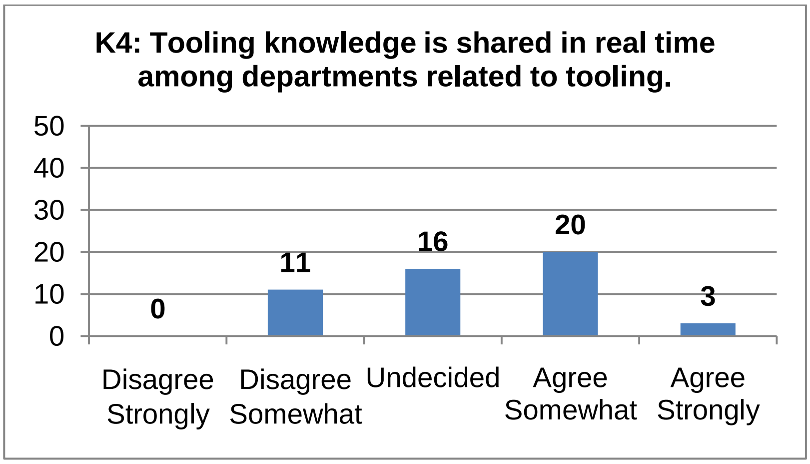
Table 4-1: Knowledge capturing, representing and sharing methods

Question	K1: Knowledge capturing methods	K2: Knowledge representing methods	K5: Knowledge sharing methods
Methods and mentioned times	1.Teaching by experienced engineers (4)	1. Platform (1)	1. Meeting (20)
	2. Training (5)	2. Training (5)	2. Platform (11)
	3.Standard parts database(2)	3. Meeting (2)	3. Training (10)
	4. Design handbook (3)		4. Shared folder (2)
	5. Meeting (1)		5. A3 (1)

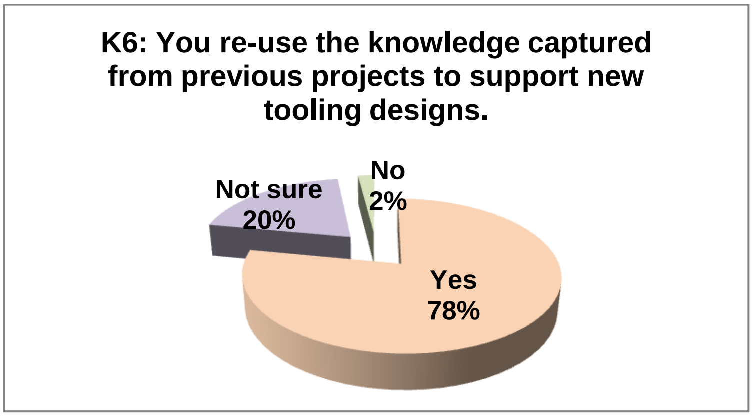
Figure 4-6-(a) indicates that 32 (64%) respondents demonstrated positive attitudes toward the working environment's role in supporting knowledge sharing. Figure 4-6-(b) illustrates that only 23 (46%) people regarded the knowledge sharing as timely. 78% of respondents re-used captured knowledge to aid new tooling designs (Figure 4-6-(c)) and affirmed its importance. 48 (96%) respondents agreed the importance of building a knowledge-based environment (Figure 4-6-(d)).


K3: Your working environment enables people to collaborate with others to share knowledge.
50
40
30
20
10
0
1
8
9
32
0
Disagree Strongly
Disagree Somewhat
Undecided
Agree Somewhat
Agree Strongly

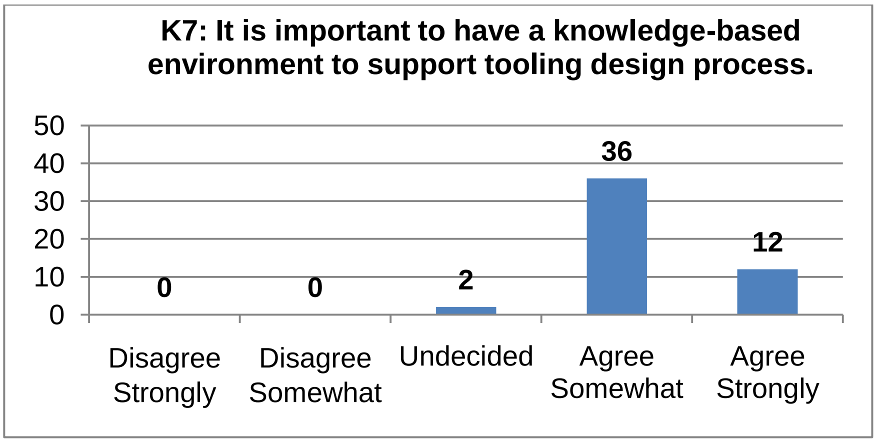
(a)


K4: Tooling knowledge is shared in real time among departments related to tooling.
50
40
30
20
10
0
0
11
16
20
3
Disagree Strongly
Disagree Somewhat
Undecided
Agree Somewhat
Agree Strongly

(b)


K6: You re-use the knowledge captured from previous projects to support new tooling designs.
Not sure 20%
No 2%
Yes 78%

(c)



(d)

Figure 4-6: Results of K3, K4, K6 and K7 questions

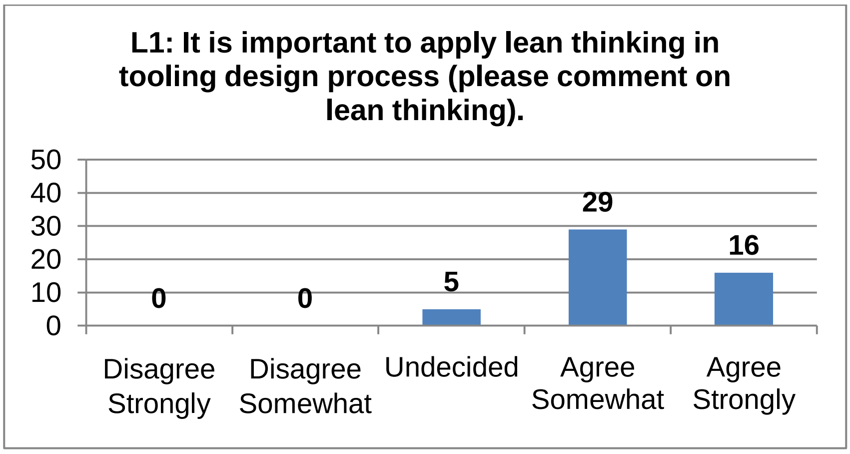
Conclusion: Table 4-1 and Figure 4-6 both show the deficiencies of Company A in managing tooling knowledge. Table 4-1 indicates that formal methods used to manage knowledge were not applied. Figure 4-6 illustrates clearly that the working environment did not enable knowledge sharing completely; tooling knowledge sharing promptness also requires enhancement. Respondents demonstrated that benefits can be gained from knowledge reuse, such as aiding a new design and increasing tooling design efficiency. Therefore, it is necessary to develop a knowledge-based environment for tooling design process.

4.4.4 Lean in Tooling Design Process

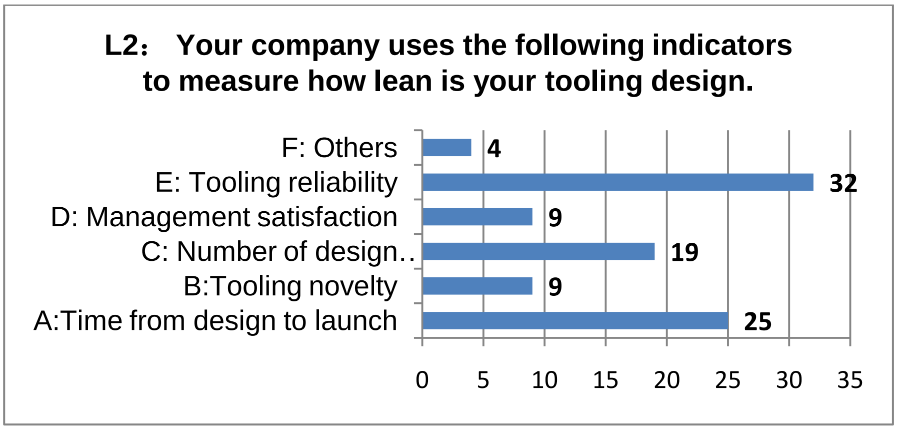
1. Lean thinking and lean indicators

The bar charts in Figure 4-7-(a) and (c) show that most respondents favoured the importance of lean thinking for tooling design process. However, comments in Appendix B indicate that people in Company A did not have a thorough understanding of lean thinking. There are 32 respondents who gave comments on lean thinking in question L1. Among them, only 1 respondent mentioned the consideration of customer requirements. 2 respondents gave comments which were not related to lean. For a lean tooling design, only 7 respondents showed that tooling manufacturability should be considered. 22 respondents only considered waste elimination, time and cost saving (see A.4-L1 in Appendix B).

The bar chart in Figure 4-7-(b) illustrates that although respondents answered this question according to the tooling design practice in Company A and affirmed the role of indicators in optimising tooling design, 19 respondents among 27 people who gave comments denied that Company A had lean indicators to measure lean for tooling design (see A.4-L2 in Appendix B).



(a)



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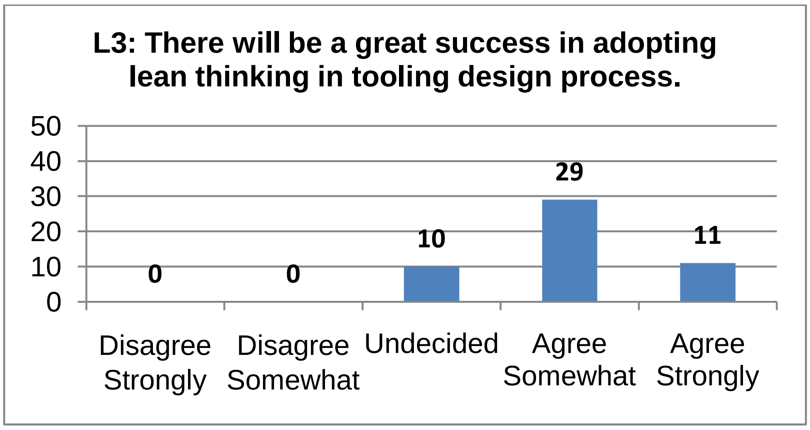


(c)

Figure 4-7: Lean thinking and lean indicators investigation

Conclusion: Respondents in Company A did not have a comprehensive understanding of lean thinking in terms of tooling design. They mainly focused on cost and time reduction and design efficiency increase which are lean manufacturing considerations and did not have methods to measure lean performance.

2. Value stream mapping tool for tooling development

Figure 4-8 illustrates that although 33 respondents showed agreement to this question, they did have a partial understanding about the importance of value stream mapping tool. Comments in A.4-L2 in Appendix B indicate that 10 respondents among 13 people who gave comments directly stated that Company A did not have this map.

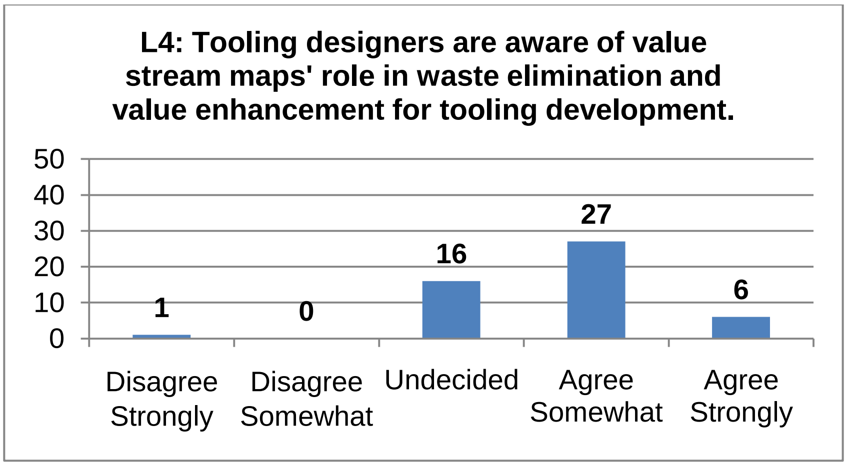


Figure 4-8: Value stream mapping tool for tooling development

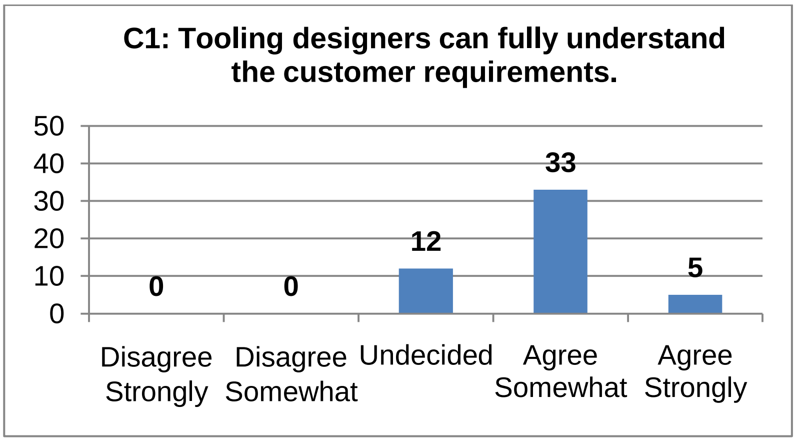
Conclusion: A value stream map can help describe all steps related to tooling development. At each stage, people can identify improvement opportunities. However, people in Company A have not yet realised the importance of value stream mapping for tooling development and thus have not implemented such a map.

4.4.5 Lean Design Tools

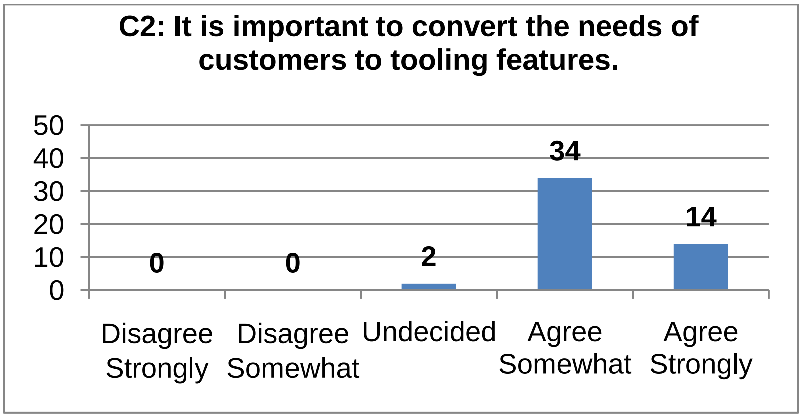
4.4.5.1 Customer requirements stage

This part is mainly used to determine 1) whether tooling designers are customer focused or not; and 2) whether QFD method has been used or not. The results can be seen in Figure 4-9.

Although nearly all (48) respondents knew the importance of customer focus (see Figure 4-9-(b)), all the respondents of the customer workshop and two thirds of respondents in fabrication workshop were not sure whether tooling designers can fully understand customer requirements (see C1 results in Appendix B). Figure 4-9-(c) shows that only 2 respondents thought Company A had applied QFD to tooling design.



(a)



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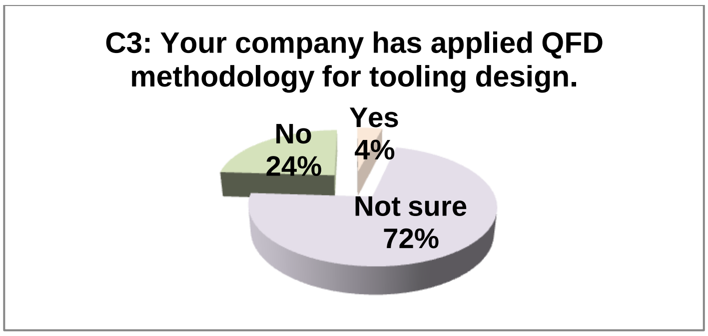


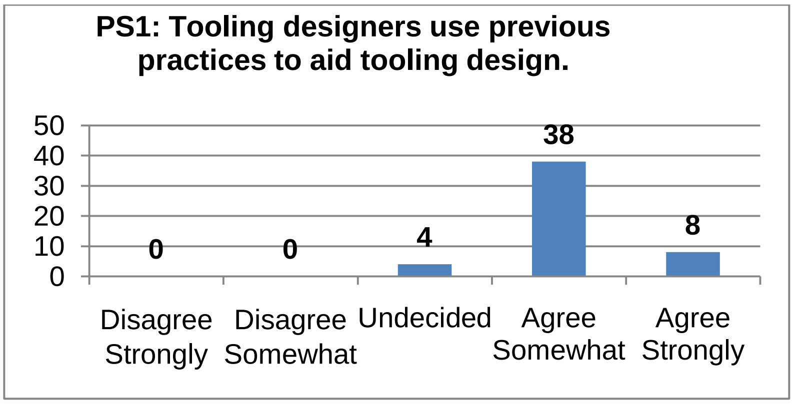
(c)

Figure 4-9: Results of customer stage questions

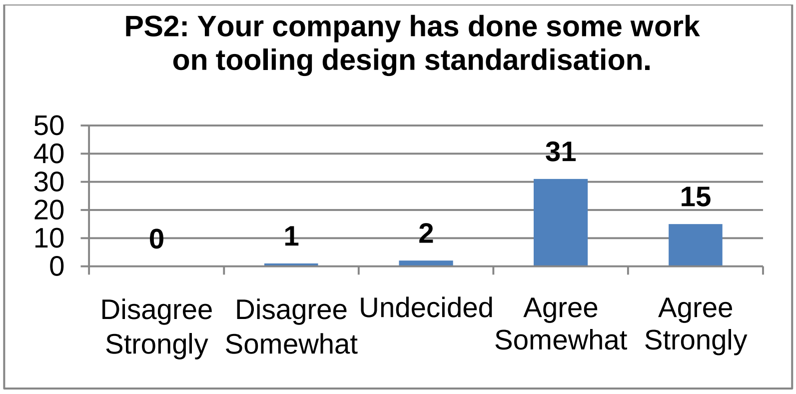
Conclusion: Tooling designers are not completely customer focused. QFD has not been widely applied in Company A.

4.4.5.2 The use of previous practices and standardisation

Figure 4-10 shows that previous design practices and standardisation methods have been applied in Company A. There are 18 respondents who gave comments about tooling design standardisation. However, they only focused on standardisation of tooling parts and components. Among them, 12 respondents suggested that standardisation should be improved, such as making the use of standardisation more universal and building or improving databases for tooling parts (see A.4.3.2 in Appendix B).



(a)



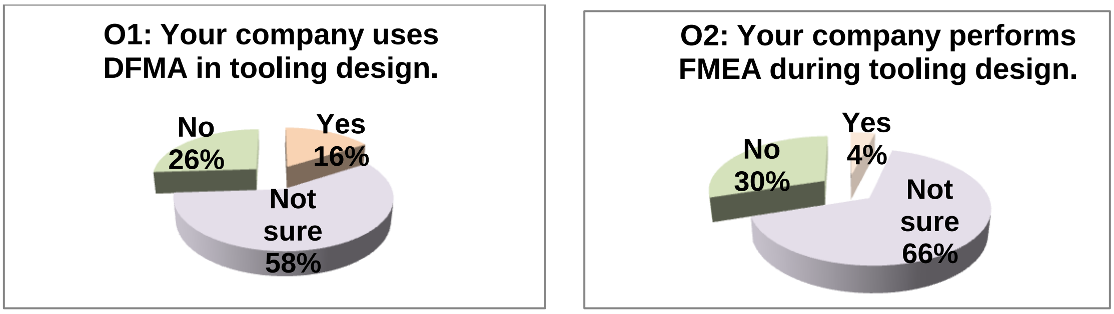
(b)

Figure 4-10: Previous practices and standardisation

Conclusion: Tooling design standardisation in Company A is restricted to tooling parts or components standardisation. Moreover, this kind of standardisation was not applied well and still needed improvement.

