Multiple Commodities Optimization of Lean Technology Infusion for Automobile Manufacturer

by

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M.S. Civil Engineering
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Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

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Abstract:

The multiple technology infusion process is complex and uncertain. This complexity and uncertainty conventionally makes automobile technology infusion very difficult to be nimble or lean. In the technology development arena, the spotlight of the technology value has been unintentionally scattered. The loss of focus on end-use customer's value results in multiple technology development flows that are uncoordinated and hampering each other.

This thesis proposes a new framework. Not only does it overlay the Lean Enterprise framework onto the fuzzy front end of the technology infusion arena, but it also integrates the knowledge chain and the brand portfolio concepts together and forms a clearly defined value map with specific value carriers, infusion tasks, and supporting capacities for each categories of technology value stream.

This thesis, then, formulates the new framework. This Network-in-Network framework unifies the multiple uncoordinated technology value streams into an integrated value stream. It has two levels: (a) On the top, the system-level is an integrated value stream shared by multiple technology commodities flowing through different pathway. This integrated value steam quantifies the value of the end-use customer by assessing critical system factors, like time span of the infusion and the impact of uncertainties. (b) At the bottom, the low (local) level comprises multiple task networks that each supports its own gateways, so that it addresses the diversity of different technology development tasks while promoting local efforts in achieve technical success.

Finally, this thesis explores resource allocation of cycle-time for the task network with the goal to swiftly rotate engineering resource across task network boundaries. This resource allocation tries to maintain the integrity of the information flow so that it shares the semi-finished information within the engineering team as a means to provide the necessary flexibility to absorb variations.

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To my wife, Lihua for her support and endurance over the past two years of my SDM study.

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Chapter 1

Thesis Introduction

1.1 Problem Statement:

Original automobile manufacturing firms (hereafter, automobile firms or firms) have many different categories of technologies that range from basic research, system technology and down to component innovation. Due to the diversities of these technologies, many categories of the technologies require unique development processes. As a whole, the firm's automobile technology infusion is composed of multiple independent technology infusion processes (hereafter, multiple technology infusions), which infuses the technologies into automobile products or services to enhance a firm's competitiveness in delivering end-use customer's value. Unfortunately, these multiple technology infusions are complex and uncertain. The complexity and the uncertainty conventionally make an automobile firm's technology infusion very difficult to be either nimble or lean.

Furthermore, in the automobile technology arena, the spotlight of the technology value has been unintentionally scattered. The loss of focus on end-use customer's value results in multiple uncoordinated technology infusions (hereafter, multiple uncoordinated infusions), which are hampering each other.

The goal of this study is to fundamentally accelerate the value delivery of multiple technology infusions under rigorous business and operation constraints. The focus of this thesis is to propose a framework to merge multiple uncoordinated infusions into an integrated one shared by multiple technologies (hereafter, integrated technology infusion). As a result, the value stream of the integrated technology infusion (hereafter, integrated value stream) not only decouples the complexity of the multiple uncoordinated infusions but also overlays the Lean Enterprise framework onto the technology infusion process.

1.2 Industrial Trends in vehicle technology innovation:

a) Technology innovation becomes a dominant factor to decommoditize the product:

Good vehicle products are the heart of a healthy automobile firm, and solid vehicle technology is the engine to propel good products. In the new millennium, vehicles of high volume production become a way of the past. More and more customers have started to look at a vehicle beyond their basic transportation need; they want a vehicle to act as an instrument to amplify their life style experience.

With recent advance of Computer Aided Design (CAD) tools, the styling of the vehicle has become less and less distinguishable. During this transition, technology gradually gains a dominant role in fighting against product commodization, by differentiating one firm's product from her competitor's, in a tightly competitive market. As an evidence of that, the recent popularity of the near luxury vehicles ($28,000- $35,000 vehicles, such as Jaguar X type or Lexus ES 300) mirrors the growth of this consumer preference trend [Mayne, 2001]. These near luxury vehicles equip ample new technologies to entice their potential buyers in hope to stand out from their rivals. The obvious advantage of using technology as a competitive edge is that the tacit knowledge held by or inherent in the technology itself; this inherency makes technology very difficult to be emulated by a firm's competitor. Additionally, the high stake in product architectural changes associated with the core technology implementations (i.e. the architecture of vehicle platform or powertrain) makes competitor emulation very costly. Therefore, innovation of technology contributes to highly sustainable end-use customer value.

b) Technology contributes to the Sustainability of the corporation:

Sustainability means meeting the needs of present generation without compromising future generations [Jay Richardson, Heritage 2000 Manager of Ford Motor Company]. In a more constructive sense, sustainability improves the way of life for future generations so that they can enjoy more prosperous life than we do. There are two viewpoints regarding how technology contributes to sustainability.

In the big picture, automobile technologies play important roles in constructing the way of life for both current and future generations in terms of how people construct their life, how they consume the scarce natural resources (i.e. energy, raw materials, etc), and how they interrupt environments (i.e. the clean air, Ozone, etc). In a meaningful way, technology not only bridges the current generation's needs and the future generation's life, but also opens the window to explore the far-reaching opportunities in improving the world.

In the small scale, technology determines the future affluence of the corporation in serving its customers through either existing or new products/services. In addition, the profits generated from such operations guarantees the prosperity of the firm to continue its service into the years to come.

c) Digital device makes vehicle platform to be highly accessible to innovation:

As many hardware components of today’s vehicle gradually transform from conventional mechanical devices to digital-mechanical devices, the rate of technology changes becomes immensely faster. The tight marriage between digital technologies (i.e. computer, communication) and vehicle design has made vehicle platform highly accessible to innovation. It can enhance the functionality of a vehicle without significant cost penalty in updating the conventional hard tools (such as implanting the anti-roll-over software function into the anti-brake control module to enhance the stability against roll-over). This leads to the beginning of a new era of automobile digital innovation that further embraces the innovations.

d) Technology globalization leads to shorter technology shelf life:

The rapid advance of communication technology (such as the Internet) has enabled the application technology to be quickly dispersed across many traditional boundaries, including both geographic boundaries (e.g., nationality) and industrial boundaries (e.g., aerospace, computer, etc). Within the industry, application innovations also become the responsibility shared among many firms and their suppliers. This sharing leads to the creation of new classes of suppliers: technology suppliers (in contrast to part and service supplier) and mega system suppliers (who are in charge of subsystem integration, including technology innovation). These supplies can swiftly transfer many application technologies across traditional boundaries existing in automobile firms by making these technologies simultaneously available to many automobile firms. This swift transfer shortens the monopolizing life of application technology.

Even among the competing automobile firms, it becomes a norm to share the efforts and the results of developing radical technology with high risk, high investment (i.e. fuel cell technology) through Joint Venture (JV) or collaboration agreement to achieve high degree of technology utilization. This kind of sharing has tremendously shortened the emergent life of the radical technology.

1.3 Application of the Lean in a rapidly changing environment:

For years, the application of the Lean Principles (hereafter, Lean) has made tremendous success in the manufacturing side of the automotive business by streamline process, cutting waste, improving product quality, and maximizing the stability in a constant changing environment. As the progress continued, many automobile firms had spread the success of applying Lean to many non-traditional manufacturing activities (such as corporate finance, purchasing, human resource, and customer servicing, product design); many new applications also achieved noticeable success. In most cases, however, the more fluid (i.e., fuzzy, not being solidly defined, or constantly evolving) in the application domains, the more complex and more challenging is the applications of Lean. This trend commonly occurs when we try to push the limit of applying Lean to the upstream activities of an enterprise (such as the research and technology development) where the process tends to be so ambiguous that the resulting value streams becomes less transparent. Regarding the adaptation of Lean, it was thought that the technology infusion in the upstream domain is less suitable (or more difficult) than that in the downstream domain to adapt the Lean Principles because of the complexity inherent in the infusion and the variations generated from the exogenous or endogenous sources. However, on the positive side, the complexity of Research and Technology (R&T) really harbors the growth of *Muda* (or the waste) and the fuzziness of R&T blinds the firm from the throughput growth potential. Therefore, R&T provides a greater field to implement the Lean Principles.

1.4 Integrating multiple technology flows into an integrated value Stream:

Since technologies can be characteristically different, automobile firms conventionally categorize their technologies into three different categories: (1) breakthrough technology related to radical changes in technology, (2) architecture technology concerning the system changes, and (3) derivative technology pertaining to incremental changes [Henderson & Kim, 1990]. Because each technology category requires different levels of knowledge, expertise, and resources, automobile firms divide their R&T processes into three tiers: (1) basic research, (2) core engineering, and (3) technology implementation. Each tier sequentially possesses or owns a portion of the tasks in the technology infusion as independent projects. This leads to the lack of infusion continuity between two consecutive tiers and results in poor implementation.

With the intention to remedy this drawback, we propose a framework that integrates multiple uncoordinated infusions into an integrated technology infusion. The integrated technology infusion can be analogous to a sequential network flow of multiple commodities. At this point, each commodity represents a different technology, and each monitoring gateway within the network represents a tier. Using this analogy, each technology or commodity flows through different paths within the network and shares parts of network. Therefore, based on this setup, we can integrate multiple uncoordinated infusions into an integrated value stream that is shared by multiple technologies.

1.5 Optimizing Integrated Value Stream:

One way to optimize the integrated value stream is to adjust the composition of technology portfolio to achieve balanced resource usage by preventing the rise of the bottleneck comes from resource contention. In the integrated value stream, each technology or commodity consumes a portion of the network resources, but it brings different levels of benefit to the network. However, whenever there is an imbalance between tasks and available resources, the imbalance commonly withholds the tasks to form a waiting queue that causes a job delay and results in a bottleneck (or a system constraint). These bottlenecks (constraints) of the network paths may impose some restrictions on certain categories of technology, while allowing other technologies to flow right through. In most cases, it is the less critical (or low yield) technology that routinely blocks the passage of a critical or high yield technology, and this blockage leads to loss of end-use customer value. In the meantime, multiple local constraints demand high level of corporate resource to support the flow of technology development. As the consequence, the scarce resource contentions among multiple interconnected constraints make the planning and execution of multiple technologies very difficult. Managing integrated value stream requires a higher degree of system planning than managing multiple disintegrated technology infusions. A good system optimization can be an extremely valuable tool in identifying the priorities of the resource assignment in a highly complex environment with multiple constraints.

1.6 Pursuing system improvements under constraints:

Besides the complexity of the technology, in today's complex business and technical world, most of the systems contain numerous interconnected operational and business constraints. Many of these constraints intensely interact each other in forming multiple potential bottlenecks and make system engineer too difficult to identify the locations of the bottlenecks and the amount of the slacks (waste) hidden inside the system. Without such information, the Lean practitioners may wrongly reduce the critical capacity of the bottleneck to hurt throughput or they may over cut the slack of the non-constraint process by changing a nonbonding constraint into a bottleneck. This makes the practice of Lean extremely hard to progress if Lean practitioners are frequently confronted by emergence of these constraints while they are frustrated with the negative outcomes. Therefore, it is desirable to adopt some sort of system engineering tool to systematically identify system slacks (waste) or system bottlenecks before executing Lean.

In the area of identifying bonding constraints of the system (i.e., constraints that currently limit the throughput of the system), many system engineers tend to use Time History Simulation to gain a snapshot of the primary bottleneck (bonding constraints). However, not only is this approach time consuming in tracing the symptoms to the root cause, but it also embeds the weakness of not being able to gain a wide range of other decision supporting information. These decision supporting information include: (1) the possible throughput increase of relaxing bonding constraints (e.g., the shadow price, defined in optimization terminology as the throughput increase per unit of bonding constraints relaxation), (2) the range (e.g., bonding constraints relaxation range before other emergent constraints become bonding), and (3) slackness (which may seem as potential waste) of all nonbonding (non active) constraints. Without this information, it becomes very difficult for system engineers to prioritize an effective pathway to either eliminate waste or increase throughput. This leads to the merit of a Constrained Optimization tool, (e.g. such as Linear and Non Linear Programming [LP & NL]), or the merit of Dynamic Programming (DP) tools, which have the inherent capability to gain wide insights on all of the potential bottleneck information and lead to a more robust execution of the Lean.

1.7 Focus of the study:

The focus of this study will concentrate on both qualitative and quantitative approaches of applying the Lean in an integrated technology infusion. The focuses are:

- To explore the root cause of slow clock speed in technology infusion (Chapter 2);
- To explore the value stream in R&T and propose qualitative frameworks to incorporate the Lean Enterprise Principles (Chapter 3);
- To study the integration of the multiple technology infusions into an integrated value stream in the context of schedule uncertainty, resource constraints, profitability, and autonomy (Chapter 4); and
- To discuss the engineering resource optimization of the innovation network to promote knowledge sharing across boundaries (Chapter 5).

1.8 References:

1. Henderson, Rebecca M. & Clark, Kim B., 1990, " Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Establish Firms", Administrative Science Quarterly, 1990, Vol. 35, pp 9-30.
2. Mayne, Eric, 2001, "Baby Boom", Ward's AutoWorld, October, 2001, page 36, http://ww.WardsAutoWorld.com.
3. Womack, James P., Jones, Daniel T. and Roos, Daniel, 1990, "The Machine that changed the world," (NY) Rawson Associates, ISBN 0-06-097417-6.
4. Womack, James P. and Jones, Daniel T., 1996, "Lean Thinking", (NY) Simon & Schuster, ISBN 0-684-81035-2

Chapter 2

Clock Speed of Technology Infusion

2.1 The slow clock speed of the traditional three-tier R&T process:

Conventionally, automobile companies organize their Research and Design (R&D) activities based on the metaphor of a three-tier organization: (1) basic research, (2) core-engineering activities, and (3) product development activities. [Hauser and Florian, 1996]. The organization principle behind this three-tier arrangement is to facilitate resource utilization while striving for the functional excellence of the tier. Accordingly, each tier is separately managed under designated budget and resource, but each retains its coordination through the technology council on the corporate level.

Figure 2.1 shows a simplified layout of a traditional three-tier R&D infusion process. It illustrates that these three tiers are linked together in a conservative Waterfall format and with buffers between consecutive tiers. Inside each tier, each of the functional or product group acts independently and reports to the head of its division (i.e. Science and Research division, Core Engineering division or Product/Process Engineering divisions). Subsequently, the Technology Council acts only as the mediator among the divisions to coordinate the technology priorities.

For every budget year, the technology council consolidates the entire "technology want list" from individual customer groups of manufacturing, marketing and strategic planning. After consolidating of the want list, the technology council jointly prioritizes the want list, based on the strategic priorities of the corporation. The functional departments of each tier then initiate project bids, by matching their functional expertise with the "prioritized want list" under its own resource and budget guidelines. At this point, most of this governing power falls upon functional departments of the hierarchy management chain (the divisions) and the technology council generally has minor influence over the content of the technology projects and their associated resource distribution. At the end of the technology creation, the semi-finished product of each tier will be placed in the technology "bookshelf," hoping that it will be picked up and further be implemented by the product design teams (based on product design team's own discretion). Under this system, most of the technologies created by the functional departments tend to put high priorities in supporting their own needs, while ignoring the wants from other functional departments; this results in major performance discrepancies at system level.

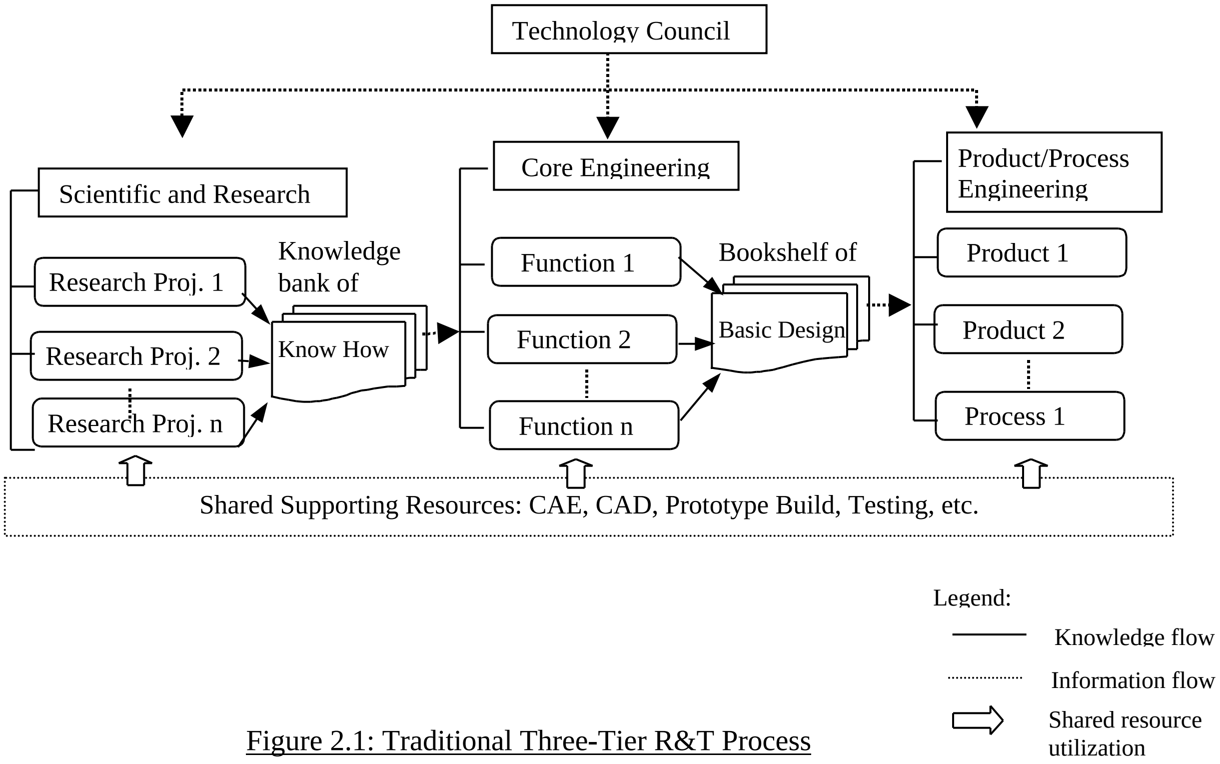


Figure 2.1: Traditional Three-Tier R&T Process

The other major pitfall of this kind of layout is the absence of synchronization and coordination among the tiers, if all three tiers consider their own resource utilization to be a high priority. Among the tiers, the imbalance between the annual budget and resources frequently lengthens the queue of the technology bookshelf. As indicated in Figure 2.1, the queue becomes longer when every functional department routinely initiates its own technology projects in hopes of improving its own functional excellence. In a full spectrum of technology developments, each and every department also wrestles for the scarce shared resources from the firm's supporting organizations, which commonly include Computer Aided Engineering (CAE), Computer Aide Design (CAD), component/subsystem testing, and the like. Therefore, not only the out-of-synchronization retards the clock speed of the overall technology infusion process, but also the lack of coordination on sharing resource aggravates the delay of the technology development.

2.2 The implication of slow clock speed in the traditional technology infusion:

One primary weakness of today's technology infusion by automobile firms is their slowness and inflexibility to meet consumer's demand, rather than the lack of innovations. This slowness and inflexibility of the traditional technology development frequently amplifies and propagates unexpected variations throughout the system; the amplification and propagation (of the variations) makes the entire technology infusion process volatile and unpredictable. This volatility and unpredictability compel many firms to adopt a sizeable Finished Goods Buffer (FGB) as a precaution or safety net mechanism (i.e. the knowledge bank of the "Know How" or the bookshelf of "Basic Design" of Figure 2.1).

The large FGB is expected to isolate the negative variance from the predictable and cost-sensitive downstream Product Design (PD) activities. However, the side effect of a large FGB is that the merits of technology innovations quickly vanish as they are waiting on the shelf. The adoption of a FGB not only delays the timing of technology application but also diminishes the throughput of the entire system.

On the other hand, the rapid growth and evolution in information and communication technologies constantly disseminates the latest product innovations across all industries to the consumers. This dissemination accelerates the clock-speed of consumer demand and widens the "gap in clock-speed", leading to a "vicious cycle" of System Dynamics (SD) [Sterman, 2000].

A valuable SD model created by Bokshorn implied the "gap in clock-speed" as the difference between the "ideas backlogged" and the "products in development" by placing emphasis on the life cycle of innovative ideas, instead of on the dynamic impact of the "Variations of Clock Speed" [Bokshorn, 2001]. In order to help us to trace the dynamic impact of the Clock-Speed variations, we create a separate SD model (Figure 2.2) to supplement Bokshorn's model. As indicated in Figure 2.2, the Technology development speed is a function of the firm's Technology Capacity, and this Technology development speed determines the Technology finishing rate. After the technologies have been developed, the Technology-shelving-rate and the Technology-application-rate determine which proportion of technologies goes to Technology book-shelf, and the remainder will goes directly into application (Technology Delivered). The book-shelved technology may get the second opportunity for the application if the system has a good bookshelf-application-rate. The bottom portion of Figure 2.2 indicates that the quality of the technology is a function of Technology System Adaptability and Variations in Clock Speed. The Quality of the Technology affecting the Rework rate and determines the amount of Technology Rework.

Within the system, many of the rates are directly or indirectly controlled by the Variation in Clock Speed, which is the difference between consumer's Technology Demand Clock Speed and firm's Technology-development-speed. As shown in Figure 2.2, the "positive feed back loops" (such as the thick line loops of "A-B-C-D-E-A" and "A-F-D-E-A") greatly intensify clock-speed variation throughout the entire system; the increase of clock-speed variation not only increases the vanishing rate of technology value but also degrades the quality of technology further. Because further degradation of quality will boost the technology-shelving rate and the rework rate, in the meantime, this degradation diminishes the application rate of technology. Consequently, the degradation of quality leads to a further increase of the variation of clock-speed.

However, although the compounding effect from the clock-speed variance and the quality degradation will plunge the throughput of technology infusion, the reduction in clock-speed variance enables automobile firms an opportunity to optimize customer value by synchronizing their technology infusion speed with technology demand speed.