4.4.5.3 DFMA and FMEA

Figure 4-11 shows that only 8 people selected “yes” to question O1 and 2 respondents answered “yes” to question O2. However, although these people confirmed the use of DFMA and FMEA in Company A, they did not have a clear understanding about DFMA and FMEA. For example, in terms of DFMA, only two respondents mentioned the consideration of manufacturability during design stage.



(a) **(b)**

Figure 4-11: DFMA and FMEA using status

Conclusion: Company A did not implement DFMA and FMEA widely.

4.5 Summary

In order to have a clear understanding about the problems that exist and the status of lean implementation in the tooling design process in Company A, some findings from internal documents and questionnaires were summarised and presented in Table 4-2.

Table 4-2: Internal documents and questionnaire findings in Company A

Category	Question focus	Situation
Lean Status		Shop-floor level
Lean Knowledge	1. Lean thinking	Incomprehensive understanding
	2. Lean measurement in tooling design	1. Respondents not familiar with lean indicators; 2. No written criteria for lean measurement in tooling design.
	3. Lean design tools	1. Such lean design tools (VSM, QFD, DFMA, FMEA) not used widely. 2. Tooling parts standardisation not applied well.
Concurrent Engineering	1. Concurrent work	Separate work and follow a linear work flow;
	2. Communication	1. Not frequent and low efficiency; 2. Meeting held only when problems occur.
	3. Set-based design	Not used universally.
KBE	1.Tooling knowledge	No formal methods to capture, represent and share tooling knowledge.
	2. Working atmosphere for knowledge sharing	Not completely enabling knowledge share.
Necessity to develop this framework	Motivation to improve	High

Respondents from Company B and Company C did not provide enough comment while answering the questionnaire. Therefore, some aspects were difficult to capture, and are shown as blank in Table 4-3.

Table 4-3: Questionnaire results from Company B and Company C

Category	Question focus	Company B Situation	Company C Situation
Lean Status			
Lean Knowledge	1. Lean thinking	Incomprehensive understanding	Incomprehensive understanding
	2. Lean measurement in tooling design		
	3. Lean design tools	Most of them not known	Just FMEA been mentioned
Category	**Question focus**	**Company B Situation**	**Company C Situation**
CE	1. Concurrent work		
	2. Communication		
	3. Set-based design		
KBE	1.Tooling knowledge	No formal methods to capture, represent and share knowledge	No formal methods to capture, represent and share knowledge
	2.Working atmosphere	Enabling knowledge share	Enabling knowledge share
Necessity to develop this framework	Motivation to improve		

Therefore, it can be concluded that respondents from the three companies did not have a comprehensive understanding of lean knowledge, such as lean thinking and lean indicators. They focused on waste elimination and did not consider how to add value. Regarding the application of lean tools and methods, although standardisation had been adopted, its application was inconsistent. Most of the lean tools such as VSM for tooling development, QFD, DFMA and FMEA had not been widely used in these companies.

Tooling design requires information from the customer, designer, process engineer and manufacturing engineer. Concurrent engineering has been identified as a useful approach to allow functional teams to work together efficiently. However, there were no cross functional teams and communication efficiency still needed to be enhanced in Company A.

Tooling design is a knowledge-intensive activity. The experience and lessons learned from previous design projects can significantly influence new designs. However, tooling knowledge in Companies A, B and C was not well managed.

Although Company A concentrated on lean manufacturing and had not developed a specific lean model or framework for tooling design process, people in this company were interested in the concept and had a high expectation of the role of lean in the tooling design process.

5 Lean Framework Synthesis

5.1 Introduction

A lean framework for the tooling design process in Chinese aerospace is synthesised in this chapter, based on the identified factors influencing lean implementation in the literature review and information acquired from the questionnaire analysis. This chapter introduces how this framework is developed and details the elements this lean framework contains. Figure 5-1 illustrates the development flowchart of the lean framework.

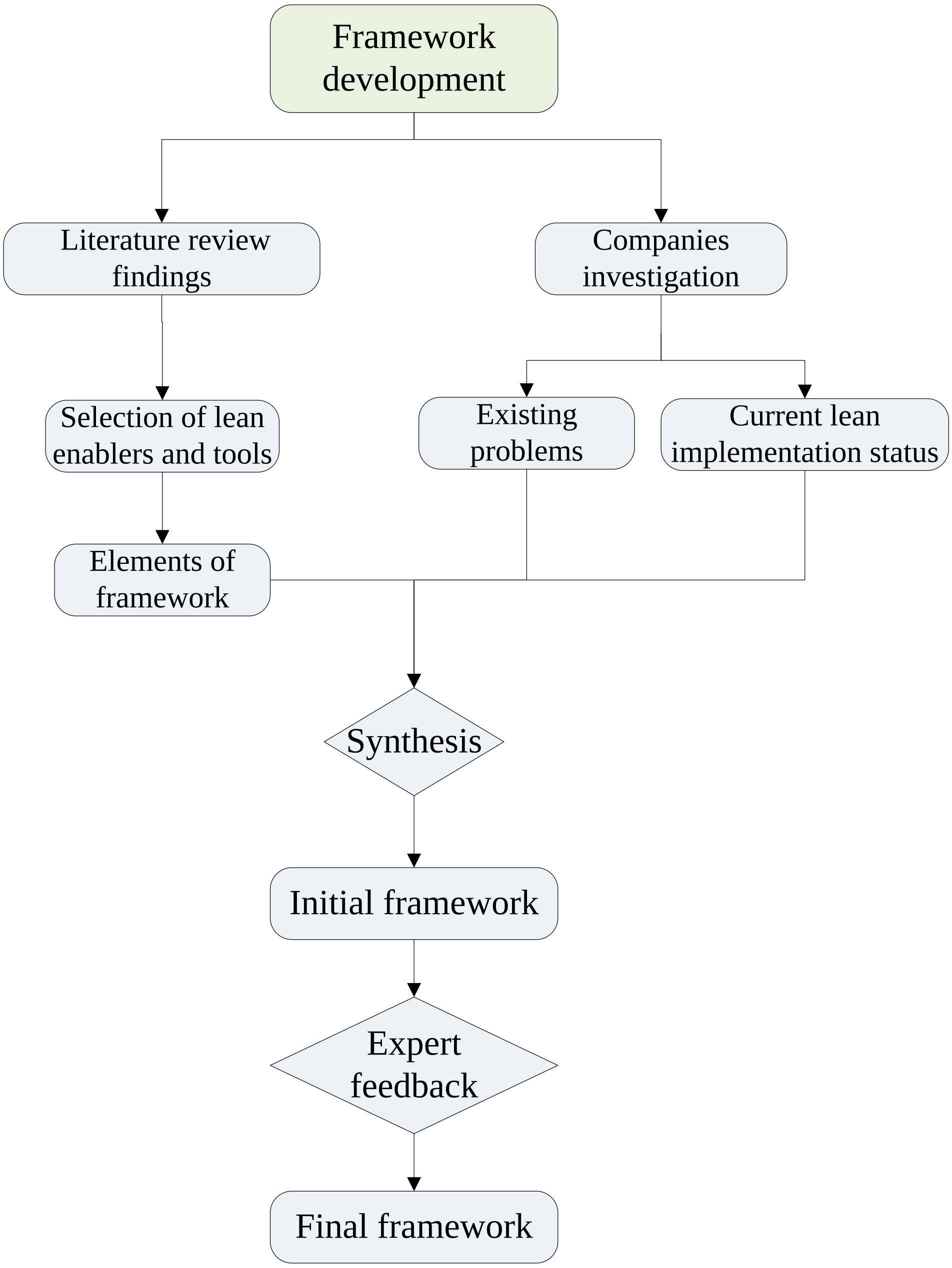


Figure 5-1: Framework development flowchart

5.2 Literature Review Finding

Figure 5-2 illustrates some critical factors influencing lean implementation found in lean models and frameworks in Chapter 2.4.3. Figure 5-2 suggests that besides the lean tools, leadership commitment and culture and people involvement are all critical for lean implementation. Concurrent engineering and knowledge environment are two core enablers for lean PD and lean PPD.

Key aspects / Author	Leadership	Culture	Process management	Employee engagement	Tools and techniques	Knowledge-focus	CE
Morgan and Liker (2006)	√	√	√	√	√	√	√
Dennis (2002)		√			√		
Convis (2001)		√(philosophy)		√	√		√(team work)
Hines et al (2004)		√(strategy)			√		
Li (2010)	√	√(strategy& goals)		√	√		
Hines et al (2008)	√	√(strategy& behaviour)	√	√	√		
Wan and Chen (2009)					√		
Ronald (2003)	√	√(strategy & vision)					
Womack et al (1990)	√						√(team work; communication; simultaneous development)
Karlsson and Ahlstrom (1996)		√(strategy)					√
Ward (2007)						√	√(SBCE)
Mague (2009)			√			√	√
Wurtemberg et al (2011)			√	√	√	√	√(cross-functional team)
Al-Ashaab et al (2011)		√				√	√
Khan et al (2011)	√	√				√	√(SBCE)

Figure 5-2: Key aspects for lean implementation

Therefore, two factors (leadership and culture), two enablers (concurrent engineering and knowledge environment) and selected lean design tools will be considered in this lean framework. Besides the lean design tools mentioned in Chapter 2.4.2.3 (such as QFD, DFMA and FMEA), standardisation, which is commonly used in Toyota's product design (Morgan and Liker, 2006) and applied in these three investigated companies, is also included.

5.3 Company Investigation Results

5.3.1 Data Analysis Results

Data results in Chapter 4 reveal some problems in some Chinese aircraft manufacturing companies. They are summarised in Table 5-1.

Table 5-1: Problems found in data collection

Problem 1	People have a weak lean knowledge background.
Problem 2	Members from different departments related to tooling design do not work concurrently. They follow a linear work flow. Communication between different departments is not smooth and efficiency is low.
Problem 3	In terms of tooling knowledge, there are no regulated methods to capture, represent and share it.
Problem 4	Some commonly used lean design tools such as QFD, DFMA, FMEA and VSM are not used broadly in the three investigated companies. Standardisation for tooling parts and components needs improvement.

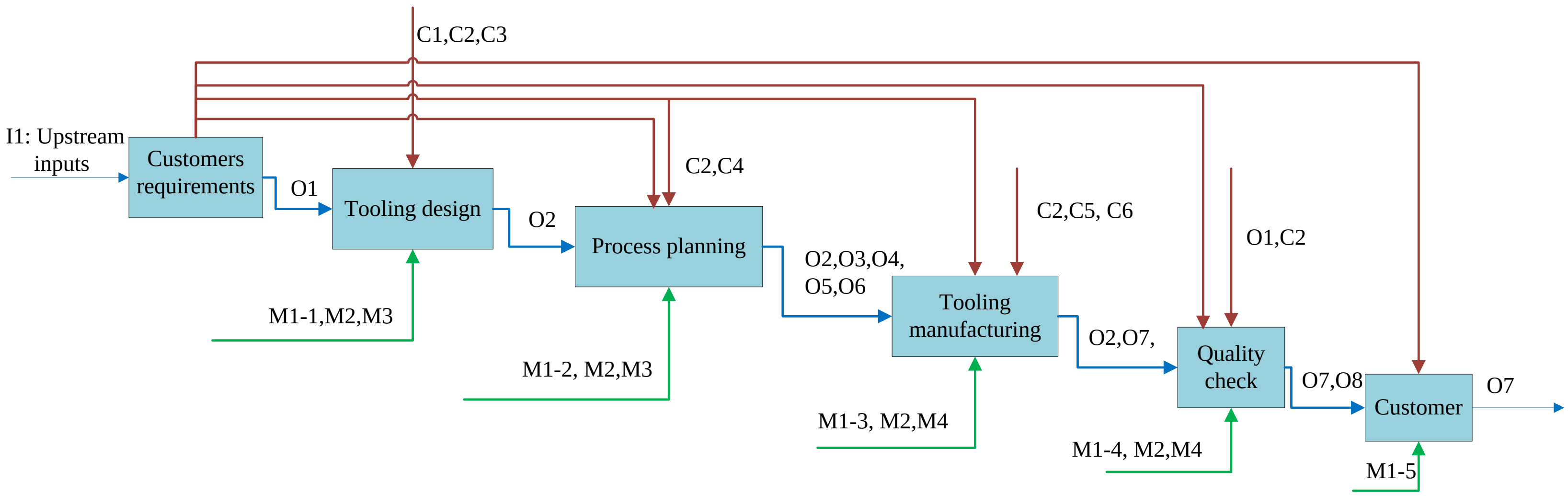
5.3.2 An IDEF0 Map for Tooling Development in Company A

Figure 5-3 below shows a flowchart of tooling development procedure. It also a flowchart of a tooling design process: it begins with the delivery of the customer requirements and ends when tooling is delivered to the customer.

This IDEF0 map is used to introduce two kinds of information. Firstly, it shows that the tooling design is not a separate process. It is related to downstream processes such as process planning, fabrication and quality check. It can be seen from this map that one output of tooling design-O2 (tooling drawings and 3D models) is the input of the three aforementioned processes. However, it seems that employees followed a linear flow which meant that process planning engineers and tooling manufacturing engineers began their work after tooling design drawings were delivered to them. This echoes with Problem 2 in Table 5-

1. Therefore, it is necessary to build an efficient concurrent work environment to improve this situation.

Secondly, this IDEF0 map can also help show the information and knowledge flow in tooling development. Previous tooling design practices can aid new tooling designs. Studies of eleven world-leading companies proved that a successful design process can deliver lessons or best practices to inform future design projects, including design ways, methods and some relevant design information (Design Council, 2007). However, in Company A, the final output of a tooling design process is tooling itself. The lessons learnt or best practices were not summarised. Therefore, the knowledge environment will be considered in this lean framework.



C1: Tooling design handbooks

C2: Company regulations

C3: Previous tooling design practices

C4: Process handbooks

C5: Material and fabrication specification

C6: Manufacturing capability

M1: Personnel: 1. designers & 2. process engineers & 3. fabrication engineers and workers & 4. quality engineers &5. customer

M2: Tools: CAD & CATIA software& others

M3: Internet & intranet

M4: Facility

O1: Tooling design order

O2: 2D drawings &3D models of tooling

O3: Tooling part process procedure

O4: Fabrication procedure

O5: Fabrication instruction

O6: NC code

O7: Final Tooling

O8: Validation report

Figure 5-3: An IDEF0 map for tooling development procedure in Company A

5.3.3 The Fishbone Diagram for a Lean Tooling Design

Figure 5-4 shows the elements which can help achieve a lean tooling design. In this diagram, the factors which need to be strengthened or added to Company A are marked in orange boxes. Under the branches of pink boxes, the purple sub-branches represent the elements existing in Company A that need improvement; whereas the red ones have not been implemented in Company A. Therefore, during framework development, the researcher found some methods to improve the purple elements and added some red ones to the lean framework.

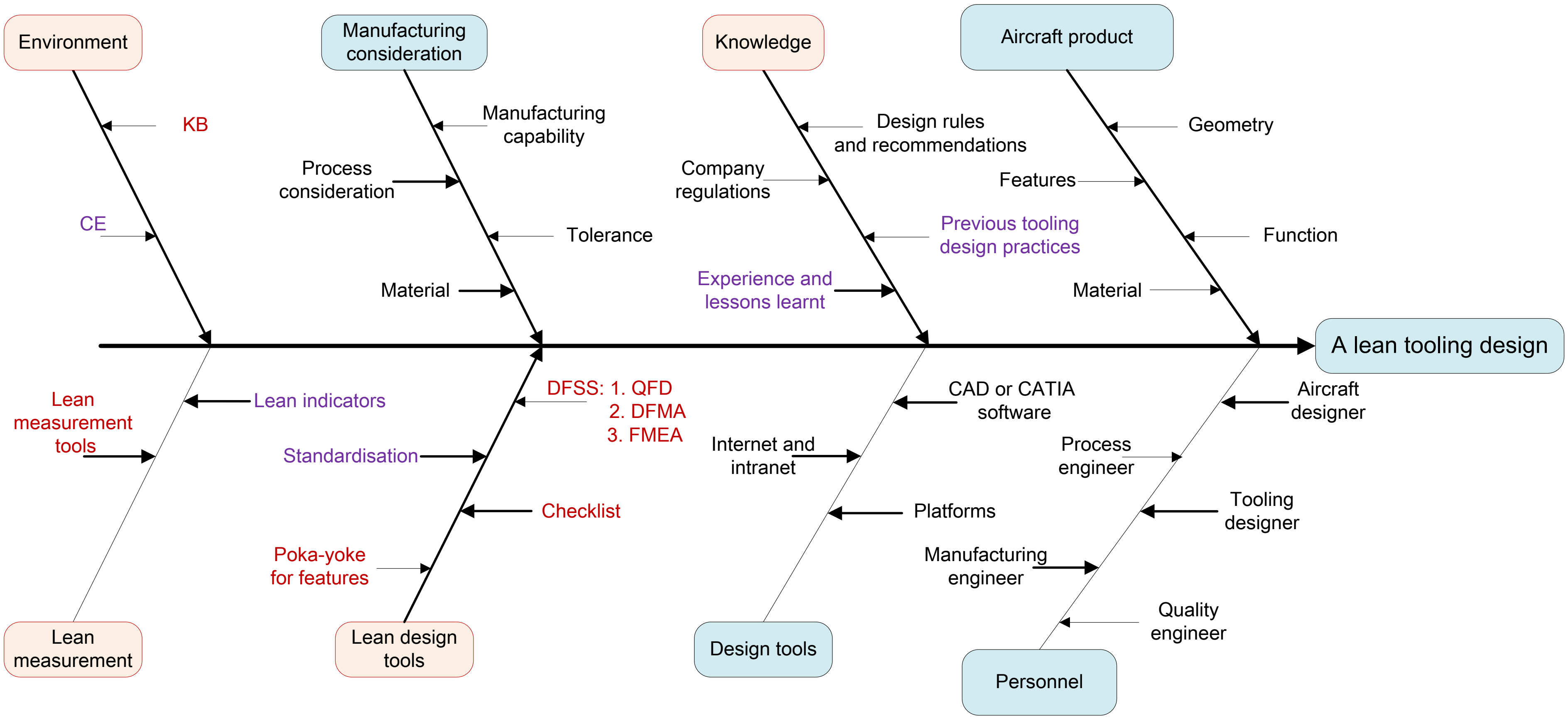


Figure 5-4: A fishbone diagram for a lean tooling design

5.4 The Lean Framework Synthesis

Based on the literature review findings (Figure 5-2), in order to solve problems in Table 5-1, improve the tooling design process in Figure 5-3, and perfect the corresponding elements in Figure 5-4, a lean framework will be developed in this chapter.

The IDEF0 map (Figure 5-3) and the fishbone diagram (Figure 5-4) illustrate the lack of tooling design process in case companies in respect of achieving lean, which is also the gap for the framework development. The lack mainly manifests in four aspects, which are lean knowledge gap, lean tools, CE and KB environment and lean measurement (see Figure 5-4). These aspects echo with problems found in data analysis results (see Table 5-1).

Achanga et al. (2006) presented four critical factors leading to a successful lean project: leadership and management, financial capabilities, skills and expertise of employees, and organisational culture. Among them, leadership and organisational culture echo with the findings in literature (Figure 5-2). The Design Council (2007) also stated that in order to achieve a successful design process, good leadership is required. Therefore, leadership and culture will be considered first in this framework synthesis.

5.4.1 Leadership

In China, employees are used to following leaders (Chen and Meng, 2010). Therefore, a leader’s attitude towards lean can influence employees’ enthusiasm for lean transformation. Therefore, the first step for lean change is the involvement of leaders.

The role of leaders in lean implementation in the tooling design process can be exerted by the following:

1) Give support to lean training and participate in the training (solving Problem 1 in Table 5-1 simultaneously).

2) Establish lean tooling design goals and plans for lean implementation, and commit to achieve them without stopping uncompleted;

3) Build lean implementation systems or procedures for tooling design process;

4) Encourage employees' involvement in all the lean transformation activities and establish employee incentive policies.

5.4.2 A Lean Tooling Design Culture

According to Baines et al. (2006), in western countries and Japan, lean has variations in terms of content and perspective. Western enterprises focus on lean by applying tools and techniques. However, in Japan, philosophy and culture are placed above other factors. At the heart of Lean PD in Toyota is culture change.

Culture is one of the key elements influencing lean implementation as shown in Figure 5-2. Culture can influence people's daily work and the rate of improvement. Chen and Meng (2010, p. 55) suggested that "culture change is the foundation for Chinese to really master the essence of lean production". Therefore, in this research, the researcher will build a lean tooling design culture.

The lean tooling design culture includes four aspects: 1) all the people involved share a common lean tooling design goal; 2) people are all customer-focused; 3) people commit to continuous improvement; 4) people understand job responsibility clearly. Developing a lean tooling design culture can be achieved by the company:

1. Conscientiously promoting lean management systems and making lean knowledge as the basic quality for employees. This can be achieved by lean training (solving Problem 1 in Table 5-1).

2. Setting up lean tooling design teams and launching activities of innovative improvement, with the aim of achieving continuous improvement.

3. Enhancing employees' awareness of responsibility and overall consciousness.

4. Promoting visual management during tooling design process.

5. Establishing a learning environment for employees (Good for tooling design knowledge sharing: one part of Problem 3 in Table 5-1).

Leadership commitment, senior management support and employee participation are the key factors influencing the development of a lean culture. Moreover, leaders play an important role in making decisions. Therefore, lean tooling design culture building should be conducted from top to bottom.

Lean culture development is a long-term task. Therefore, it runs through the whole lean framework implementation.

5.4.3 Environment Building

In this section, tooling concurrent design and tooling design knowledge-based environment are developed. The elements and enablers of each environment will be introduced as follows.

5.4.3.1 Tooling Concurrent Design Environment

1. The reasons for a tooling concurrent design environment consideration

Figure 5-3 and Problem 2 in Table 5-1 illustrates that members related to tooling design process in Company A follow a linear work and communication efficiency between them is low. This can lead to tooling redesign or rework if tooling cannot meet customer or manufacturing requirements. Eventually, tooling design time will be extended and waste will be generated.

In order to improve this situation, the company should facilitate earlier participation by downstream engineers in the work. Downstream engineers should start their work when the tooling design begins, thus enabling problems to be found and solved as early as possible. Moreover, Chapter 2.3.5.2 shows that regarding assembly tooling design, in order to reduce the tooling manufacturing cycle, some tooling components (such as some braces and pillars) should be fabricated before the tooling is finalised. Therefore, it is necessary to build a tooling concurrent design environment.

2. The enablers for a tooling concurrent design environment

Zhu (2001) listed four elements which comprise concurrent engineering, namely: 1) organisation; 2) communication; 3) requirements; and 4) product development processes. Based on these elements, there are five enablers for tooling concurrent design environment: 1) Team and teamwork technology; 2) Computer-aided collaborative environment; 3) QFD; 4) Tooling Process Design (TPD); and 5) DFMA.

(1). Team and teamwork

Integrated Project Team (IPT) will be first appointed. It is a cross-functional tooling team, consisting of members from different departments with relevant skills and experience, such as tooling designers, process and manufacturing engineers.

Patterns of communication among team members also play an important role in a cross-functional team. In this research, regular meetings as a coordination mechanism will be chosen to keep everyone informed and updated on the progress and status of tooling design, as well as to actualise a parallel process with contributions from different functions. Effective communication among team members can also guarantee knowledge sharing and re-use.

(2). Computer-aided collaborative environment

Team members of IPT are from different departments and different specialised fields. Therefore, it is necessary to build a computer-aided collaborative environment. This environment can help transfer the right message at the right time to the right persons and therefore make the correct decisions quickly. For tooling design, corresponding design and methodology databases also need to be built. These databases can help collect previous tooling design and management experience and reuse it.

In Company A, Product Data Management (PDM) system has been used to manage the information regarding the tooling life cycle and it is also a computer-supported platform for tooling-related engineers' cooperation. Therefore, PDM will be incorporated in this computer-aided collaborative environment.

(3). Quality Function Deployment (QFD)

QFD is an important lean tool for customer requirements gathering and analysis. It will be introduced in detail in Stage 3.

(4). Tooling Process Design (TPD)

Tooling process design here includes considerations such as whether the tooling process can add value or not and whether the process time can be shortened or not. TPD can help achieve process effectiveness and flexibility.

(5). Design for Manufacturing and Assembly (DFMA)

DFX is one of the enablers for concurrent engineering (Zhu, 2001). DFX includes DFA (Design for Assembly), DFC (Design for Cost), DFE (Design for Environment), DFIC (Design for Inspection and Testing), DFM (Design for

Manufacturing), DFP (Design for Productivity), DFQ (Design for Quality), DFR (Design for Recycle ability), DFSS (Design for Service ability and Support ability).

DFX aims to consider as many elements influencing product life cycle as possible. Therefore, problems existing at the design stage will be solved, thus avoiding product redesign in the later stages.

For tooling design, manufacturability and assemblability are comparatively important considerations; therefore, DFM and DFA are included in this part. DFM and DFA will be combined as DFMA to be introduced in stage 3.

In conclusion, with these five enablers, tooling concurrent design environment can be developed. This environment helps realise tooling's concurrent design, allows the sharing of incomplete information between different members in time and shortens the tooling design process time.

5.4.3.2 Tooling Design Knowledge-based Environment

1. The reasons for a tooling design knowledge-based environment consideration

Although knowledge is essential for the tooling design process (refer to Chapter 2.3.5.2), there are no formal methods to manage the knowledge in Company A (see Problems 3 in Table 5-1). Figure 5-3 also illustrates that a tooling design process in Company A ends with tooling itself without consideration of capturing best practices. However, these practices can help a new tooling design process. Therefore, developing a tooling design knowledge-based environment is another consideration in this framework.

2. The considerations of building a tooling knowledge-based environment

Sun (2011, p. 9) stated that "KM is about managing KLCs and their processes". Concerning KLC (Knowledge Life Cycle), Sun suggested three main stages: knowledge identification, capture and representation based on a comparison of different researchers. Rules are commonly used to capture and represent knowledge because they can be easily captured and applied to knowledge systems. Some rule-based approaches are composed by IF-THEN rules (Sun, 2011). Moreover, it is necessary to store captured knowledge from previous projects in databases where engineers and designers could refer to get help.

Therefore, rules and databases will be selected to help capture and represent tooling knowledge. A3 reports will be used to share tooling knowledge and information in this framework.

(1). Rule-based and case-based design process of tooling

Rules and databases have been identified as common tools to capture, represent and reuse knowledge. Therefore, the researcher incorporated these tools for tooling design in this framework. Figure 5-5 shows the relationship between tooling design and rules, case databases. The rule-based and case-based tooling design relates to the standardisation of tooling parts which can help enrich the standard parts/ components databases.

For a tooling design assignment, firstly a tooling designer retrieves cases from the case data-base according to the design requirements and rules, and then selects the most similar. After that, cases will be taken out of the data-base, and analysed and modified by the designer for a new design. Finally after completion of the detailed design, a new case will be obtained and saved in the case data-base for future use.

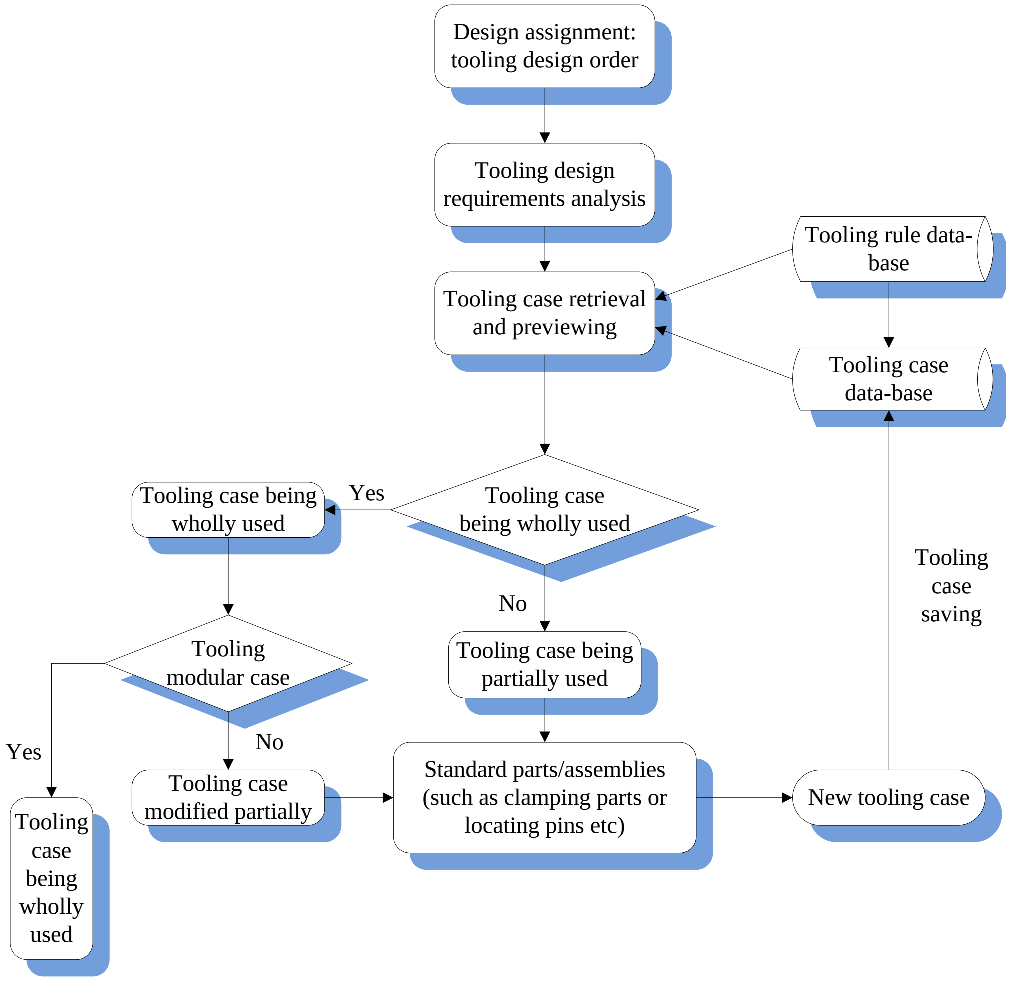


Figure 5-5: Rule-based and case-based tooling design process

Regarding the tooling process planning and tooling fabrication, corresponding case databases also can be built. Process planners and fabrication engineers can refer to them to help edit process sequence and program NC (Numerical Control) codes respectively. However, due to research time limitation, these rules and cases databases will be included in future work.

(2) A3 report

A3 report is defined because information is displayed on A3 size paper. Toyota has developed three kinds of A3 report related to different objectives, which are status, information sharing, problem report (Morgan and Liker, 2006, p. 270).

Writing an A3 report is regarded as a process of transferring knowledge from tacit to explicit. Therefore, it is much easier to share tooling knowledge using an A3 report within the company.

In terms of tooling design process, the A3 report will be tailored to document experience and lessons learnt from previous design process. It usually comprises the following contents: 1) problems generated during a tooling design process; 2) solutions; 3) lessons learnt (new design, fabrication methods, novelty); and 4) effective lean methods used. After one tooling design process ending, cross-functional team members noted the four contents. By using this visual knowledge sharing tool, employees related to the tooling design process will have a broad knowledge background in tooling design, material, heat treatment and fabrication. This can help reduce tooling redesign and rework rate.

5.4.4 Lean Design Tools Application

In this phase, under concurrent and knowledge-based environment, four commonly used lean design tools will be applied during the tooling design stage: standardisation and DFSS (QFD, DFMA and FMEA).

5.4.4.1 Tooling Design Standardisation

In TPDS, design standardisation is defined as "standardization of product/component design and architecture" (Morgan and Liker, 2006, p. 100). Tooling design standardisation refers to the standardisation of design methods and tooling parts or components.

1. (1) The design method standardisation means that for the same series of aircraft part or component, the design of a tooling will be regulated. These regulations will be documented or under the visual management. Tooling designers can refer to it when designing a fixture or jig for the same series of aircraft products. It can help different designers choose the similar locating or clamping type and design the similar tooling structure, which can simplify the work of tooling designers and fabrication engineers.

(2) The other standardisation means that composing elements of tooling (locating, clamping and supporting elements) are standardised and stored in a standard parts library. When tooling design orders are assigned, designers can download corresponding elements from the library and make changes. This library will be established in CATIA and CAD design platforms initially.

2. A case study for tooling design standardisation

There is a case study illustrating these two kinds of tooling design standardisation. A vacuum milling fixture for aircraft ribs manufacturing was chosen to display how such standardisation influences tooling design, process planning and tooling fabrication.

Regarding the height of the pad of the supporting base in Figure 5-6, if there is no standardisation, different designers would choose different values. Therefore, in order to avoid this situation, the height should be regulated as a fixed value (30mm) for the same series of aircraft ribs. Tooling designers can refer to this when designing a new tooling.

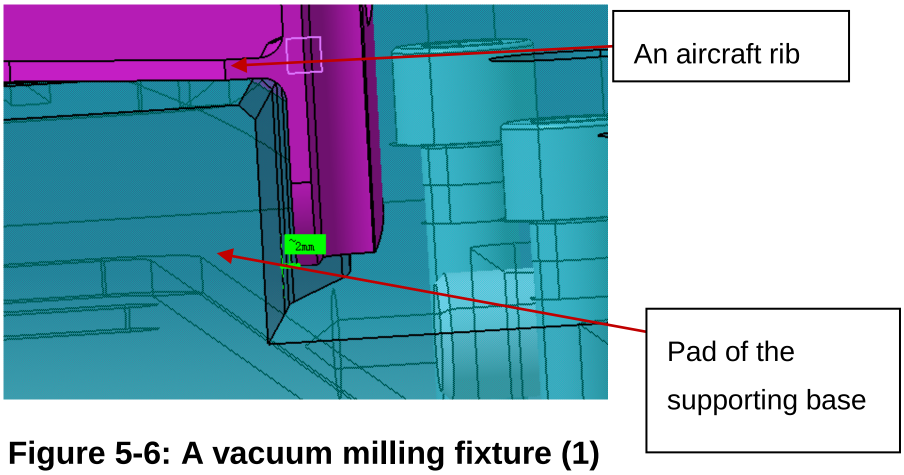


Figure 5-6: A vacuum milling fixture (1)

Figure 5-7 shows two kinds of sealed grooves: A and B. In this case, the distance between “Sealed groove A” and “Border of the supporting base” is fixed as 4mm. Regarding sealed grooves of B type, the horizontal or perpendicular distances between two of the B type sealed grooves are also designed equally, which can decrease the workload of process engineers (such as the NC programming).

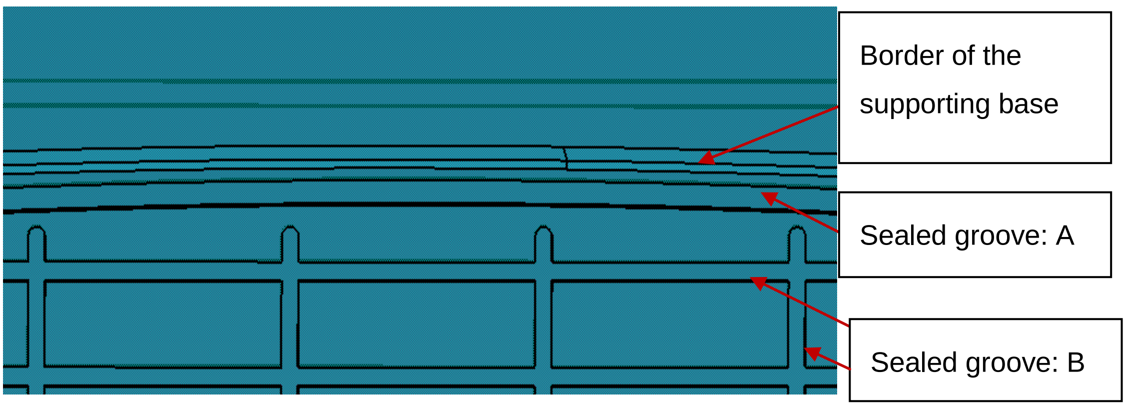


Figure 5-7: A vacuum milling fixture (2)

Figure 5-6 and 5-7 explains the tooling design method and tooling parts standardisation. In Company A, for a specific kind of tooling (such as vacuum milling fixtures), different designers choose different supporting base dimensions or clamping elements although the aircraft parts have a similar profile. This can unnecessarily add to the working time of designers, process engineers and fabrication workers. In order to avoid such kind of time waste, it is necessary to standardise the design method and elements of tooling.

In conclusion, by using these two kinds of standardisation, design and manufacturing time and cost can be reduced. Without them, tooling designers have to spend much time repeating tooling model building. Concerning tooling fabrication, these two kinds of standardisation also can contribute to selecting the machine cutter with the same parameters and avoid unnecessary cutters change and guarantee process continuity.

5.4.4.2 DFSS

Regarding DFSS, it is applied at the early stages of product development. Yang (2010) stated that for different design stages, different DFSS tools are adopted.

1. Quality Function Deployment (QFD)

The key to implementing QFD is: 1) to prioritise customer requirements; and 2) to transform customer requirements to specific technical and quality control requirements (CIRI, 2008). As a customer-driven product development managing method, QFD is also a quality management tool achieved by the cooperation of cross-functional teams. QFD deploys the customer requirements to design process, and guarantees product design and manufacturing to meet customer requirements. By building multidisciplinary teams, QFD can also help combine different functional teams to different stages of product development (Chan and Wu, 2002).

For different products, in order to allocate customer requirements and deploy them to each process of product development, different QFD decomposition models are needed. With regard to tooling development, a QFD with four decomposition houses of quality is illustrated in Figure 5-8. It shows customer requirements to be the basic input for QFD. The requirements first need to be collected and analysed. The requirements are then deployed gradually and converted to tooling technical requirements, to key parts characteristics, to key process and fabrication requirements. During the process deployment, the output of the previous step is the input of the next step. After these four steps, requirements can be deployed to the whole tooling development.

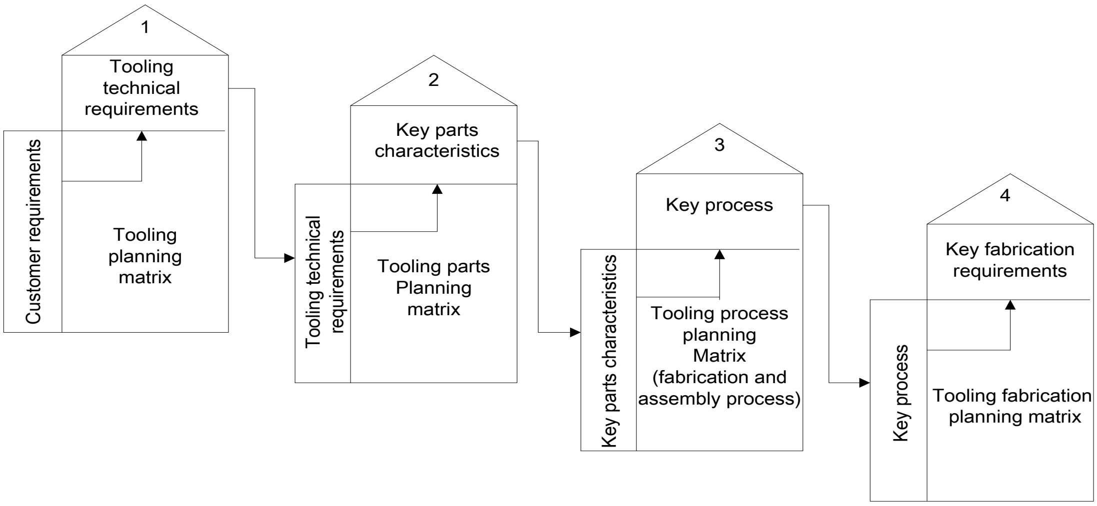


Figure 5-8: QFD decomposition models for tooling

Therefore, by using QFD, tooling design quality can be guaranteed and the tooling fabrication also can meet the customer requirements. In QFD, collaboration between different departments is needed, thereby demonstrating the necessity of building a concurrent environment. QFD also can strengthen this environment during the tooling design process.