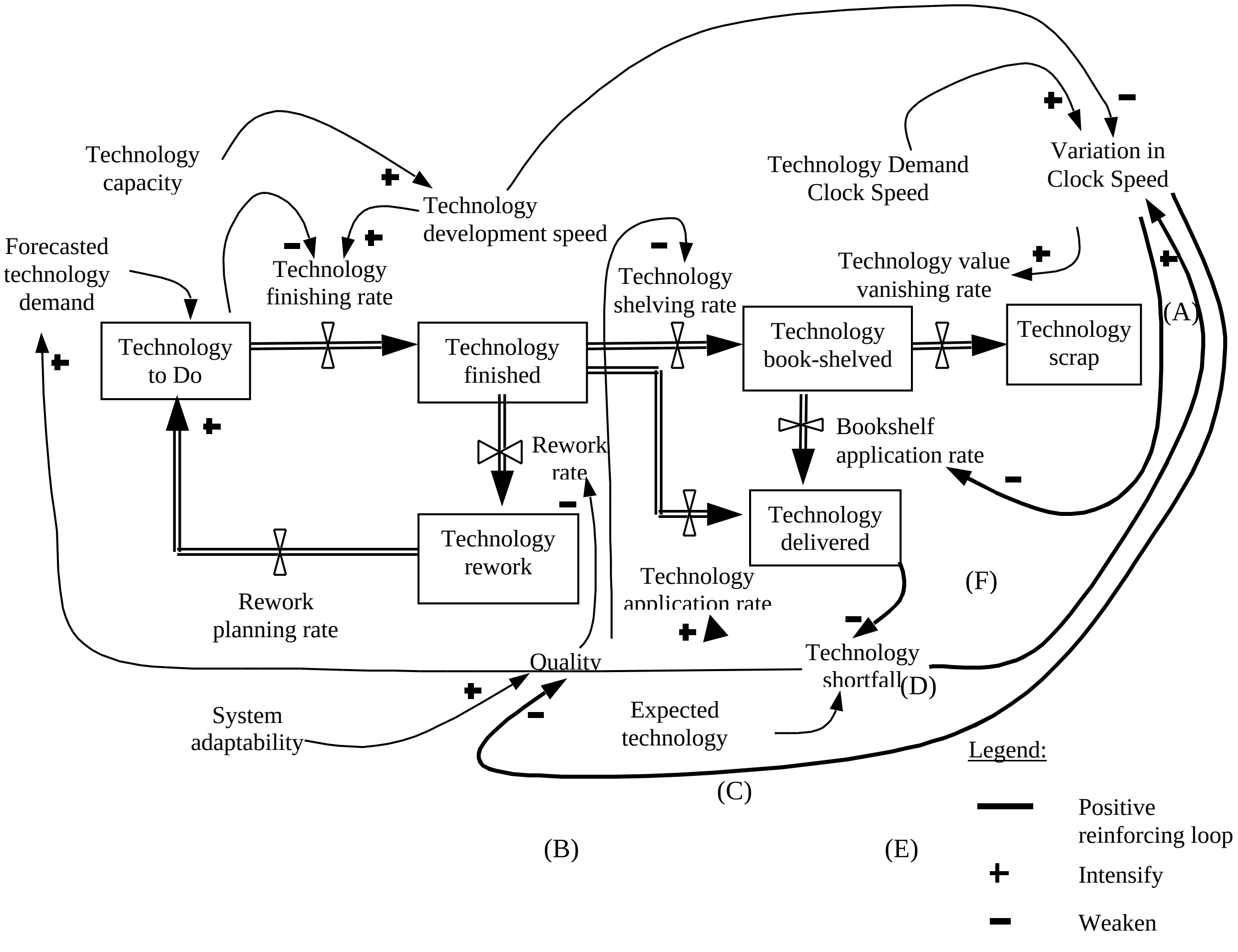


Figure 2.2: The Impact of Technology Clock Speed Variation (SD)

In addition to the variation of clock-speed, Figure 2.2 also highlights the significance of the technology throughput in achieving "Optimal First Delivered Unit Quality." As the unit quality increases, the technology rework rate and the technology shelving rate decrease, and in the meantime, the direct technology application rate increases; these changes in rate lead to an increase of the technology throughput. Accordingly, either reducing the variation in clock speed or enhancing the system adaptability can boost the quality of "Design In Process" (DIP) technology inventory and further increase system throughput [Reinertsen, 1997].

In recent years, the rapid advance in communication and computer technology has greatly reduced the time of design tasks but without visible enhancements in the area of infusion methodology. This advance leads to the variation of the clock speed between the customer's demand and technology delivered, continues to grow. Furthermore, in the R&T area, automobile firms frequently follow the old waterfall mentality with a functionality-focused mindset (vs. consumer-focused mindset). The ill combination of the waterfall mentality and the "batch and queue" production practice fundamentally impedes the speed of technology infusion. The focus of this research is to integrate multiple technology infusions with the Lean Principles to enhance the clock speed of technology infusion.

2.3 Learning from Ford ‘s Technology Development:

The inefficiency of the traditional (i.e., “Waterfall” type) technology infusion system had greatly impeded Ford's ability in delivering technology to her customer. Under Ford’s push type technology development, less than 10% of the bookshelf technologies were actually implemented into production in her traditional Technology Development Process (TDP). The remaining bookshelf technologies depleted themselves on the technology bookshelf. This depletion, in most cases, had never been even contributing to "lesson learned" or so-called organization "absorptive capacity" [Cohen and Levinthal, 1990].

The huge investment waste and the opportunity loss caused by the depletion had recently caught Ford's senior management's attention. In January 2001, Ford overhauled TDP and replaced it with the Big Bang process (i.e., a technology infusion process of a pull type) (Figure 2.3). The focus of the Big Bang process is to quickly pull technology through Premier brand vehicles in order to deliver distinguishable technologies nimbly to consumers [Mayne, 2001]. After successfully deploying the technology to the Premier brand, platform engineers can diffuse technology further to the remaining brands, leading to high efficiency in harvesting value across the entire spectrum of the vehicle brand portfolio. At Ford, the spectrum of brand portfolio includes the Premier brand (e.g., Volvo, Jaguar, and Lincoln), the Volume brand (e.g., Ford Taurus, Explore, F-150), the Value brand (e.g., Ford Escort, Ranger), and the Comfort brand (e.g., Ford Crown Victory).

The intangible benefit of this first-to-market approach is that the quick application of the technology on the Premier band vehicles can implant the vivid image of technology innovator deeply onto Ford's trust mark (i.e. the "*Ford Motor Company*" is a trust mark to legitimate all Ford's brands). This trust mark then can be shared as a solid platform in backing up other vehicle brands.

In order to facilitate the Big Bang process, Ford has fundamentally strengthened its leadership on how senior managers lead the technology infusion process. On the top management level, the Vice President (VP) of the Core Engineering becomes the champion of the Big Bang process who hosts the periodical progress review for each project and provides the timely assistances to pave for the success of technology implementation. On the project level, the leader of the Big Bang project changes from a regular technical employee to a technical manager to enhance his or her leveraging power to manage the process (Table 2.1 of Figure 2.5).

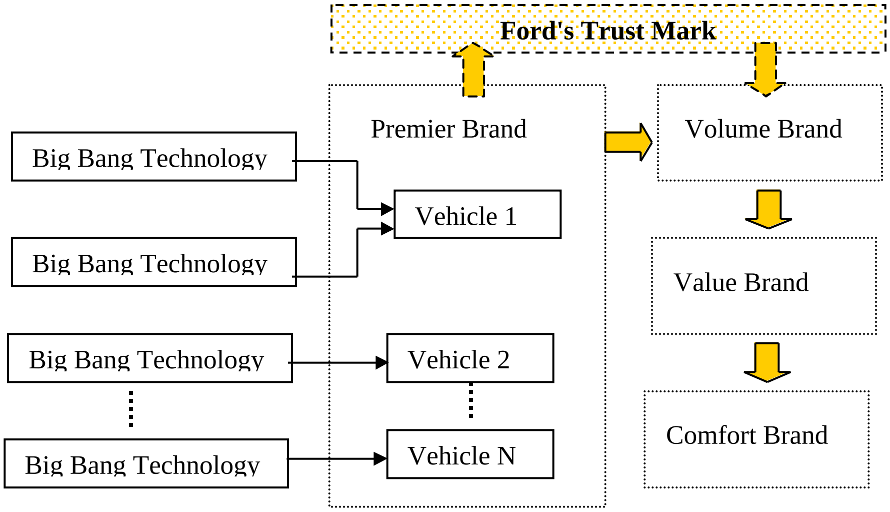


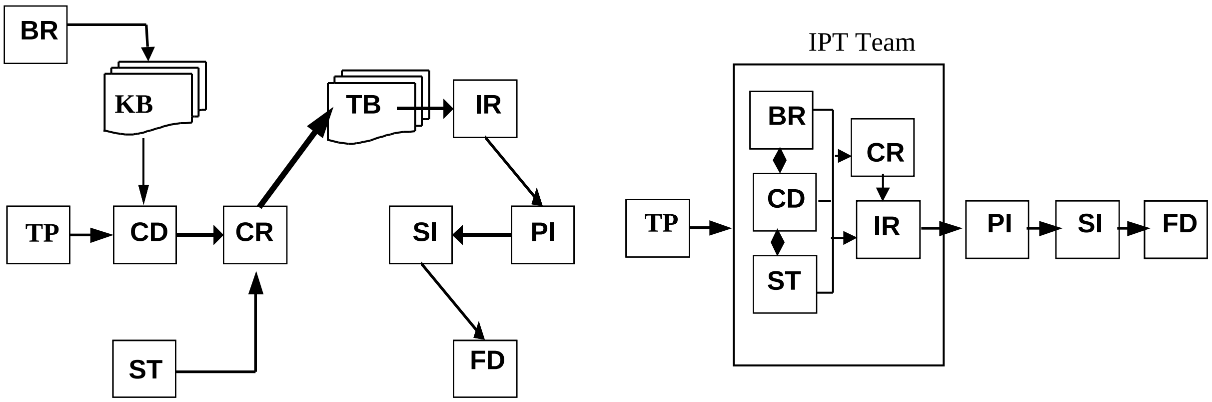
Figure 2.3: Big Bang Technology Diffusion Path

Comparing with the TDP, key changes of the Big Bang process include: (1) process streamline, (2) single piece flow, (3) adoption of the Integrated Product Team (IPT), (4) the synchronization of technology between the development and application by eliminating bookshelf, and (5) a unification of the global technology infusion efforts with multiple local focuses (Figure 2.4, Figure 2.5).

(1) In the process streamline, the Big Bang process achieves significant reduction of "flow time" by integrating multiple disjointed processes into a coherent IPT development process. (2) In order to facilitate single piece flow, the Big Bang process matches the "load" of projects to Ford's technology capacity so that the number of the projects has been tremendously reduced. (3) In adoption of the IPTs, the Big Bang's IPT team enlarges its traditional engineering IPT

membership to include non-engineering enterprise-level functional members, such as purchasing, manufacturing, and testing. The addition of these new IPT memberships not only widens the expertise of the IPT but also strengthens vital communication across the barriers of functional organizations, leading to a significant reduction of the idle time. (4) Furthermore, the Big Bang process eliminates the technology bookshelf by synchronizing technology between development and application. The elimination of the bookshelf not only keeps the value steam flowing without interruption, but also psychologically challenges Ford's engineers to optimize system's "First Delivered Unit Quality" by removing the cushion of safety net, in terms of the technology bookshelf [LAI, 1998]. (5) The Big Bang process unifies multiple local technology development into a global technology infusion effort with multiple local focuses to address the local diversities (e.g. meeting local regulations, local affordability, or local customer usage, etc). These unified technologies then can act as the backbone to propel the Generic Architecture Process (GAP) in unifying the vehicle platforms.

Detailed comparisons between the TDP and the Big Bang process in the context of the "Five Fundamental Concepts of Lean [Womack and Jones, 1996]" and leadership behavior [LAI, 1998] are summarized in Table 2.1 (Figure 2.5).



TDP Process

Big Bang Process

Legend:
TP: Technology planning
BR: Basic research
KB: Knowledge bookshelf
CD: Core technology development
ST: Supplier technology development
CR: Concept readiness certification

TB: Technology bookshelf
IR: Implementation readiness certification
SI: Supplier implementation
PI: Product implementation
FD: Fabrication and delivery

Figure 2.4: Process Schematic between the TDP and Big Bang process technology development

Table 2.1: Comparison between the TDP and Big Bang process in the context of the Lean

	Lean	**TDP**		**Big Bang**	
Value Definition	End-use customer	No	Corporate	Semi	Lead Customer
Value Steam	Clear defined value channel	No	General application without clear defined value channel	Yes	Through technology diffusion curve led by brand vehicle
Pull	Respond to the demand of the customer	No	Push system by functional department	Semi	Semi Pull system by vehicle center
	Has well defined value channel	No	No specific implementation product or process target	YES	Pre-selected implementation vehicle platform
Flow	Without interruption	Weak	Two phases development process: Concept ready (CR) and implementation ready (IR).	Better	Single phase development process
	No buffer	No	Huge CR, IR bookshelves	Yes	No bookshelf.
	Single piece flow	No	Multiple pieces flow by partially funded project resources.	Yes	Single piece flow by matching number of projects with organization capacity
	Integrated Product Team (IPT)	No	Functional organization	Yes	Integrated Technology team
	Minimum order to implementation time	Weak	More than 7 years	Better	Less than 4 years
Perfection	Optimal First Delivered Unit Quality	Weak	Less than 10% implementation rate	Strong	Target at more than 80% implementation rate
Leadership	Governance	Weak	By function chief of individual Technology council	Strong	By VP of Core Engineering
	Team Leader	Weak	Technical supervisor/ Technical engineer	Strong	Technical manager
	Global participation	No	Regional team only	Strong	Global team with local focus

Figure 2.5: Table 2.1 Comparison between the TDP and Big Bang process

2.4 Summary of Technology Infusion Clock Speed:

The variation of the duration becomes one of the major root causes of the slow clock-speed in the technology infusion. The discontinuities of the value stream (like the value stream of the technology bookshelf) quickly deprive the merits of technology from end-use customers. The randomness of multiple technology value streams, together with overloaded projects, further retards the speed of the infusion. In the following chapters, a lean technology infusion framework will be defined and detailed by expanding the spirit of Ford's Big Bang technology infusion process. This new framework will adopt many key Lean Principles into the technology value stream with the objective to improve the clock-speed of the technology infusion.

2.5 References:

1. Bokshorn, Sylvie, 2001, "A System Dynamics Study of Ideation in R&D", Master Thesis, of System Design and Management Program (SDM), Massachusetts Institute of Technology.
2. Cohen and Levinthal, 1990, "absorptive Capacity: A new perspective on Learning and Innovation", Administrative Science Quarterly, 128-152. Administrative Science Quarterly.
3. Hauser, John and Zettelmeyer, Florian, 1996, The "Three Tier Metaphor" of "Metrics to Evaluate R, D&E", research briefing for Research Technology Management, November 1996, (MA) "International Center for Research on the Management of Technology (ICRMOT) at M.I.T.'s Sloan School of Management, Cambridge, MA 02142, web site, http://web.mit.edu/icrmot/www/.
4. LAI, 1998, "The Lean Enterprise Model," Lean Aerospace Initiative, Massachusetts Institute of Technology, July 1998.
5. Mayne, Eric, 2001, "Can Premier Automotive Group Answer the Call to Save Ford?", Ward's AutoWorld, October, 2001, page 32, http://ww.WardsAutoWorld.com .
6. Reinertsen, Donald G., 1997, "Managing The Design Factory", The Free Press, a division of Simon & Schuster Inc., ISBN 0-684-83991-1, pp 11-16.
7. Rogers, Everett M., 1983, "Diffusion of Innovations", NY: The Free Press, 1983, 3rd ed., pp 241-270
8. Sterman, John D, 2000, "Systems Thinking and Modeling for a Complex World," McGraw-Hill Higher Education, 2000, ISBN 0-070231135-5.

Chapter 3

Technology Value Stream in the Lean Enterprise

3.1 Technology "S" curve: Technology Racing model and Technology category

The innovation "S" curve initiated by Foster has been widely adopted by many technology and innovation researchers in their representing the life cycle of breakthrough innovation [Foster, 1986]. The "S" curve is an important foundation to understand the basic competition mechanism at each stage of the technology life cycle (Figure 3.1). In the "S" curve, the vertical axis represents the functionality of the technology, and the horizontal axis represents the amount of effort used by technology development. During the infant phase, the innovator strives for a minimum functional growth with a large amount of efforts. As the technology progresses to maturity, the "S" curve exhibits a rapid growth of functionality with little amount of incremental effort [Utterback 1994]. As the technology enters the mature phase, the rapid functional growth decreases.

This "S" pattern leads to a “Technology Racing” model [Henderson, 2001]. It states the following:

(1) The competition of technology tends to be based on Secrecy or Intellectual Property (IP) protections against competitors at the Infant phase.

(2) After a dominant design has been reached, the competition becomes a speed race of the functional improvements to gain market share during the Growth phase.

(3) This competition finally pushes the product innovation into a commodity and results in competitions either on cost, which manifests itself in the form of a price war or competition on standards, which becomes a monopoly.

The Secrecy, the Speed, and the Cost are three different competition modes that can be easily corresponded to the three categories of the product technology portfolios: breakthrough technology, architecture technology, and derivative technology [Henderson and Clark, 1990]. Based on Henderson and Clark, breakthrough technology competes on secrecy; architecture technology represents the speed competition in technology development after the dominant design emerges into defined architecture; the derivative technology represents the price competition after the technology becomes a commodity. In few exceptions, products may continue to enjoy high profits by gaining the status of Industrial Standards (e.g. the OnStar system) to avoid fierce price war.

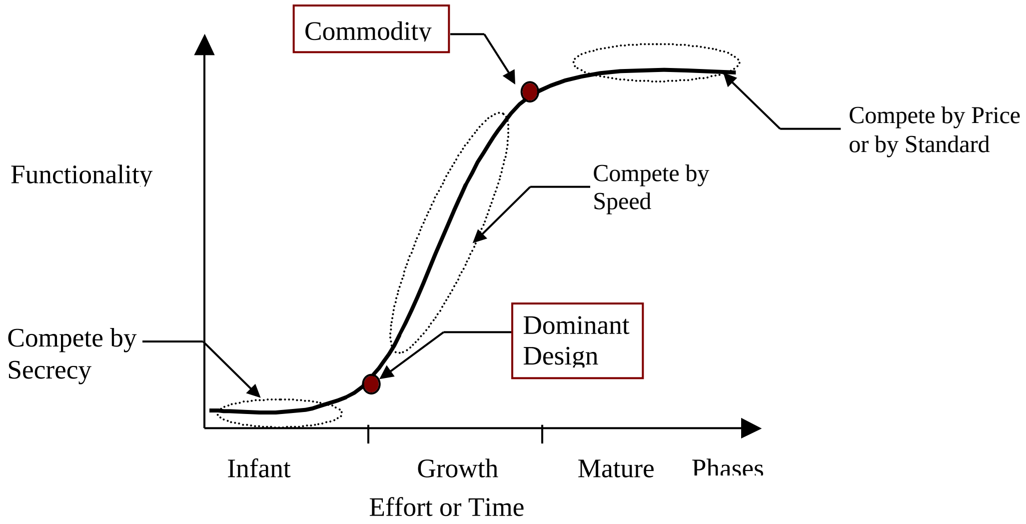


Figure 3.1: Technology Racing Model [Henderson, 2001]

3.2 Five fundamental concepts of the Lean thinking:

In the lean technology framework, we adopt the five basic concepts: specifying value, identifying the value stream, flowing, pulling, and perfecting [Womack and Jones, 1996]. The merits of these five Lean Concepts are to convert the mindset from technology-focused into customer-focused so that value can be delivered and defined by end-use customer (hereafter, customer). These five Lean Concepts also imply the elevation of Lean though the steps.

3.3 Specifying End-use customer's value:

From the Lean perspective, the value of the technology shall be defined solely by customers. The intention of this value specification is to prevent the surfacing of self-serving interest that is initiated by the local organization and does not contribute to customer's "dimensions of merit" (i.e., value to the end-use customer in terms of time, price, functionality, quality, and the like) [Hauser, 1984].

Specifying the technology in terms of customer's "dimensions of merit" further provokes a thinking out of the technology box: namely, to deliver value to consumers, instead of technology itself. In the case of improvements of corporate efficiency, these improvements shall quickly transform corporate efficiency to the "dimensions of merit" so that all potential customers will benefit either through adding value to the existing products or through creating extra value with new products or services.

A rapid transformation from technology to customer's value is vital to gain competitiveness of the technology by picking up the essential critical mass to compete against other emergent technologies with similar functionality. This "critical mass" phenomenon can be accelerated by the tipping effect of network externality [Henderson, 2001] (i.e. One quick example of this network externality for the automobile example is the recent surge of the Anti-Brake System [ABS] that propels every safety-conscious customer to “must own” after his/her next door neighbor purchased a vehicle with it.). As shown in Figure 3.2, the network externality tends to tip the technology market to the most promising technology deemed by consumers, which usually occurs when technology externality exceeds 50%, and the market share shies away from less promising technology when customer deems that it is not popular.

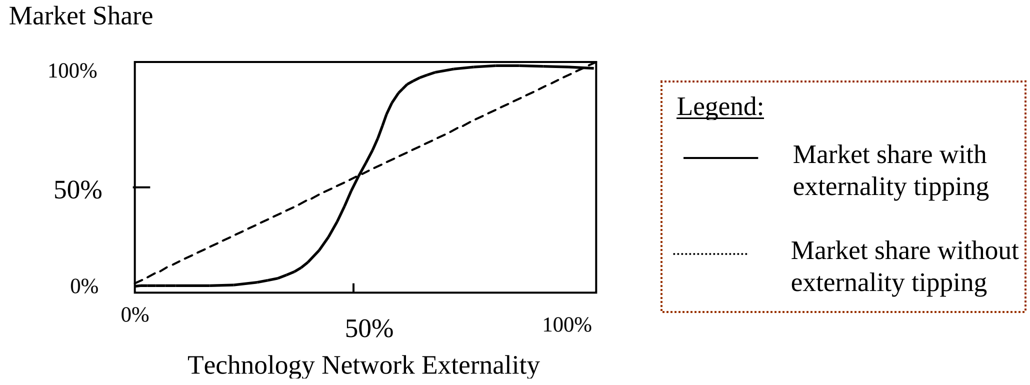


Figure 3.2: The Tipping effect on technology network externality [Henderson, 2001]

3.4 Identifying technology value stream and value carrier:

In the view of value path, the value streams are easily classified into two types: consumer value stream and enterprise value stream (Figure 3.3). While the consumer value stream enhances existing customer's "perceived technology merit" [Crawley, 2000] or "dimensions of merit" [Hauser, 1984], the enterprise value stream transfers the internal efficiency gains to benefit the future customer.