2. Design for Manufacturing and Assembly (DFMA)

DFMA can help tooling designers consider the downstream concerns as early as possible. It is an important tool for achieving lean design.

Figure 5-9 presents the procedure and procedural considerations of DFMA. Prior to analysis, four tooling databases (design feature database, fabrication feature database, fabrication process database and assembly feature database) and DFMA evaluation system should be established. Databases are featured, as Yang et al. (2004) stated they can help achieve a good visualisation and can be the public information arena for different stages of product development (design, process planning and fabrication).

The analysis should be conducted based on databases. During tooling manufacturability analysis, fabrication routing, manufacturing methods and cost evaluation, and company equipment reliability will be considered. The tooling assembly analysis should include both part level factors and assembly factors. Completion of the analysis will generate a report to be checked by the evaluation system. If the results meet the requirements, fabrication process planning can continue, otherwise tooling will be redesigned.

Moreover, under tooling concurrent design environment, based on DFMA, tooling designers and manufacturing engineers can cooperate to optimise tooling design and avoid problems early.

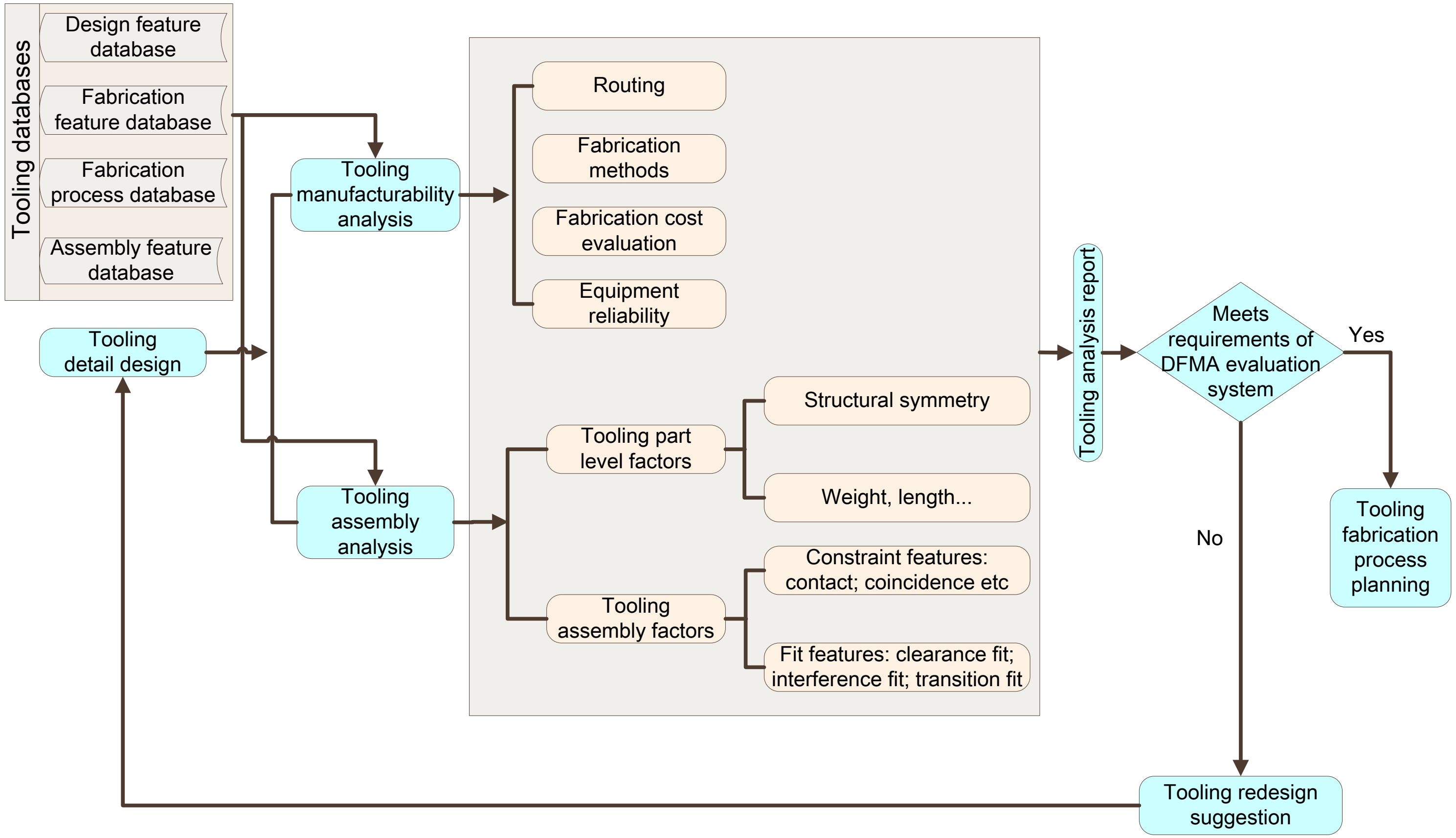


Figure 5-9: Considerations in tooling's DFMA analysis

According to Crow (2007), by comparing with a traditional approach, Figure 5-10 illustrates that the combination of CE and DFMA (which are considered to be the key elements of lean design) can impact a product development schedule to a large extent (see the lower bar). For example, in Figure 5-10, time of 'Build, Test, Fix Redesign Iterations' can be reduced from 55% to 22%. Therefore, it is obvious that the combination of tooling concurrent design environment and DFMA in this framework can also significantly reduce tooling design process time.

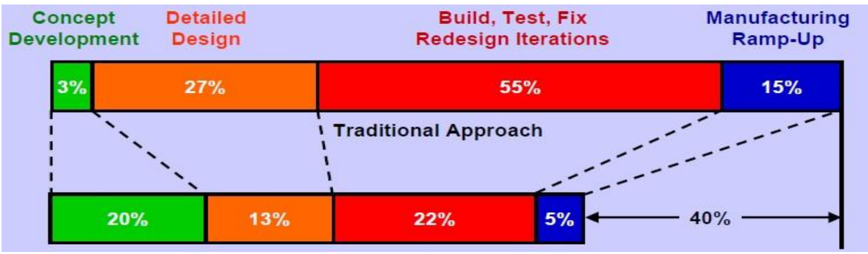
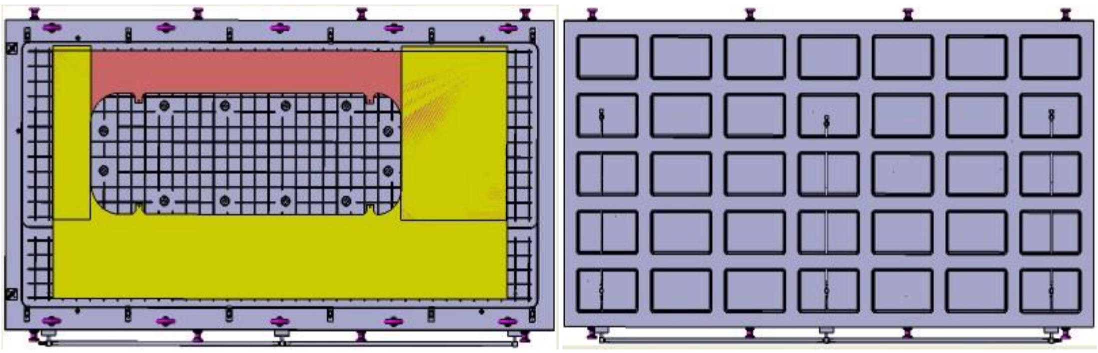


Figure 5-10: The influence of CE and DFMA in development schedule (Crow, 2007)

3. Failure Mode and Effects Analysis (FMEA)

The Design Council (2007) stated that FMEA can help identify and eliminate the risks during a design process. As mentioned previously, there are four levels of FMEA, but in this research, the FMEA is restricted to the design level. In the following section, a vacuum milling fixture in Figure 5-11 was chosen as an example to illustrate the use of FMEA in the tooling design phase.



(a) (b)

Figure 5-11: A vacuum milling fixture for aircraft skin manufacturing (a: top view; b: bottom view)

Table 5-2: FMEA used for a vacuum milling fixture

Function	Potential Failure Mode	Potential Effects of Failure Mode	Potential Cause(s) of Failure Mode	Current Design Controls	Corrective/Preventive Actions	Responsible People/ Date
Help mill aircraft skins	Lack of absorbability	▪ Aircraft skins cannot be absorbed during the milling process. ▪ The milling machine may be broken.	▪Insufficient absorbed area. ▪ Small vacuum degree. ▪ Leakage of the pipeline.	Tooling design reviews	▪ Design referring to design books/ experience of skilled designers/ similar previous successful design practices. ▪ Absorbability proof. ▪ Seal the pipeline according to guidelines and do test/ experiment.	Tooling designer A

Table 5-2 illustrates a modified FMEA with a common failure mode for the vacuum fixture in Figure 5-11. By sharing this, designers and manufacturing workers can consider the potential risks and find corresponding ways to avoid them. By using FMEA during the tooling design stage, the risk of tooling failure can be reduced. FMEA used in the tooling design stage is also advantageous as it helps:

1) Balance tooling design requirements and design proposals;

2) Decide tooling manufacturing and assembly requirements;

3) Provide information for the establishment of tooling experiment plan;

4) Provide a reference for the analysis of an actual situation of tooling use, the assessment of tooling rework and the development of advanced tooling design.

To conclude, shortage of lean tools (Problem 4 in Table 5-1) for tooling design in Company A is filled by standardisation, QFD, DFMA and FMEA. Therefore, lean tooling design teams can apply these tools to aid a tooling design project.

5.4.5 The Final Lean Framework

Morgan and Liker (2006) suggested a lean transformation roadmap, which emphasises the importance of lean preparation, lean tools application, lean projects pilots building and lean sustainment. Hines et al. (2008) also suggested milestones of lean maturity, including five stages which can be seen in Figure 5-12.

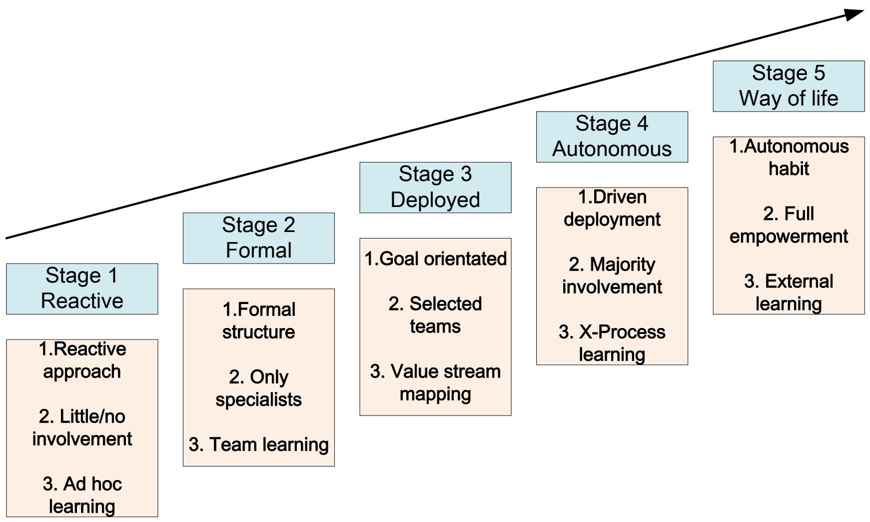


Figure 5-12: The milestones of lean maturity (Hines et al., 2008)

Based on the lean roadmap, lean maturity milestones and according to the tooling design situation in case companies, in this section, Figure 5-13 summarises the elements mentioned in Chapters 5.4.1-5.4.3 and displays the framework with four stages. Figure 5-13 illustrates that the lean framework has four stages with leadership and lean tooling design culture at both sides. Each element composing the lean framework is introduced as follows.

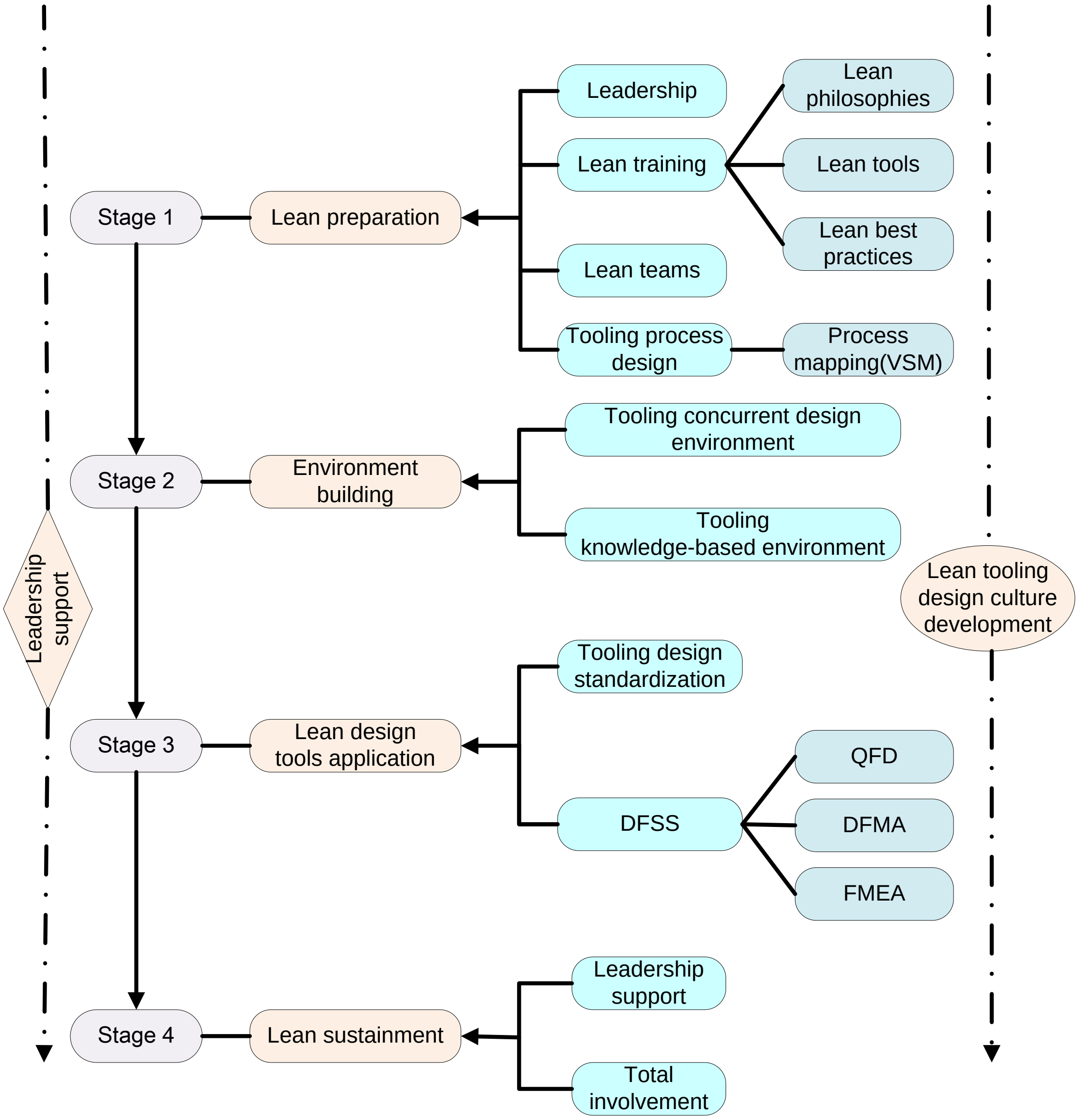


Figure 5-13: The final lean framework for tooling design process

Stage 1: Lean Preparation

Due to the weak lean knowledge background, the first stage for the framework is lean preparation. In this stage, a leader with an ambition to undertake a lean transformation and with lean knowledge background should be selected first.

Then, under this leader's support, people's awareness of lean should be heightened. Lean training, which includes lean philosophies, lean tools and techniques, lean practices and lean case studies, is beneficial to establishing such awareness and the training must involve all the people related to the tooling design process. Following this training, the lean goals are oriented and lean teams are selected.

The process design stands out in literature review as a driver of lean culture development (Atkinson, 2010).Therefore, tooling process design should be initiated at this stage. VSM as a tool to improve value stream can be used to help find process improvement opportunities, including mapping the current state, finding improvement opportunities and forecasting future direction.

Stage 2: Environment building

After the awareness being built, at second stage, tooling concurrent design and tooling knowledge-based environment are developed. Elements of each environment have displayed in Chapter 5.4.3.

Stage 3: Lean design tools application

In this stage, the lean team chooses a tooling design project to employ the supportive tools mentioned in Chapter 5.4.4. Chapter 5.4.4 has also introduced how to use these tools

Stage 4: Lean sustainment

In the final stage, leadership dominates this sustainment. With consistent leadership support, all members related to the tooling design process are empowered to get involved in continuous improvement. Employees who gain lean achievement for tooling design or put forward good lean suggestions should be given corresponding incentive bonuses. Employee enthusiasm about lean should be maintained unless lean becomes a habit and part of the organisational culture.

5.5 Summary

This chapter introduced the development procedure and elements of the lean framework. This framework is developed based on a literature review and company survey findings and aims to improve the tooling design process.

6 Validation of the Lean Framework

6.1 Introduction

This chapter illustrates how the lean framework is validated. It includes two validation stages: an initial validation and a final validation. The structure of this chapter is as follows: Sections 6.2 and 6.3 respectively introduce the validation methodologies for two stages. Section 6.4 summarises the whole chapter.

6.2 Initial Validation

Before the lean framework (Figure 5-5) is finalised, an initial framework was generated. The researcher invited an academic expert to validate this initial framework and share some lean knowledge which in turn could aid the refinement of the framework.

This academic expert who is from Cranfield University has rich experience in lean. He is an active researcher in the following areas: collaborative product development, concurrent engineering, knowledge-based engineering and lean product development. His research projects have a strong focus on industrial applications. He has published around 30 research papers in major international journals and internationally refereed conferences as the researcher/co-researcher.

An interview was undertaken as part of this validation. There are few lean tooling design frameworks in literature. Therefore, the perspective of the academic expert is sought to enhance the framework developed in this research. After analysing the suggestions from the expert, the initial lean framework in Figure 6-1 was modified and the new framework shown in Figure 5-5 was achieved.