Inside these two value streams, there exist many interconnected value chains, and each value chain contains multiple value outlets. For example, technology innovations can profit through either the product markets or the idea markets [Gans and Stern, 2001]. The technology manager should carefully align the potential value stream outlets to the firm's strategic priorities by conforming to the assessment of the technology trajectory [Christensen, 1997] as well as the firm's capability on appropriability and complementary matrix [Henderson, 2001; Teece, 1998].

Henderson categorizes the technology infusion into three major phases: value creating, value capturing, and value delivering [Henderson, 2001]. We extend the definition of this categorization by summarizing these three phases into a unified value stream map (hereafter, value map) (Figure 3.3). This value map highlights the components of technology infusion across three different organizations (i.e., Science and Research, Core Engineering, as well as Product Design and Manufacturing) by clearly defining the tasks, the challenges and the supporting capacities of each phase.

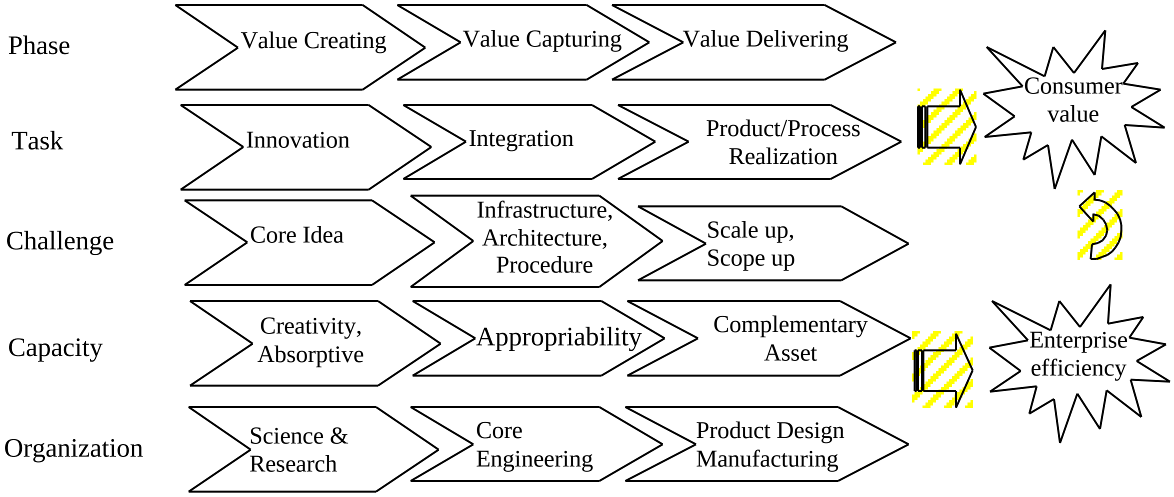


Figure 3.3: Technology Value Stream Map

(1) In the phase of value creating, the main challenge of the automobile firms is how to transform knowledge into Core Ideas with an identifiable economic potential through innovations. Therefore, these Core ideas become the value output of firm's Science and Research organization. In order to facilitate the innovation, the Science and Research organization needs to build up its capacities on Creativity and Technology Absorptiveness.

(2) Following the phase of value creating is the phase of value capturing. In this value-capturing phase, the top challenge here is how to merge the product architecture and the

technology innovations [Teece, 1998] through integration. During the integration, Core Engineering managers need to make an intelligent but difficult "fusion" choice between creating a new value chain to accommodate the technology (in forms of infrastructure, architecture, or procedure as shown in Figure 3.3) and integrating technology into existing value chains [Gans and Stern, 2001; Henderson and Clark, 1990]. Typically, the choices of infrastructure are internal manufacturing facilities, external supplier chains for components, and channels of product delivery and service. The choices of architecture include brand portfolio, product platform, and functional or architectural layout. The choice of procedure tends to be less visible to the outside customer, although it is vital for the internal operation. The procedure represents an internal discipline to guide the design and production communities, which typically includes the process and product standards. The competitive edge of this phase relies on the Appropriability capacities of the firm, which includes the Intellectual Properties (IP) protection or other means to prevent competitor from emulating firm’s technology creation.

(3) In the last phase, value delivering, the main challenge is how to effectively scale or scope up to maximize consumer economic return during the process of Product or Process Realization. At this stage, the firm fully relies on its well-established complementary assets (such as product design, manufacturing, supply chains, marketing and servicing) as the competition advantages to prevail the technology.

In the area of defining a value product, most researchers and technology developers routinely analogize the technology value steam as a form of information flows throughout various design activities, but they fail to specify the “value carrier” of each activity in the value stream**.** The weakness of this analogy is that it accepts the output product but the output product does not contain solid customer value and becomes more or less self-serving in some situations. The most common example of this weakness is that of the intricate science publication produced from the

Research organization of the firm. Many of them perform well in transferring value within the research community, but they fail to respond to the value pull by her downstream Core Engineering. This failure leads to a question of "what are the value carriers in each stage of the technology infusion process?"

In the stage of innovation, the science community claims that the value product is the knowledge or the absorption capability. From the end user perspective, however, none of the absorption capability adds direct value to the customer in terms of "dimensions of merit." Therefore, before we trace the flow of the technology value chain, we need to carefully define the “value transfer product” of each process. As shown in Figure 3.3, the key product from the Research organization of the automobile firm shall be the "Core Idea", which not only can exhibit clear merit potential for the customer but also can easily be captured by the downstream Core Engineering organization. The Core idea can be defined as a product concept that solidly bonds the knowledge and innovation in the form of potential products, which exhibit high value potential to firm's customers. As for the Core Engineering activities, the value product shall be defined in terms of new technology architecture and infrastructure so as to immerse the core idea into the product or process. As for Product Development (PD), the output product shall be the realization of the technology through product or process implementation.

3.5 Flowing without interruption:

In the Lean definition, the Flow concept is to make the value chain flow without interruption. Two situations commonly impede the continuity of flow of the value stream. The first is the discontinuity of the value stream outlets; it blocks the flow of the technology value stream within the product portfolio. The second is the blockage by the technology buffer; it delays the technology flow. The discontinuity of the outlet commonly relates to how well a firm projects its technology value steams into her product brand portfolio. Since this outlet issue has not been widely discussed before, it is worthwhile to discuss the value stream in brand portfolio first before moving to the internal buffer issue.

a) Proliferate technology diffusion into brand portfolio without the interruption:

In demanding technology, different groups or categories of customers commonly have different clock-speeds. Figure 3.4 illustrates the Customer Satisfaction as a function of Technology Lag Time for four different automobile customer groups (C1 to C4) [Cain, 1997]. The C1 customer group represents the Early Adopter who demands the technology in higher clock-speed and whose customer satisfaction drops precipitously with time. The C2 group is the Early Majority, the value seeker, who strikes for the balance between functions and cost so that he or she has slower clock-speed than C1 group. The C3 group is the Late Majority, the price seeker, who tends to hold on until the technology become very affordable and has higher tolerance to technology lag time. Finally, the C4 group represents the Laggards who wish to hold on to the familiar environment and who do not welcome technology innovation [Rogers, 1983].

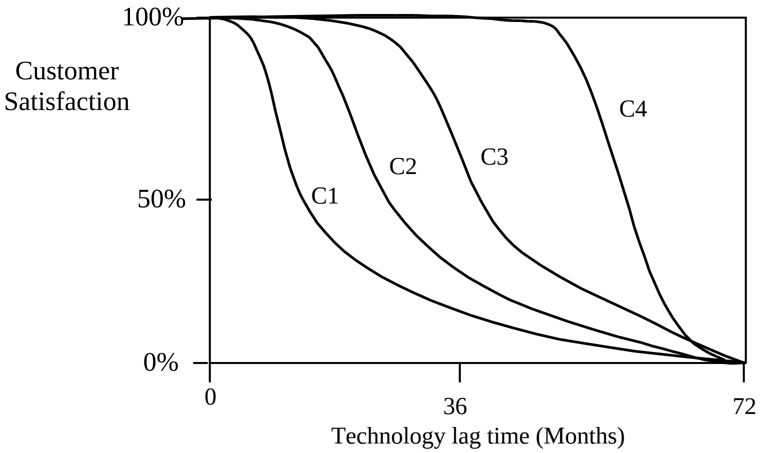


Figure 3.4: Customer Satisfaction as a Function of Technology Lag Time [Cain, 1997].

By understanding the differences of clock-speed among various customer groups in technology demand, automobile firms commonly map their brand strategies onto the technology diffusion curve in hopes to effectively diffuse the technology throughout various brand vehicles. As shown in the top panel of Figure 3.5, the technology diffusion curve tends to be shaped as the Bell shaped Normal distribution with several chasms across the spectrum [Moore, Geoffrey, 1999]; where each chasm represents discontinuity or potential interruption in technology diffusion. Chasms commonly result from the inability in meeting the "dimensions of merit" for the next group of customers or the failure in marketing the technology.

In order to make the value stream proliferate without interruption, automobile firms should intentionally position lucrative brands across the chasms to induce the value stream proliferating. The bottom panel shows the overlapping of the brands across the technology diffusion curve where the Technology brand tends to covers C1 (i.e., the group of Early Adoption), and the Premier brand tends to cover the chasm A between C1 and C2 (i.e., the group of Early Majority). This leads to the Volume brand to overlap the chasm B between C2 and C3 (i.e., the Late Majority), and the Value brand to cover the chasm C between C3 and C4 (the Laggards). Finally, it leaves Comfort brand for the Laggards C4. One key advantage of mapping the technology brand is that the value stream could effectively proliferate into multiple brands by meeting its unique "dimensions of merit" in a timely manner.

From the perspective of the enterprise value steam, mapping technology onto brand portfolio provides the firm a with unique opportunity to capitalize a full stream of market potential by effectively scoping up and scaling up. The scoping up shares similar technology architecture among multiple products; in the meantime, engineers tailor specific technology components to support individual product needs in order to enhance its brand's identity. On the other hand, the scaling up spreads similar technology through multiple volume applications in order to shave production unit cost.

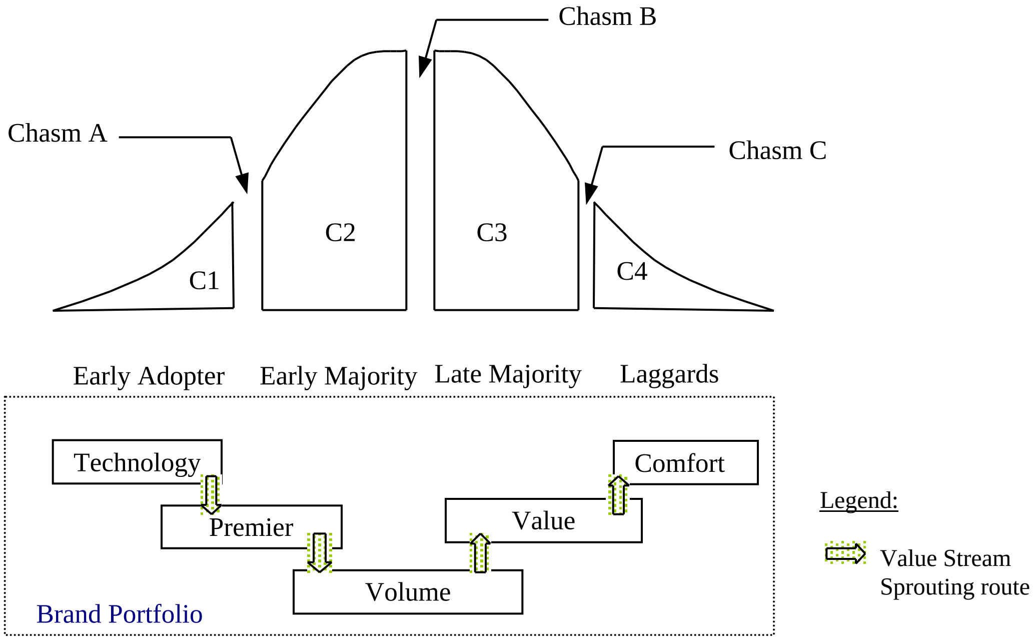


Figure 3.5: Overlay of Technology Diffusion curve and Brand portfolio

b) Single piece flow without buffer:

In general, most technology exhibits high degrees of uniqueness or dissimilarity. Therefore, at least in theory, a technology product shall be the ideal product to be processed in a Lean and single piece flow pattern so that it could bypass the clumsiness of mass production's batch and queue. Nevertheless, the uncertainty of the technology task duration routinely disturbs the highly synchronized development plan, and it pushes highly synchronized tasks away from their well-planned schedule. This out-of-synchronization phenomenon and its associated weaknesses induce many functionally organized R&T groups to adopt a huge work-in-process (WIP) queue in hopes to maximize their resource utilization under constantly changing environments. However, the existence of a huge WIP actually increases flow time and further retards system throughout. Two solutions to the problem are: (i) the adoption of an Integrated Product Team (IPT), and (ii) the Adaptive Life Cycle approach [Highsmith III, 2000].

1. The adoption of an IPT team integrates discrete functional staffs into a single team structure; it will effectively enhance internal coordination within the cross-functional organization and promote information flow across functional boundaries by preventing the surfacing of bottlenecks generated by information holdup.
2. On the other hand, the incorporation of the Adaptive Life Cycle approach closely integrates an open spin-off loop of Speculating, Learning and Collaborating modes; it will compel the IPT team to dynamically explore the scope of technology development within its available resources to accommodate high in-progress changes initiated by the dynamic marketing or technology changes.

Accordingly, both the IPT and Adaptive Life Cycle approach can be effective tools to internally damp out the duration and scope uncertainties.

3.6 Pulling to respond to ever change requirement of the customer:

The challenge of technology development is that the content of the technology seems to be constantly challenged by innovation evolution, customer preference change, market competition, or phasing in of regulatory requirements. The challenge commonly results from misplacing technology developers' mental focus on the content of the technology, rather than our focus on the merit of the end-user. The dimensions of merit for each customer group has been held very steady in the past, and it is most likely to be relatively predictable in the near future. Therefore, by shifting the focus from ever changing technology contents or market competition to a more predictable end-user merit, organizations can better focus on how to meet the customer needs, rather than on how to respond to market wants. Again, engineers working on the upstream of the technology value chain shall focus on customer value and they shall carefully define the value carriers in order to transfer the value to downstream activities. In the meantime, engineers working on the downstream activities need to focus on their best practices that effectively transform these value-transferring inputs to value-transferring outputs.

3.7 Perfecting by eliminating waste and creating value:

There are two schemes of perfecting: one is eliminating waste; the other is creating value.

a) Eliminating Waste:

In the technology infusion process, we commonly find seven categories of waste: They are (1) duplication waste, (2) redundancy waste, (3) logistic waste, (4) defect waste, (5) information (communication) waste, (6) resource/time waste, and (7) over/under production waste.

(1) The duplication waste, often referred as the "not invented here" syndrome, commonly leads many functional organizations to repeat similar technologies so that the organizations could justify their existence or fight for their credits of technology innovation.

(2) The redundancy waste commonly results from obsolete processes from the old business practice, so that it does not contain value in an updated business practice.

(3) The logistic waste occurs mainly because of the improper sequence of tasks, and it results in blocking the process either by waiting for specific information or by repeating a loop of tasks due to out-of-date information.

(4) The defect waste has two subcategories: one directly relates to the breadth of the technology, and the other relates to the quality of the technology. The quality defect means the final quality of the technology delivered does not meet the quality demand of the customer thus requires either an upgrade or redevelopment of the technology. The breadth of technology waste is due to the narrow breadth of the technology scope in the early stage of the technology development funnel which does not provide enough breadth to accommodate high potential technology ideas in a early stage of the development cycle (Figure 3.6).

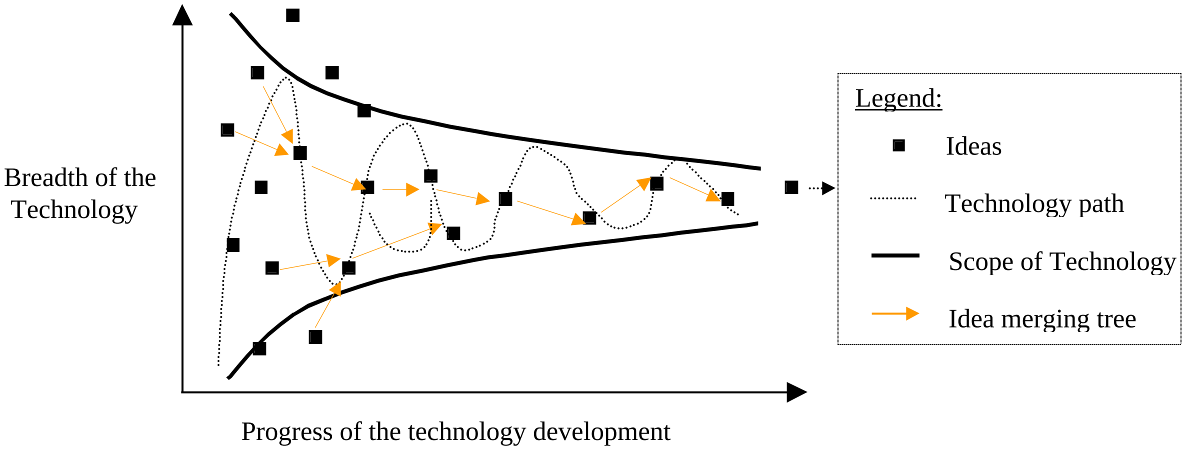


Figure 3.6: Technology Development Funnel

Figure 3.6 illustrates that in the early stage of the technology development cycle, many ideas within the technology funnel have gone through multiple cycles of evaluation, selection, de-selection, and merging. Any attempt to skip this evolution and merging process may lead to an uncompetitive outcome, which requires repeating the entire technology development process in order to catch up with the emergent technology trends or customer requirement changes.

(5) The information and communication wastes mean the loss of efficiency during the process of transporting information. This efficiency loss comes from either information content loss or the extra efforts in storing, retrieving, or reformatting information.

(6) Both the resource waste and the time waste commonly relate to the choice of methods about how organizations deploy its resources. For example, in the early stage of the technology development, organizations commonly have their choices of methods to perform their feasibility study either by choosing cost effective method with less accuracy such as the Computer Aided Engineering (CAE) tool or by expensive method with long lead time but precise physical testing). In the fuzzy front end of the technology, waiting for precise hardware testing for the technology development is extremely expensive and time consuming. Nevertheless, in most of the time, we need such critical information in order to validating quick CAE tools. Therefore, it makes logical sense to form two parallel validation processes: (1) the inner fast turn around CAE validate process for quick exploring the multiple design alternatives and (2) a slow, precise outer physical verification testing to gain the confidence on CAE.

(7) Finally, the over/under production waste is defined by McManus as creation of unnecessary data and information, information over-dissemination or the pushing, not pulling type of data [McManus, 2000].

All of these seven categories of wastes cause either time delay or inefficient use of enterprise resources (such as staff, budget, or equipment). Therefore, they should be eliminated.

b) Creating value:

In a non-demand constrained business scenario, a creation of value may present greater opportunity than an elimination of waste. The technology managers, in such a case, shall carefully evaluate the options of when and where they should "relax" the bottleneck constraints in order to achieve higher system performance and gain higher returns. The constraints may be represented as business constraints (budgets), resource constraints (such as staff and equipment), or logistic constraints (such as shop rules to designating certain jobs to certain engineering teams). In an effort to relax the constraints, however, all three types of constraints can be expressed in terms of cost functions. When the potential return is greater than the cost of relaxing constraints, adding extra cost presents a valid business option to relieve the bottleneck in exchange for greater return. Just as an example, some firms have a rigid policy (logistic constraint) against outsourcing of technologies concerning critical powertrain component to its highly competent component supplier. This policy sometimes hinders the powertrain performance in a firm's product. Therefore, it may present a valid business option to provisionally relax the outsourcing constraint by creating a Joint Venture (JV) to enhance the customer's value without losing control over critical powertrain architecture decisions.

The common pitfall of the constraint relaxation is that most technical managers tend to overstate the gains through the "market price" derived from the unconstrained throughput increase, rather than the gains through the "shadow price" (i.e., the optimum value increase per unit of single constraint relaxation in terms of optimization terminology) of the throughput gain derived under the constrained scenario. In today's complex business world, many constraints tend to interrelate with each other. Therefore, the relaxation of a single constraint may activate remaining non-bounding constraints and result in a gain that is less than the "market price" gain. The blindness in promoting unconstrained market price gain as the throughput improvement projection can lead to overspending of valuable resources.

3.8 Knowledge infrastructure enables the value chain:

The concept of knowledge infrastructure is built on top of the "Knowledge Vector Chain and Scalar Chain" which is proposed by Eiichi Tanabe [Tanabe, 2000]. Tanabe claimed that there exist two kinds of knowledge chains: the vector chain and the scalar chain. The vector chain vertically links activities that directly involve developing and producing a product, while the scalar chain horizontally links knowledge elements. Therefore, the scalar chain integration has a potential utility, rather than an immediate product use.

From value stream perspective, the Vector Knowledge chain is the part of the value stream that flows the value of knowledge to its implementation products, while the Scalar Knowledge chain interconnects various value streams so that it either facilitates the exchange of knowledge across the value streams or enhances the value-adding capacity of the process.

Figure 3.7 illustrates the conceptual layout of the vector chain (the solid arrows) and scalar chain (the dotted matrix grids), in terms of how the various value streams flow through the internal organizations (top row) and the external supply chains (bottom row) for different categories of technology (left column). Figure 3.7 also illustrates how various value streams eventually diffuse into vehicle brand structure (right column). The Vector Knowledge chain also represents a continuous evolution of value carriers between the internal and the external organization flow. The Scalar Knowledge chain is extremely difficult to be codified. In many occasions, it represents the interconnections of many expert groups. Each group has it own tacit code in transmitting and interpreting information, and each acts based on social connectivity outside of the management control. A rich environment (i.e. technology forums) and a good infrastructure (i.e. knowledge management) in Scalar Knowledge chains can build up a firm's capacities in technology absorptive or capabilities in knowledge integration in connecting the Scalar Knowledge chain to the Vector Knowledge chain.

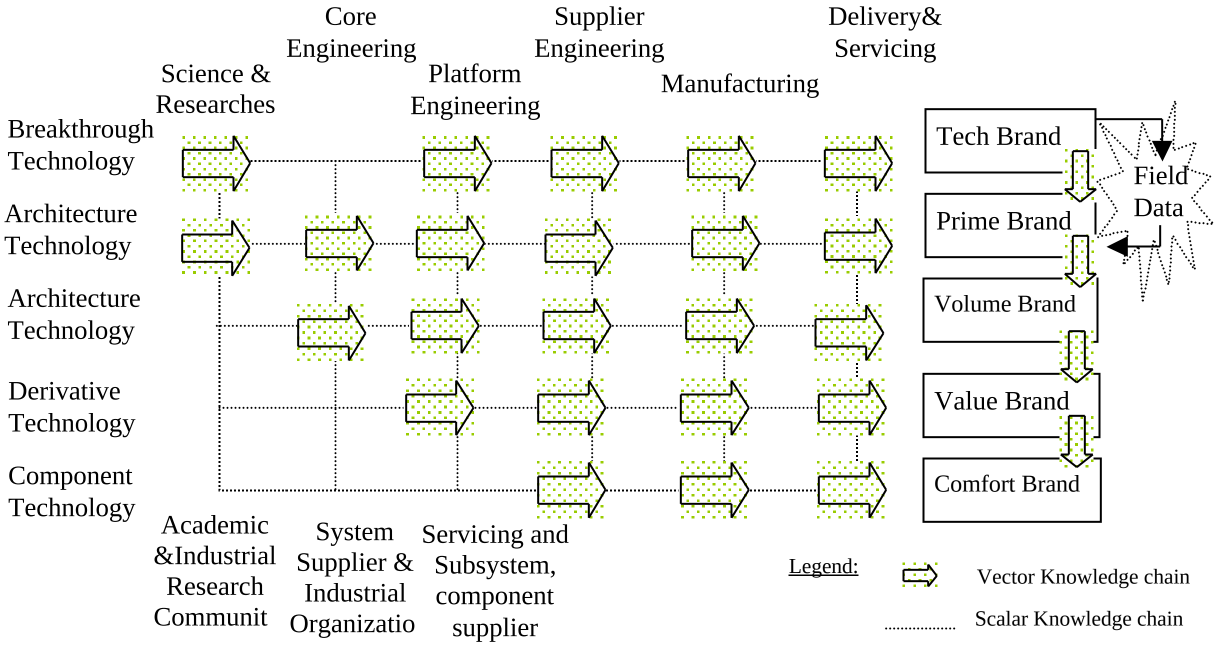


Figure 3.7: The flow of knowledge chain in organization and product

In Figure 3.7, the category of Breakthrough technology can proficiently flow directly from the Science& Research to the Technology Brand vehicle in order to achieve the shortest "order to delivery time." This short flow time can greatly facilitate the firm’s capabilities to gain a valuable knowledge from the consumer by getting the first hand field-usage-data from a small pool of technology fleet. In the past several years, General Motors has successfully used this approach to pilot her Electrical Vehicle (EV1) program to gain crucial customer field-usage-data through limited deployment of EV1 in strategic geographic regions. The immediate benefit of this approach is that the vast amount of customer usage data can become available to Core Engineering so that Core Engineering can immediately transform these field experiences to improve firm's design specifications before moving into volume production.

Moreover, in order to take advantage from the economy of scale and scope, the Premier brand and Volume brand shall only implement the architecture technology defined by the Core Engineering architecture team. In other words, during the period of architecture development, the Core Engineering needs to diligently maintain individual brand with distinguishable "dimensions of merit" under the shared architecture to avoid either losing brand identity or cannibalizing the brand.

As for the Value brands, firms need to focus on the adoption of derivative product innovation and process innovation so that they can squeeze the critical needed efficiency to fight the price war. It is reasonable to assign Platform Engineering as the starting origin of the value chain so as to shorten the "order to delivery time". Under this setup, Platform Engineering will be in charge of both developing derivative technologies and implementing process improvement under a predefined architecture in order to maintain the integrity of the architecture.

As for the Comfort brand, the implementation shall focus on the component innovation and the process standardization changes. These changes are presumed to be less noticeable to the customer but they contribute to the Economy of the Scale (EOS) by effectively sharing common components and processes across multiple platforms or processes. Since the component supplier is the main knowledge stockholder for the component design, the supplier shall be the starting origin of the value chain instead of Core Engineering or Scientific Research. The full benefit of appointing different value chain origins for various technology value chains is that it effectively reduces the span of the chain so as to provide quick response in meeting the changes of consumer demand.

From the knowledge supplier-chain perspective, the focus for the Science and Research organization of the automobile firm is exchanging knowledge within academic and industrial research communities so as to facilitate value creation and establish organization "absorbing capacity” [Cohen; Levinthal, 1990]. Similarly, Core Engineering needs to merge the technology architecture with industrial standards, such as ASME and key system suppliers' best common practices, through the connectedness (i.e. connections to the knowledge holders), so that it will expand its value capturing capacity [Lim, 2000]. Core Engineering shall also incorporate itself with Technology Suppliers on transferring key "know-how" from these Technology suppliers into product specification or design. Meanwhile, Platform Engineering needs to expand its capacity on quality of the technology by gauging information from Product Servicing (e.g. dealer service facilities) and subsystem/component fabrication suppliers.

By merging Tanabe's Knowledge Chain concept with Cohen's Absorptive Capacity frameworks, we can establish a Reinforcing Capacity model of the knowledge flow to interpret the reinforcing behavior among the Vector Knowledge, Scalar Knowledge, Absorptive Capacity and Organization Capacity. Figure 3.8 shows the Organization Capacity Model of Knowledge Chain, and it illustrates the significance of the Feedback Knowledge in enhancing its organization's knowledge processing capacity. In most cases, the Feedback Knowledge effectively reinforces the knowledge absorptive capacity of the organization. This enhanced absorptive capacity then will further boost the digestion of Scalar Knowledge inputs and strengthen the efficiency of the organization capacity in transforming Vector Knowledge input into valuable knowledge output.

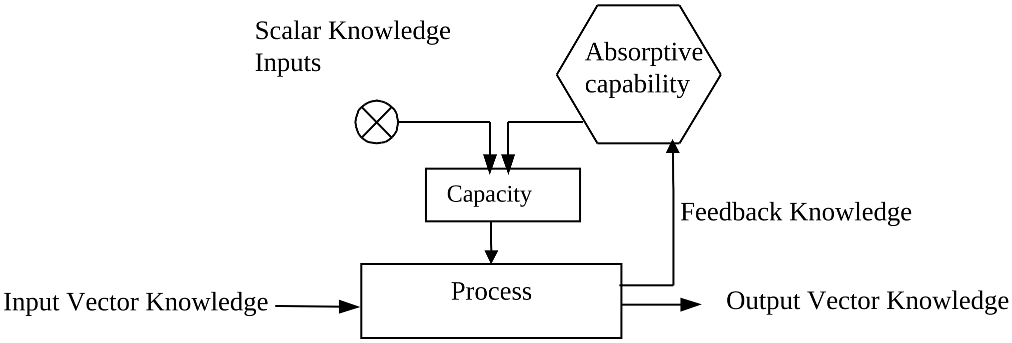


Figure 3.8: The Reinforcing Capacity Model of the Knowledge flow

3.9 Trust is the backbone in connecting the Knowledge Chain:

Trust shall serve as the backbone to connect the knowledge chain either within the corporation or among intra-enterprise entities, such as knowledge suppliers or technology partners. Within the corporation, the firm shall establish a clear incentive and reward system to promote the culture of trust on its knowledge sharing. For knowledge exchange among the inter-enterprise, there are two available arguments: Carlile recommends establishing a boundary object, which serves as a media for exchanging of knowledge across boundary [Carlile, 2000]; and Gans and Stern recommend using the Venture Capitalism type of contract to "ironclad" the Intellectual Property right [Gans and Stern, 2001]. Both arrangements can easily fall apart if the exchange does not contain a clearly shared value (trust) protocol among the transferring parties.

Accordingly, a clear protocol based on the mutual trust shall contains a value "contract" to guard the honesty among the transferring parties. To avoid breaking the knowledge chains, all parties should resist the short-term temptation of breaching the trust in order to keep the knowledge chains intact. The technology managers of the automobile firms, who commonly serve as the leaders of the knowledge chains, should invest much needed attention to promote knowledge flow across the boundaries and to safeguard the integrity of the boundary object.

3.10 Summary:

In this chapter, the technology value-stream map has been proposed to specify the value carrier for each stage of the multiple technology value stream flows (Figure 3.3), while the span of different technology's value stream flow has been streamlined to reduce the "order to delivery time" (Figure 3.7). Furthermore, the "five fundamental concepts of the Lean Thinking" also have been expanded into this fuzzy front end of the technology infusion arena as a corner stone in establishing the Lean framework. In the following two chapters, chapters four and five, we will further immerse the concept of technology value-stream map and the concept of multiple flows of technology knowledge chains into an integrated value stream model. This value stream model expresses a conceptual layout of multiple commodities Network-in-Network value stream flow to facilitate the evaluation of the value portfolio composition, organization of engineering expertise and allocation of supporting resources.

3.11 References:

1. Cain, Joel W., 1997, chapter 3.4.1, pp 122, " Relationship between customer satisfaction and lead time" in "Role of Variance in Manufacturing System Design: The Impact on Capacity Planning and Capital Investment Decision", Master of Science Thesis in Mechanical Engineering, MIT.
2. Carlile, Paul, 2000, "A Pragmatic View of Knowledge and Boundaries: Boundary Objects in New Product Development", Sloan School of Management, Massachusetts Institute of Technology, carlile@mit.edu, August 15, 2000.
3. Christensen, Clayton M., 1997, "The innovator's Dilemma, (MA) " Harvard Business School Press, 1997, pp 3-28.
4. Cohen and Levinthal, 1990, "absorptive Capacity: A new perspective on Learning and Innovation", Administrative Science Quarterly, 128-152. Administrative Science Quarterly.
5. Crawley, Ed, 2000, "System Architecture" rev 2.0, MIT SDM lecture, Fall 2000.

6. Emiliani, M.L., 1998, "Lean Behavior," Management Decision 36/9[1998] 615-613, MCB University Press [ISSN 0025-1747].
7. Foster, R., 1986, "Innovation, The Attacker's Advantage," (NY: Summit Books, Simon and Schuster, 1986), pp. 88-111.
8. Gans, Joshua S. and Stern, Scott, 2001, "The Product Market and the Market for "ideas" Commercialization Strategy for Technology Entrepreneurs", (MA: Sloan School of Management, MIT, Cambridge, MA 02142, email sstern@mit.edu or available at: www.mbs.unimelb.edu.au/jgans/research.html.
9. Hauser, John R, 1984, "Consumer Research to Focus R&D Projects," Journal of Product Innovation Management, Vol. 1, No 2, January, 70.84.
10. Hauser, John and Zettelmeyer, Florian, 1996, The "Three Tier Metaphor" of "Metrics to Evaluate R, D&E", research briefing for Research Technology Management, November 1996, (MA) "International Center for Research on the Management of Technology (ICRMOT) at M.I.T.'s Sloan School of Management, Cambridge, MA 02142, web site, http://web.mit.edu/icrmot/www/.
11. Henderson, Rebecca, 1998b, "Cross-Function Teams Valuable, But Sometimes Counter Productive," MIT 5th Annual Research Directors' Conference, May 6 1998.
12. Henderson, Rebecca M. & Clark, Kim B., 1990, " Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Establish Firms", Administrative Science Quarterly, 1990, Vol. 35, pp 9-30.
13. Highsmith, James A. III, 2000, "Adaptive Software Development, A Collaborative Approach to Managing Complex Systems," Dorset House Publishing Co., INC, ISBN 0-932633-40-4.
14. Lim, Kwanghui, 2000, "The many Faces of Absorptive Capacity: Spillovers of Copper Interconnect Technology for Semiconductor Chips", Academy of Management (2000), NBER Productivity Lunch, MIT Innovation Seminar, Sept. 28, 2000.
15. Moore, Geoffrey A., 1999, Crossing the Chasm, Rev., ed., (NY: Harper Collins, 1999), pp 9-62.
16. McManus, Hugh, 2000, "Lean Engineering: Lean Beyond the Factory Floor, A Framework for Lean Engineering", Fall 2000, MIT, Integrating the Lean Enterprise's lecture notes, Lean Aerospace Initiative (LAI),
17. Tanabe, Eiichi, 2000, "Knowledge Chain in the Clock-speed-Based Organization," Master Thesis of System Design and Management Program, MIT. , May 2000.
18. Teece, David J., 1998, "Capture Value from Knowledge Assets: The New Economy, Markets for Know-How, and Intangible Assets", California Management Review, Vol. 40, No. 3, spring 1998.
19. Utterback, James, M., 1994, "Mastering the Dynamics of Innovation", (MA: Harvard Business School Press, 1994), pp 23-55.

Chapter 4

Integrated Technologies Infusion Value Stream Optimization

4.1 Introduction to value stream optimization:

The prime objective of the integrated technology infusion is to deliver optimal end-use customer value under limited resources. As discussed in Chapters 2 and 3, there are three main categories of technologies within the automobile industry: the breakthrough, the architecture, and the derivative technologies. Each technology contains inherent diversities in its development processes. These diversities, which include the specific task pathways, the resource consumptions, the value propositions, and the development durations, are embedded under each gateway for particular category of technology. This chapter explores the optimization of the system-level network by maximizing the composition of the technology portfolio within financial and resource constraints. In the following chapter, Chapter 5, the focus will be shifted to optimization of the technology network on the sub-system level by minimizing the balance between network flow time and resource utilization within operational constraints. The joint efforts between system and sub-system optimizations shall lead to a robust solution in delivering optimal customer value while providing much needed flexibilities to absorb local variations.

4.2 The concept of "Network in Network" layout:

A robust technology infusion framework demands consistency in the evaluation format across multiple uncoordinated infusions, and at the same time, it needs to provide suitable flexibility to accommodate the diversities of different technology tasks. The demand of consistency and the need for flexibility lead to the formation of a "Network in Network" technology infusion layout by decoupling task specific complexities away from the technology value stream (Figure 4.1).

Figure 4.1 shows the detailed process flow of the Ford TDP process by articulating the major tasks in each phase of the process. As depicted in Figure 4.1, the automobile technology infusion can be subdivided into four major phases: (1) technology planning, (2) internal and external development, (3) implementation, and (4) fabrication, distribution, and service. Each of the four major phases can be further subdivided into gateways with multiple development tasks. For example, during the phase of Technology Planning, the major tasks are (i) collecting the wanted technology from Vehicle Center (VC) and Marketing, (ii) planning of technology strategy and (iii) assigning of technology to specific forum, and (iv) allocating of budget and resource to specific department. As indicated in Figure 4.1, in the task assignment, some component technologies may be assigned to the suppliers under the supervision of the Core Engineering, while the remaining can be done in-house. Furthermore, the architectural technologies are assigned to Core Engineering; in the meantime, Core Engineering and Science & Research divisions share some part of basic researches. Since most of these technologies are unique, their tasks and pathways are not exactly the same. This difference makes the whole technology infusion complex to manage.

Nevertheless, by carefully looking into this process chart, we realized that it is highly desirable to decouple the phase gateways from their diversified tasks in an attempt to form an integrated value stream shared by multiple technologies. By doing this, the operational tasks then can be clustered into multiple task networks and they will support the designated gateways. This realization leads to the formation of the "Network in Network" concept.

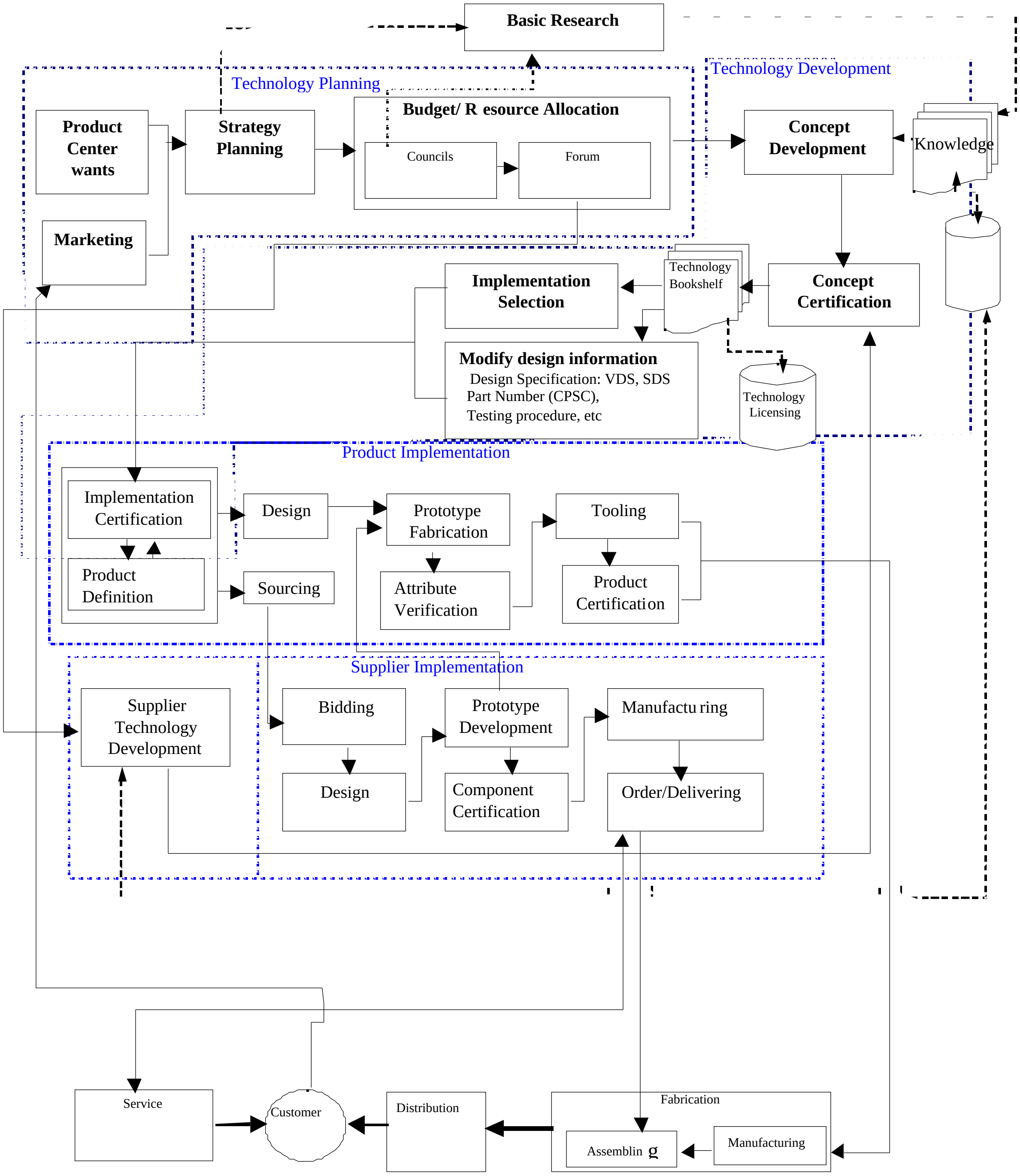


Figure 4.1: Technology Infusion Process

In a sense, the concept of "Network in Network" is an extension of Lean Enterprise's value stream framework by merging multiple uncoordinated, unconnected value streams (e.g. The Basic

Research or Supplier Technology Development of Figure 4.1) into an integrated value stream, which is shared by multiple technology commodities.

In the "Network in Network" layout (Figure 4.2), the system-level network represents the flow of multiple technology commodities through a series of sequentially connected gateways. Each of the gateways represents a collection of sub-system task networks for each technology (i.e. a unique task network per gateway for each technology). The individual sub-system task network represents a network of specific tasks with multiple interconnected task sequences in supporting system-level gateway of specific technology per each gateway.