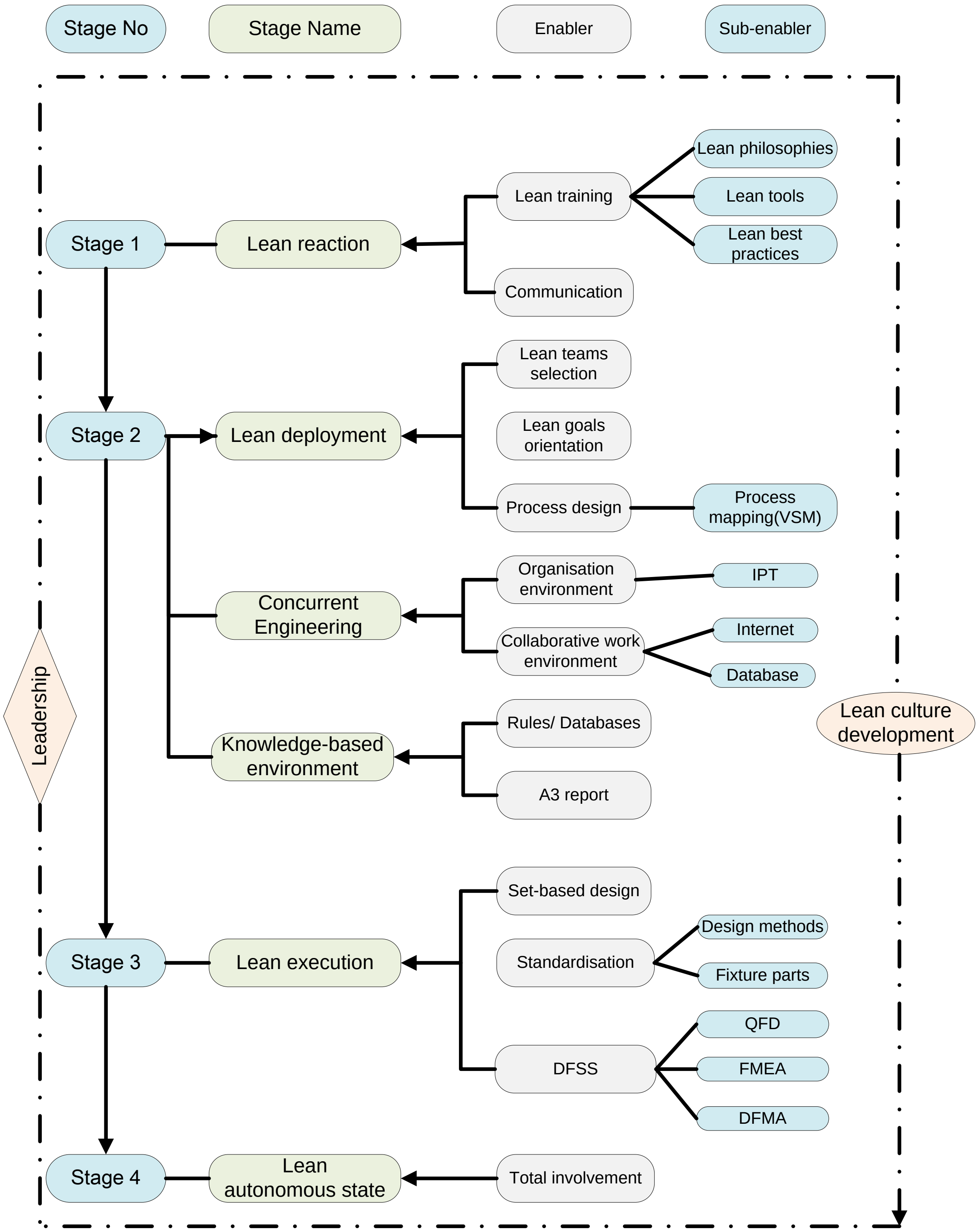


Figure 6-1: The initial lean framework for tooling design process

6.2.1 Interview Contents

Five questions were asked during this interview. These questions focused on elements and lean tools contributing to lean design, and methods for developing CE and KBE. The expert also provided some suggestions to improve the initial framework (Figure 6-1).

6.2.2 Interview Results

Four interview results are summarised as follows. The detailed interview questions, answers and suggestions are included in Appendix C.

Result 1: In order to achieve a lean tooling design, this expert suggested the following: 1) the importance of maximising customer value by converting customer requirements into tooling features; 2) the considerations of tooling manufacturability, assemblability and lean manufacturing.

Result 2: In terms of lean tools for product design, DFM, DFA, FMEA, Robust design, Poka-yoke for features and knowledge environment were suggested.

Result 3: Regarding knowledge-based environment, this expert suggested considering Knowledge Life Cycle (KLC) and finding methods to manage KLCs. Regarding CE for tooling design process, the expert advised paying attention to improvement of communication efficiency between tooling designers and fabrication engineers.

Result 4: Some comments about the initial framework from the expert are summarised as follows:

1) This framework needs to be simplified.

2) It is better to map the tooling design process in Company A and use a fishbone diagram to show elements contributing to lean tooling design, which can help identify weaknesses in Company A.

3) CE should be considered in the conceptual design stage of the aircraft. Set-based design also should be a consideration of aircraft designers. It is relatively late to consider them at the tooling design stage.

6.2.3 Interview Results Analysis

The interview results illustrate some correlation between the expert and the researcher. For example, customer-focus and consideration for manufacturability, assemblability is important for lean design. DFM, DFA, FMEA, and knowledge management are suggested by the expert and are also included in the lean framework developed by the researcher. Therefore, these elements will be kept.

Regarding the initial framework, the researcher made some modifications which are:

1) In terms of the simplifications of the initial framework, some elements in stage 1 and stage 2 were regrouped. Moreover, some detailed information in stage 2 was removed.

2) An IDEF0 map for tooling development procedure in Figure 5-3 had been designed before the interview. A fishbone diagram for a lean tooling design is a good suggestion. Therefore, the researcher added a fishbone diagram to this thesis and found improvement opportunities for the tooling design process.

3) In terms of CE and set-based design, the researcher held a different opinion with the academic expert. Tooling as a product has similar development processes with aircraft. Therefore, CE and set-based design also can be used to aid tooling design. However, instead of CE, in this framework, a tooling concurrent design environment aiming to improve the communication efficiency between tooling design and some downstream processes, and shorten tooling development cycle is developed.

Concerning set-based design, many concepts should be considered at the beginning and with the final decision progressively reached. However, for tooling design, some small and simple fixtures can be finished in one or two weeks. The best design proposal can be decided in just one or two meetings. Therefore, it may not need set-based design for small fixtures. However, large and complicated jigs which take months to finish may benefit from this design method. Therefore, tooling designers can make the decision whether to use set-based design according to the tooling difficulty. There are two examples in Figure 6-2 and Figure 6-3 used to illustrate different complexity levels of the tooling design.

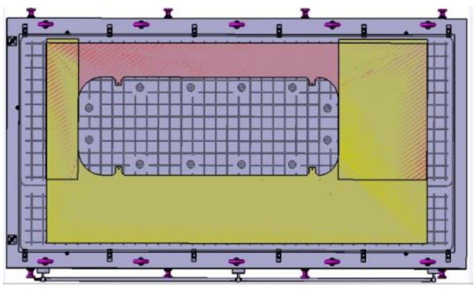


Figure 6-2: A vacuum milling fixture for aircraft skin manufacturing (simple)

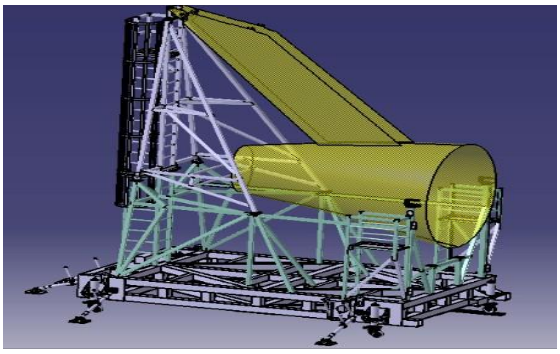


Figure 6-3: A jig for the assembly of cone and after fuselage (complicated)

In conclusion, the changes can be seen by comparing Figure 6-1 and Figure 5-5. After the initial validation and modification, the framework in Figure 5-5 will be validated in the following section.

6.3 Final Validation Methodology

There are three academic experts and three industry experts from Company A responsible for the final validation. These experts' information can be seen in Table 6-1 and Table 6-3 respectively. They were invited to participate in a questionnaire with some open-ended questions. Their feedback was acquired, analysed and used to refine the lean framework in Figure 5-5.

6.3.1 Validation Questions

These questions, aiming to discover the clarity, practicability of the framework and whether it needs improvements or not, were presented as follows:

(1) How understandable is this lean framework?

(2) How implementable is this lean framework?

(3) Based on your experience, what benefits will be received after implementing the lean framework?

(4) Based on your experience, how can this lean framework be improved?

6.3.2 Academic Expert Judgement

6.3.2.1 Academic Experts' Information

The three academic experts' expertise and achievements were illustrated in Table 6-1. Expert 1 and Expert 2 were familiar with product design process. Expert 3 had done research on process improvement.

Table 6-1: Academic experts' expertise and achievement

	Title	Main research field	University; published papers
Expert 1	Dr	Collaborative engineering; Product design and optimisation; CAD model about design retrieval and reuse; DFM	Zhejiang University; Nearly 100 academic papers
Expert 2	Dr	CE; Digital Design and Manufacture; Advanced manufacturing system; Research aiming at large aircraft engineering	Nanjing University of Aeronautics and Astronautics (NUAA); More than 80 academic papers
Expert 3	Dr	Manufacturing Engineering; Sustainable product development; Process improvement	Cranfield University; 8 papers and worked on industrial projects from Airbus and Rolls-Royce etc.

6.3.2.2 Validation Questionnaire Answers from Academic Experts

The researcher presented the lean framework in a meeting. These experts participated and answered the questionnaires.

Table 6-2: Questionnaire results from academic experts

Question 1. How understandable is this lean framework?
Expert 1: It is understandable.
Expert 2: This lean framework can be understood.
Expert 3: The framework is well structured and understandable.
Question 2. How implementable is the lean framework?
Expert 1: It could be implemented.
Expert 2: This framework can be implemented if people know CE, DFMA and so on.
Expert 3: It depends on the real tooling design situation. This lean framework can be implemented in companies which have similar tooling design processes and lean implementation status as the case company.

Question 3. Based on your experience, what benefits will be received after implementing the lean framework? Expert 1: It can help shorten tooling design time. Expert 2: Company can refine its tooling design process. Expert 3: It may help avoid tooling scraps. **Question 4. Based on your experience, how can this lean framework be improved?** Expert 1: It is better to take more characteristics of tooling design into account. Expert 2: It will be much better if there are some case studies. Expert 3: It is a little general.

6.3.2.3 Validation Results Analysis

According to the answers in Table 6-2, it can be seen that this framework has understandability, feasibility and also has potential to improve the tooling design process. Concerning the improvement suggestions from Expert 1 and Expert 3, in this framework, lean design tools (QFD, tooling design standardisation, DFMA, FMEA) were all customised for tooling design situation. Regarding the improvement suggestion of doing case studies from Expert 2, in this research, due to time limitation and also because lean is a long-term task, case studies should be included in future work.

6.3.3 Industry Expert Judgement

6.3.3.1 Industry Experts' Information

Table 6-3 introduces information about the three experts in Company A. They were familiar with tooling design and had a lean knowledge background.

Table 6-3: Industry experts' information

	Job title	Years in Company A
Expert 1	Director of tooling design department	About 15 years
Expert 2	Assistant of tooling design department	More than 10years
Expert 3	Tooling design supervisor	More than 6 years

6.3.3.2 Validation Questionnaire Answers from Industry Experts

Table 6-4 shows the industry experts' answers to the validation questions. A summary about the lean framework in Appendix D was given by three industry experts to support their comments.

Table 6-4: Questionnaire results from industry experts

Question 1. How understandable is the lean framework?
Expert 1: The framework can be understood easily.
Expert 2: It is easy to understand.
Expert 3: It has clear stages and it is reasonable and evidential.
Question 2. How implementable is the lean framework?
Expert 1: This framework can be applied in my company to help improve the tooling design process. It has feasibility and leaders in my company will give full support to lean transformation.
Expert 2: This lean framework can be implemented in my company. In terms of concurrent work environment and tooling knowledge environment, my company has a background.
Expert 3: It can be implemented in my company. My company is ready for a lean transformation. However, there are no formal and systematic methods or guidelines to help it. According to the lean framework, I believe that my company can follow it to achieve a lean tooling design process.
Question3. Based on your experience, what benefits will be received after implementing the lean framework?
Expert 1: It can help increase tooling design efficiency, reduce tooling rework and enhance team cohesion.
Expert 2: (1) It can help achieve tooling modular design. Tooling parts and components can be standardised.
(2) It can reduce tooling design and fabrication cycle time and cost.
(3) Tooling design quality can be improved and tooling rework can be avoided.

Expert 3: It can improve tooling design reliability, reduce quality problems and maintenance costs, and shorten tooling development cycle. More importantly, it can help develop a lean culture, which can change previous tooling design ideas and philosophy.

Question 4. Based on your experience, how can this lean framework be improved?

The comments about the lean framework from these three experts are summarised as follows:

1. In terms of stage 1 (lean preparation), they regarded VSM as an important tool for lean transformation, but it has not been applied in their company. They thought that improvement opportunities in tooling design should be found first. VSM can help achieve this aim. They posed a question about VSM, which is "whether VSM for tooling development is included in this research or not?".

2. Regarding stage 3 (lean tools application), the tooling design supervisor mentioned that tooling design standardisation also should include tooling design procedure standardisation. FEA (Finite Element Analysis) for tooling design was mentioned.

6.3.3.3 Industry Validation Results Analysis

Questionnaire results showed that the lean framework can be implemented in company A. Concerning the benefits after implementing this lean framework, a consensus that tooling design efficiency can be increased, rate of tooling rework and redesign can be reduced and tooling development cycle can be shortened, was reached by these three experts.

Regarding the question about whether corresponding VSM for tooling development is included in this research or not, the researcher replied that mapping the value stream for tooling development needs to be familiar with all the processes related to tooling development. Moreover, it needs the joint efforts of tooling designers, process and manufacturing engineers. This mapping also needs much time to conduct according to the real situation of tooling development. Therefore, VSM is just recommended as a method and this research does not include the detailed information.

Regarding the suggestion of tooling procedure standardisation, different tooling requires different design procedures. In terms of some complicated assembly jigs which bear much load (see Figure 6-3), design procedure should include FEA (Finite Element Analysis) to help analyse structure strength which can avoid tooling failure during aircraft assembly. However, design of some small drilling or milling fixtures (see Figure 6-2) does not need to include FEA. Therefore, different types of tooling (such as fixtures, jigs, mold tooling) require different standard design procedures. Without a broad knowledge of different tooling, it is hard to achieve this standardisation, but this can be included in the future work.

6.4 Summary

This chapter introduced two stages of validation. During these validations, the framework was refined. In the final validation stage, academic and industry experts both showed positive attitudes to the framework's clarity and feasibility and affirmed that some potential benefits can be realised after the framework implementation.

Due to research time limitation, some suggestions mentioned by these experts will be considered in future work such as developing a VSM for the tooling development processes and standardisation of the tooling design procedure.

7 Discussion

7.1 Introduction

This research developed a lean framework for the tooling design process in Chinese aerospace based on a literature review and data collection from three Chinese aircraft manufacturing companies. In this chapter, the researcher discusses the research and the research limitations.

7.2 Discussion

There is little published literature about improving the tooling design process by using lean techniques. Although there is little information available, the researcher developed an understanding how lean elements influence the design process, which could be used to facilitate the tooling design process.

A questionnaire was used to facilitate data collection. Respondents from three Chinese aircraft manufacturing companies were invited to participate in this questionnaire. The questionnaire was sent to respondents from different departments involved with the tooling design process. This provided a broad understanding of tooling design within Chinese aerospace. However, there was one disadvantage to this questionnaire approach. The questions posed were developed from findings in the literature review and mainly focused on lean tools implementation status. However, it would have been much better if the researcher had included real problems encountered in the tooling design processes by an on-site investigation. During data analysis, there was a difficulty in analysing questionnaire results, because occasionally respondents gave answers beyond the questions posed. However, this difficulty did not influence the data results.

In the validation process, it is difficult to validate the lean framework by doing a case study, because lean is long-term and a difficult task which can be seen from a lean transformation roadmap suggested by Morgan and Liker (2006). Therefore, the framework was validated by academic experts and industry experts. The validation included two stages: an initial validation and a final validation. The initial validation was conducted in the middle phase of this research. Therefore, the researcher was able to modify the initial framework according to the expert's suggestions. For the final validation, although the experts confirmed the understandability, feasibility and usefulness of the lean framework, some suggestions such as using VSM to map tooling development processes and standardising the tooling design procedure are not adopted in this framework due to time limitation.

During the framework implementation, some difficulties may occur. Firstly, many aircraft companies in China are state-owned. Employees in state-owned companies in China are unwilling to change as the selection mechanism of "survival of the fittest" does not exist in these companies. Secondly, this framework is not a prescriptive formula in which results can be calculated by entering some parameters. A further issue with this framework implementation is that people may lose patience and stop it halfway. In order to solve these problems, incentive mechanisms must be built. It is necessary also to remember that Toyota's practices took years to be successful. For this framework, it takes 2-4 months for the initial preparation including getting leadership support, undertaking awareness training and selecting lean teams. The benefits of applying lean tools and technologies to tooling design pilots can be seen after using these tools months or years later. Therefore, leaders and employees should conduct the framework from a long-term point of view and should not hope for quick success.

Studies have shown that the implementation of lean manufacturing can improve company performance and help achieve millions of dollars in savings (Honeywell, 2002; Welch and Byrne, 2002). Therefore, in terms of the benefits realised by using lean manufacturing, the lean considerations in this framework will definitely improve tooling design process and help aircraft manufacturing companies achieve financial benefits. Figure 7-1 and Figure 7-2 illustrate the existing company structure and tooling design process in Company A. Figure 7-3 and Figure 7-4 demonstrate the new structure and tooling design process after implementing the lean framework.

Figure 7-1 shows the different tooling-related departments' structure. These departments are defined according to their functions in Company A. Figure 7-1 and Figure 7-2 both illustrate a linear work flow which can cause the extension of tooling design time. This layout and tooling design process can also cause tooling redesign and tooling manufacturing problems which eventually lead to resources waste.

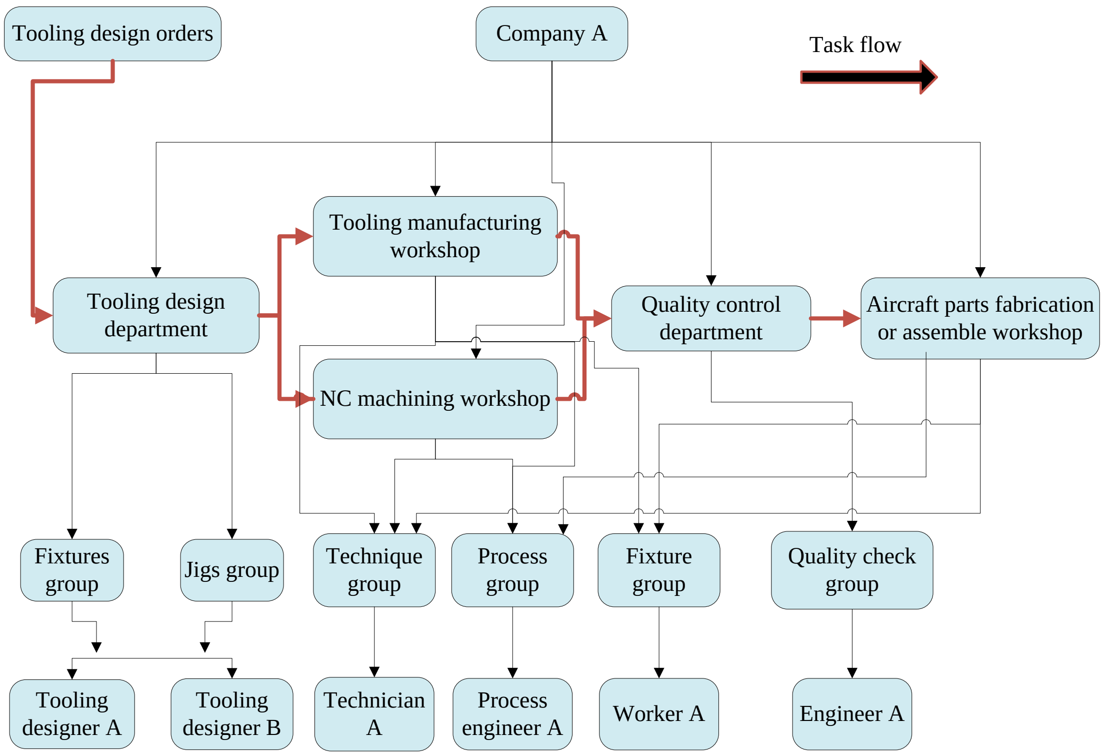


Figure 7-1: Existing department structure in Company A

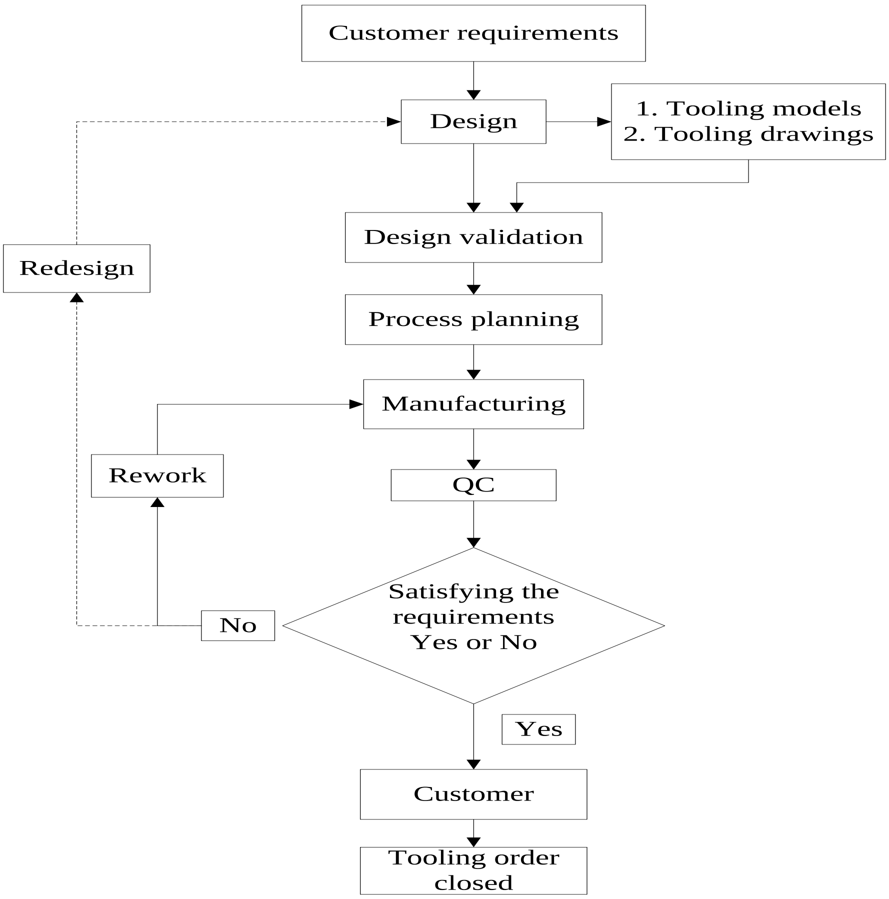


Figure 7-2: Existing tooling design process in Company A

In the proposed structure, Figure 7-3 shows that when a tooling design project order is delivered, a lean design team called IPT(Integrated Project Team) is responsible for the project with a common lean tooling design goal. IPT is a cross-functional team with team members belonging to their departments as well as the tooling design project. IPT could help solve tooling design problems quickly, share tooling knowledge easily, improve the communication efficiency between different members and reduce the feedback loop time. Figure 7-4 illustrates how tooling design, process planning and tooling fabrication are conducted in parallel under the tooling concurrent design environment and knowledge environment. During the design process, tooling designers also will consider process planning, fabrication problems with the aid of tooling databases and guidelines. With the new structure and the proposed process, tooling design efficiency can be increased and tooling redesign or rework can be reduced.

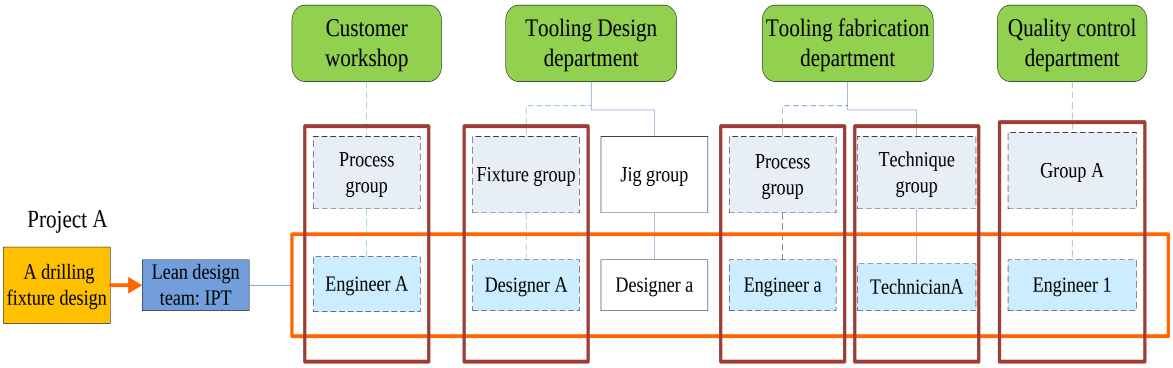


Figure 7-3: Proposed structure after implementing the framework

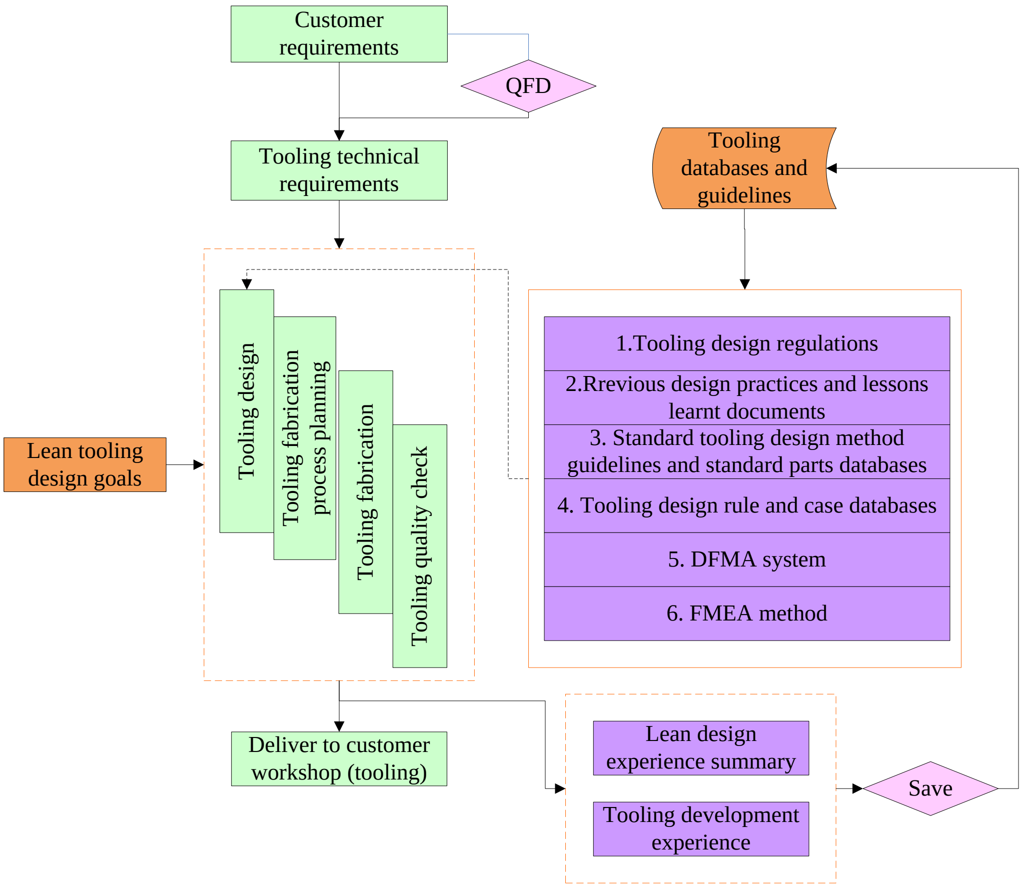


Figure 7-4: Proposed tooling design process after implementing the framework

7.2.1 Research Contribution

Firstly, for practioners, in China, there are many aircraft companies which have similar situations to these investigated companies. These companies can apply this framework to start their lean journey and improve the tooling design process. Although the main case company (Company A) is a Chinese aircraft manufacturing company, the framework could be applied to other fields and in other countries. Generally speaking, it is applicable in companies which want to undertake a lean transformation for product design. However, it needs modification according to the real conditions of particular companies. Taking the selection of lean tools as an example, for tooling design process, standardisation can help increase design efficiency and DFMA also can help reduce redesign and rework. Therefore, these two tools were emphasised in this lean framework. In service companies, design standardisation and DFMA may not be the main focus.

Turning to the contribution to knowledge made by the project, the research contributes to the area of lean product development. First, the aircraft tooling design process was illustrated using an IDEF0 map. This allows elements influencing the aircraft tooling design process to be quickly identified and improvement opportunities captured, using the visual aspect of the process. Secondly, a framework was developed suitable for an aircraft tooling design process in the Chinese aerospace industry. This contributes to the aircraft tooling design knowledge domain. Regarding the tooling design environment, there is a contribution to knowledge regarding the communication necessary for effective cooperation between tooling designers, tooling fabrication engineers and quality engineers. Concerning the tooling design knowledge environment, there is also a contribution to knowledge regarding the capturing and reuse of tooling design rules and previous tooling design cases. Within the arena of tooling concurrent design and tooling knowledge management, there is a contribution to lean tool adaptation for the tooling design process. Finally, for future research in the area of lean tooling design, the proposed framework can act as a reference.

7.2.2 Research Limitations

In aerospace, the tooling design process has a relationship with aircraft design and some downstream processes such as process planning, tooling fabrication and quality check. However, this research mainly focused on improving the relationship between the tooling design process and downstream processes.

Lean is a philosophy which can encourage people to find ways to produce product with less resource. For the tooling design process, any activity can help reduce tooling design time and avoid tooling redesign and rework could be considered in the lean research field. However, this research focused on the lean techniques and enablers. Advanced methods used in aircraft industries were not considered. Such methods are MBD (Model Based Definition) and determinant assembly of tooling in aircraft field.

MBD has helped Boeing achieve a digital assembly without engineering drawings. This method can improve the communication efficiency among aircraft design, tooling design and tooling fabrication. MBD can increase downstream engineers' responsiveness to the changes made by the upstream engineers and help avoid product redesign and rework. MBD also can reduce the waiting time generated from the procedure of converting 3D models of aircraft or tooling to 2D drawings. The MBD's role can help achieve a lean process.

Determinant assembly as a method to achieve a reduction in tooling has been applied in Airbus. This method can simplify tooling design and fabrication greatly and eventually reduce cost and lead-time. Lack of considering these advanced methods in tooling field limits the contribution of this framework.

8 Conclusions

This research developed a framework with considerations of leadership, culture, concurrent work environment, knowledge-based environment and selected lean design tools. The lean framework aimed to improve the tooling design process in Chinese aerospace and this aim was achieved by the following four objectives. Namely: (1) Identify elements influencing lean implementation from LM, Lean PD and Lean PPD; (2) Investigate the tooling design situation in the Chinese aerospace industry; (3) Apply the identified enablers and lean approaches to synthesise a lean framework; and (4) Validate the proposed framework through academic and industry experts' judgement.

During this research, a literature review was conducted to identify key elements influencing lean implementation. Questionnaires were used to collect data in Chinese aerospace companies. An IDEF0 for a tooling design process and a fishbone diagram for a lean tooling design were mapped to find the deficiencies of tooling design in Company A. With the deficiencies in the tooling design process improved and solved, a lean framework was developed. The developed framework was validated by academic and industry experts. Based on experts' comments, some potential benefits generated by implementing the framework include:

1) Lean knowledge background can be improved.

2) The collaboration between different functional departments related to tooling design can be enhanced.

3) The rate of tooling redesign and rework can be reduced.

4) The tooling design process can be improved.

9 Future Work

The following four aspects for further development of this framework could be:

1) Develop corresponding rules and databases construction for tooling design knowledge-based environment, standardisation and DFMA;

2) Add the detailed VSM for tooling development and the standardisation of tooling design procedure into this framework.

3) Investigate the methods of assessing lean performance and consider them during the framework implementation.

4) Pilot an application of this framework in one Chinese aerospace company by an action research.

Regarding further research of achieving a lean tooling design process, one consideration may be:

Connect lean with advanced tooling design and assembly methods, such as MBD and determinant assembly of tooling.

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APPENDICES

Appendix A: Questionnaire—A Lean Framework for Tooling Design Process in Chinese Aerospace

The questionnaire is to be used as part of an MSc Research project entitled "A lean framework for tooling design process in Chinese aerospace" at Cranfield University. This questionnaire aims to collect information about tooling design process in Chinese aerospace and then develop a lean framework.

Thanks for taking part in this research. The questionnaire is anonymous and confidential. The questions can be finished in 20 minutes. An analysis of results can be sent to you if required.

Note: 1. Please write your choice(s) (e.g. A, B, or C…) and give your comment in the box. If you choose other, please list it out. For "yes/no" and "disagree/agree" questions, please tick your choice (√) in the box.

2. Before you answer the questions, you should keep in mind the following short introduction of lean tools first. It can help finish the questionnaire easily.

※ **QFD: Quality Function Deployment**

QFD is a systematic method used in the design stage. It can help guarantee the requirements coming from customer or market accurately shifting to each stage of product development processes. QFD has been renowned in many organisations due to its role of gathering, analysing and prioritising customer requirements.

※ **DFMA: Design for Manufacturing and Assembly**

DFMA can optimise design to make product parts easier to be manufactured and assembled. It can also emphasise potential problems in the different life stages of a product

※ **FMEA: Failure Mode and Effect Analysis**

FMEA is an analysis methodology for identifying potential failure modes and reasons. It can provide corresponding actions to prevent failure happening in the product development cycle.

A.1 Respondents' general information

G1. What is your main job?

A. Tooling designer

B. Process engineer

C. Quality inspector

D. Manager (director, team leader, etc)

Other:

G2. How long have you been in this company?

A. <one year

B. ≥one year <three years

C. ≥three years <five years

D. ≥five years <ten years

E. ≥ten years

G3. Your company has used lean approaches in tooling design.

Yes	Not sure	No

If yes, please enumerate and comment on these lean approaches:

A.2 Concurrent engineering

CE1. During tooling design process, members from different departments work concurrently.

Yes	Not sure	No

If yes, please comment.

CE2. It is important to consider some alternatives of tooling design concepts at the beginning.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

CE3. You consider many design concepts first and then reduce them progressively throughout the tooling design process.

Yes	Not sure	No

A.3 Knowledge management

K1. Your company has methods to capture tooling knowledge (tooling design and fabrication knowledge) (such as If-then rules).

Yes	Not sure	No

If yes, please enumerate and comment on these knowledge capturing methods.

K2. There are some methods to represent tooling knowledge (tooling design and fabrication knowledge) (such as IDEF0, UML) in your company.

Yes	Not sure	No

If yes, please enumerate and comment on these knowledge representation methods.

K3. Your working environment enables people to collaborate with others to share knowledge.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

K4. Tooling knowledge is shared in real time among departments related to tooling.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

K5. Please specify how you share knowledge: such as meetings, A3 report or others.

K6. You re-use the knowledge captured from previous projects to support new tooling designs.

Yes	Not sure	No

If yes, please comment.

K7. It is important to have a knowledge-based environment to support tooling design process.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

A.4 Lean tools in tooling design process

A.4.1 Lean thinking and lean indicators

L1. It is important to apply lean thinking in tooling design process.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

Please comment on lean thinking.

L2. Your company uses the following indicators to measure how lean is your tooling design (tick all that apply).

A.	Time from design to launch	B.	Tooling novelty
C.	Number of design alternations	D.	Management satisfaction
E.	Tooling reliability	F.	Other

Other: ____________________

Please comment on the used indicators.

L3. There will be a great success in adopting lean thinking in tooling design process.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

L4.Tooling designers are aware of value stream map's role in waste elimination and value enhancement for tooling development.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

Please comment on this value stream mapping tool.

A.4.3 Lean design tools

A.4.3.1 Customer requirements Stages

C1. Tooling designers can fully understand the customer requirements.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

C2. It is important to convert the needs of customers to tooling features.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

C3. Your company has applied QFD methodology for tooling design.

Yes	Not sure	No

If yes, please comment on QFD.

A.4.3.2 The use of previous practices and standardisation

PS1. Tooling designers use previous practices to aid tooling design.

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

PS2. Your company has done some work on tooling design standardisation (please comment).

Disagree Strongly	Disagree Somewhat	Undecided	Agree Somewhat	Agree Strongly

Please comment on the standardisation (efficiency).

A.4.4 Other efficiency tools

O1. Your company uses DFMA in tooling design.

Yes	Not sure	No

If yes, please comment on DFMA.

O2. Your company performs FMEA in order to identify potential future issues during tooling design.

Yes	Not sure	No

If yes, please comment on FMEA.

End of questionnaire.

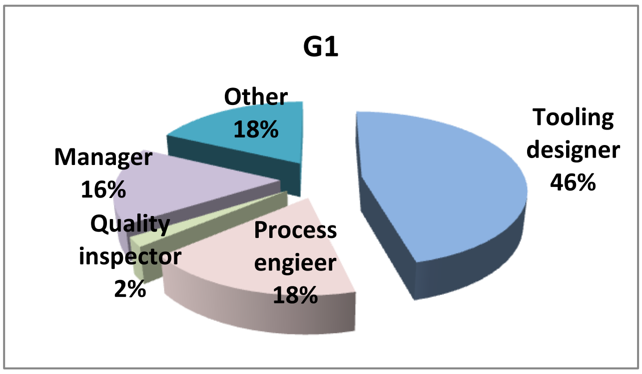
Thanks for your time.

E-mail: yafang.yang@cranfield.ac.uk

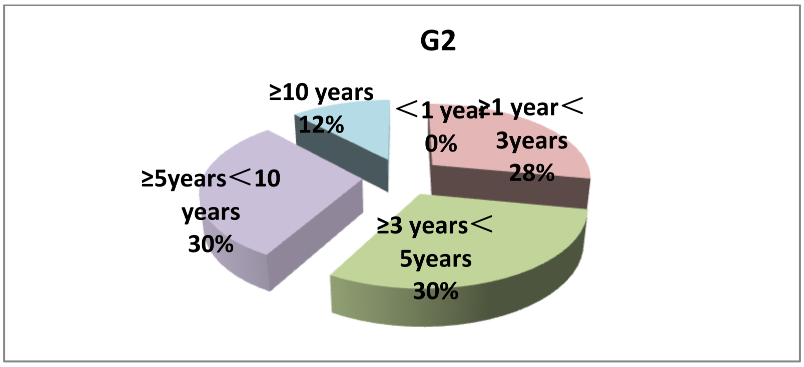
Appendix B: Results of Questionnaire in Company A

A.1 Respondents' general information

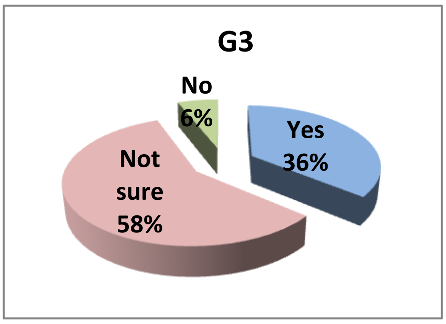
G1. What is your main job?