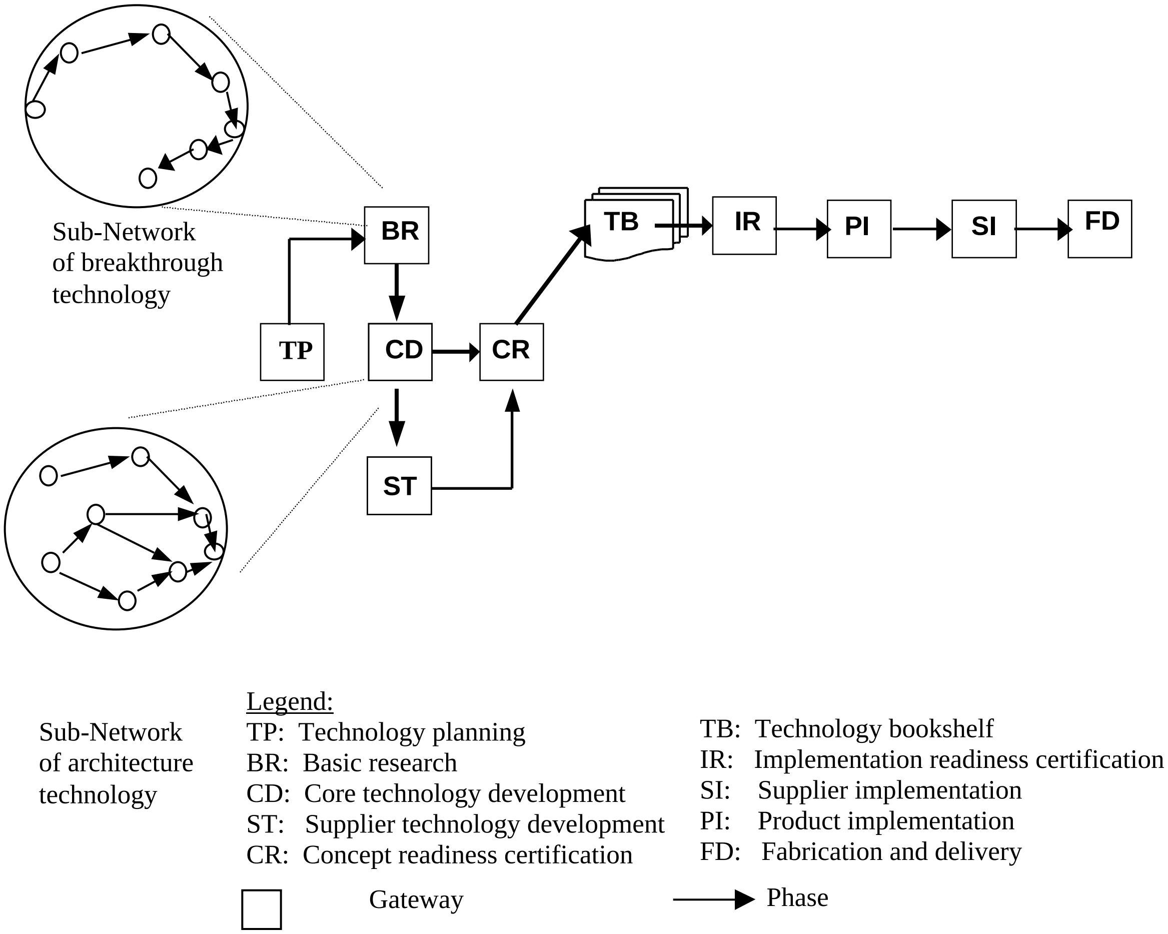


Figure 4.2: The "Network in Network" Technology infusion process

With the "Network in Network" layout, technology portfolio managers can objectively exert consistent financial measures over an integrated value stream with multiple technology commodity flows while the functional managers can have close control of detail task operations over the local task network. The clear benefit of this kind of merging is that the new layout provides a uniform platform to facilitate the management of firm's multiple technologies portfolio.

The other immediate merits for this "Network in Network" layout are listed as follows:

- The ability to accommodate the diversity of the different technology developments,
- The ability to isolate duration variation within the task network,
- The ability to minimize system-level complexity while reducing cross sub-network independence,
- The ability to integrate specific engineering knowledge into the task management network,
- The ability to disguise apparent network complexity under multiple levels of network to facilitate communication and understanding,
- The ability to empower local management control, and
- The flexibility to accommodate local sub-network reengineering.

4.3 Management perspective of the "Network in Network" framework:

From the management perspective, the "Network in Network" framework can also be seen as a new business model for managing the technology infusion process. This new business model exhibits several major advantages over the traditional waterfall technology process. They are:

1) It promotes a mental breakthrough from a rigid task flow and replaces it with a multiple flexible task networks. Within each individual task network, the order of task execution can be dynamically adjusted according to a state of the progress, instead of an order being confined by a preset schedule. The breakup of a rigid schedule will then further promotes a

result-oriented mindset to replace the conventional workflow mindset [Highsmith III, 2000].

2) It clusters together relevant tasks into a task network so promoting the practice of "Interactive Concurrent Development" by sharing partially finished information within the local task network and consequently stimulates innovation.
3) It maintains the information integrity of the task network and, in the meantime; it promotes the vital tacit knowledge sharing and growth across the boundary of the functional organization and the product team. (In this "Network in Network" format, there is a core IPT team for each technology infusion project with the responsibility to maintain proper value stream flow; while each local task network draws in integrated functional teams to support a cluster of the tasks within the task network. Upon finishing the cluster of the tasks, the functional team can be rotated to other task networks by supporting other similar technology developments. Through this approach, vital knowledge and experience can be transferred across the "boundary" without losing dedication on current project.)
4) It further energizes the local team to strive for swift technology delivery since the customer's value of the value stream is highly perceptible to individual task networks; in the meantime, an individual's achievement can be easily verified against the well-set goal of each gateway.

4.4 System-level multiple commodities infusion network (value stream):

Figure 4.2 shows the simplified ten-gateways infusion value stream, which includes Technology Planning (TP), Basic Research (BR), Core Technology Development (CD), Supplier Technology Development (ST), technology Concept Ready certification (CR), Technology Bookshelf (TB), technology Implementation Certification (IR), Product Implementation (PI), Supplier Implementation (SI), and Fabrication/Delivery (FD). Each of the gateways represents the performance of a collection of the tasks that consume specific amounts of network-shared resources (e.g. the staff, task duration, material cost, and scratch, etc) by different technology commodities.

Inside the system-level network, a technology of a specific category may utilize a specific pathway to progress its technology development. As an example, the breakthrough technology uses the specific pathway of TP-BR-CD-CR-TB-IR-PI-SI-FD to fully capture tacit knowledge of the Scientific and Research staff (Figure 4.3a). In the mean time, the architecture technology detours the BR gateway by using the pathway of TP-CD-CR-TB-IR-PI-SI-FD and the derivative technology takes on its unique pathway of TP-CD-ST-CR-TB-IR-PI-SI-FD in order to have early incorporation of the subsystem or component expertise from the suppliers (Figure 4.3b, and Figure 4.3c respectively).

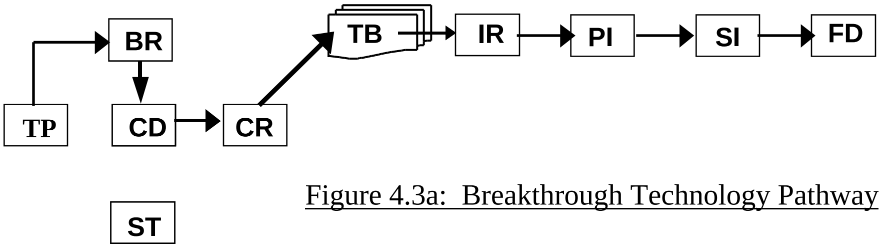


Figure 4.3a: Breakthrough Technology Pathway

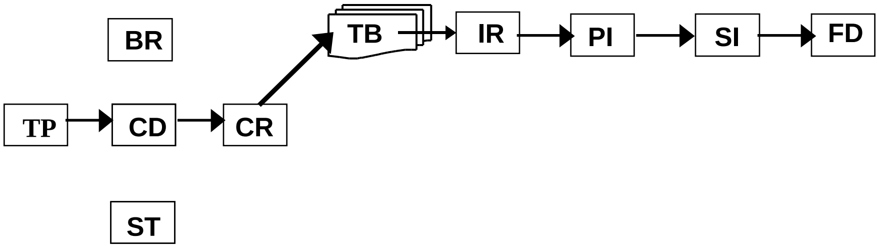


Figure 4.3b: Architecture Technology Pathway

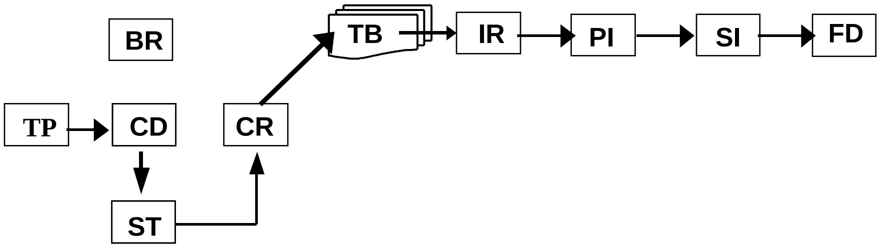


Figure 4.3c: Derivative Technology Pathway

With the purpose of enhancing the flexibility of the optimization application, a binary matrix variable **ROUTE** is declared to capture the pathway uniqueness of different technologies. As shown in Figure 4.4, the variable **ROUTE** (i, j)=1 indicates technology i will pass through gateway j. Otherwise, variable **ROUTE** (i, j)=0 indicates technology i will bypass gateway j and leap to the following gateway. The immediate benefit of using such a control matrix is that it provides the system engineer an extended capability to quickly explore the variety of combinations of different routes by switching **ROUTE** matrix on-and-off. The **ROUTE** matrix of Figure 4.4 reflects three different pathways of the Figures 4.3a, b, and c. As an example, for the pathway of 4.3b, the pathway detours the gateway of BR which sets the index **ROUTE** (2,2)=0.

$$ROUTE(i,s)=\begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad where \quad i = techno\log y\_type \quad and \quad s = gateway$$

Figure 4.4: The **ROUTE** matrix

4.5 Stochastic duration uncertainty:

The fuzziness of the technology development commonly makes the duration of an individual phase highly unpredictable. This duration uncertainty is one of the major contributors of the slow clock speed for technology infusion as previously discussed in section 2.2. In small scale, a single project duration overrun not only increases its own staffing cost but also dissipates its potential application value, in most cases. In large scale, a single project overrun may drain the scarce resources of the network, and this drain will block other critical technology developments. Therefore, this duration uncertainty commonly becomes one of the major sources of variation in the technology infusion. In the past, unfortunately, most of the automobile firms have left this issue under-addressed that the impact of the duration uncertainty on value stream has not been well quantified. The lack of awareness of duration uncertainty and its impact on the value stream can lead to ill selection of technologies when the automobile firm composes its technology development portfolio.

This study adopts an independent stochastic probability function **PROB** to prescribe the system level duration uncertainty. The independency assumption of the stochastic function simply means that there is no duration correlation among individual development gateways. This assumption is open to challenge in a real situation. However, these data of duration correlation are too hard to quantify in the fuzzy technology development process.

In order to simplify the optimization algorithm and to further trim down the complexity of stochastic uncertainty, this study adopts the assumption that a single system duration probability function with three preset levels: the optimistic (25%), the most likely (50%), and the pessimistic (25%) (Figure 4.5). These three levels of uncertainty represent a step approximation (i.e. 25-50-25%) of the probability density function distribution. They can effectively address the skewed distribution property of the duration uncertainty. The tendency of duration overrun is higher than that of under-run which otherwise cannot be fully captured by the statistical mean and standard deviation used in the PERT method [Steward, 1995].

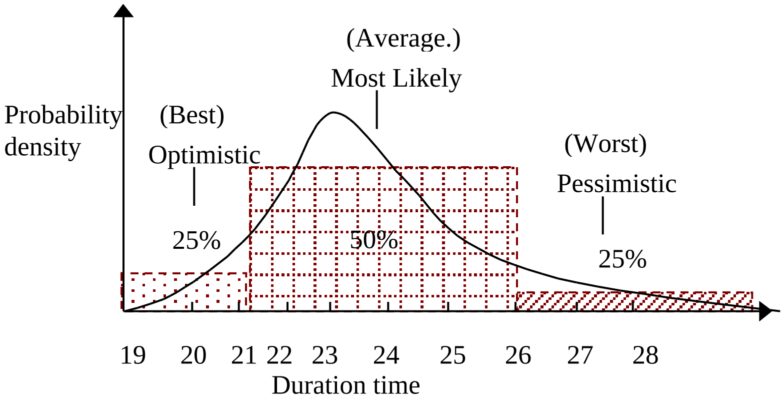


Figure 4.5: Duration Uncertainty Distribution

4.6 Optimization objective:

To solidly quantify the "value" of the integrated value stream, this thesis uses the objective financial measure of Net Present Value (NPV) of the technology portfolio as its solely optimal objective function, so that the dissipation of technology value over a stretched span of the technology infusion could be properly accounted for. To further simplify the value stream calculation, all benefits and costs are assumed to have monetary value, and they are incurred only at the gateways as indicated in Equations 4.1 and 4.2:

$$Max \quad Total\_NPV = \sum_{i=1,m} \sum_{j=1,n} PROB(i) \times NPV(i,j) \times JOB(j) \qquad \cdots Equation \quad 4.1$$

$$Where \quad NPV(i,j)$$

$$= \sum_{s} \frac{REVENUE(i,j) - MATERIAL(i,j) - LABOR(i,j)}{(1+I)^{T}} \qquad \cdots Equation \quad 4.2$$

$$and \quad LABOR(i,j) = Number\_of\_Staff(i,j) * Base\_Salary * Duration(i,j)$$

Figure 4.6: Technology Value stream Objective Equations

In Equation 4.1, the decision variable of the optimization will be the number of projects being allocated annually for each category of technology (denoted by the variable **JOB)**. The total technology portfolio NPV is a weighted summation of the individual technology NPV over the stochastic distribution of three levels of duration uncertainty. The summation indicator **i** is the index of the technology uncertainty level, which ranges from optimistic through average to pessimistic. At the same time, indicator **j** denotes the technology types (i.e. breakthrough, architecture, and derivative) being summarized. The **JOB** variable describes the amount of technology category **j** is allocated annually (e.g. number of projects for each category of technology). Thus, the total NPV can be accumulated from a double summation of individual technology NPV over numbers of job allocation as well as over stochastic distribution of duration uncertainty.

Equation 4.2 indicates that each individual technology NPV is a summation of the discounted revenue, material cost, and labor cost over the entire value stream (where the summation indicator **s** denotes the accumulation through each gateway of the technology value stream). Equation 4.2 also indicates that the labor cost is a function of gateway duration. The variable **I** of Equation 4.2 represents the corporate discount rate, which commonly has an annual rate ranging from 12% to 20%, to account for the opportunity cost of the capital. This entire value stream is then converted into a present value through a compound interest calculation of an accumulated duration **T** (**T** is defined as the accumulated duration of upstream gateway durations **t** to gateway **s**). The Compounding effect of the duration **T** over the revenue and cost stream implies the existence of non-linearity optimization behavior.

4.7 **Balancing Constraints and accumulated duration T**:

The balancing constraints are a set of equations that maintains the balance of the commodity flow within the technology infusion network (i.e. the inflow of the gateway shall be equal to outflow of the gateway plus the gateway's consumption). In this technology infusion network, each technology progresses through individual gateways (denoted by **s**). Some of technology ideas will be proved to be less vital and stop its development to become scrap, while the remaining ideas will keep progressing through the gateway. In order to capture this behavior, we formulate the success job of the value stream through the parameter of "**Good(i,s)**" (Equation 4.4). This parameter is calculated by removing the scrap in each development gateway (i.e. by multiplying the success rate of the previous stage with a factor that is one minus the scrap rate of the present stage, as detailed in the equivalent constraint in Equation 4.4). If the routing is detoured, the success rate does not change from the previous stage.

$$\begin{aligned}
&if \quad route(i,s) = 1\left("yes"\right) \ : \\
&\quad GOOD(i,s) = GOOD(i,s-1) \times (1 - SCRAP(i,s)) \qquad \cdots Equation \ \ 4.4 \\
&else: \\
&\quad GOOD(i,s) = GOOD(i,s-1)
\end{aligned}$$

$$Acc\_Duration\_T(i,s,j) = \sum_{k=1}^{s} DURA(i,s,j) * ROUTE(s,j) \qquad \cdots Equation \quad 4.5$$

$$where \quad i = uncertainty \quad level, \quad s = gateway, \quad and \quad j = technology \quad types$$

Figure 4.7: Technology Value Stream Mass Balancing and Duration Equations

Equation 4.5 shows the formulation of the accumulated duration T as the accumulation of upstream gateway's durations up to individual technology pathways (Figure 4.7).

4.8 Downside protection constraints:

Downside protection is one of the system-level performance constraints to guard against catastrophic loss under the worst uncertainty scenario. When NPV is chosen as the exclusive optimization objective function, the algorithm represents a hidden bias against a low risk, moderate return technologies. In order to counter balance this drawback, we implement the Benefit/Cost (B/C) ratio as a supplementary downside protection constraint to guard against the loss. The full technology portfolio shall exceed both the B/C threshold of the stochastic mean and the threshold of individual duration uncertainty scenario (i.e. optimistic, most likely and pessimistic). Equations 4.6 and 4.7 are the formulas for estimating downside protection (Figure 4.8). Here, Equation 4.6 expresses that the stochastic mean B/C ratio of the entire technology portfolio shall exceed B/C_{avg} ; Equation 4.7 states that the B/C for every duration uncertainty scenario (optimistic, most likely and pessimistic) shall all exceed its own B/C_s target. Present Benefit (*PV_Benefit*) and Cost (*PV_Cost*) in Equations 4.6 and 4.7 are calculated from Equations 4.8 and 4.9, respectively.

$$\frac{\sum_{i=1..3} PROB(i) * PV\_Benefit(i)}{\sum_{i=1..3} PROB(i) * PV\_Cost(i)} \leq B / C_{avg} \qquad \cdots Equation \quad 4.6$$

$$\bigcup_{i=1..3} \frac{PV\_Benefit(i)}{PV\_Cost(i)} \leq B / C_s(i) \qquad \cdots Equation \quad 4.7$$

$where$

$\bigcup: \quad means \ \ the \ \ union \ \ of \ \ the \ \ success \ \ over \ \ all \ \ sub - domain \ \ s,$

$i = uncerta\,\text{int}\,y \quad level,$

$$PV\_Benefit(i) = \sum_{j=1..n} \frac{REVENUE(i, j)}{(1 + I)^T}, \qquad \cdots Equation \quad 4.8$$

$$PV\_Cost(i) = \sum_{j=1..n} \frac{Material(i, j) + Labor(i, j)}{(1 + I)^T} \qquad \cdots Equation \quad 4.9$$

NOTE: “uncertainty” in 4.7 above should ALL be in italics

Figure 4.8: Downside Protection Equations 4.6, 4.7, 4.8 and 4.9

4.9 Constraints and data:

From the hierarchy point of view, constraints can be categorized into two major hierarchy levels: global level and local level. For example, the staffing constraints can be viewed as either global or local. The staffing constraints in the global level represent the total number of the technology staff over the entire span of the technology infusion process, and the constraints in the local level may be the number of the specialists of specific gateway (such as the scientists of the Research organization). Similarly, the system may contain the material purchasing budget for whole technology portfolio, and it may assign specific amounts of the material budget to the Science and Research division to guarantee the effort in searching new business opportunities.

Furthermore, from the source perspective, constraints can also be categorized as: (1) the resource constraints, (2) the supply and demand constraints, (3) the performance constraints, and (4) the balancing constraints (as described in section 4.6). Table 4.1 shows the combinations of the constraint matrix that system engineers can use it to selectively incorporate into their optimization model to investigate the impact of the constraints on value stream throughput (Figure 4.9).

TABLE 4.1: COMBINATIONS OF CONSTRAINT MATRIX		
Resource	Staff	Total, Specialist, Generalist
	Budget	Purchasing material, Staffing cost
	Facility and equipment	Facilities, Specific equipment, Shared Equipment
Supply & demand	Supply	Raw material
	Demand	Product, Revenue
Performance	Quality	Quality, Cost
	Duration	Overall development duration, Specific duration between critical gateways
	Downside protection	Risk, B/C ratio
Balancing	Flow	
	Logistic	And, OR, XOR relationship

Figure 4.9: Table 4.1: The combinations of Constraint Matrix

In general, the system-level constraints can be described in terms of the summation of the specific sub domain attributes over the entire system-level domain, while the local-level constraints can also be expressed as a Union of success of similar local constraints over individual sub-domains respectively. While Equations 4.10 and 4.11 exemplify the system constraint and the local constraint, the former double-summarizes sub-domain cost over the entire system domain by aggregating sub-domains over technology **j** and gateway **s**; the latter requires every gateway's purchasing budget to be less than certain specific amount.

$$\sum_{s} \sum_{j=1,n} MAT(s,j) \times GOOD(s,j) \times JOB(j) \leq Total\_MAT\_BUDGET \quad \cdots Equation \quad 4.10$$

$$where \quad MAT: \quad Material \quad \cos t \quad of \quad each \quad gateway, \; of \quad each \quad techno\log y$$

$$\bigcup_{s} \sum_{j=1,n} MAT(s,j) \times GOOD(s,j) \times JOB(j) \leq Gate\_MAT\_BUDGET(s) \quad Equation \quad 4.11$$

$$where$$

$$\bigcup: \quad means \quad the \quad union \quad of \quad the \quad sucess \quad over \quad all \quad sub-domain \quad s,$$

$$MAT: \quad Material \quad \cos t \quad of \quad each \quad gateway, \; of \quad each \quad techno\log y.$$

Figure 4.10: Resource Constraints Equations 4.10 and 4.11

As previously discussed, most of system-level input data rely on the optimization output result from the individual sub-system task network. In order to facilitate the bi-level optimization scheme, our system is semi-automatic though a data sharing media that allows two levels of optimization data to be automatically transferred through the data sharing media (such as direct memory access, the Microsoft Excel spreadsheet or database files [Lingo User's Guide, Chapters 8 to 11] (Figure 4.11). In some cases, the output results from the sub-network optimization requires further processing by third party software before they are transformed into the valid information for system-level value stream optimization input.

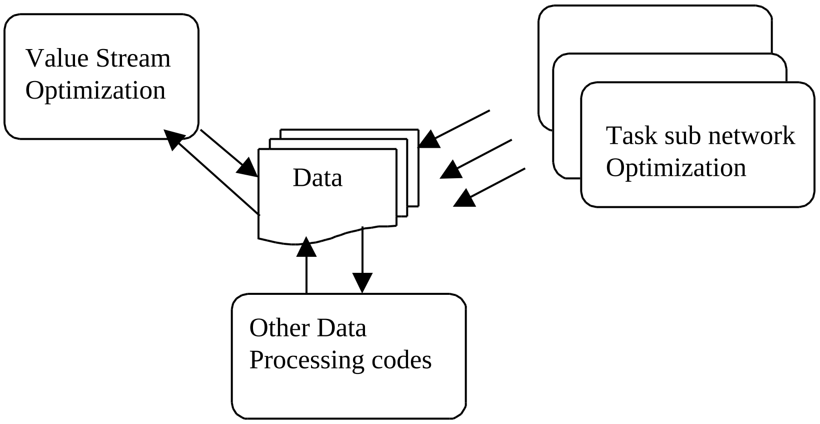
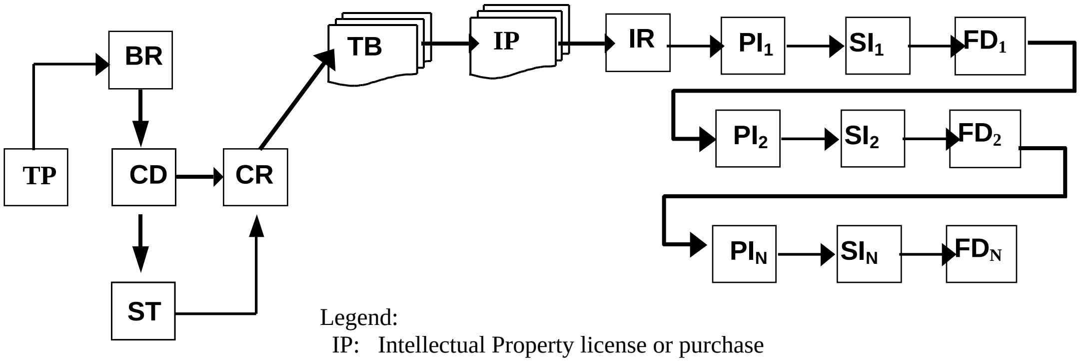


Figure 4.11: The bi-level Optimization system configuration

4.10 Baseline LINGO system level model and its associated variations:

Appendix A-1A lists the baseline LINGO model of the system-level value stream optimization [refer to Lingo User's Guide [2] for LINGO specific grammar], and appendix A-1B documents the sample optimization results. This baseline model can be further extended to include its expanded its capabilities to address common needs of technology portfolio managers. These capabilities include (i) expanding the number of technologies by either including hybrid type of technology as a new category of the technology, or (ii) extending the number of gateways to account for the annuity type of revenue stream which resulted from multiple platform applications (as shown by Figure 4.12 for three repeating platform implementations) or Intellectual Property (IP) licensing. The IP licensing can provide either a lump sum or annuity revenue stream at the gateway of Technology Bookshelf.



Legend:
IP: Intellectual Property license or purchase
PI$_n$: Product Implementation n
SI$_n$: Supplier Implementation n
FD$_n$: Fabrication & Delivery n

Figure 4.12: Value stream of multiple technology implementations

4.11 Summary of Technology value stream optimization:

The Network-in-Network framework proposed in this chapter unites multiple technology value streams into an integrated value stream shared by multiple commodities. The integrated value stream not only can be used as the planning platform for managing the multiple technology infusions, but also becomes the foundation for implementing the adaptive development process for local task network management. In the following chapter, we will explore the methodology for the planning and managing of the innovation network.

4.12 References:

1. Highsmith, James A. III, 2000, "Breaking the workflow Mindset" in Chapter 9 of "Adaptive Software Development, A Collaborative Approach to Managing Complex Systems," Dorset House Publishing Co., INC, ISBN 0-932633-40-4.
2. Lindo, 2001, "Optimization Modeling with Lingo," fourth edition, Lindo System Inc., 2001, ISBN 1-893355-00-4.
3. Lindo, 2001, "Lingo: User Guide", Lindo System Inc., 2001, http://www.lindo.com.
4. Steward, Donald V., 1995, chapter 6.1, pp 121-124, " System Analysis and Management, Structure, Strategy and Design ", http://gaia.ecs.csus.edu/~ssteward.

Chapter 5

Innovation network Optimization

5.1 Introduction:

The automobile technology task-network symbolizes a cluster of technology infusion actives in supporting system-level value stream gateway (Figure 5.1). Each task network deeply embeds the tacit knowledge of engineering know-how about how to transform technologies into end-use customer value and how to increase the necessary process proficiency in order to support such transformation. As a result, the management of such complex technology task networks demands an integrated strength, based on both engineering expertise and project management skills, in order to master a delicate balance among the quality of technology, resource utilization and swiftness of the technology development.

In the past, traditional project management tools, such as Critical-Path-Method (CPM) and Project-Evaluation-and-Review-Technique (PERT), have been successfully applied to managing many mature task networks whose processes are solidly defined. Nevertheless, when dealing with the fuzzy stage of the technology innovation, these tools show their inherent weakness in managing variations. Furthermore, these traditional project management methodologies routinely undermine the vital basis that captures either the tacit knowledge of innovation or the importance of shearing firm's core competence across multiple boundaries, in terms of both organization and product line boundaries.

The goal of this chapter is to focus on how to manage this fuzzy state of the innovation task network to better accommodate task variations, and how to promote resource sharing and knowledge transferring across multiple boundaries.

5.2 Task network:

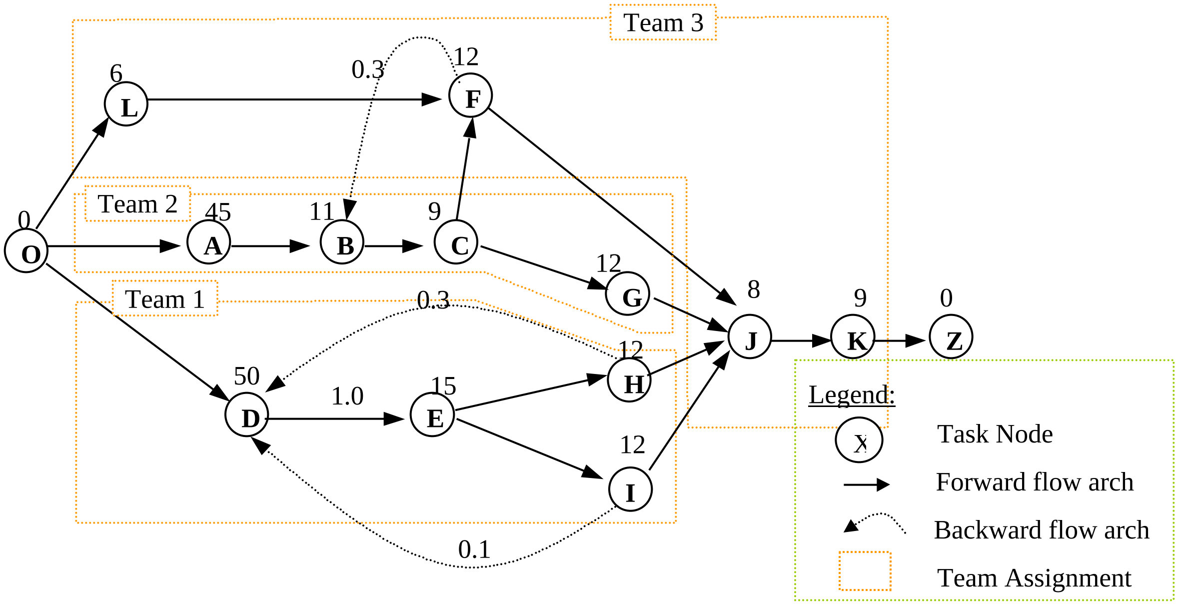
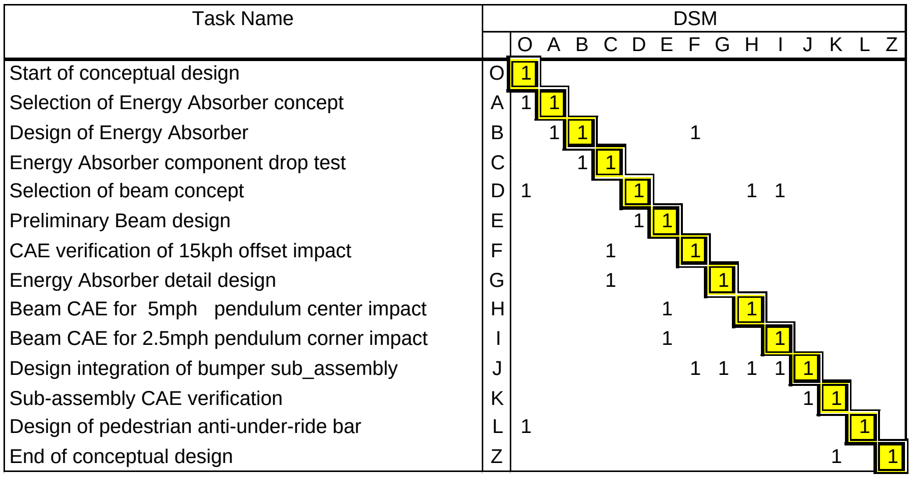


Figure 5.1: Task network of bumper technology development



Task Name		O	A	B	C	D	E	F	G	H	I	J	K	L	Z
Start of conceptual design	O	1													
Selection of Energy Absorber concept	A	1	1												
Design of Energy Absorber	B		1	1				1							
Energy Absorber component drop test	C			1	1										
Selection of beam concept	D	1				1				1	1				
Preliminary Beam design	E					1	1								
CAE verification of 15kph offset impact	F				1			1							
Energy Absorber detail design	G				1				1						
Beam CAE for 5mph pendulum center impact	H						1			1					
Beam CAE for 2.5mph pendulum corner impact	I						1				1				
Design integration of bumper sub_assembly	J							1	1	1	1	1			
Sub-assembly CAE verification	K											1	1		
Design of pedestrian anti-under-ride bar	L	1												1	
End of conceptual design	Z												1		1

DSM

Figure 5.2: DSM of bumper technology development

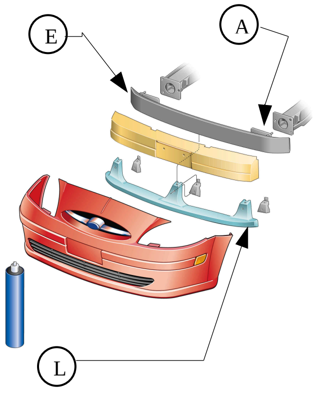


Figure 5.3: Bumper hardware

The task network is a graphical representation of the task flow by unveiling its inherited task dependencies. As an example, Figure 5.1 shows a task network of vehicle bumper technology (refers to Figure 5.2 for associated tasks and Figure 5.3 for the layout of bumper hardware). In this task-on-node layout, each task is denoted as a node having a designated task ID with its associated resource consumptions (e.g. particularly, task duration for cycle time and flow time optimization). The solid arrow arch between each pair of task nodes represents the forward processing flow of the network while the dotted curved arrow arch is corresponding to the backward reprocessing flow. The number superscripted above each arch indicates the dependency coefficient of the arch to account for the correlation strength between the nodes (use dependency coefficient of 1.0 for non specified arches).

5.3 Component-based task network management:

Many traditional manufacturing firms inherit the practice of component-based technology management, which originated from their manufacturing and assembling side of operations. The inherent strength of this component-based mentality is that it holds a strong link to detail component knowledge by promoting component superiority with clear accountability to keep all engineers focused. However, on the other hand, component-based management shows clear deficiency from the perspectives of system integration and process synchronization, and this deficiency commonly results in a lengthy development cycle with sub-optimal system level performance. The dashed boxes indicated in Figure 5.1 mirror the staffing allocation, based on this conventional hardware component division among three engineering teams after considering merely the function expertise of a specific hardware component. Here, Team 1 is responsible for the bumper beam design, Team 2 is in charge of the Energy Absorber (EA), and Team 3 is assigned with dual responsibilities of component based pedestrian protection design and system integration of the bumper assembly.

5.4 Task network dependencies:

Within technology task network, there are two major types of dependencies that exist among the tasks; and they are: (i) the apparent sequence of the assembly, and (ii) the implicit information flow. In general, the sequence of the assembly only exhibits the backward dependencies (i.e. the forward task only can be performed upon the finishing of all of its backward dependent tasks) while the information flow promotes both the backward and the forward dependencies (i.e. backward task relies on the feedback information from some of its forward tasks). The static dependencies of the task network can be visually displayed in the form of the Dependency Structure Matrix (DSM) [Steward, 1995]. This DSM can acts as an effective tool to facilitate management discussion or cross-team communication.

In the DSM matrix (Figure 5.2), the element of $\mathbf{X_{ij}}$ denotes the dependency of task **i** on task **j**. The lower left matrix triangular zone contains the backward dependencies of the task network, whereas the upper right triangular zone encloses forward dependencies. As the technology infusion makes progress, these forward information dependencies routinely lead to undesirable backward (upstream) task iterations by reprocessing the updated feedback information from its forward dependent tasks. The ripple effect of these task iterations is then spread throughout the entire task network and leads to harsh network schedule delay. Furthermore, during the dynamic operation, the schedule delay can be further amplified by the variation of task durations, which is consistently overturning the backward (none task repeating) dependencies into forward (task repeating) dependencies and results in further delay.

5.5 Restructure task network:

For an unprecedented technology network, it is necessary to go through a crucial structuring process to reorganize the chaos of the task sequence in order to trim down unnecessary task iterations. The partitioning and tearing of the DSM effectively serves this restructuring purpose well by minimizing the significances of the forward dependencies within the network [Steward, 1995, chapter 3]. On the other hand, for some mature technology processes, the natural evolution of the task network, over time, restructures their task sequence by making DSM logically organized. There are many literature references describing the DSM methodology [MIT DSM web site]. Therefore, to avoid unnecessary duplication, the author skips the reiteration of the DSM structuring process and uses a structured (re-sequenced) DSM (Figure 5.2a) as the starting point to construct the task network.

5.6 Expand the task network to account for the task iterations:

There are two methods to account for accumulated resource consumption of the task iteration. In the first method, we can lump the collective resource consumption onto the original task node without an expansion of the task network. Under this method, the collective resource consumption needs to be tediously accumulated over numerous processing loops (among backward and forward processing iteration) to account for all iterative resource consumptions. The second method, the more intuitive method (which is being used in this thesis), expands the original task network by adding repetitive node to account for each of the task iterations (**m** repeating nodes for **m** iterations) then rejoining repetitive nodes with original processing dependencies (Figure 5.4 is the expanded task network of Figure 5.1's bumper network with single iteration). For illustration purpose, the resource consumption (i.e. task duration) of the repetitive node is assumed to be a fraction of original node's resource consumption (which can be algebraically calculated through multiplying the dependency coefficient of the arch to the target node over the worst network path). For example, the duration of node D1 (Figure 5.3) is equals to 15, which is the longest path between the 0.3*50 and 0.1*50 while the duration of node E1 is set to be 4.5, which is the longest path between the (0.3*1.0)*15 and (0.1*1.0)*15.

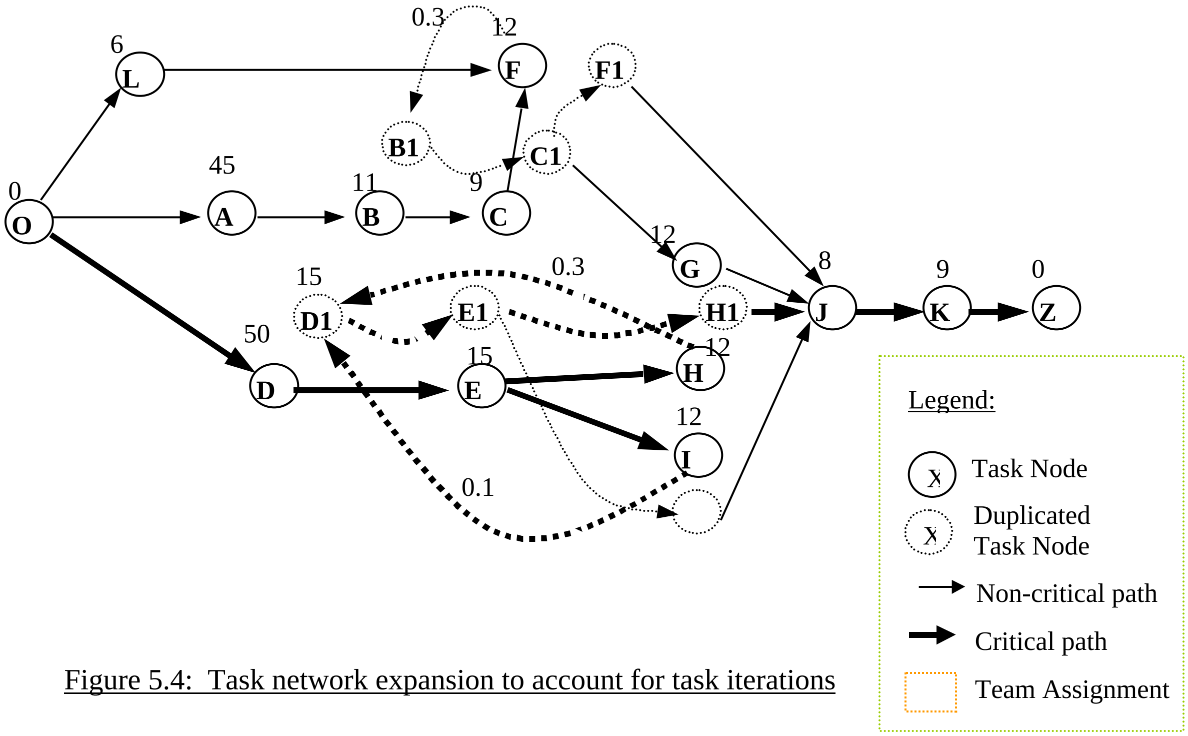


Figure 5.4: Task network expansion to account for task iterations

5.7 Identify unbounded critical path: CPM, PERT:

The identification of the non-resource bounded critical path (CP) by CPM and PERT can generally serve as a useful guide for an effective resource allocation which shortens the overall network flow time through maximum concurrent processing. The CPM methodology, developed in the late 1950s, identifies the critical path by forwardly accumulating the earliest starting time of task nodes over the network and then by reversibly tracking the latest starting time of the backward node from network's ending node. Concurrently, the PERT method has expanded the duration expression of the CPM with a stochastic Beta probability distribution [Nahmias, 1997] to account for duration variation.

In this thesis, the author modified an optimization model (Appendix A-2A) from the LINGO PERT template ["Lingo: User Guide", pages 52 to 55] to identify the critical path of the task network (Appendix A-2B). This model calculates the Early Start time (ES) of the node by accumulating maximum duration to that node over all paths plus the node's own duration **T**. Subsequently, the Late Start time (LS) then can be backward calculated as the minimum deprived time for node over all paths minus node's own duration **T**. Finally, Slack Time (SLACK) is the time difference between the LS and ES. The path connected by all zero slack time nodes then is identified as the critical path of the network.

In critical path calcualtion, this thesis continues the duration definition, based on the 3-levels stochastic distribution, which was defined in chapter 4 (the optimistic, most likely, pessimistic defined in section 4.5), in wishing to maintain proper definition consistency. The variation among this 3-levels stochastic duration often leads to a distinct critical path under different uncertainty scenarios. In the bumper network example (refer to SLACK information of Appendix A-2B), the network critical path for the most-likely (the 50% probability scenario) will be O-D-E-H-D1-E1-H1-J-K-Z (as the marked thick line in Figure 5.4). However, for the pessimistic scenario, the critical path immediately switches to the path of O-D-E-I-D1-E1-I1-J-K-Z. The constant switching of the critical path among different uncertainty scenarios make the critical path information less vital to support resource allocation decision-making.

5.8 Resource allocation to delivery short flow time:

The goal of the traditional resource allocation is to achieve the shortest flow time of the network by weighting against the possible flow time delay as the priority to guide resource allocation [refer Steward, 1995, chapter 6.13 for detail resource priority formulations]. These formulations use the ES and Late Finish (LS) of the CPM. For comparison reason, let us disregard the possibility of critical path switching under various uncertainty scenarios (section 5.7) and utilize the most-likely (50% probability) critical path as a guide for resource allocation.

Figure 5.5 shows the allocation of the resources under this flow-time minimization scheme with a continuation of the three engineering teams assumption used in the previous bumper innovation example (Figure 5.1 of section 5.3). The lower right corner of Figure 5.5 shows the load sequence of three teams, whose tasks are assigned to teams in achieving the shortest flow time of the network. As we can see from here, the assignment partition of the task team is mildly fragmented, when Team 3 is heavily broken off from its inherent information flow; this breakage may lead to severe communication delay. Furthermore, both the cycle times and the idle times among the team are unevenly spread which may lead to fairness or fatigue issues. On the positive side, owing to the in-time support of the team 3, the whole network flow time can be streamlined to match the non-resourced bounded CPM flow time (117.1 days).

The whole flow time scheme is devised to support the critical path with an assumption that critical path will not vary during the execution. Nevertheless, in real situations, the critical path frequently switches from one pathway to another; this swap leads to the supporting of the expired critical path. In addition, this scheme is inherently sensitive to the duration variations on its critical team assignment (the team holding the critical path such as the team 1 of Figure 5.5). Small variation turbulence on critical path may cause lengthy delay that cannot be bailed out by other team.

The other obvious deficiency of this flow-time team assignment scheme is that the cycle time of each team is widely stretched to cover nearly the entire span of the network (with multiple idle times between tasks like the team 3 after executing the task L has long idle time before the execution of task I). This idle time prevents the rotation of the design team and leads to possible resource contention among multiple task networks. Furthermore, the long retention of the design team further stalls tacit knowledge sharing across project boundaries that often requires a human agent to serve as transferring mechanism.