G2. How long have you been in this company?



G3. Your company has used lean approaches in tooling design (If yes, please enumerate them and comment).



Comments:

01. I do not know what lean methods are. The situation I met is that the clamping block in workshops has different categories for different lower mould plates (one part of tooling).

06. 1) Systematic summing-up methods: Tooling design designers are encouraged to develop standard parts after one kind of fixture is finished. It can necessitate a new design and increase efficiency. 2) Modularisation: Tooling designers use rapid design software (CATIA) and standard parts to lessen design time and manufacturing cycle.

However, only few designers use these methods and these methods need to be regulated.

10. There are tooling standardisation, modularisation and some research about flexible fixtures. However, these methods need further improvement and should be strengthened.

11. In fixture design, we use hydraulic clamping method to save clamping time. In assembly jig design, we use automatic control methods which can enhance locating precision more or less.

12. We use FEA method and it is effective.

13. We have CATIA training.

16. We use quality and alteration control method.

21. There are optimisation and FEA methods, but these methods are not universal and need to be strengthened.

24. New material is used in cutting tools.

27. FEA and tooling rapid design are used by tooling designers.

28. Standard and modular design methods can enhance design efficiency and shorten design cycle. However, these methods are not applied well.

44. There are tooling rapid locating and clamping methods. It can shorten fixtures' fixing and adjusting time.

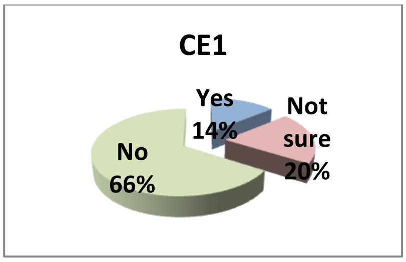
46. We have MBD and SPC (Statistical Process Control) methods.

47. There are assembly simulation and structure strength analysis methods which are in DFMA and FMEA categories. These methods can enhance design quality effectively.

48. I have heard of six sigma method, but I do not know whether it is effective or not.

A.2 Concurrent engineering

CE1. During tooling design process, members from different departments working concurrently (If yes, please comment).



Comments:

01. Yes, but we just discuss with customer workshop engineers to decide the feasible design proposal at the beginning.

02. No. I discuss with process and manufacturing engineers about the tooling manufacturability when tooling drawings are sent to them. This can cause tooling redesign and rework. Therefore, my company should conduct concurrent work to improve this situation.

03. NO. The communication between different departments is not smooth. Therefore, maybe concurrent working style can improve this situation.

04. Not sure. Although sometimes they work together, the responsibility is not clear enough.

06. No. People do not work concurrently. When a problem occurs, they hold meetings to solve it. The communication is not timely.

10. Yes. I think concurrent working style will be effective to speed up the tooling design and fabrication. The process can be simplified and the quality of tooling design and fabrication also can be guaranteed.

11. No. Most of the time, we follow such a working style: when tooling design finishes, process begins, and then manufacturing starts. I think that concurrent work can avoid many problems, such as tooling redesign and rework.

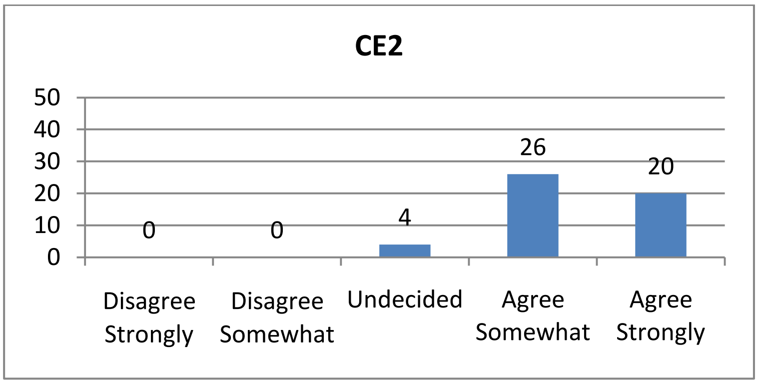
13. Yes. The differences between customer requirements and tooling design can be solved timely which can avoid tooling rework.

14. No. However, I regard that concurrent working style can make communication and work more efficient. My company should apply it.

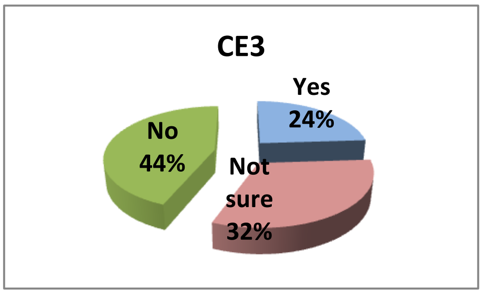
16. I am not sure, people work in their own offices. However, I think concurrent working style can help determine the design proposal, customer and process requirements quickly. This method also can help tooling design process go smoothly.
17. No.
19. I am not sure, but I think it should be effective somewhat.
20. No. However, concurrent work should be conducted. It can avoid some problems generated when tooling are launched into use and guarantee the customers' requirements.
21. No
22. No.
23, 24. Not sure. People meet together to solve problems sometimes. The communication is not smooth.
27. No. However, I think it is beneficial to decide the final design proposal.
29. No
31. No
32. Yes, it has some effects and can help designers have a good understanding of company manufacturability.
33. No. In my opinion, tooling designers should consider the manufacturability and design some easily fabricated tooling without influencing the function. Therefore, it is necessary to work concurrently.
34. Not sure.
38. No. The efficiency is not high.
39. No. People of different departments do their own work and communicate when problems occur.
41. No.
42. No. When some problems occur, related people will sit together to discuss and find ways to solve these problems.
44. No, but I think concurrent working style can help deliver the requirements between process engineers and tooling designers easily. After that, the design cycle can be shortened and design efficiency can be increased.
45. Yes.
47. Yes. However, there are deficiencies on coordination and communication which can lead to tooling alteration and rework.

48. Not sure. People sometimes join together to solve problems. I think concurrent work style can improve work efficiency much, but there is still some counterwork existing.
49. No

CE2. It is important to consider some alternatives of tooling design concepts at the beginning.

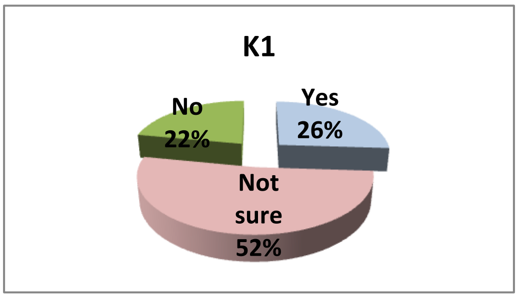


CE3. You consider many design concepts first and then reduce them progressively throughout the tooling design process.



A.3 Knowledge management

K1. Your company has methods to capture tooling knowledge (tooling design and fabrication knowledge) (such as If-then rules) (If yes, please enumerate and comment).



Comments:

02. The experienced ones teach and help the younger ones to design fixtures. Basically I am satisfied with this method.

06. We usually do training to capture knowledge.

11. We use standard parts database to capture knowledge.

12. People just build intranet to capture knowledge, but we have not used it.

13. We use training material, design regulations and standards to capture knowledge.

16. We have the following methods to capture knowledge: training, the experienced helping the young ones, intranet materials and design handbooks.

18. Yes, but I have not used it.

20. We have the following methods: training, asking from experts and proposal meetings. These methods have many uncertainties and it is hard to standardise them.

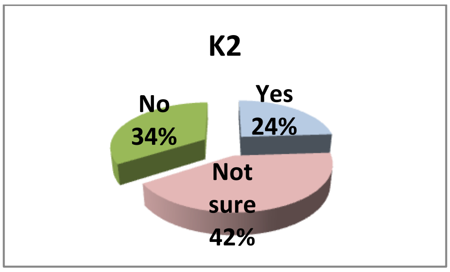
21. We have such methods: the experienced designers helping the young and doing practice in the workshop to help capture knowledge.

25. We have standard parts database to capture knowledge, but it is not used broadly.

27. We have training to capture knowledge.

49. We have tooling design handbooks to capture knowledge. However, the updating is not in real time.

K2. There are some methods to represent tooling knowledge (tooling design and fabrication knowledge) (such as IDEF0, UML) in your company (If yes, please enumerate and comment).



Comments:

11. We use some platforms which have tooling data to represent tooling knowledge, such as CPC and M cube.

13. We have training materials and samples to represent knowledge.

15. There are internal design training materials which can represent knowledge.

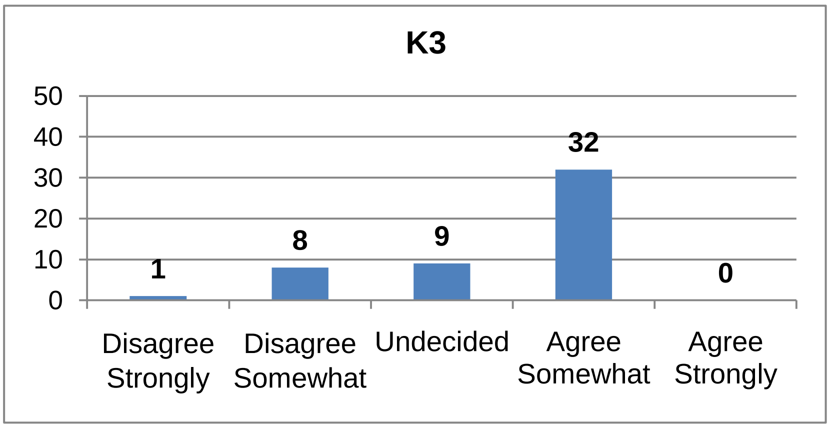
16. We have such methods to represent knowledge: training and experience communication meetings between departments related to tooling.

21. We have some rapid design tools to represent knowledge. However, it needs to build reasonable databases or tools.

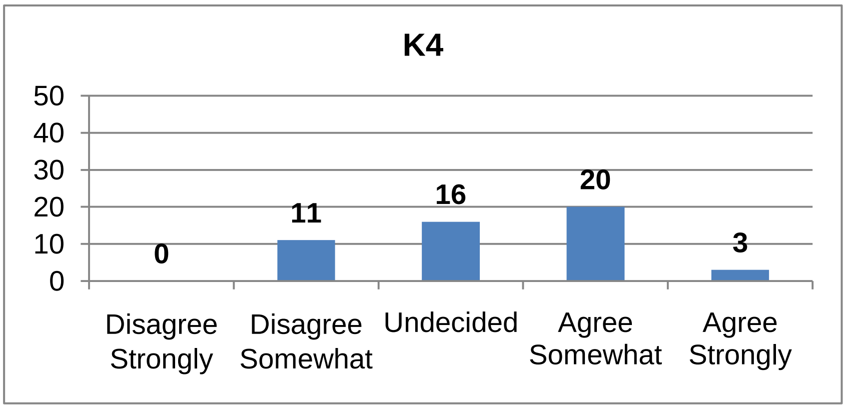
27. We have training to represent knowledge.

46. We have training and communication meetings to represent knowledge.

K3. Your working environment enables people to collaborate with others to share knowledge.



K4. Tooling knowledge is shared in real time among departments related to tooling.



K5. Please specify how you share knowledge: such as meetings, A3 report or others.

Comments:

01. Morning meeting (learn from yesterday's work and plan for today)
02. Meeting
03. Meeting
04. Meeting and discuss face to face
05. Oral communication
06. Intranet platform, morning meetings, review meetings, work summary and experience sharing meetings
07. Platform
08. No
09. Meeting
10. Discussion face to face or on phone
11. Meeting
12. Meeting, training and intranet
13. Training
14. Meeting, training
15. Meeting, materials circulated for perusal
16. Communication based on the tooling 2D drawing and 3D model
17. Intranet and meeting
18. Meeting and training
19. Intranet platform
20. Proposal discussion meeting and proposal review meeting
21. Shared folder and software
22. Shared folder
24. Training video and lectures
25. Training
26. Intranet
27. Shared platform
28. Training and meeting
29. Intranet sharing and meeting
30. Daily communication

31. Platform

32. Communication face to face and tooling design review meeting

33. Meeting and technical paper

34. Intranet

35. Intranet

41. Training

44. I am not familiar with this kind of methods.

46. Meeting, A3 report and technical training

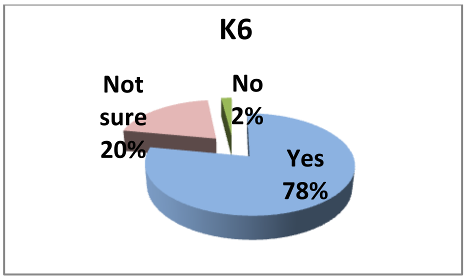
47. Lecture and meeting.

48. Meeting

49. Technical report, review meeting and work report

50. Meeting

K6. You re-use the knowledge captured from previous projects to support new tooling designs (If yes, please comment).



Comments:

01. It can enhance efficiency.

02. It just has a little effect.

04. Experience is valuable, but innovation is also essential.

05. Both success and failure experiences are beneficial.

06. It is important, because design work can be improved by experience and innovation.

07. It is very useful and can help reduce design time.

08. It can enhance efficiency.

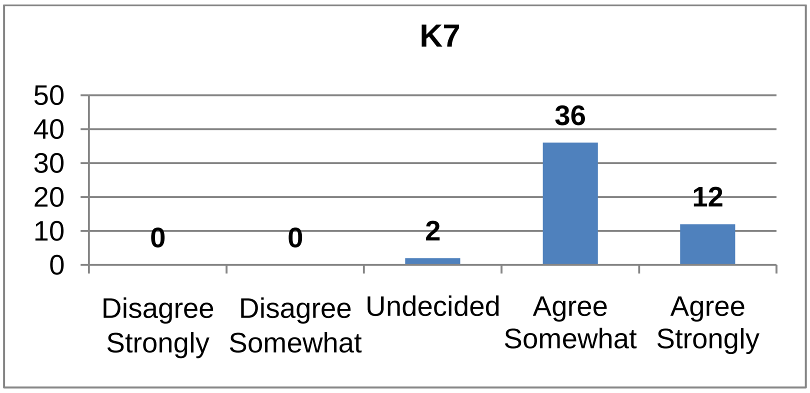
09. Experience can avoid the same type tooling's redesign.

11. Experience learned from previous design can guarantee tooling reliability.

12. It can reduce design time.

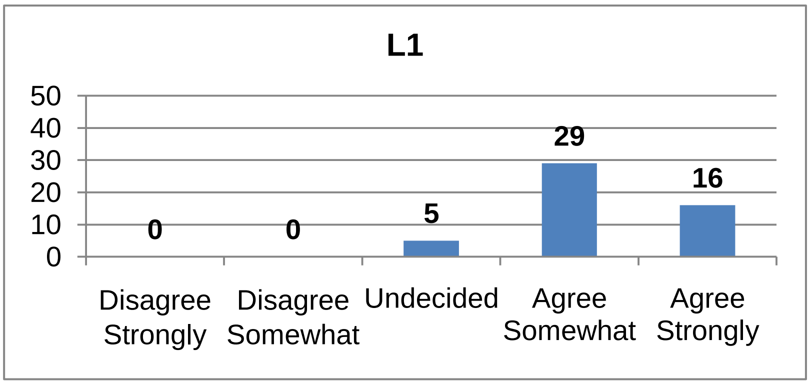
14. It can help do some innovation based on experience.
15. Experience is important.
18. It can help get a new idea and save design time.
19. Experience learned from previous design can help get some design thoughts and do some improvement.
20. The captured knowledge can be used in a new design in time.
21. It is a great help for young designers' progress. It is a good idea to build such knowledge database.
23. The knowledge reuse needs to be strengthened.
24. The captured knowledge is just used as a reference. People should adopt new and advanced knowledge coming from the domestic and international countries.
25. It is beneficial for a new design.
26. Knowledge learned from previous projects is useful experience.
27. I refer to some successful design cases when I design a new tooling.
28. It can optimise a new tooling design.
29. There are some good effects, such as speeding up design and optimising design method.
31. It is very convenient to help design a new tooling.
38. Learning from experience has a good effect.
41. Basically it is just copy. New modes or methods are not worked out.
42. Regarding a same type of tooling, designers can refer to previous ones.
46. Tooling design experience is somewhat important.
47. Capturing knowledge from the best design cases can help designers identify key points of design and determine a design proposal quickly.
48. Experience is very important.
49. There is a certain reference value.

K7. It is important to have a knowledge-based environment to support tooling design process.



A.4 Lean in tooling design process

L1. It is important to apply lean thinking in tooling design process (Please comment on lean thinking).



Comments:

01. Lean thinking means profit maximisation (money).

02. Lean thinking means time, workforce and money saving.

04. Lean thinking means cost saving, waste elimination and profit increasing.

05. Lean thinking means iterative work reduction.

06. In tooling design, lean thinking means that under the condition of satisfying customers' requirements, people find ways to shorten design and fabrication cycle time, reduce cost and guarantee product quality.

08. Lean thinking means cost saving and efficiency increase.

09. Lean thinking means the tooling structure is reliable with a lowest cost.

10. Lean thinking means improvement of product quality and reducing fabrication cost continuously.

11. Under the premise of guaranteeing the validity of a design, people should consider the feasibility of fabrication and the convenience for use.
13. Lean thinking means more outcomes, higher speed, better quality and less cost.
14. The purpose of lean thinking is to improve product quality, reduce cost and improve tooling design ability.
16. Under the premise of tooling function being guaranteed, people need to consider shortening design time, reducing fabrication cost and making it easy to use. Therefore, the overall profit can be increased.
17. A lean tooling should have a good performance in the following aspects, such as practicability, processability, economy and safety.
19. Lean thinking means using limited resource such as time and workforce efficiently to produce a product.
20. If lean can be considered in the early design stage, a series of problems can be avoided. Lean thinking can reduce cost, increase efficiency and improve quality dramatically.
21. Lean thinking means excellent design, lean manufacturing and keep improving. Tooling designers should have a lean sense and apply it to daily work.
24. Lean thinking means more outcomes, higher speed, better quality and less cost.
25. For tooling design, lean thinking should be standardised and regulated.
26. Lean thinking means simple and efficient.
28. Lean thinking means waste elimination
29. Lean thinking can help reduce product error and reduce cost.
31. Regarding lean thinking, during tooling design, the efficiency of fabrication and tooling use should be considered.
32. Applying lean thinking to tooling design process means that: 1) the consideration of manufacturability during design stage; 2) working in parallel.
36. A lean tooling design should be both reasonable for design and fabrication.
40. Lean thinking means that based on shared knowledge and information, people react quickly and respond correctly.
41. Regarding lean thinking, tooling need to be improved based on summary and experience.

42. Lean thinking means that tooling designers should pay attention to tooling fabrication when they design a tooling.

44. For tooling, lean refers to reliability of tooling and convenience for use.

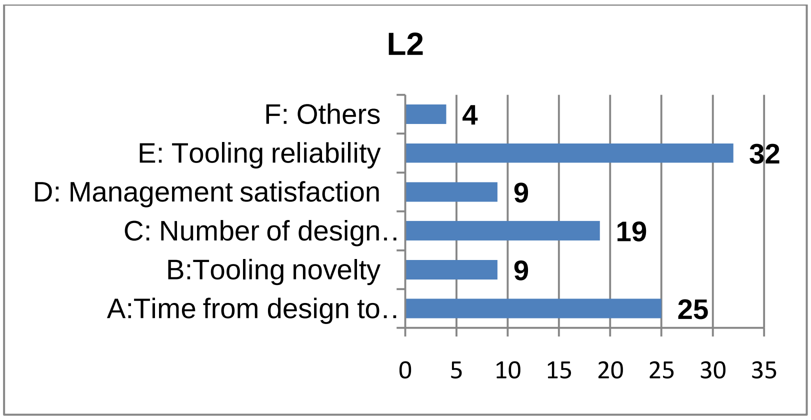
45. For the users, lean thinking means that under the condition of ensuring quality and safety, the workforce should be reduced and efficiency be increased.