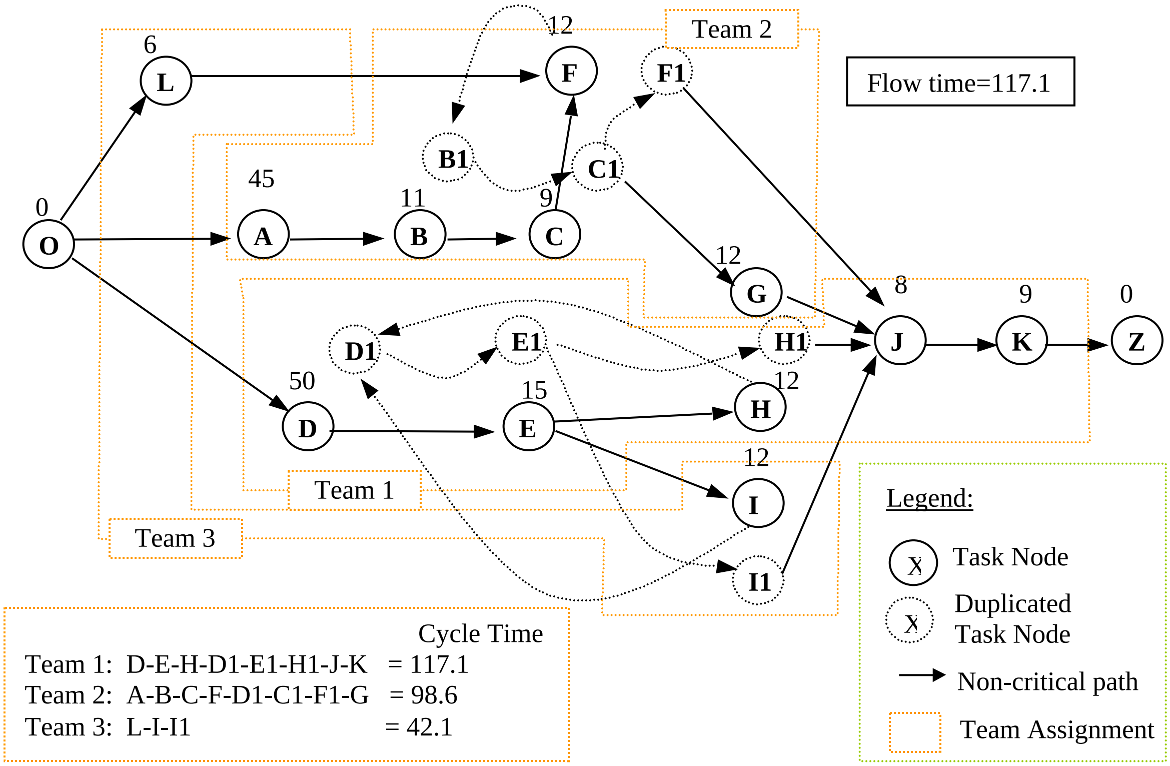


Figure 5.5: Resource allocation to minimize flow time

5.9 Resource allocation to optimize Cycle Time:

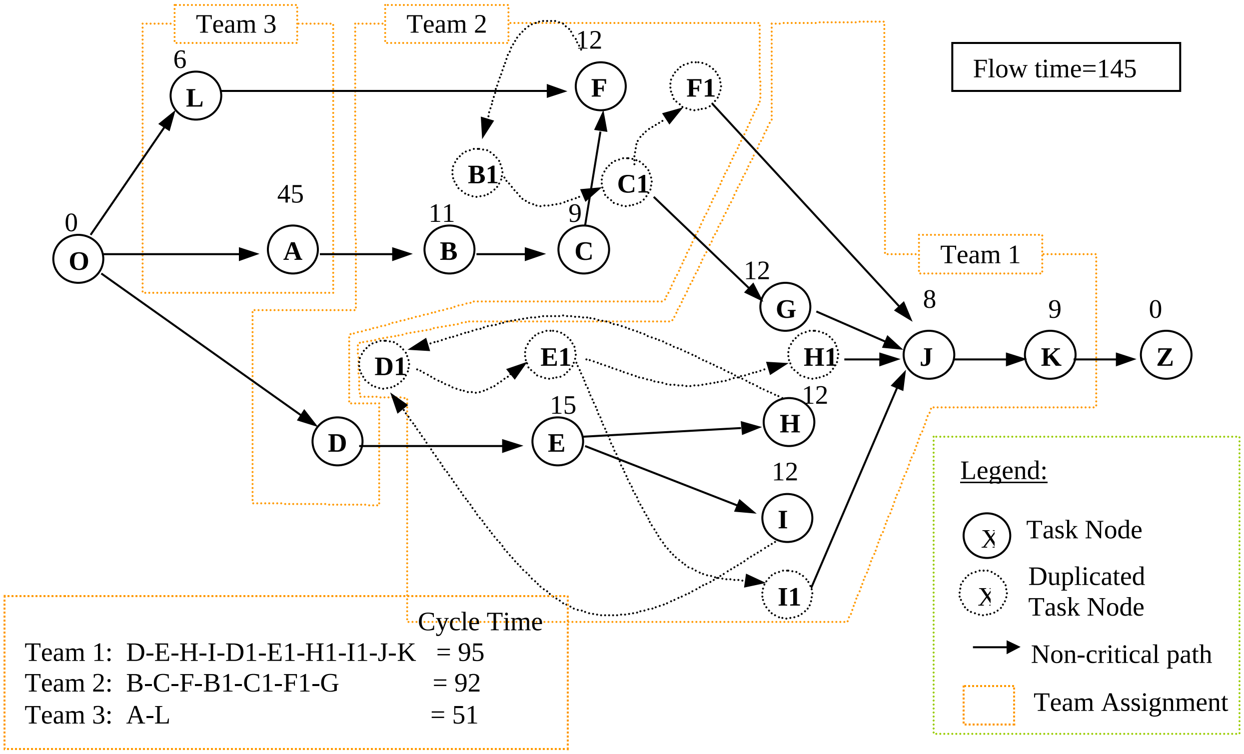
In this section, the author intends to transplant the cycle time optimization of the manufacturing workstation-balancing-loading scheme to the resource management of the technology network. The spirit of the algorithm is to preserve the dependency relationship among the tasks within the partition of the team (i.e. constraint ii below), at the meantime optimizes the cycle time of the task network (i.e. the Objective function below). This algorithm embeds the sprit of cellulous manufacturing system by forming working cell to promote team's ability of sharing each other's workload in order to absorb uncertainty variations. The optimization model (Appendix A-3) is derived from the Lingo Assembly Plant Balancing template ASLBAL ["Lingo: User Guide", pages 361 to 364, ASLBAL model]. The three partition policies of the scheme are listed as the constraints of the Linear Programming, and these three constraints are:

i. Each task must be assigned to one engineering team,
ii. Precedence relations must be observed amongst the tasks, and
iii. All engineering team's cycle time must be less than overall network cycle time.

The Objective function of the optimization will be minimizing overall network cycle time.

5.9.1: Resource allocation without task ownership constraints

Figure 5.6A reveals the results of engineering team partition for this scheme, which shows significant flow time (24%) increase and is deemed as not satisfactory. The cycle time among the three teams seems to be evenly distributed, just as the algorithm intends to achieve. The visual observation of the results shows that some duplicated tasks have been assigned to different teams, and this assignment requires additional task transferring time in real operation (Figure 5.6A). Therefore, an additional set of constraints has been introduced to remedy this weakness.



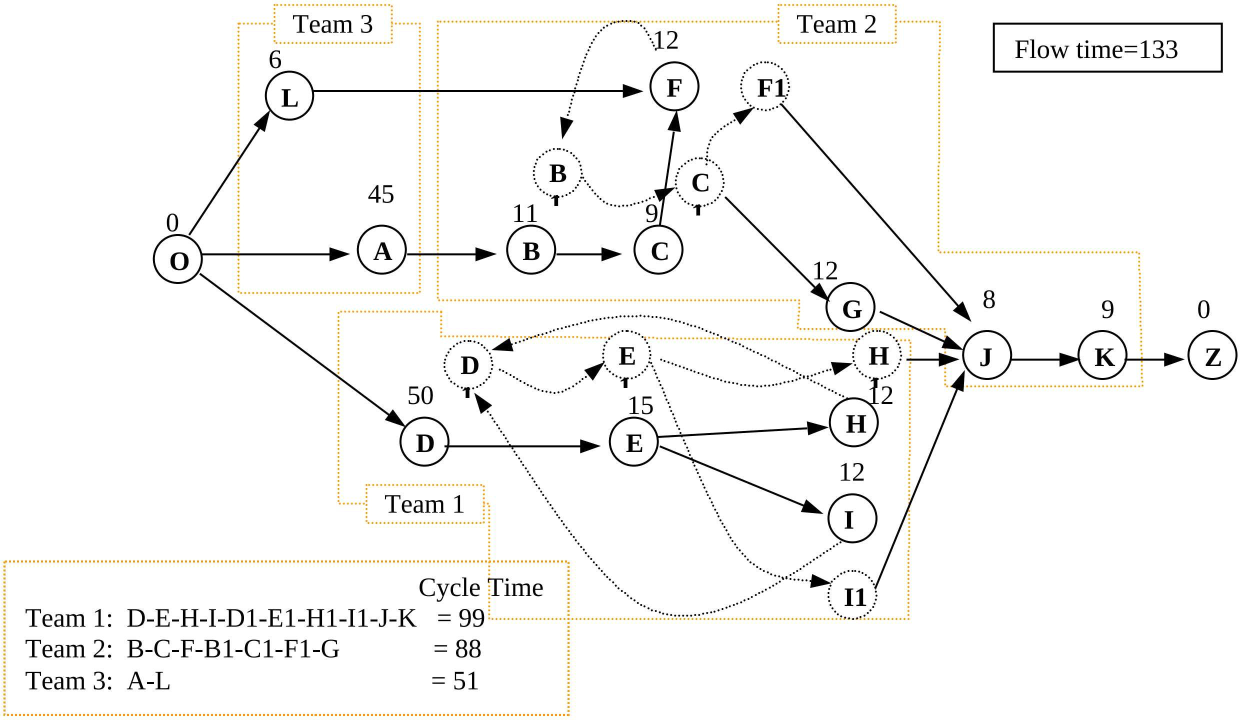
Cycle Time
Team 1: D-E-H-I-D1-E1-H1-I1-J-K = 95
Team 2: B-C-F-B1-C1-F1-G = 92
Team 3: A-L = 51

Figure 5.6A: Resource allocation to minimize cycle time (3 teams)

5.9.2: Resource allocation with task ownership constraints

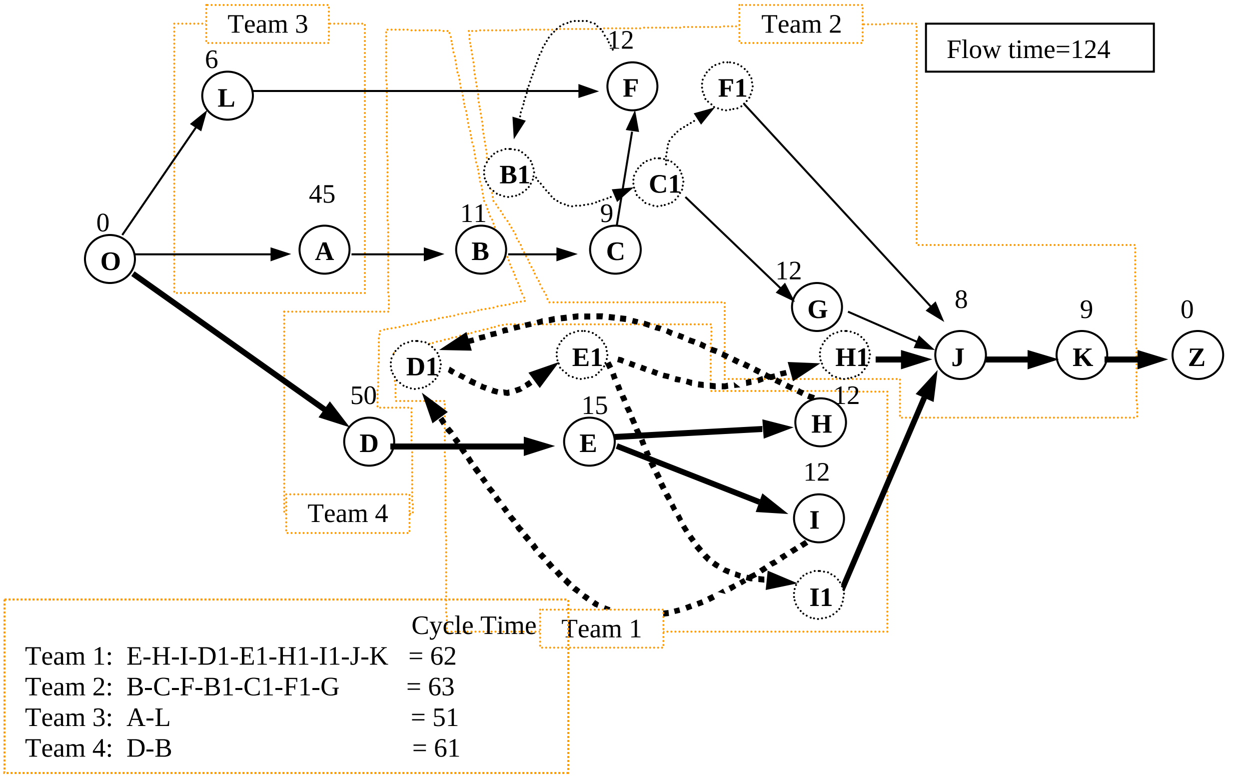
Figure 5.6B shows the partition results under these additional task ownership constraints. This partition slightly improves the network flow time with minor degradation on cycle time. By examining the exact partition of Figure 5.6B (13.5% increase over the flow time optimization result of Figure 5.5), it unveils the benefit of conserving "precedence relations amongst the tasks"; it contains most of the iteration within the same engineering team which, in actual operation, can enable the sharing of semi-finished information within the team itself.

Figure 5.7 show the partition of four, instead of three, engineering teams with similar task ownership constraint sets shown in Figure 5.6B. The results show that the flow time is just slightly over (6%) the optimal flow time of Figure 5.5 with evenly distributed cycle time among all four teams.



		Cycle Time
Team 1:	D-E-H-I-D1-E1-H1-I1-J-K	= 99
Team 2:	B-C-F-B1-C1-F1-G	= 88
Team 3:	A-L	= 51

Figure 5.6B: Resource allocation to minimize cycle time with task ownership (3 teams)



		Cycle Time
Team 1:	E-H-I-D1-E1-H1-I1-J-K	= 62
Team 2:	B-C-F-B1-C1-F1-G	= 63
Team 3:	A-L	= 51
Team 4:	D-B	= 61

Figure 5.7: Resource allocation to minimize cycle time with task ownership (4 teams)

5.10 Summary for Innovation network Optimization:

From the previous bumper design example, we can clearly see the strengths of the cycle-time resource allocation scheme, in terms of keeping information chain intact and paving the ways for sharing semi-finished information. The short cycle time of the engineering team also enables the swift rotation of the engineering resources to the other task network and allows the tacit knowledge of technology infusion to spread across the project boundaries. Therefore, the cycle-time task allocation has a clear advantage over the traditional flow-time task allocation scheme.

In short, when managing the innovation network, an automobile firm should place high focus on resource sharing and knowledge transferring across boundaries instead of merely shortening single project flow time. Then, they should place their second focus on how to capture multiple information flow within the same team so that the team has the ability to use semi-finished information within the team. Finally, the third focus should be placed on how to enhance the team's flexibility to self absorb task variations within the team itself by avoiding localizing all critical path tasks on a few teams.

5.11 References:

1. "Lingo: User Guide", Lindo System Inc., 2001, http://www.lindo.com.
2. MIT DSM web site, http://web.mit.edu/dsm.
3. Nahmias, Steven, 1997, Chapter 8: Project Scheduling of "Production and Operations Analysis", 3rd edition, ISBN 0-256-19598-0
4. Steward, Donald V., 1995, "System Analysis and Management: Structure, Strategy and Design ", Chapter 2 http://gaia.ecs.csus.edu/~steward.

Appendix A-1A: Technology Value Stream Optimization Model

A-1A is the Lindo Optimization model, which simulates a multiple commodities technology value stream of end-use customer value. The output of this model will be the optimal portfolio composition within multiple global and local constraints. In this model, three types of technology commodities share common value stream network but with their own distinct pathways.

```
MODEL:
! Multiple commodities Sequential process network;
! Model of capacity planning by maximize the NPV of technology infusion;
! TP: Technology Planning;
! BR: Basic Research;
! CD: Internal Technology Concept Development;
! ST: Supplier Technology Development;
! CR: Concept Ready certification;
! TB: Technology Bookshelf;
! IR: Implementation Ready certification;
! PI: Product Implementation;
! SI: Supplier Implementation;
! FD: Fabrication and Delivery;
 SETS:
    IM/1..100/;                             ! Variable used as the counter
for the months;
    PHASE/TP BR CD ST CR TB IR PI SI FD/;   ! 10 phases of the TI;
    TECH/BT AT DE/;                         ! 3 Technology type:
breakthrough, architecture, derivative;
    UNCER/WORST AVE  BEST/;                 ! 3-uncertainty level;
    T1(PHASE,TECH,UNCER): DURA;             ! Duration;
    T2(PHASE,TECH):  STAFF, MAT,REV, SCRAP; ! Staff, Mat, Revenue, Scrap
rate;
    T3(PHASE,TECH): ROUTE,GOOD;             ! Route;
    T4(TECH):DEMAND_MIN,DEMAND_MAX, JOB;    ! Minimum Tech. demand,
Revenue;
    T6(UNCER):  PROB, PV_B, PV_C, BC_ratio, BC_ratio_t; ! Probability of
uncertainty;
    T7(UNCER, TECH): NPV_CM, NPV_CL, NPV_R; ! NPV of material cost, MPV of
labor cost and NPV of Revenue;
    T8(UNCER,PHASE,TECH): ACCTIME;          ! Accumulative consumption
time;
 ENDSETS
 DATA:
 ! 12% annual Discount rate= 1% monthly discount rate;
   YRATE = ?; !0.12;
 ! B/C ratio target;
   BC_ratio_total=1.2;
   BC_ratio_t=0.5  1.2   1.4;
 ! Monthly Labor cost=120k/12;
   UNIT_LABOR = 10;
 ! Annual material budget Constraints  = 40M;
   MATBUDGET = ?; ! 40000;
 ! Internal Staff limit of 400 engineer;
```

```
   MAXSTAFF= 400;
 ! Technology minimum demand;
   DEMAND_MIN = 2  10   10;
! Technology minimum demand;
   DEMAND_MAX = 20 50 70;
 ! Uncertainty;
   PROB = 0.25 0.5 0.25;
 ! REVENUE;
     REV=  0.0   0.0   0.0   !TP;
           0.0   0.0   0.0   !BR;
           0.0   0.0   0.0   !CD;
           0.0   0.0   0.0   !ST;
           0.0   0.0   0.0   !CR;
           0.0   0.0   0.0   !TB;
           0.0   0.0   0.0   !IR;
           0.0   0.0   0.0   !PI;
           0.0   0.0   0.0   !SI;
         40000 10000  2000;  !FD;
! Duration Input;
   DURA =  9.0   7.0   4.0   8.0   6.0   3.0    4.0   3.0   2.0     !TP;
          60.0  30.0  14.0  50.0  25.0  12.0    4.0   3.0   2.0     !BR;
          40.0  20.0  10.0  30.0  20.0  10.0    6.0   5.0   3.0     !CD;
         -10.0  -8.0  -4.0 -12.0 -10.0  -6.0   -4.0  -4.0  -2.0     !ST;
          20.0  18.0  10.0  16.0  12.0   6.0   10.0   6.0   2.0     !CR;
           4.0   3.0   1.5   2.0   1.0   0.5    1.0   0.8   0.5     !TB;
          24.0  12.0   8.0  16.0  10.0   6.0   12.0   6.0   4.0     !IR;
          35.0  28.0  17.0  30.0  20.0  10.0   16.0  12.0   6.0     !PI;
          20.0  16.0  10.0  15.0  12.0   6.0   10.0   8.0   6.0     !SI;
          15.0   9.0   5.0  10.0   8.0   5.0   10.0   8.0   5.0 ;   !FD;
  ! Staffing headcount input;
    STAFF= 4.0   2.0   2.0   !TP;
          10.0   0.0   0.0   !BR;
           6.0   5.0   1.0   !CD;
           2.2   3.0   2.0   !ST;
           4.0   2.0   1.0   !CR;
           2.0   1.0   0.3   !TB;
           4.0   4.0   6.0   !IR;
           8.0   3.0   2.0   !PI;
           4.0   1.5   2.4   !SI;
           4.0   1.4   1.3;  !FD;
   ! material cost input;
    MAT=  26.0  13.0  13.0   !TP;
         100.0   5.0   5.0   !BR;
         100.0  50.0  10.0   !CD;
          20.0  20.0  80.0   !ST;
         120.0  30.0  10.0   !CR;
           2.0   1.0   1.0   !TB;
         24.0   60.0  20.0   !IR;
         200.0 100.0  50.0   !PI;
         100.0  50.0  20.0   !SI;
         100.0  40.0  20.0;  !FD;
   ! scrap input;
    SCRAP=0.02   0.01  0.01   !TP;
          0.20   0.00  0.00   !BR;
```

```
          0.16   0.05  0.02   !CD;
          0.16   0.05  0.02   !ST;
          0.00   0.00  0.00   !CR;
          0.24   0.10  0.15   !TB;
          0.30   0.15  0.15   !IR;
          0.60   0.20  0.10   !PI;
          0.00   0.00  0.00   !SI;
          0.00   0.00  0.00;  !FD;
   ! route input;
    ROUTE= 1.0   1.0   1.0  !TP;
           1.0   0.0   0.0  !BR;
           1.0   1.0   1.0  !CD;
           0.0   1.0   1.0  !ST;
           1.0   1.0   1.0  !CR;
           1.0   1.0   1.0  !TB;
           1.0   1.0   1.0  !IR;
           1.0   1.0   1.0  !PI;
           1.0   1.0   1.0  !SI;
           1.0   1.0   1.0; !FD;

! Export date to MS Excel file;
@OLE( 'C:\My Documents\project\TD.XLS', 'JOB_Allocation')=JOB;
@OLE( 'C:\My Documents\project\TD.XLS', 'BC_ratio_t')=BC_ratio_t;
@OLE( 'C:\My Documents\project\TD.XLS', 'BC_ratio')=BC_ratio;
@OLE( 'C:\My Documents\project\TD.XLS', 'PV_B')=PV_B;
@OLE( 'C:\My Documents\project\TD.XLS', 'PV_C')=PV_C;
@OLE( 'C:\My Documents\project\TD.XLS', 'GOOD')=GOOD;

ENDDATA
! The Route assignment variables are binary integers;
@FOR (T3: @BIN(ROUTE));
! Convert the annual discount to monthly discount rate;
( 1 + MRATE) ^ 12  =  1 + YRATE;
!
! Decision variable:  JOB;
! Object function: Maximize NPV;
  MAX = T_NPV;
  T_NPV=@SUM(UNCER(I):PROB(I)*(PV_B(I)-PV_C(I)));
  @FREE(T_NPV);
  @FOR(UNCER(I):
   @SUM( TECH(J): NPV_R(I,J)*JOB(J)) = PV_B(I);
   @SUM( TECH(J): (NPV_CM(I,J)+NPV_CL(I,J))*JOB(J)) = PV_C(I);
   @FREE(PV_B(I));
   @FREE(PV_C(I));
    );
! Financial constraints on B/C ratio;

  @SUM(UNCER(I):PROB(I)*PV_B(I))/@SUM(UNCER(I):PROB(I)*PV_C(I)) = BC_a;
[BCA]  BC_a >= BC_ratio_total;
  @FOR(UNCER(I):
   (PV_B(I) /PV_C(I)) = BC_ratio(I);
   BC_ratio(I) >= BC_ratio_t(I)
  );
```

```
! calculate the accumulated good job rate of each development phase;
  @FOR(TECH(K):
       @FOR(PHASE(J)| J #GT# 1 #AND# ROUTE(J,K) #EQ# 1:
        GOOD(J,K)=GOOD(J-1,K)*(1-SCRAP(J,K))
       )
  );
  @FOR(TECH(K):
       @FOR(PHASE(J)| J #GT# 1 #AND# ROUTE(J,K) #LT# 1:
        GOOD(J,K)=GOOD(J-1,K)
       )
  );
  @FOR(TECH(K):
       @FOR(PHASE(J)| J #LE# 1:
        GOOD(J,K)=(1-SCRAP(J,K))
       )
   );

! calculate the ACCTIME accumulated time for each period;
   @FOR(UNCER(I):
    @FOR(TECH(K):
       @FOR(PHASE(J)| J #GT# 1 :
        ACCTIME(I,J,K)=ACCTIME(I,J-1,K)+DURA(J,K,I)*ROUTE(J,K)
       )
     )
   );
   @FOR(UNCER(I):
    @FOR(TECH(K):
      @FOR(PHASE(J)| J #LE# 1:
       ACCTIME(I,J,K)=DURA(J,K,I)
      )
    )
   );

! calculate the labor cost stream NPV_CL for each period;
 @FOR(UNCER(I):
  @FOR(TECH(J):

@SUM(PHASE(K):GOOD(K,J)*@FPL(MRATE,ACCTIME(I,K,J))*STAFF(K,J)*DURA(K,J,I)*
UNIT_LABOR)= NPV_CL(I,J);
 ));
! calculate the material cost stream NPV_CM for each period;
 @FOR(UNCER(I):
  @FOR(TECH(J):
   @SUM(PHASE(K):GOOD(K,J)*MAT(K,J)*@FPL(MRATE,ACCTIME(I,K,J)))=
NPV_CM(I,J);
 ));

! calculate the revenue stream NPV_R for each period;
 @FOR(UNCER(I):
  @FOR(TECH(J):
   @SUM(PHASE(K):GOOD(K,J)*REV(K,J)*@FPL(MRATE,ACCTIME(I,K,J)))=
NPV_R(I,J);
 ));
```

```
! Max material budget constraints;
[Budget]  @SUM( PHASE(I):
   @SUM(TECH(J):MAT( I, J)* GOOD(I,J)* JOB(J))
  )<= MATBUDGET;
! Calculate the "mass balance" for good job;
! Min. successful job constraints;
@FOR(TECH(I):
    @FOR(PHASE(J)| J #GE#10:  JOB(I)*GOOD(J,I) >= DEMAND_MIN(I)
    )
  );
@FOR(TECH(I):
    JOB(I) <= DEMAND_MAX(I);
   ! Make the Y's binary;
    @GIN( JOB(I));
);

END
```

Appendix A-1B: Technology Value Stream Optimization Example

Assumptions:

The developed model assumes ten technology process steps stretching from technology planning until fabrication and delivery as detailed in Figures 4.3a, 4.3b and 4.3c. The model simulates three technology types such as breakthrough, architecture, and derivative technologies. For each technology types it assumes a distinct end-use customer value (40 million for breakthrough technologies, 10 million for architecture technologies and 2 million for derivative technologies).
There is 3-levels of duration uncertainty level range from Pessimistic (25%), Most Likely (50%) to Optimistic (25%).
The annual corporate discount rate is assumed 12% and expenditure for annual engineering labor cost is $120,000 per engineer per year.

Constraints:

The following constraints are embedded in the Lingo statements:
The total technology Material budget was set to be less than $40M (the budget is derived from a typical R&D spending budget of two percent of annual sales).
For every duration scenarios, all Benefit/Cost ratios shall exceed predetermined thresholds.
With this amount of employees the organizational capacity is under 20 for breakthrough, 50 for industry first, and 70 for derivative projects.
Remaining successful technologies need to exceed the demand of each technology categories (2 for breakthrough, 10 for architecture, and 10 for derivative projects.

Inputs:

The following inputs are embedded in the data segment of the Lingo model:
Duration for all steps – obtained from interviews with technology planning office. These durations are dependant upon the particular technology type.
Routing matrix to government the different pathway for different technology
Materials cost
Labor cost
Scrap rate
Headcount consumption

Optimization Results:

Annual allocation of projects	Breakthrough	Architecture	Derivative
	15	50	70

Financial Returns	Duration Uncertainty		
	Pessimistic	Most Likely	Optimistic
BC_ratio threshold	0.50	1.20	1.40
BC_ratio	0.71	1.27	2.55
Present Value of Benefit ($1000)	$148,989	$208,137	$293,585
Present Value of Cost ($1000)	$209,279	$163,870	$115,092
Net Present Value (NPV) ($1000)	-$60,290	$44,267	$178,492

Phase	% of Remaining Worthy Technology		
	Breakthrough	Architecture	Derivative
Technology Planning (TP)	98%	99%	99%
Basic Research (BR)	78%	99%	99%
Concept Development (CD)	66%	94%	97%
Supplier Technology (ST)	66%	89%	95%
Concept Ready (CR)	66%	89%	95%
Technology Bookshelf (TB)	50%	80%	81%
Implementation Ready (IR)	35%	68%	69%
Product Implementation (PI)	14%	55%	62%
Supplier Implementation (SI)	14%	55%	62%
Fabrication and Delivery (FD)	14%	55%	62%

Appendix A-2A: CPM LINGO MODEL

A-2A is the Lindo Optimization model, which to identify the critical path of the task network (Appendix A-2B). This model calculates the Early Start time (ES) of the node by accumulating maximum duration to that node over all paths plus node's own duration **T**. Subsequently, the Late Start time (LS) then can be backward calculated as the minimum deprived time for node over all paths minus node's own duration **T**. Finally, Slack Time (SLACK) is time difference between the LS and ES. The path connected by all zero slack time nodes then is identified as the critical path of the network. The precedent relationships and duration data are embedded in the data section of the model. Appendix A-2B shows the output CPM result table and a graphic identification of the critical path on the network.

```
MODEL:
 ! This model expands the PERT template provided by Lindo;
 SETS:
   ! The set of tasks to be assigned are A through K,
     and each task has a time to complete, Time;
   TASK/   O
           A  B  C  D  E  F  G  H  I  J  K  L
           B1 C1 D1 E1 F1 H1 I1
                                           Z/; ! Number of task;
   UNCER/WORST AVE BEST/: PROB;                    ! 3-uncertainty level;
   T1 (TASK, UNCER): DURATION, ES, LS, SLACK;
   ! Some predecessor, successor pairings must be
     observed(e.g. A must be done before B, B
     before C, etc.);
   PRED( TASK, TASK)/ O,A    O,D    O,L
                      A,B    B,C    C,F    C1,G   F1,J    G,J
                      L,B    D,B    D,E    E,H    E,I
                      H1,J   I1,J   J ,K
                      H,D1   I,D1   D1,E1  E1,H1  E1,I1
                      F,B1   B1,C1  C1,F1
                      K,Z/: EFFECT;
   ! There are three engineering teams;
   TEAM /1..3/;

   ! X is the attribute from the derived set TXS
     that represents the assignment. X(I,K) = 1
     if task I is assigned to engineering team K;
 ENDSETS

 DATA:
   !
   ! Uncertainty;
   PROB = 0.25 0.5  0.25;
   ! There is an estimated time required for each task:;
   !          W    A    B   ;
   DURATION = 0    0    0   !O;
             53   45   20   !A;
```

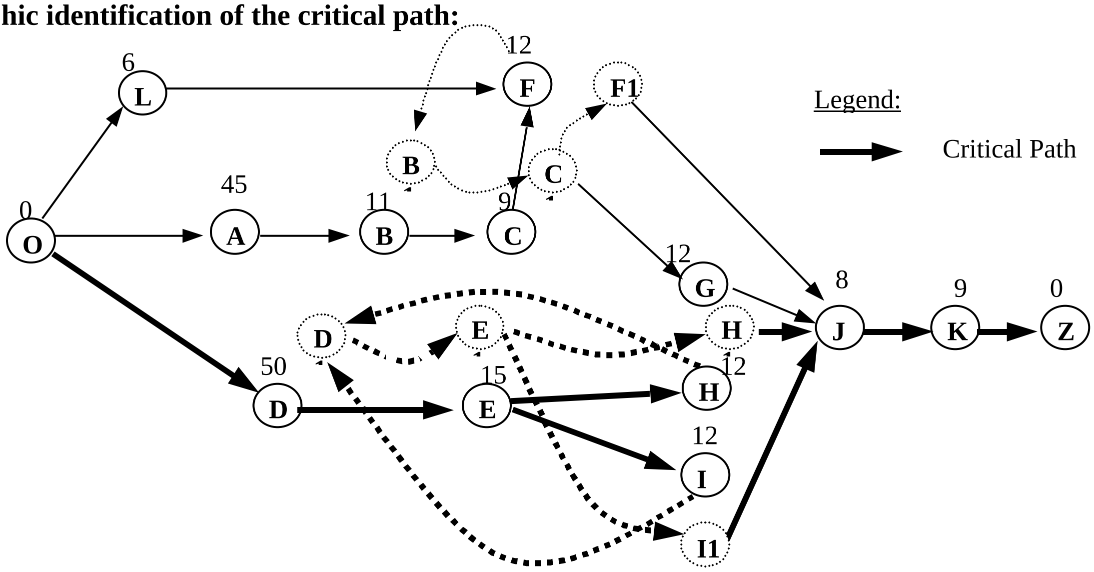
```
             13   11    9   !B;
             12    9    7   !C;
             70   50   42   !D;
             21   15   11   !E;
             15   12   11   !F;
             14   12   10   !G;
             16   12   10   !H;
             19   12    9   !I;
             12    8    6   !J;
             13    9    7   !K;
              9    6    5   !L;
             3.9   3.3  2.7 !B1;
             3.6   2.7  2.1 !C1;
            21    15   12.6 !D1;
             6.3   4.5  3.3 !E1;
             4.5   3.6  3.3 !F1;
             4.8   3.6  3.0 !H1;
             5.7   3.6  2.7 !I1;
              0    0    0;  !Z;

  ! Export results to MS Excel Spreadsheet;
   @OLE( 'C:\My Documents\project\fileb1.XLS', 'DURATION')=DURATION;
  @OLE( 'C:\My Documents\project\fileb1.XLS', 'ES')=ES;
  @OLE( 'C:\My Documents\project\fileb1.XLS', 'LS')=LS;
  @OLE( 'C:\My Documents\project\fileb1.XLS', 'SLACK')=SLACK;
 ENDDATA
 INIT:
  ES=0;
  LS=0;
 ENDINIT

  !---Modify from Lindo:PERT template --------------;
  ! Calculate the none resource bounded Flow time   ;
  !-----------------------------------------------;
  @FOR(UNCER(L):
   @FOR( TASK( J)| J #GT# 1:
    ES( J,L) = @MAX( PRED( I, J): ES( I,L) + DURATION( I,L))
  ));
  @FOR(UNCER(L):
   @FOR( TASK( I)| I #LT# LTASK:
    LS( I,L) = @MIN( PRED( I, J): LS( J,L) - DURATION( I,L));
  ));
  @FOR(UNCER(L):
   @FOR( TASK( I): SLACK( I,L) = LS( I,L) - ES( I,L)
  ));
  LTASK = @SIZE( TASK);
  @FOR(UNCER(L):
    ES( 1,L) = 0;
    LS( LTASK,L) = ES( LTASK,L);

  );

END
```

Appendix A-2B CPM results of Bumper task network example

Output CPM result table:

TASK	None resource constrained CPM											
	ES			LS			SLACK			LF		
	worst	avg.	best	worst	avg.	best	worst	avg.	best	worst	avg.	best
O	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	0.0	0.0	0.0
A	0.0	0.0	0.0	28.5	5.1	22.0	28.5	5.1	22.0	81.5	50.1	42.0
B	70.0	50.0	42.0	81.5	50.1	42.0	11.5	0.1	**0.0**	94.5	61.1	51.0
C	83.0	61.0	51.0	94.5	61.1	51.0	11.5	0.1	**0.0**	106.5	70.1	58.0
D	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**	**0.0**	70.0	50.0	42.0
E	70.0	50.0	42.0	70.0	50.0	43.9	**0.0**	**0.0**	1.9	91.0	65.0	54.9
F	95.0	70.0	58.0	106.5	70.1	58.0	11.5	0.1	**0.0**	121.5	82.1	69.0
G	117.5	88.0	73.8	129.0	88.1	73.8	11.5	0.1	**0.0**	143.0	100.1	83.8
H	91.0	65.0	53.0	94.0	65.0	54.9	3.0	**0.0**	1.9	110.0	77.0	64.9
I	91.0	65.0	53.0	91.0	65.0	55.9	**0.0**	0.0	2.9	110.0	77.0	64.9
J	143.0	100.1	83.8	143.0	100.1	83.8	**0.0**	**0.0**	**0.0**	155.0	108.1	89.8
K	155.0	108.1	89.8	155.0	108.1	89.8	**0.0**	**0.0**	**0.0**	168.0	117.1	96.8
L	0.0	0.0	0.0	72.5	44.1	37.0	72.5	44.1	37.0	81.5	50.1	42.0
B1	110.0	82.0	69.0	121.5	82.1	69.0	11.5	0.1	**0.0**	125.4	85.4	71.7
C1	113.9	85.3	71.7	125.4	85.4	71.7	11.5	0.1	**0.0**	129.0	88.1	73.8
D1	110.0	77.0	63.0	110.0	77.0	64.9	**0.0**	**0.0**	1.9	131.0	92.0	77.5
E1	131.0	92.0	75.6	131.0	92.0	77.5	**0.0**	**0.0**	1.9	137.3	96.5	80.8
F1	117.5	88.0	73.8	138.5	96.5	80.5	21.0	8.5	6.7	143.0	100.1	83.8
H1	137.3	96.5	78.9	138.2	96.5	80.8	0.9	**0.0**	1.9	143.0	100.1	83.8
I1	137.3	96.5	78.9	137.3	96.5	81.1	**0.0**	0.0	2.2	143.0	100.1	83.8
Z	168.0	117.1	96.8	168.0	117.1	96.8	**0.0**	**0.0**	**0.0**	168.0	117.1	96.8

Graphic identification of the critical path:



Appendix A-3: Cycle Time Optimization LINGO MODEL

The optimization model (Appendix A-3) is derived from the Lingo Assembly Plant Balancing template ASLBAL ["Lingo: User Guide", pages 361 to 364, ASLBAL model]. The three partition policies of the scheme are listed below (as the constraints of the Linear Programming).

The Three Constraints are:

iv. Each task must be assigned to one engineering team,
v. Precedence relations must be observed amongst the tasks, and
vi. All engineering team's cycle time must be less than overall network cycle time.

The Objective function of the optimization will be minimizing overall network cycle time of the engineering teams. Inside the model, there are additional job ownership constraints to enforce the repetitive job assigning to original engineering team.

Model:

```
MODEL:
 ! This model expands to include the backflow of the job for reprocessing;
 ! Add the assumption of the repeating task shall be done by the same
team;
 ! This model modified the ASLBAL template provided by Lindo
 ! Process line balancing model;
   ! This model involves assigning tasks to engineering team
     in an technology development process so bottlenecks can be avoided.
     Ideally, each station would be assigned
     equal amount of work.;
 SETS:
   ! The set of tasks to be assigned are A through K,
     and each task has a time to complete, Time;
   TASK/   O
           A  B  C  D  E  F  G  H  I  J  K  L
           B1 C1 D1 E1 F1 H1 I1
                                                Z/;     ! number of the
task;
   UNCER/WORST AVE  BEST/: PROB; ! 3 uncertainty level;
   T1(TASK, UNCER): DURATION;
   ! Some predecessor, successor pairings must be
     observed(e.g. A must be done before B, B
     before C, etc.);
   PRED( TASK, TASK)/ O,A    O,D    O,L
                      A,B    B,C    C,F    C1,G   F1,J    G,J
                      L,B    D,B    D,E    E,H    E,I
                      H1,J   I1,J   J ,K
                      H,D1   I,D1   D1,E1  E1,H1  E1,I1
                      F,B1   B1,C1  C1,F1
                      K,Z/: EFFECT;
   ! There are 3 engineering teams;
   TEAM /1..3/;
   INDEX/1/;
   T2(INDEX): CYCLE_TIME;
   T3(TEAM): CYCLE_TIME1;
```

```
   TXS( TASK, TEAM): X;
   ! X is the attribute from the derived set TXS
     that represents the assignment. X(I,K) = 1
     if task I is assigned to engineering team K;
 ENDSETS

 DATA:
   !
   ! Uncertainty;
   PROB = 0.25 0.5  0.25;
   !EFFECT= 1.0   1.0   1.0
            1.0   1.0   1.0   1.0   1.0  1.0
            1.0   1.0   1.0   1.0   1.0
            1.0   1.0   1.0
            0.8   0.7   1.0   1.0   1.0
            0.9   1.0   1.0   1.0
            1.0;
   ! There is an estimated time required for each task:;
   !          W    A    B   ;
      DURATION = 0    0    0   !O;
             53   45   20   !A;
             13   11    9   !B;
             12    9    7   !C;
             70   50   42   !D;
             21   15   11   !E;
             15   12   11   !F;
             14   12   10   !G;
             16   12   10   !H;
             19   12    9   !I;
             12    8    6   !J;
             13    9    7   !K;
              9    6    5   !L;
             3.9   3.3  2.7 !B1;
             3.6   2.7  2.1 !C1;
            21    15   12.6 !D1;
             6.3   4.5  3.3 !E1;
             4.5   3.6  3.3 !F1;
             4.8   3.6  3.0 !H1;
             5.7   3.6  2.7 !I1;
              0    0    0;  !Z;

  ! Export results to MS Excel Spreadsheet;
   @OLE( 'C:\My Documents\SDM\Thesis\project\taskb1.XLS', 'ASS2')=X;
   @OLE( 'C:\My Documents\SDM\Thesis\project\taskb1.XLS',
'Cycle_time')=CYCLE_TIME;
   @OLE( 'C:\My Documents\SDM\Thesis\project\taskb1.XLS',
'DURATION')=DURATION;
 ENDDATA
 INIT:
    X=0;
 ENDINIT
  !----- Modify from Lindo: ASLBAL template -------;
  ! Optimize the Cycle time by distributing tasks  ;
  ! to available engineering team.                  ;
```

```
  ! *Warning* may be slow for more than 15 tasks   ;
  !------------------------------------------------;
  ! For each task, there must be one assigned team;
  @FOR( TASK( I): @SUM( TEAM( K): X( I, K)) = 1);

  ! Precedence constraints;
  ! For each precedence pair, the predecessor task
    I cannot be assigned to a later engineering team than its
    successor task J;
  @FOR( PRED( I, J):
   @SUM( TEAM( K):
    K * X( J, K) - K * X( I, K)) >= 0);

  ! For each engineering team, the total mean time for the
    assigned tasks must be less than the maximum
    cycle time, CYCTIME;
   @FOR( TEAM( K):
     @SUM(UNCER(L):
      @SUM( TXS( I, K): PROB(L)*DURATION( I,L)  * X( I, K)
     )) = CYCLE_TIME1(K);
     CYCLE_TIME1(K)<=CYCTIME;
    );

    CYCLE_TIME(1)= CYCTIME;
  ! TALENT CONSTRAINT;
   X(5,2)=1;      ! TASK D is assigned to team 2;
  ! Task ownership constraints:
  @FOR(TEAM(K):
     X(3 ,K)=X(14,K);   ! B, B1;
     X(4 ,K)=X(15,K);   ! C, C1;
     X(5 ,K)=X(16,K);   ! D, D1;
     X(6 ,K)=X(17,K);   ! E, E1;
     X(7 ,K)=X(18,K);   ! F, F1;
     X(9 ,K)=X(19,K);   ! H, H1;
     X(10,K)=X(20,K);   ! I, I1;
  );
  ! Minimize the maximum cycle time;
   MIN = CYCTIME;

  ! The X(I,J) assignment variables are
    binary integers;
  @FOR( TXS: @BIN( X));

END
```

<u>Output Results</u>: The task assignment table

TASK	Team			
	1	2	3	4
O	1	0	0	0
A	1	0	0	0
B	0	0	1	0
C	0	0	1	0
D	0	1	0	0
E	0	1	0	0
F	0	0	1	0
G	0	0	1	0
H	0	1	0	0
I	0	1	0	0
J	0	0	1	0
K	0	0	1	0
L	1	0	0	0
B1	0	0	1	0
C1	0	0	1	0
D1	0	1	0	0
E1	0	1	0	0
F1	0	0	1	0
H1	0	1	0	0
I1	0	1	0	0
Z	0	0	1	0
Cycle time=	122			