48. Lean thinking means energy saving, efficiency increase and design optimisation.

49. Lean thinking means cost reduction, efficiency increase and product optimisation.

50. Lean thinking means that products are most economical and practicable.

L2. Your company uses the following indicators to measure how lean is your tooling design (tick all that apply).



Comments:

Respondents of 01, 02, 03, 05, 10, 11, 20, 21, 25, 28, 31, 34, 41, 42, 44, 45, 48, 49, 50 shared a similar opinion that they do have some of these indicators to control tooling quality and design time. However, they were sure that there were no specific and regulated measurement standards for lean in tooling design.

01. AC.

02. I have not heard this concept.

03. These indicators are not used obviously.

05. ABCDE. F: Tooling type and weight.

06. No. My company has not begun to measure and assess how lean a tooling design is.

10. AE.

11. ABCDEF F: Fabrication cost and customer feedback

12. No. There are no indicators to measure how lean a tooling design is.

14. No.

16. ACDE. These indicators are ambiguous and not regulated.

18. No

20. ADEF. F: Time reduced from design to fabrication.

These indicators can help manage tooling, improve tooling reliability and tooling quality.

21. ABE. Choice A can help guarantee aircraft fabrication time. Choice E can ensure the product quality.

23. C.

24. BCE.

25. AE.

28. D.

31. ABE.

34. C.

36. ACDE. There are no specific lean measurement standards for tooling design.

41. E. Reliability is the most important one.

42. A. It is not reasonable, because people just focus on the cycle time.

44. AE. Tooling novelty (B) should reflect the facility of operation, structure reliability and precision requirement.

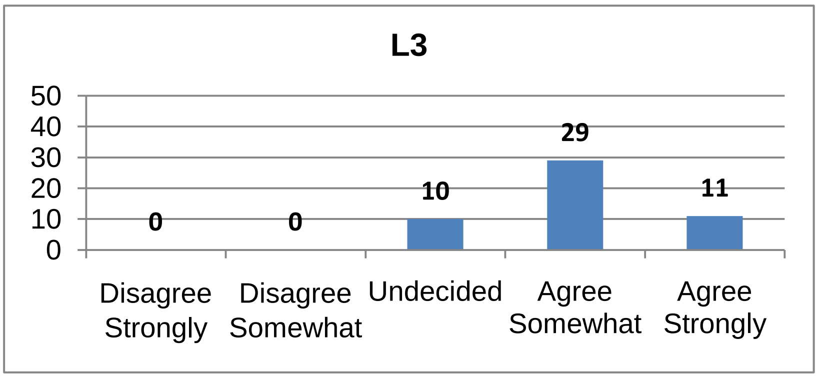
45. E. Reliability is more important than other indicators.

48. AE.

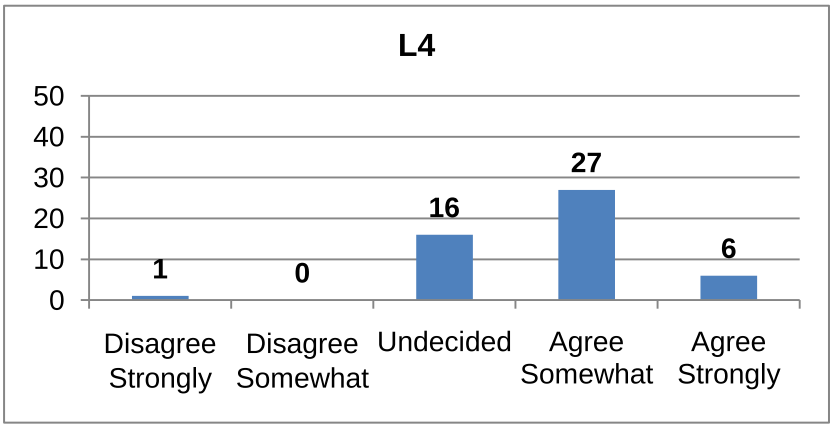
49. ABCDEF. F: Tooling fabrication cost and tooling processability.

50. E. Other indicators are ignored except reliability.

L3. There will be a great success in adopting lean thinking in tooling design process.



L4. Tooling designers are aware of value stream map's role in waste elimination and value enhancement for tooling development (please comment).



Comments:

03. I do not know what value stream map is. There is just something in the intranet platform which can display the state of tooling design.

04. I agree. It is useful for people to check the state of tooling design, but my company does not have such map.

06. In my company, tooling designers seldom consider this.

11. There is no such map. However, during tooling design, designers pay attention to negotiate with engineers in customer workshop to fully understand their requirements.

14. There is no such map. It is necessary to develop it.

16. I am sure that my company does not have this kind of map.

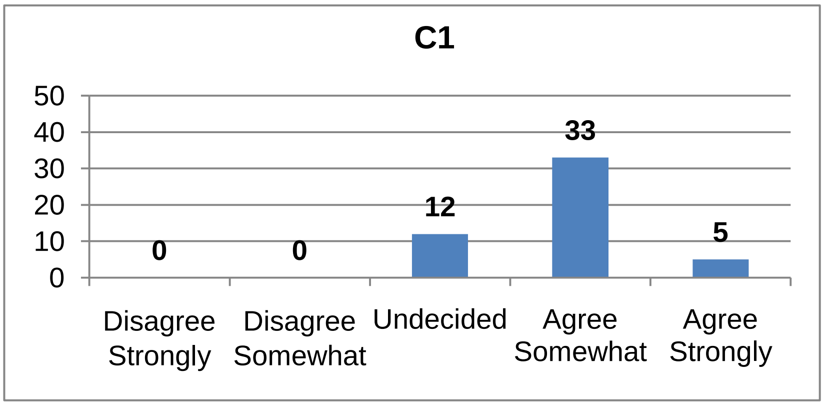
20. My company does not have this kind of map now.

21. This kind of map is in concept phrase and has not been regulated. I advise to do some research about this.
23. My company does not have this map.
25. This kind of map can eliminate design time.
31. My company should develop this map.
40. This kind of map can help people analyse each stage of tooling development qualitatively and quantitatively and find reasons for some problems.
48. This kind of map is effective to shorten procedure time.

A.4.3 Lean design tools

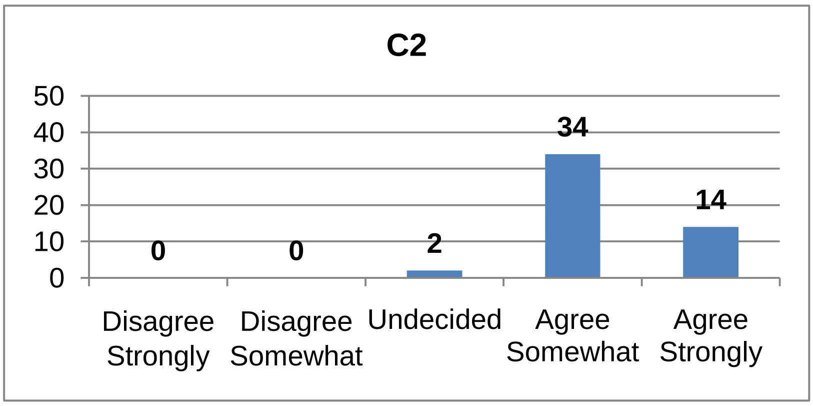
A.4.3.1Customer requirements stages

C1. Tooling designers can fully understand the customer requirements.

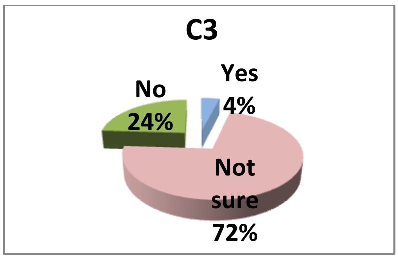


As illustrated in the bar chart, 12 (24%) respondents were not sure whether tooling designers can understand customers' requirements completely or not. Among them, there are two tooling designers, two managers (coming from fabrication and customer workshop respectively), four process engineers of fabrication workshop, one quality inspector and three engineers of customer workshop. It can be concluded that all respondents (one manager, three process engineers) of customer workshop doubted that tooling designer can fully understand their requirements. Two thirds of respondents from fabrication workshop were also not sure about this question.

C2. It is important to convert the needs of customers to tooling features.



C3. Your company has applied QFD methodology for tooling design (If yes, please comment on QFD).



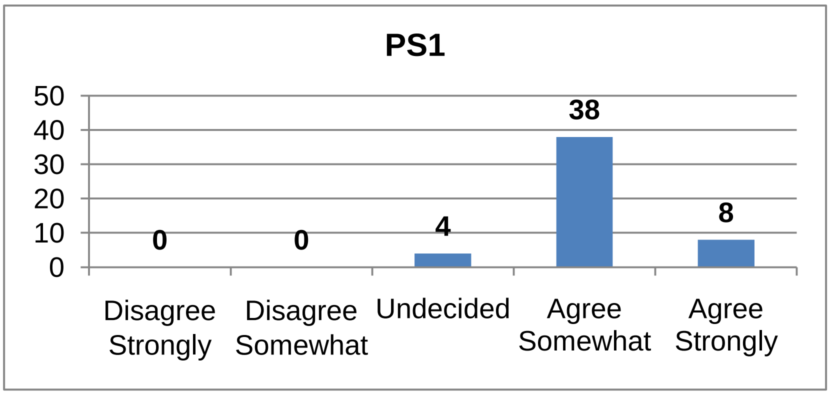
Comments:

13. It can avoid such problems: tooling cannot be fabricated or tooling cannot be used after fabrication.

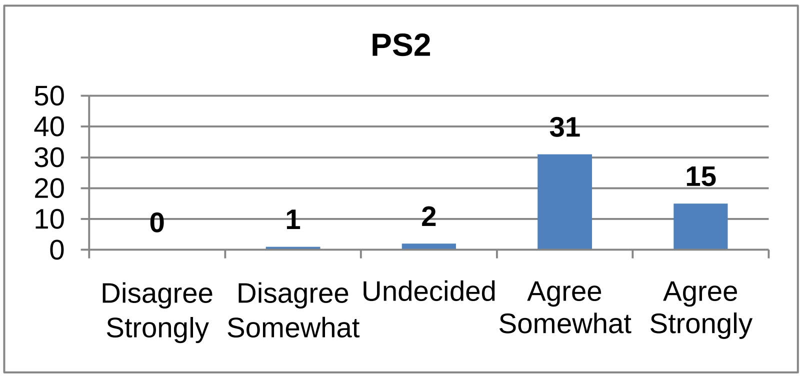
24. Not sure.

A.4.3.2 The use of previous practices and standardisation

PS1. Tooling designers use previous practices to aid tooling design.



PS2. Your company has done some work on tooling design standardisation (please comment).



Comments:

03. There are many tooling parts in standard databases currently, but assemblies are not enough.

06. There are some standard tooling parts. These standard parts have some effects, but people should extend the use of them.

09. My company has done some work on tooling parts standardisation. However, more standard parts' and assemblies' databases need to be improved.

13. My company has developed some standard parts and these parts are used to save money and aid a new tooling design.

15. Tooling designers just develop some standard parts. These parts are reusable. Using them can reduce design time and save cost.

16. My company just standardise some tooling parts. Some modules also should be standardised. The application scope should be extended.

17. There are still some designers who do not refer to standard tooling parts during tooling design.

20. We just develop standard tooling parts. Tooling design and fabrication time can be saved by using these standard parts. Therefore, people should apply standard parts as often as possible.

21. Tooling designers consider the use of standard parts, but the use is not broad and it needs to be improved.

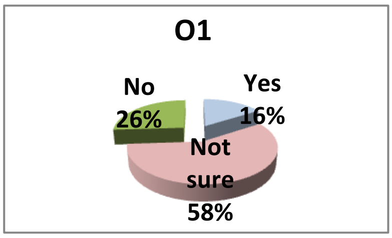
24. There is just standardisation of tooling parts.

25. Tooling department has done work on the standardisation of tooling parts

27. Standardisation of some tooling parts has been done. I think that use of standard parts can help save design time and improve efficiency.
32. Standardisation of tooling parts has been conducting, but the effects are not obvious.
36. I think that besides standardisation of tooling parts, tooling design procedures also need to be standardised. During tooling fabrication, using standard parts can also save much time.
40. My company mainly focused on tooling components standardisation. This standardisation work needs to be optimised continuously.
44. My company pay attention to standardise tooling parts. Standard design procedure is also beneficial to reduce cost and increase efficiency.
48. The use of standard parts can reduce design time, but it needs improvement.
49. The standard parts databases should be updated.

A.4.4 Other efficiency tools

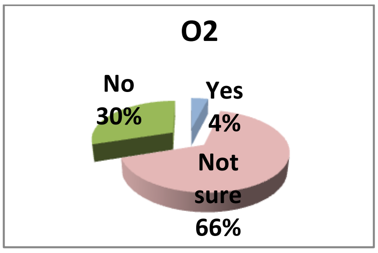
O1. Your company uses DFMA in tooling design (please comment on DFMA).



Comments:
05. Yes. It is a good method.
06. Yes. This method is very necessary and can guarantee tooling validity and product quality.
13. Yes. DFMA can avoid many problems, such as tooling cannot be fabricated or it is hard to do tooling maintenance.
21. Yes. DFMA can help improve tooling reliability, reduce quality problems and maintenance cost. It can also shorten tooling development cycle time.
24. Yes. DFMA is beneficial to tooling optimisation.
46. Yes. DFMA is effectively somewhat.

47. Yes. By focusing on fabrication and assembly requirements, the designed tooling will be more reasonable and be easy to be manufactured.

O2. Your company performs FMEA in order to identify potential future issues during tooling design (please comment on FMEA).



Comments:

24. Yes. FMEA can prevent potential failure problems effectively.

47. Yes. FMEA can guarantee some quality requirements in the early stages of tooling design.

※ Questionnaire Results from Company B

1. General information results: The respondent is a process engineer with more than 5 years' experience and she was not sure whether Company B had applied some lean approaches or not in tooling design.

2. Concurrent engineering: The designers, process and fabrication engineers did not work together. Although the respondent thought that set-based design is important, she was not sure whether the concepts would decrease throughout tooling design process or not.

3. Knowledge management: Although the respondent was not sure whether knowledge capturing, representing, sharing methods had been used in Company B or not, she strongly agreed to develop a knowledge-based environment for tooling design.

4. Lean tools: In terms of VSM, QFD, DFMA, FMEA, the respondent chose the answer of "Not sure", which indicates that these lean tools had not been implemented well in Company B. However, standardisation of tooling parts had been applied in Company B.

※ Questionnaire Results from Company C

1. General information results: The respondent is a process engineer with more than 5 years' experience and she was sure that Company C had applied some lean approaches in tooling design but there was no enumeration about these approaches.

2. Concurrent engineering: The members related to tooling design process did not work together. The respondent thought that set-based design is important and stated that set-based design had been used in Company C.

3. Knowledge management: Although the respondent was not sure whether knowledge capturing, representing, sharing methods had been used in Company C or not, she agreed to develop a knowledge-based environment for tooling design.

4. Lean tools: She was not sure whether QFD, DFMA had been used in Company C, but she mentioned that FMEA was being used. Moreover, she agreed with the importance of VSM, standardisation (tooling parts) and lessons learned from previous practices.

Appendix C: The Interview Questions and Results for Initial Validation

This interview lasted for 35 minutes. The questions and answers were collected in the following part.

Question 1: What elements can contribute to achieving a lean tooling design?

Answer: The academic expert explained the lean design principle in detail.

Lean design can be defined from three aspects “maximise customer value representation; ensuring the elimination of harm to its end user and environment of operation as well as assuring waste and resources are minimised during manufacture”. The academic expert also elaborated these aspects which are:

(1) Maximise customer value through geometrical reasoning

(2) Simplicity that ensures manufacturability and assemblability

(3) Eliminate harm to the (a) end-user, (b) manufacture, (c) service

(4) Simultaneously lean manufacturing consideration

a) Minimise waste for (a) manufacture, (b) service

b) Minimise resources for (a) manufacture, (b) operation, (c) service.

The value here mainly relates to customer requirements. Regarding tooling design, this value should be maximised by converting it to some tooling features which are distinct from competitors.

Question 2: Based on your experience, what lean tools are more important for product design?

Answer: DFM, DFA, Poka-yoke for features, FMEA, Robust design. Knowledge environment, Checklist (knowledge can be put into the checklist to make sure that designers consider all relevant factors during product design).

Question 3: I want to develop a knowledge-based environment for my lean framework. Do you have any recommendations that can help develop such environment easily?

Answer: You should find methods to help manage knowledge life cycles, which means considering ways of knowledge identification, capturing, representation and sharing.

Question 4: Are there any methods helping develop CE (some procedures or stages)?

Answer: In your research, you should consider how tooling designers communicate with manufacturing engineers efficiently.

Question 5: This is my framework. Could you have a look and give me some advice to help refine it?

Answer: (1) The framework is too complicated and you should do some simplification. There are too many initiatives and you should focus some of them.

(2) You should use a fishbone diagram to show what elements can lead to a lean tooling design. Then, you find out which elements are important and which are commonsense.

(3) You should map your tooling design procedures with IDEF0. After finishing the map, you should consider “how am I going to enhance this work, how can I make the work better, faster and cheaper”.

(4) You connect the IDEF0 map with the fishbone diagram to find out what is missing for the lean tooling design aim. It is an “as-is” practice. You find out what is missing and then you bring some actions to it. After that, the framework can be generated.

(5) CE and set-based design should be considered at the product conceptual design phase (at the beginning of the project). In your research, it should be at aircraft conceptual design phase. Therefore, it is late to consider CE and set-based design at tooling design stage.

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Appendix D: Industry Experts' Comments and Suggestions for the Lean Framework

In Company A, lean manufacturing for tooling fabrication began in 2003, but there are no methods to help improve the tooling design process. This lean framework is what Company A needs. We have a high expectation about it and want to implement it under Yang's help when she comes back to my company.

Firstly, concerning lean, employees in my company know little about it although lean manufacturing has been implemented for almost ten years. Therefore, a lean training is a good start for my company's lean journey. VSM for tooling development can help us find improvement opportunities. Therefore, it is right to consider it at the beginning. However, how does VSM for tooling development look like? Does your research include it?

Secondly, in terms of environment building, my company has corresponding foundations for CE and standard tooling parts databases although both need improvement. These foundations are still useful to help build concurrent design environment and tooling design knowledge-based environment. Concerning tooling design knowledge, my company does not have corresponding tools and methods to manage it. The researcher's consideration in this framework fills this gap.

Thirdly, regarding lean tools, tooling parts or components standardisation has begun, but there are few outcomes. We know that DFMA is important for the design stage. During tooling design, although we consider manufacturability and assemblability, there are no formal regulations to guide us. In this framework, the researcher has given a clear DFMA analysis model. My company will follow this model to establish corresponding databases and implement it. FMEA also can help identify potential risks existing in tooling design. Therefore, we will consider trying this method during our tooling design. However, QFD should be efficient, but we cannot offer much comment.

Finally, we agreed that lean should finally become my company's culture and should be followed by every member. Therefore, it is very necessary to build a lean tooling design culture.

To conclude, this lean framework stages is clear, reasonable and easy to follow. It is necessary for the improvement of tooling design process in my company. The following benefits can be achieved after all the elements of this framework are equipped: (1) tooling design efficiency can be increased; (2) tooling redesign or rework can be reduced; (3) tooling design process cycle can be shortened.

By three industry experts